Deliverable 6.3
Economic, Environmental and Disposability Impacts of Novel Treatment Technologies for Low-Level and Intermediate-Level Solid Organic Wastes

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Abstract

A high-level assessment of the economic, environmental and disposability impacts of the novel treatment technologies for low- and intermediate-level solid organic wastes is presented. The assessment focuses on the following treatment combinations:

- Incineration of mixed organic waste and Ion Exchange Resins (IERs) and compaction and cementation of the ashes
- Incineration of mixed organic waste and IERs and Hot Isostatic Pressing (HIP) of the ashes
- Incineration of mixed organic waste and IERs and encapsulation of the ashes in geopolymer
- Molten Salt Oxidation (MSO) of IERs and encapsulation of the spent salts in geopolymer.

The novel treatments are assessed across a set of assessment areas in comparison to a baseline consisting of compaction and cementation of mixed waste and direct cementation of IERs. Overall, it is found that the novel treatment technologies typically provide benefits in terms of material environmental impact, package disposability and the disposal and storage costs for the product drums. This is offset however by the safety and cost impacts of the additional facilities, the process energy requirements and the uncertainties associated with a novel technology.

Keywords

Value Assessment, Disposability Assessment, RSOW, HIP, MSO, Geopolymer

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Table of Contents

List of Acronyms

AFIC	Active Furnace Isolation Chamber
BFS	Blast Furnace Slag
DGR	Deep Geological Repository
EC	European Commission
GSG	General Safety Guide
HIP	Hot Isostatic Press
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IER	Ion Exchange Resins
ILW	Intermediate Level Waste
LCA	Lifecycle Assessment
LCC	Lifecycle Costing
LLW	Low Level Waste
MSO	Molten Salt Oxidation
PPE	Personal Protective Equipment
RAG	Red Amber Green
RLOW	Radioactive Liquid Organic Waste
RSOW	Radioactive Solid Organic Waste
TRL	Technology Readiness Level
VLLW	Very Low Level Waste

1 Introduction

The PREDIS project (PRE-DISposal management of radioactive waste) was a research and innovation action granted by the European Commission's (EC) Euratom Research Programme targeting the development and improvement of activities for the characterisation, processing, storage and acceptance of Low- and Intermediate-level (LLW/ILW) radioactive waste streams. The focus was on treatment and conditioning of metallic materials, Radioactive Liquid Organic Wastes (RLOW) and Radioactive Solid Organic Wastes (RSOW) arising from nuclear plant operations, decommissioning and other industrial processes.

Work Package six (WP6) of the PREDIS project was concerned with the treatment and conditioning of RSOW. In WP6, options for the treatment and conditioning of thermally treated RSOW were developed and investigated. This document is one of the primary outcomes of WP6 Task 6.7 which is focused on the economic and environmental impact of the implementation of the investigated technologies.

1.1 Aims and Objectives

This deliverable (D6.3) is dedicated to the preliminary evaluation of the economic, environmental and disposability impacts of the novel treatment technologies considered in WP6. This analysis, also termed value assessment, brought together research results in terms of waste loading, conditioning matrix performance, process cost, and product disposability to form a picture of the overall performance of the treatment technology. These results were compared with current waste management practices to provide an evaluation of how the novel treatment technologies perform against current practices.

The overarching objective of this deliverable is to provide technology developers and end-users with an objective assessment of the performance of novel waste management routes across the full waste management lifecycle (from treatment through to disposal) to support decision making and industrial application of these technologies.

1.2 Scope, Interfaces and Exclusions

RSOWs considered in PREDIS WP6 include mixed solid organics and spent Ion Exchange Resins (IERs). A detailed description of available thermal treatment processes for this type of waste is provided in Deliverable 6.1 [1].

The value assessment work undertaken in Task 6.7 draws on the Lifecycle Assessment (LCA) and Lifecycle Costing (LCC) analyses undertaken under WP2. At the time of writing, the full results of this analysis are not available; instead, the results of a preliminary analysis which quantifies the relative magnitude of the environmental impact of different treatment scenarios is used to inform the assessment of the environmental impact. The LCA analysis results will be available in PREDS deliverable D2.9.

This work also relies heavily on results from research activities undertaken during PREDIS WP6, and on the methodology documented in the THERAMIN project [2].

Dedicated value assessment activities, including a workshop with research partners and end-users, were undertaken in preparation of this deliverable, and were summarised in [3]. This report supersedes Milestone MS47.

2 Methodology and Approach

2.1 Value Assessment Principles and Methodology

Value Assessment is a form of multi-criteria cost benefit analysis that provides a methodology for assessing and comparing the technical, economic, safety and environmental performance of alternative waste management options. It was used to perform a strategic analysis of the performance of alternative waste management options studied under WP6.

The value assessment process is outlined in Figure 1 [2]. For WP6, the process started with the identification of waste type and treatment/ conditioning technology combinations (called variant scenarios) for comparison with the typical current waste management approach used for these waste types, called the baseline scenario. These scenarios and the rationale behind their selection are presented in Section 2.2.

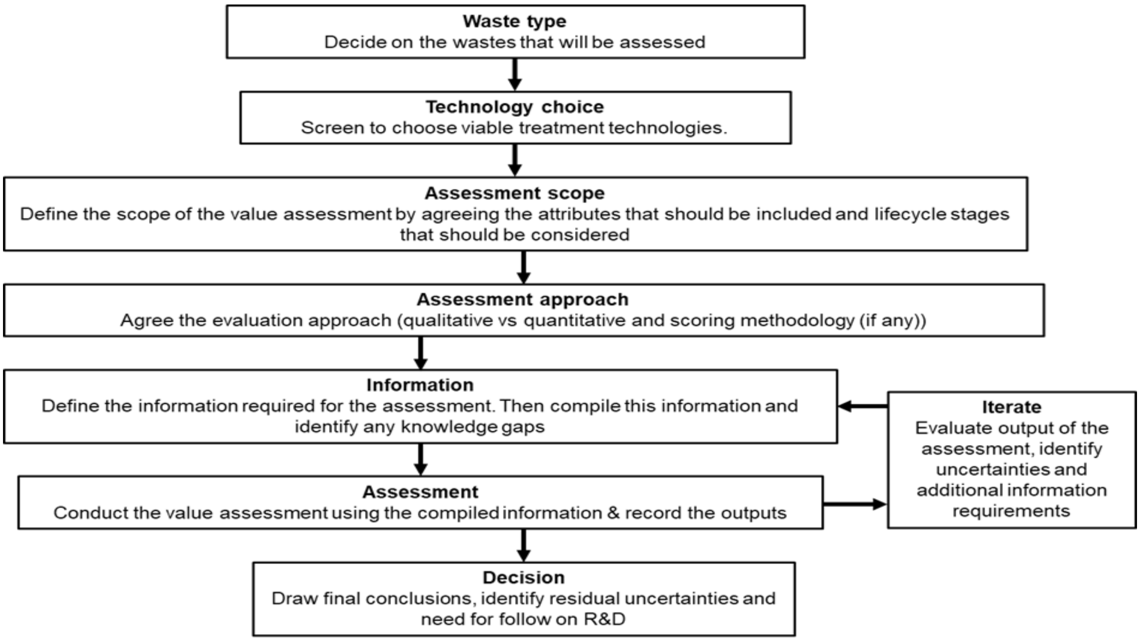
Research work in WP6 targeted the treatment and conditioning of RSOW. Having identified representative scenarios, it was necessary to develop a list of attributes covering potential areas that may differentiate novel RSOW treatment and conditioning technologies from the current waste management approaches. To make the analysis more targeted and systematic, it was also necessary to identify the relevant stages in the waste management lifecycle. These are discussed in Section 0. The attributes considered for this exercise and justifications for significant exclusions are presented in Appendix 2.

The assessment adopted a high-level and qualitative approach and was undertaken on a comparative basis to allow comparison of each technology against its respective baseline, rather than being compared against each other. The generic nature of the assessment is a necessary feature, given the wide variation in national contexts, potential disposal routes and waste management strategies that might be considered.

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

Wasteform disposability was assessed separately from the other value assessment areas, consisting of an internal assessment of the disposability risks for each of the wasteforms, followed by targeted engagement with WP6 partners to develop agreement on the assessment results. The approach to disposability assessment is presented in Section 2.3.

Figure 1: Process flow diagram for the value assessment process



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

2.2.1 Scenario Identification and Selection

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

- Case Study Inputs to LCA/LCC from Milestone 44 [4].
- Thermal processes used for the thermal treatment of RSOW described in Deliverable D6.1 [1].
- Experimental results from research on RSOW ashes conditioning with geopolymer, presented in Deliverable D6.2 [5].
- Experimental results from research on geopolymer encapsulation of radioactive liquid organic waste undertaken under WP5 [6].
- LCA/LCC scenarios discussed with the University of Manchester (UoM) during a workshop held on 27/09/2023 [7].
- Feedback from PREDIS Partners and End-Users gathered during the 2023 annual meeting held in December 2023 in Madrid.

Waste type/technology combinations that have been modelled as part of the LCA/LCC were previously selected in consultation with individual WP partners and have been included in the value assessment. A review of the decision to focus on treatment of ashes arising from the IRIS process was undertaken and concluded that this focus was still relevant and adequate for this task. To prevent any technology or national bias, incineration at a plant specifically using the IRIS process is not prescribed in the scenarios; instead, any incinerator yielding ashes with similar properties could be envisaged. For the value assessment, however, data was gathered for the IRIS process due to the availability of relevant information from the CEA as a PREDIS partner, and previous consensus on its use as a representative example.

Raw waste is assumed to comprise a mixture of low- or intermediate-level mixed waste and IERs, in line with results reported in D6.1 [1]. IERs and mixed waste are assumed to be present in their untreated form with a mass ratio of 1:2, in line with data provided by the CEA [8].

Three scenarios for the disposal of IRIS ashes were selected as a result of this analysis:

- Hot Isostatic Pressing (HIP) of ashes followed by cement encapsulation of the HIP cans in a standard 200 L drum container.
- Ash compaction followed by cement encapsulation of the resulting pellets in a standard 200 L drum container.
- Direct ash conditioning using tuff-based geopolymers in a standard 200 L drum container.

In addition, to better cover the range of work undertaken in PREDIS WP6, an alternative thermal treatment technology, Molten Salt Oxidation (MSO) was also considered. MSO consists of the oxidation of organic waste in a bed of molten carbonate salt (in PREDIS, the salt bed consisted of pure Na_2CO_3). The primary waste product from this process is the spent salts, consisting of a mixture of carbonate salts and the oxidised residue of the organics. PREDIS considered the immobilisation of spent MSO salts by geopolymer encapsulation, and this formed the fourth variant scenario considered.

Each scenario was allocated a number, based on the following convention:

- The first number refers to the Work Package (WP6).
- The second number refers to waste type.
- The third number refers to the treatment and conditioning process.
- Scenarios with the label "B" represent the baseline for waste type "x". For example, scenario 6.1.B is the baseline scenario for all the scenarios based on the first waste type, here mixed organics and spent IERs.

A single baseline scenario was selected to compare the first three selected variant scenarios against, thus enabling comparison against a consistent baseline. The main factors used in determining the baseline were:

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

The baseline used for LCA and LCC modelling considers that there is no thermal treatment of the raw waste and considers the compaction of a waste surrogate [9]. The baseline scenario for value assessment is consistent in so far as no thermal treatment process is assumed to occur. However, to reflect current waste management practices, and in particular differences between the conditioning processes for IERs and mixed organics, the baseline for value assessment considers that the two waste streams comprising the feed for the IRIS process are conditioned separately:

- mixed organics are assumed to be loaded into sacrificial drums and supercompacted into pucks which are then loaded into a 200 L drum and grout encapsulated.
- IERs are encapsulated in cement in a 200 L drum.

For comparison with the variant scenarios that consider treatment of IRIS ashes, a hypothetical waste package is considered which represents a mixture of the packages produced by these two conditioning processes. The defining attributes of the package are an interpolation of the properties of each package weighted by the assumed mass fraction of the respective contributing wastes. The main characteristics of the hypothetical waste package used for the baseline scenario were derived using data from COVRA [10] [11], the Dutch waste management organisation, and are summarised in Table 3.

The baseline for comparison with the MSO scenario, baseline 6.2.B, considers direct cementation of IERs in a standard 200 L drum container. The detailed characteristics of this baseline are the same as those of the IER package that fed into baseline 6.1.B and are summarised in Table 1.

The main characteristics of the variant and baseline scenarios are summarised in Table 1 and Table 3. Process inputs/outputs are summarised in Table 2.

Table 1: Waste type / treatment and conditioning method combinations selected as scenarios for value assessment

Waste Type	Scenario ID	Treatment step	Conditioning step 1	Conditioning step 2	Scenario origin and source organisation	Waste unit/container in LCA/LCC data
Mixed organics and IERs[1]	6.1.1	Incineration ⇨ Representative facility: IRIS (CEA)	Hot Isostatic Pressing (HIP) (University of Sheffield, NNL)	Cement encapsulation	LCA/LCC and MS44 NNL	8 L HIP can
	6.1.2		Compaction (CEA)	Cement encapsulation	LCA/LCC and MS44 CEA	200 L drum
	6.1.3		/	Tuff geopolymer (POLIMI)	LCA/LCC and MS44 POLIMI	200 L drum
	6.1.B	Supercompaction of mixed organics. None for IERs	/	Cement encapsulation	Construct. GSL[2]	200 L drum
IERs	6.2.1	Molten Salt Oxidation (MSO)	/	Geopolymer encapsulation	LCA/LCC and MS44 CVŘež	Pending data input from CVŘež
	6.2.B	None	/	Cement encapsulation	Construct. GSL[2]	200 L drum

Table 2: Summary of process inputs / outputs

Stage	Owner	Process input	Process	Process output	Next step
Treatment / incineration (scenarios 6.1.1 to 6.1.3)	CEA	Mixed organics and IERs	Incineration (representative technology: IRIS process)	IRIS ashes Secondary waste	Conditioning (rows below)
Conditioning (6.1.1)	University of Sheffield / NNL	IRIS ashes	HIP and cementation	Consolidated HIP cans cemented in a 200 L drum	Disposal (out of scope)
Conditioning (6.1.2)	CEA	IRIS ashes	Compaction and cementation	Compacted ash pellets cemented in a 200 L drum	
Conditioning (6.1.3)	POLIMI	IRIS ashes	Tuff based geopolymer	Waste conditioned in a geopolymer matrix in a 200 L drum.	

[1] IERs/mixed organics are assumed to be present with a mass ration of 1/3, in line with data provided by the CEA [14].
[2] See Section 2.2.1 for a detailed description of the baseline and its origin.

Table 3: Summary of baseline scenario waste package characteristics for baseline 6.1.B

Characteristic	Value	Justification
Waste package volume	200 L	In line with other scenarios and assumptions agreed upon in the VA methodology.
IER mass fraction	1/3	[8].
Mixed organics mass fraction	2/3	[8].
Volume of mixed organics per typical mixed organics package (uncompacted)	450 L	5x90 L compactable drums per 200 L disposal drums [11, p. 28].
Average IER volume per typical IER waste package	28 L	Derived from the mass of 45.4 kg quoted in table 5-8 of [11].
IER volume fraction	9 %	Derived based on waste mass fractions and density of mixed organics and wet ion exchange resins [11] [12].
Mixed organics volume fraction (uncompacted)	91 %	
Waste loading	26 wt%	Derived from an interpolation between the characteristics of a mixed organic package and IER waste package, package characteristics from [11] [10].
Raw waste volume	415 L	
Raw waste mass	107 kg	
Waste package tare mass (waste container plus conditioning materials)	308 kg	Table 3-2 of [10] and re-adjustment to align with calculated values.
Total waste package mass	415 kg	Derived using average mixed organic and IER waste package characteristic values from [11] [10].

2.2.2 Attributes and Lifecycle Stage Selection

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

The attributes presented in Appendix 3 of [13] were used as the starting point of this exercise. Discussions with the University of Manchester [7] led to the identification of non-differentiating attributes, and therefore to their exclusion from the evaluation.

The LCA and LCC analyses have focused on attributes for which benchmarked data against carbon footprint were available. However, value assessment can consider a wider set of attributes because it can take account of qualitative as well as quantitative evaluations and is based on a relative assessment against the baseline scenario. Therefore, the outputs of value assessment only need to determine if the novel RSOW treatment and conditioning routes have benefits or disbenefits in comparison with the baseline, which represents conventional practice. A full table of criteria is presented in Appendix 2, which includes a justification for the exclusion or inclusion of each attribute. This took into account experience and lessons learnt from the WP5 and WP4 value assessment workshops.

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

The initial assessment carried out prior to the workshop did not include weighting of criteria. Such weighting depends on the priorities of each individual Waste Management Organisation (WMO). Therefore, the discussion in Section 3 is "weighting neutral".

2.3 Approach and Methodology for Disposability Assessment

The approach taken to disposability assessment was to first define the types of facility that would be considered as potential disposal options. This was motivated by the identification of the *"capacity to dispose of thermally treated products to near surface in comparison to intermediate depth or geological disposal facilities"* as a topic area of interest at the start of the project. A broad set of generic facilities were defined consistent with the range of planned or operating LLW and ILW disposal facilities in Europe spanning from surface facilities through to Deep Geological Disposal (DGR) facilities. These facilities are described in Section 2.3.1.

Following the identification of the disposal facilities, a set of disposability areas were defined. For each disposability area, the primary considerations were outlined, including any facility-specific considerations which will impact the associated requirements. Disposability considerations are presented in Section 2.3.2.

The disposability of each of the considered wasteforms was qualitatively assessed across each of the disposability areas identified in Section 2.3.2. The performance of each waste type against each disposability area was described in terms of the potential risk to disposability, with the risk classified according to the following categories:

- **General disposability risk** where there is a general risk to disposability applicable to most waste streams and disposal concepts.
- **Concept dependant disposability risk** where there is a risk that the wasteform will not be disposable to specific disposal concepts.
- **Waste dependant disposability risk** where there is a risk that certain waste streams will produce wasteforms not suitable for disposal.
- **Risk to disposability due to uncertainty** where there is a risk to disposability due to uncertainty in the performance of the wasteform which may be reduced by further research and development.

Each assessment area was then assigned a Red, Amber or Green (RAG) rating based on the perceived severity of the outstanding risk to disposability for each of the base and variant scenarios. The criterion for each rating is presented in Table 2.4. The performance of the wasteform across all assessment areas was compared with the performance of the scenario's respective baseline to determine an overall assessment score from -2 (much worse) to +2 (much better). These results were then used as input to the value assessment. The disposability evaluation for each scenario is presented in Appendix 1.

Table 2.4: RAG ratings for the disposability of treated and conditioned RSOW wasteforms

Rating	Risk to disposability
Green	No foreseeable risk to disposability.
Amber	A risk to disposability is identified which may require further development work to mitigate or which may preclude some waste streams or disposal concepts.
Red	A significant risk to disposability is identified which is likely to preclude the disposal of the waste product to most or all types of facility.

2.3.1 Disposal concepts

In order to evaluate the disposability considerations applicable to the range of proposed or operating LLW and ILW disposal facilities across Europe, a set of five generic disposal facilities were defined at depths spanning from surface to deep geological disposal. These generic facilities are not necessarily consistent with any one facility, but instead defined to capture the broad characteristics of a single 'class' of facilities.

Each of the considered disposal concepts was given an identifier consisting of two letters and a number, with the letters indicating whether it is a Near Surface (NS), Intermediate Depth (ID) or Geological Disposal (GD) concept, and the number differentiating concepts in the same category. The considered disposal concepts are illustrated in Figure 2.2 and described in further detail in the subsections below.

In reality there is a continuum of facility depths which may be considered for underground facilities. In this report, geological disposal concepts are considered to include both DGR facilities (typically deeper than 200m) and shallower DGR-like facilities. Geological disposal concepts are distinguished from intermediate depth facilities in this report by their increased reliance on geological barriers. Disposal concepts for heat generating High Level Waste (HLW) that might be implemented in DGR or DGR like facilities are not considered.

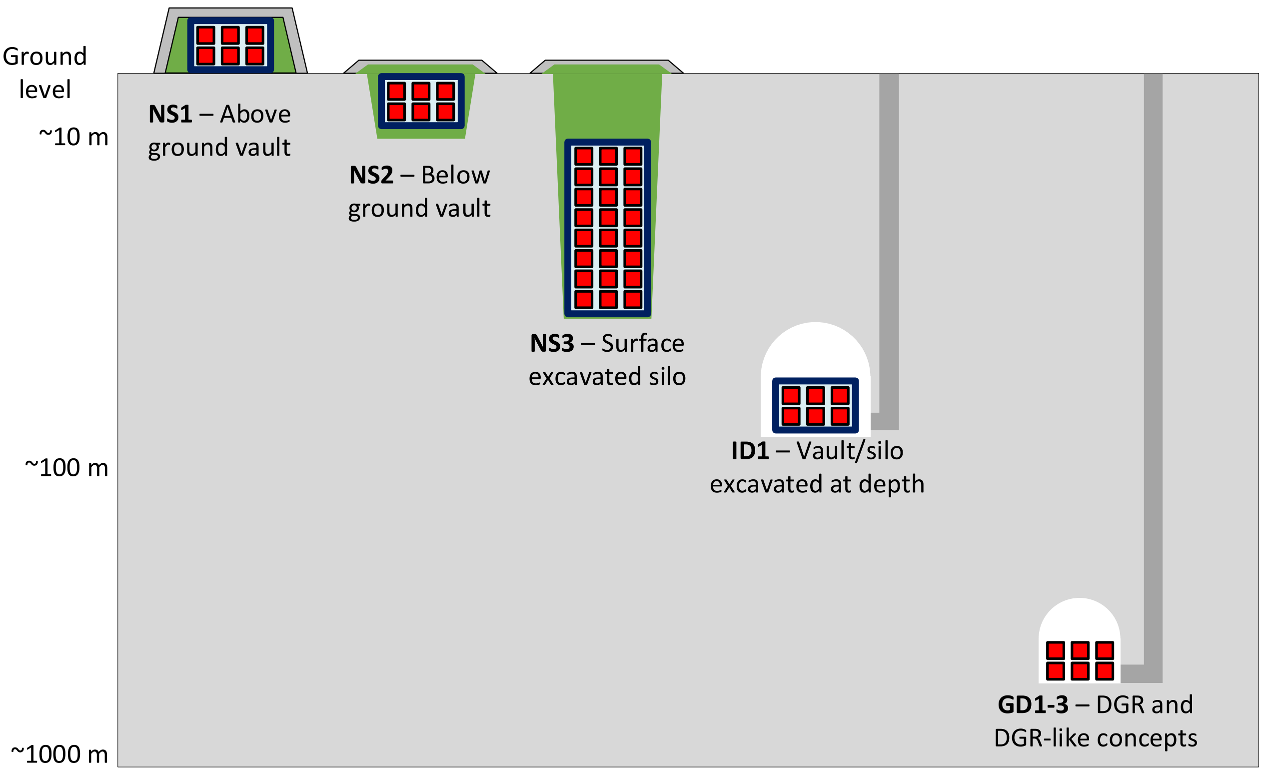


Figure 2.2: Illustration of the generic disposal concepts considered in this work. Illustration is based on reference [14].

NS1 – Above ground vault

Description: Waste is emplaced in vaults at ground level over an operational period spanning several decades, and the facility is mounded over with an engineered cover. Position above water table combined with engineered barriers and water management systems means that the waste is unsaturated (and potentially entirely dry). The position at the surface means there is risk of large-scale human intrusion following end of institutional control.

Barriers: Durable concrete or steel packages with a concrete or gravel backfill inside concrete vaults. Facility is covered by an engineered cap consisting of layers of polyethylene, clay, gravel and soil.

Depth: 0 m (natural ground level)

Wastes: LLW[3]

Examples:
- Category A facility, Dessel, Belgium
- L/ILW facility, El Cabril, Spain
- CSA, Aube, France

NS2 – Below ground vault

Description: Waste is emplaced in engineered vaults excavated from the surface which are then filled to ground level or mounded over. Waste becomes saturated after closure, with engineered barriers aimed at preventing or reducing water flow. Position at surface means there is risk of large-scale human intrusion following end of institutional control.

Barriers: Durable concrete or steel packages with a concrete backfill inside concrete vaults. Facility is covered by an engineered cap consisting of layers of polyethylene, clay, gravel and soil.

Depth: 0-20m

Wastes: LLW

Examples:
- LLWR, Drigg, UK
- RÚ RAO L/ILW facility, Mochovce, Slovakia

NS3 – Surface excavated shaft or silo

Description: Waste is emplaced in a surface excavated silo consisting of a vertical excavation from the surface to several tens of meters depth. The top of the emplaced waste is significantly (~10 m) below ground level, with the remainder of the silo containing the engineered cap. Emplacement at greater depths than other surface excavated concepts reduces the risk of human intrusion. Waste becomes saturated after closure, with engineered barriers aimed at preventing or reducing water flow.

Barriers: Durable concrete or steel packages with a concrete backfill inside concrete lined silo. The silo is capped with concrete, clay and soil.

Depth: 10-70m

Wastes: LLW

Examples:
- LILW disposal facility, Vrbina-Krško, Slovenia

[3] See discussion on waste radiological classification in Section 2.3.2.1.

ID1 – Silo or vault type facility excavated at depth

Description: Excavation of a vault or silo at intermediate depth and accessed by shaft or draft which will be subsequently backfilled. Depth provides higher degree of isolation from surface processes. Significant reliance is still placed on engineered barriers.

Barriers: Durable concrete or steel packages in a concrete lined vault which is backfilled with concrete. Plugging of access tunnels by concrete, crushed rock, clay or a mixture of these.

Depth: 50-100m

Waste: Up to ILW

Examples:
- VLJ L/ILW facility, Olkiluoto, Finland
- SFR L/ILW facility, Forsmark, Sweden
- National Radioactive Waste Repository, Bátaapáti, Hungary

GD1 – Geological disposal in High Strength Rock

Description: Disposal to a DGR (typically <200m) or a shallower DGR-like concept (100-200m) located in a low permeability high-strength rock (e.g. granite). Distinguished from intermediate depth disposal on the basis of an increased reliance on geological barriers to prevent release, and on the increased need to manage potentially heat-generating waste. Expect radionuclide transport in host rock to be dominated by advection resulting from groundwater flow through fractures.

Barriers: Concrete, steel, or other metallic packages in a vault backfilled with a cementitious grout. Host rock provides a significant barrier to radionuclide migration.

Depth: 100-800m

Wastes: Up to HLW

Examples:
- ONKALO® DGR facility, Olkiluoto, Finland
- SFL ILW facility, Sweden (Proposed)

GD2 – Geological disposal in Low Strength Sedimentary Rock

Description: Disposal to a DGR (typically >200m depth) or a shallower DGR-like concept (100-200m depth) located in a low permeability low strength sedimentary rock (e.g. clays, shales, mudstones). The low strength of the host rock means that fractures cannot be maintained and will self-seal. Expect radionuclide transport in host rock to be dominated by diffusion through the rock matrix.

Barriers: Reinforced concrete disposal container in a tunnel backfilled with a cementitious grout. Host rock provides a significant barrier to radionuclide migration.

Wastes: Up to HLW

Depth: 100-800m

Examples:
- Cigeo DGR, Meuse, France (proposed)
- DGR facility, Nördlich Lägern, Switzerland (proposed)

GD3 – Geological disposal in Evaporite

Description: Disposal to a DGR located in an evaporite (salt) formation (typically halite). Evaporites exhibit significant plastic flow (creep) which will tend to close any open fissures and excavations over time. Evaporite formations provide a dry geological environment such that there is expected to be effectively no transport of radionuclides outside of the gas phase.

Barriers: Vaults are backfilled with crushed host rock. The evaporite host rock is the primary barrier to radionuclide migration.

Depth: 200-800m

Wastes: Up to HLW

Examples:
- WIPP, New Mexico, USA
- ERAM, Morsleben, Germany

2.3.2 Disposability considerations

There are a number of factors which influence disposability, and the factors considered vary between different facilities and jurisdictions. PREDIS Deliverable 2.4 presents a review of international waste acceptance systems for radioactive waste [15]; the assessment areas adopted here are based on the areas identified in that review (see Table 3 of [15]). The identified assessment areas were screened to remove areas considered not relevant or not differentiating of the considered technologies; assessment areas screened out of the review are listed in Table 2.5.

Table 2.5: Disposability assessment areas which were screened out of consideration.

Assessment area	Description	Reason for screening out
Chemo-toxic waste	Presence of chemically toxic species, typically defined by legislation (EU water framework directive, EU REACH regulations, etc.). Examples include mercury, lead, cadmium and PFAS.	Considered treatment approaches will not introduce significant quantities of chemically toxic species. The presence of chemo-toxic species and the resulting suitability of the treatment approach will be waste-stream specific.
Reactive metals	Typically, the mass of reactive metals is limited or there is a requirement that issues with reactive metals (gas generation, expansive corrosion) are mitigated.	Considered treatment approaches will not introduce reactive metals. The presence of reactive metals and their behaviour during treatment and disposal will therefore be waste-stream specific.
Heat generation	Radiological heat generation, dependent on activity of waste.	It is assumed that waste will be LLW or ILW (including after thermal treatment), as such heat generation will not be a specific concern.
Criticality	Criticality risk is impacted by fissile element mass and the presence and configuration of neutron moderators, poisons and reflectors.	Criticality will be of concern for only a very limited subset of solid organic wasteforms that have a large loading of fissile material. It is assumed that the waste will not pose a criticality risk, consistent with the rest of the value assessment.
Management and data recording	Ability to add a durable and readable waste package label/identifier and other documentation and tracking considerations.	It is expected that suitable management and data recording processes may be developed for any of the considered treatment approaches. This area will therefore not be differentiating.

The assessment areas that were included in the review of disposability are listed in Table 2.6, along with a description of the typical requirements and considerations relating to each area, and any concept specific considerations which will impact the associated requirements. The activity content of the waste is an area of specific importance when considering disposal to facilities at different depths; this topic is therefore discussed in detail in Section 2.3.2.1.

Table 2.6: Disposability assessment areas, descriptions and concept specific considerations.

Assessment area	Description	Concept specific considerations
Physical form	Typically, there is a requirement for a physically solid and compact wasteform. Dispersible forms (such as powders) are typically prohibited.	**NS1-2:** Presence of discrete objects with high dose rate will be of concern due to the significant risk of human intrusion.
Mechanical stability	Minimum compressive strength (e.g. 10 MPa), ability of packages to withstand static loads and stacking without deformation or	**NS1-3:** Potential for freeze/thaw cycling. **NS3/ID2:** Silo type concepts typically require ability to stack packages to larger

Assessment area	Description	Concept specific considerations
	cracking.	heights than vault concepts.
Homogeneity	Immobilisation matrix typically required to be homogeneous, requiring that there is no segregation of waste/matrix.	-
Dose-rate	Dose rate (measured as contact dose or at nominal stand-off) impacts handling requirements for package. Will be impacted by waste activity and the shielding by the package and wasteform.	**NS1-3:** Near surface facilities typically have handling processes designed with minimal shielding. High dose rate packages are more likely to be unacceptable.
Surface contamination	Surface contamination typically required to be very low to minimise particle dissemination hazard, may consider both radioactive and non-radioactive contamination (e.g. salt deposits).	-
Activity content	There is typically a maximum acceptable activity content for waste packages disposed to near-surface and intermediate depth facilities. May be defined in terms of specific activity, activity concentration or total activity. Limits may be set on the activity content of individual radionuclides or based total alpha and beta/gamma activities.	Waste with higher activities and more long-lived radionuclides typically require a greater degree of containment and isolation from the surface environment. This is primarily because of their radiological impact in human intrusion scenarios. See discussion in Section 2.3.2.1.
Radiation, thermal and chemical stability	Stability of wasteform under ambient radiation, thermal and chemical conditions and under extreme conditions. Chemical conditions are typically consistent with cementitious pore water and the wasteform must be compatible with this barrier.	**NS1:** Typically require wasteform to remain stable under unsaturated or potentially dry conditions for relatively short timescales (~300 years). **NS2-3:** Typically require good stability under saturated conditions for relatively short timescales. **ID1:** Typically require good stability under saturated conditions for intermediate timescales. **GD1-2:** Good stability under saturated conditions for long timescales required **GD3:** Stability under dry conditions for long timescales required
Package	Use of standard/approved packages Maximums on package weight and size. Package performance under impact accidents. Package stacking	**NS3/ID2:** Stacking to significant heights required in silo concepts. Typically require consideration of larger drop heights than other concepts.
Putrescible, fermenting, or infectious material	Of concern for biodegradable organic materials. Limits may be specific or derived from gas, void space or chemical stability requirements. Infectious materials (such as carcasses) typically required to be excluded.	-
Void space	Presence of void space in the package. Need to consider void space that may develop within a package due to compression or degradation. Type of facility (near surface, geological disposal), facility design and geological context will impact the allowable voidage and the processes considered.	**NS1/NS2:** Tolerance to void space dependant on engineering of cap and vault. **GD1:** Potentially very tolerant of void space **GD2:** Potentially not tolerant of void space **GD3:** Moderate tolerance of void space

Assessment area	Description	Concept specific considerations
Gas generation	Generation of gases due to radiological and chemical degradation. Concerns include the over-pressurisation of the container and the creation of pathways for radionuclide migration.	-
Radiological gas generation	Generation of radiological gases. Typically, facilities place an upper limit on the production of radiological gases. Gases of concern include radon (uranium chain) and tritium or C-14 containing gases.	-
Organic content	May be prohibited generally or in certain forms (e.g. oils) or may not be added to a waste (e.g. as encapsulant). Some concepts have no limits on organic content.	-
Swelling/ shrinkage	Excessive swelling or shrinkage (over time or due to exposure to, for example, water) is typically prohibited	**NS1/NS2:** higher potential for seasonal dehydration/rehydration and thermal cycling.
Free liquids	The presence of significant free liquids is typically unacceptable.	-
Chelating/ complexing agents	Chelating/complexing agents present, or that may evolve into a package which may increase the mobility of radionuclides. Typically required to be excluded or of limited mass.	**NS1:** Unsaturated conditions reduce impact of complexing agents. Timescales of concern for evolution of complexing agents are short (~300 years). **NS2-3:** Timescales of concern for evolution of complexing agents are short (~300-10,000 years). **ID1:** Moderate timescales of concern for evolution of complexing agents (100,000 years). **GD1-2:** Timescales of concern for evolution of complexing agents are very long (up to 1,000,000 years). **GD3:** Dry conditions means that chelating/complexing agents are not a concern.
Leaching	Rate of leaching of radionuclides and hazardous chemicals into groundwater is typically required to be low. Water soluble species such as chlorides/sulphates may have to be excluded.	**NS1:** unsaturated conditions reduce impact of leaching. **DG3:** Dry conditions means that leaching is not a concern

2.3.2.1 Waste classification

An important aspect in identifying the appropriate disposal concept for radioactive waste its radiological classification, which is defined by its activity content. The activity content will typically define whether a waste may be cleared as being out of scope of radioactive substances regulation, or must be disposed of to a near surface, intermediate depth, or geological disposal facility. A number of different waste classification schemes are used across different states. The International Atomic Energy Agency (IAEA) radioactive waste classification scheme specified in General Safety Guide (GSG) 1 [16] is used here as it provides a generic example which illustrates the main considerations informing disposal to different facility types; a conceptual illustration of this scheme is illustrated in Figure 2.3.

The classification scheme considers both the activity content of the waste and the half-lives of contributing radionuclides. Higher activity content corresponds to higher classification and an increased requirement to provide isolation for the waste. The half-lives of contributing radionuclides also impact the classification; shorter lived waste may have a lower classification and lower isolation requirements than similarly active, longer lived, waste. This is because the radiological hazard from short lived radionuclides will decrease relatively quickly over time such that shallower facilities can provide sufficient containment until a large fraction of the activity has decayed away.

The RSOW considered in this report consists of LLW and ILW; that is, waste with a high enough activity that it requires disposal in an engineered facility but that has sufficiently low radiological heat generation to not require specific heat management considerations.

Individual national programmes develop their own classification schemes, including quantitative limits, based on their respective requirements. The adopted boundaries between different classifications may be based on the performance of available disposal facilities, on shielding and handling considerations or on regulatory limits. The radiological classification may be linked to the activity of certain radionuclides on the basis of, for example, dose impact. It is common for near surface disposal facilities to have more stringent limits on alpha emitting radionuclides as compared to beta and gamma radionuclides due to longer half-lives, concerns relating to the potential dose and the typically long decay chains.

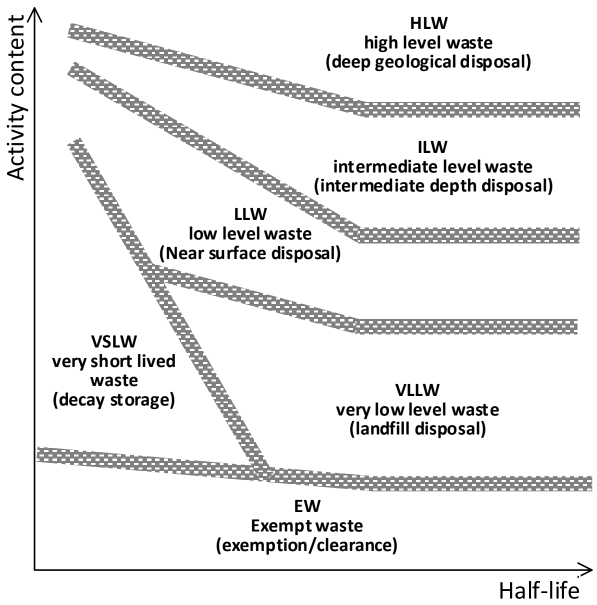


Figure 2.3: Conceptual illustration of the IAEA waste classification scheme ([16], Figure 1) reproduced with permission from the IAEA.

3 Economic, Environmental and Disposability Impacts of Novel RSOW Treatments

This section presents the assessment of the environmental, economic and disposability impacts of the novel treatment technologies. It is the synthesis of the outputs of the value assessment workshop, presented in Appendix 3, and the assessment of disposability related risks, presented in Appendix 1.

It is assumed for the assessment that the facilities for incineration and further conditioning are located on the same site (thus removing the need for transport between the two process steps).

3.1 Conditioning of ashes from the IRIS Process

Treatment scenarios 6.1.1, 6.1.2 and 6.1.3 each consist of a two-step process:

- Thermal treatment with an IRIS-like facility, followed by
- Further treatment and conditioning of the incinerator ashes.

The impacts of all treatment steps were evaluated together to determine the overall impact of the scenario. However, in order to avoid repetition given that all of the scenarios share a common thermal treatment step, the impacts of the initial thermal treatment with IRIS is discussed initially in Section 3.1.1 and referenced from the variant scenario evaluations in Sections 3.1.2-3.1.4.

3.1.1 IRIS process

IRIS is a three-step thermal treatment process developed by the CEA for the treatment of RSOW. The waste feed considered in PREDIS consisted of a 2:1 ratio of mixed organic waste and IERs. The process is implemented in rotating kilns where the first step consists of pyrolysis at 550°C, producing a liquid ‘pitch’ that is then processed in a calcining step at 900°C in an oxygen-enriched atmosphere. The off-gases arising from the thermal treatments include a volatile hydrocarbon fraction that is oxidized at 1100°C in an afterburner. The primary process product consists of calcined waste (from the calciner) and dust (from the off-gas treatment) which are assumed here to be co-processed (in subsequent sections ‘ashes’ refers to the combination of both products). In operation, the process treats approximately 4 kg/hr of waste and produces approximately 0.158 kg of ashes (0.111 kg calcine and 0.047 kg dust).

3.1.1.1 Operational Safety

From an operational safety standpoint, a typical IRIS-type incinerator has a footprint of approximately 9 m x 5 m x 8m, with some of the equipment located in gloveboxes. The footprint of the facility has an impact on the risks encountered during its construction.

Dissemination of contaminated dust was identified as the main operational risk of the incineration process. This hazard is absent under the baseline assumption of direct cementation (of IERs) and compaction followed by cementation (mixed organic solids). The health and safety risks associated with building the facilities required for incineration and further treatment and conditioning were highlighted by workshop participants. Activity concentration may also require additional radiation protection measures during the operational and decommissioning phases of the treatment facilities as compared to the baseline.

Criticality safety was discussed during the workshop and it was deemed to be a potential concern for fissile waste, due to the activity concentration that will result from both the incineration and compaction steps. Criticality safety was not discussed further under the assumption that waste streams containing fissile materials are excluded from the scope of this evaluation.

3.1.1.2 Environmental Impact

After construction, the material consumption of the incineration process is very low compared to the baseline route. On the other hand, incineration is a significantly more energy-intensive process than direct cementation.

The LCA analysis performed by the UoM demonstrated that the environmental impact of incineration is primarily due to its large energy consumption (measured in terms of global warming potential per unit mass of waste treated). The incineration step alone has a global warming potential of more than double that of the baseline compaction and cementation route. Attendees of the value assessment workshop also agreed with this conclusion.

3.1.1.3 Disposability and Long-term Safety

The IRIS process generates secondary wastes at the following rates (expressed per tonne of waste incinerated) [17]:

- 5 m^3 of liquid effluents (sodium-contaminated liquids) are generated per tonne of waste incinerated.
- One HEPA filter is changed for every tonne of waste incinerated.
- 2.5 kg of Inconel[4] per tonne of waste incinerated.

None of these secondary waste streams were deemed challenging from a disposability standpoint.

The ashes from thermal treatment are not intended for direct disposal, requiring an additional treatment or conditioning step. Therefore, disposability is not evaluated for thermal treatment on its own. The IRIS process will however destroy any organics in the waste which will resolve a number of the disposability issues related to organic waste.

3.1.1.4 Implementation

A typical throughput for radioactive waste cementation is around eight 200 L drums per day (approximately 100 kg of waste per drum). The throughput of the incineration step is estimated at 4-7 kg/hr (96 kg/24 hr), with the possibility of operating a 2x8 or 3x8 shift pattern. Based on these figures, it is natural to assume that the baseline route performs better than incineration and compaction. However, the value assessment panel agreed that, due to limited rates of waste arising, throughputs would be limited by waste availability rather than process throughput.

Compared with the baseline management route, incineration opens a novel waste management route, which is likely to positively impact national and local waste management strategies. The high Technology Readiness Level (TRL) of the technology, TRL 8, is comparable with the baseline.

3.1.1.5 Costs

During the workshop, the panel agreed that costs associated with secondary waste management could not be adequately discussed due to the lack of underpinning cost data[5]. The lack of precise cost information also hindered discussions around the cost of facility construction, operations and decommissioning. However, it remained clear to the assessment panel that the costs of building an incinerator would be a barrier to implementation when compared with the baseline management route. Depending on local regulations and on the wastestreams intended for treatment, licensing costs for the incineration facility were expected to be high.

These additional costs were considered against the increased waste loading and mass reduction achieved by thermal treatment. This will have benefits of reducing the number of final disposal packages which will have downstream benefits on disposal costs and on the size of storage and disposal facilities. Such benefits are to be considered against potentially higher handling costs due to increased waste specific activity resulting from activity concentration.

3.1.2 Scenario 6.1.1 – Incineration and HIP of ashes

Scenario 6.1.1 consists of the thermal treatment of RSOW using the IRIS process followed by the HIPing of the resulting ashes, the consolidation of HIP cans into a 200 L drum and the cementation of the drum. The HIP process has been investigated in PREDIS by the University of Sheffield and the UK NNL. Following the IRIS incineration step, this process consists of the following steps:

[4] One rotary kiln metal bar (Inconel, approximately 10 kg) is changed for every four tonnes of waste incinerated.
[5] Our request for such information was rejected by the CEA on grounds of commercial confidentiality.

- IRIS ashes are packed into an 8 L HIP can consistent with those used in the HIP rig (it is assumed that the process is designed such that additional drying of the ashes is not required).
- HIP can is subjected to bakeout in an oven.
- The lid is welded onto the HIP can.
- The can is HIPped; the process uses the simultaneous application of heat and pressure (applied isostatically via argon gas) to the can to densify it and change its properties. For ashes a ceramic wasteform is produced.
- A number of HIPped cans are consolidated into a 200 L annular grouted drum (8 HIPped cans per drum is assumed)
- The drum is flood grouted.

It is estimated that 52 kg of ash (equating to 1316 kg of unincinerated waste) would be packaged into each 200 L drum produced by this process. The total mass of the drum of cemented HIP cans would be 490 kg, with an ash loading of 11 wt%.

3.1.2.1 Operational Safety

Scenario 6.1.1 inherits the strengths and weaknesses of the IRIS thermal treatment step which were discussed in Section 3.1.1.1. Furthermore, the construction and operation of the HIP facilities (e.g. can-packing station, bakeout oven) adds additional health and safety risks compared with the baseline route. The increase in contamination risk due to the presence of fine particulates together with the potential for can failure are a weakness of this technology. However, this is mitigated by the presence of dedicated containment systems such as the Active Furnace Isolation Chamber (AFIC) which allows HIP of fissile materials. After the HIP step, the particulate dissemination hazard is well mitigated by the containment provided by the HIP can, so this is less of a concern for the consolidation and cementation steps.

*Based on the evidence assembled during this task, incineration followed by HIP have a **detrimental impact** on operational safety, when compared with direct cementation of RSOW. The construction, operation and decommissioning of two complex facilities compares badly against the simplicity of the baseline. Handling waste in a powder form adds safety challenges compared with untreated waste handling.*

3.1.2.2 Environmental Impact

The environmental impact of the incineration and HIP route is dominated by:

- The environmental impact of manufacturing steel, which is required for the HIP cans.
- The environmental cost of producing argon, which is used as the inert gas applying pressure to the HIP can.
- The energy demands of both the incineration and HIP processes.

The preliminary LCA results indicate that the global warming potential of the incineration and HIP scenario is approximately eight times greater than the baseline compaction and cementation scenario for an equivalent amount of waste treated. The environment impact of the process is dominated by the energy consumption of the incineration and HIP steps.

*The environmental impact of the incineration plus HIP is evaluated as **much worse** than the baseline. The global warming potential of the HIP route is approximately eight times higher than the current baseline.*

3.1.2.3 Disposability and Long-term Safety

Secondary waste volumes from the incineration step will arise as reported in Section 3.1.1.3. Limited amounts of housekeeping waste (such as Personal Protective Equipment (PPE)) are likely to arise from the HIP and subsequent cementation steps. Small volumes of argon gas are also likely to be discharged as non-radiological gaseous discharges. Contamination of this gas is prevented by the containment provided by the HIP can.

The assessed disposability risks relating to the finished waste (cemented, HIPped ashes) are reported in Appendix 1. As with compaction of ashes, the elimination of organics removes a number of disposability risks present in the baseline assessment. In addition, there relatively high confidence in the wasteform performance. The main outstanding disposability risks are related to uncertainty in the long-term product performance and the potential increase in radiological classification as compared to the baseline. HIPped cans may also be unsuitable for shallow near surface disposal due to the potential to be regarded as discrete objects, that may attract attention in human intrusion scenarios.

*Overall, based on the evidence assembled during the disposability and value assessment processes, the compatibility of HIPped ashes with common disposal concepts is deemed **much better** than the baseline.*

3.1.2.4 Implementation

In addition to the implementation barrier for the thermal treatment step identified in Section 3.1.1.4, the value assessment panel determined that the HIP process would also pose a number of similar challenges. There are no foreseeable barriers to the HIP process being able to match the throughput of the incineration step (the current NNL HIP rig is large enough to meet IRIS throughput). The versatility of the HIP process was recognised as being a strength, further increasing the potential positive impact that this management route could have on waste management strategies.

The HIP process was attributed a TRL of 4 to 6 for the treatment of incinerator ashes. This relatively low score is mitigated by ongoing projects in Australia, where an industrial scale HIP facility is currently being built. Such activities give confidence that the systems and technologies required for prototype demonstration and system qualification are available in the near term.

*Overall, based on the activities undertaken during this task, implementation of RSOW incineration followed by HIP could have positive impacts on waste management strategy. However, further development work is required to achieve system completion and qualification, making the implementation of the novel technology **slightly worse** than under baseline assumptions.*

3.1.2.5 Costs

Waste treatment and conditioning costs using incineration and HIP are driven by facility costs, which are much higher than for the baseline. The exact extent of this increase cannot be quantified due to the lack of cost data related to the incineration and HIP facilities.

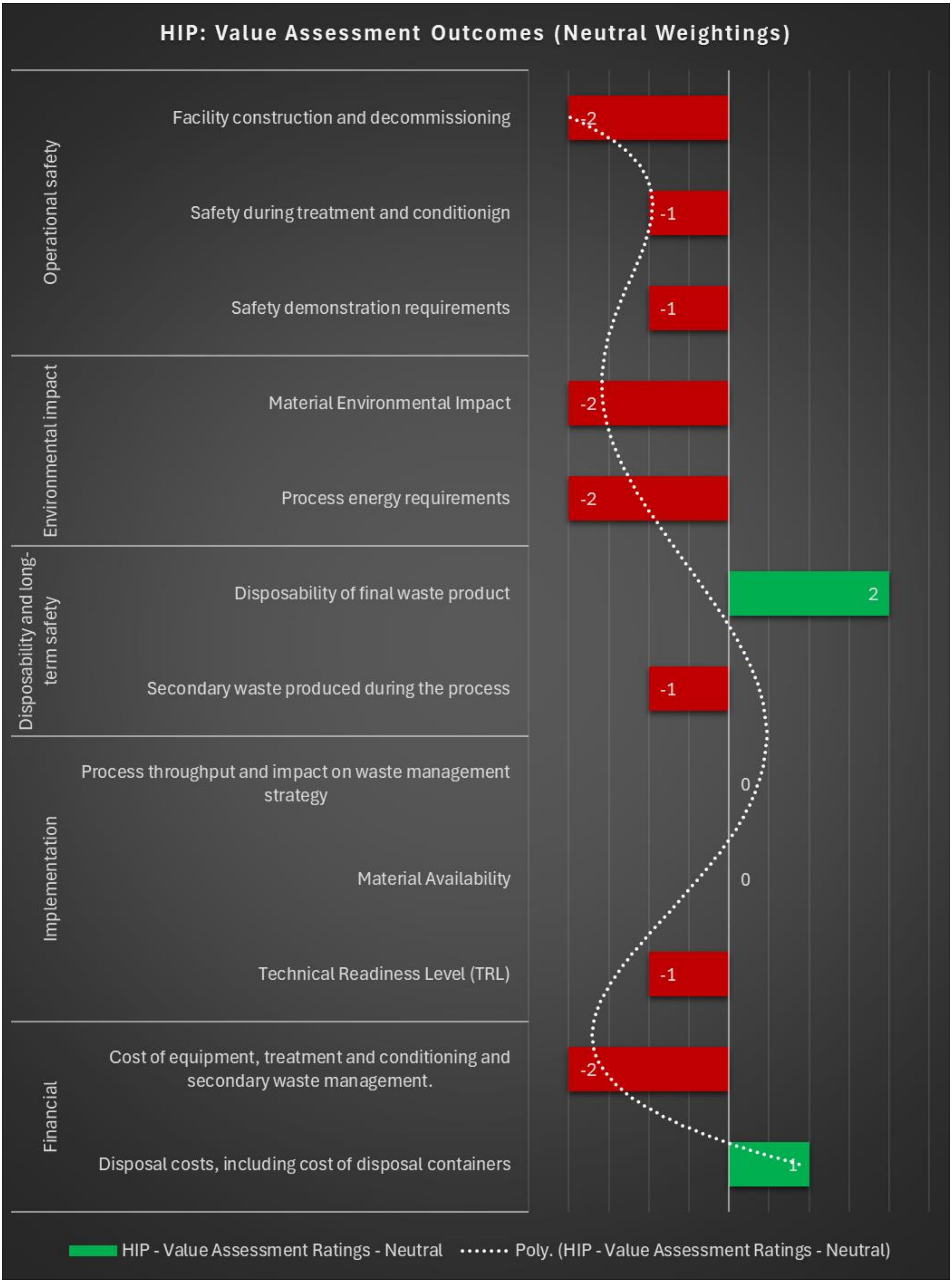
On the other hand, disposal costs are likely to decrease in line with the reduced number of disposal packages due to the higher overall waste loading. A factor 12 reduction in the number of primary waste packages compared to the baseline is estimated. This does not directly translate into the same factor of reduction in disposal costs (due to, for instance, arrangements required to accommodate the increased specific activity), but suggests that facility construction costs are likely to be significantly offset by reduced disposal costs.

The overall economic impact of the novel treatment and conditioning route is difficult to quantify in the absence of facility-related cost data for the incineration step. Having regards to the balance between the need for additional facilities, and the reduction in the number of waste packages compared with the baseline route, the novel route is deemed to be ***neutral to worse*** *in terms of cost. This conclusion should be revised if additional cost data becomes available to the user of these results.*

3.1.2.6 Summary

The value assessment results for incineration followed by compaction are illustrated in Figure 4, recognising that no overall rating should be attributed. Instead, each organisation and / or End-User might find it useful to individualise the results by applying weighting factors to each assessment area that reflect national priorities.

Figure 4: Value assessment outcomes for the RSOW incineration and HIP route



3.1.3 Scenario 6.1.2 – Incineration and compaction ashes

Scenario 6.1.2 consists of the thermal treatment of RSOW using the IRIS process and the compaction then cementation of the resulting ashes. The ashes compaction process has been investigated by the CEA as part of PREDIS. Ashes are compacted into pellets using a commercial pellet press. The pellets produced weigh around 0.5 g and are 10 mm in diameter and 0.4 mm in height. For disposal it is proposed that the pellets are consolidated into 200 L drum which is flood grouted. It is estimated that the produced waste package would have an ash loading of 160 kg (39 wt%), equating to approximately 4,000 kg of raw waste.

3.1.3.1 Operational Safety

A number of the operational safety risks for this scenario arise from the incineration step and are discussed in Section 3.1.1.1. The particulate dissemination hazard created by thermal treatment will also be present in subsequent processing steps.

The health and safety risks associated with building the facilities required for compaction and conditioning were highlighted by workshop participants. Increasing the number of process steps is also likely to result in an increase in human factor errors, and additional routes for exposure to contamination and ionising radiation. The activity concentration for the conditioning process will also be much higher as compared to the baseline. However, increasing the waste loading will result in fewer waste packages to produce, thus reducing the impact of the weaknesses highlighted above.

Overall, based on the evidence assembled during the value assessment process, operational safety is ***negatively impacted*** *by the use of RSOW incineration followed by compaction and cementation. The addition of a process step (compared to baseline assumptions), with the associated construction, operational and decommissioning costs in terms of health and safety, coupled with an increase in the risk of contamination due to the physical nature of the waste product, support this conclusion.*

3.1.3.2 Environmental Impact

The material inputs for the ashes compaction and cementation process are comparable to the inputs for the baseline process for the cementation of raw waste, consisting of waste drums and cement. The volume reduction due to the incineration step however substantially reduces material input per unit waste treated. The global warming potential of the ashes compaction and cementation route is therefore dominated by the energy used in the incineration step, and is more than double that of the baseline.

Overall, based on the evidence assembled during the value assessment process and on LCA modelling, incineration of RSOW followed by compaction ***is worse*** *for the environment than direct cementation.*

3.1.3.3 Disposability and Long-term Safety

The assessed disposability risks relating to compacted ashes are reported in Appendix 1. Incineration mitigates a number of the disposability risks associated with untreated organics present in the baseline concept. The main disposability risks relating to compaction relate to the potential increase in waste package radiological classification and uncertainty in the long-term performance of the wasteform. The potential for the pellets to be considered a discrete object poses a concept-specific disposability risk for concepts NS1 and NS2.

*Overall, based on the evidence assembled during the disposability and value assessment processes, the compatibility of cemented compacted ash pellets with common disposal concepts is deemed **better** than the baseline.*

3.1.3.4 Implementation

The relatively low TRL of ashes compaction for disposal (TRL 2) was recognised as a disadvantage, although equipment and industrial processes from the pharmaceutical industry are likely to be used to speed-up process scale-up (powder compaction is a common process in this industry). A cementation process for the pellets has also not been developed, and there would be a need to develop one which produces a disposable product.

*Overall, based on the evidence assembled during this task, implementation of the incineration and compaction route is **more challenging** than implementation of the baseline route. Whilst high process throughputs are not required, the immaturity of the compaction technology might pose a challenge to implementation. This can be overcome by continuous Research and Development funding.*

3.1.3.5 Costs

The workshop identified that the costs for this scenario would likely be dominated by the construction and licensing of the incineration facility, with the compaction and cementation facility making a smaller relative contribution, comparable to the baseline facility.

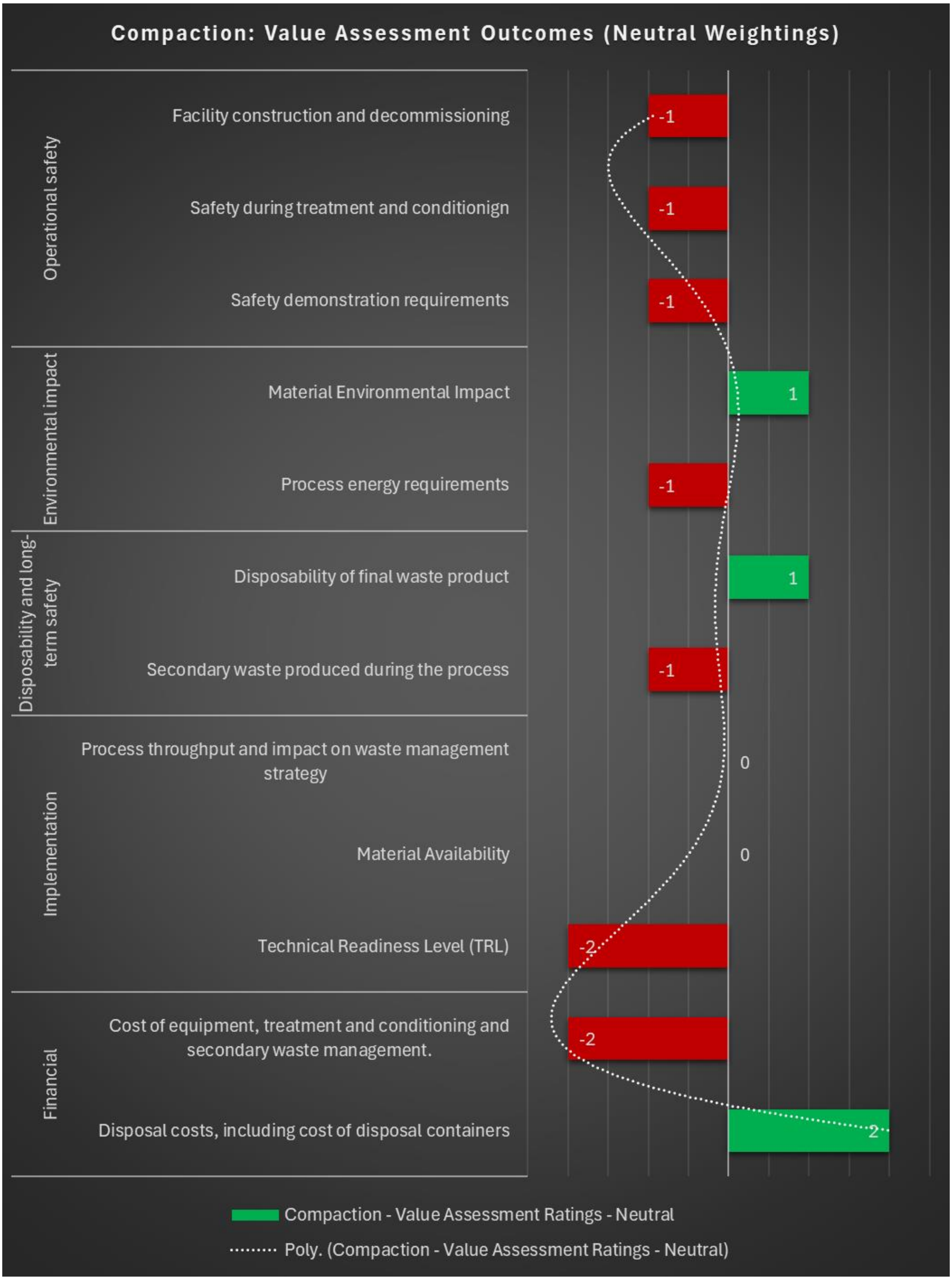
The additional cost of constructing and operating the treatment facility was considered against the increased waste loading and mass reduction achieved by thermal treatment. Approximately 4,000 kg of raw waste produce one 200 L drum of compacted pellets, which means there is a factor 38 reduction in the number of primary waste packages produced as compared to the 107 kg of raw waste conditioned per 200 L drum in the baseline. This does not directly translate into the same factor of reduction in disposal costs (due to, for instance, arrangements required to accommodate the increased specific activity), but suggests that facility construction costs are likely to be significantly offset by reduced disposal costs.

*The overall economic impact of the novel treatment and conditioning route is difficult to quantify in the absence of facility-related cost data for the incineration step. Having regards to the balance between the need for additional facilities, and the reduction in the number of waste packages compared with the baseline route, the novel route is deemed to be **neutral** in terms of cost. This conclusion should be revised if additional cost data becomes available to the user of these results.*

3.1.3.6 Summary

The value assessment results for incineration followed by compaction are illustrated in Figure 5.

Figure 5: Value assessment outcomes for the RSOW incineration and compaction route



3.1.4 Scenario 6.1.3 – Incineration and Geopolymer Encapsulation

Scenario 6.1.3 consists of the thermal treatment of RSOW using the IRIS process and the encapsulation of the ashes in the tuff based geopolymer developed by POLIMI. The geopolymer encapsulation process consists of the grinding of the ashes, followed by the mixing of the ground ashes with the geopolymer precursor powders. The resulting mixture is then mixed with the activator, which is a sodium hydroxide solution. The mixing may take place inside the disposal package (a 200 L drum), or a mix-and-pour approach could be adopted.

The final package consists of a 200 L drum of geopolymer with a total mass of 420 kg and an ash loading of 80 kg (19 wt%). Approximately 2,000 kg of raw waste would produce a single product drum.

3.1.4.1 Operational Safety

The impact of the incineration step on safety is reported in Section 3.1.1.1. In addition, the use of alkali activators in geopolymers adds a chemical hazard that is not present in a cementation plant. Apart from this chemical hazard, cementation and geopolymer conditioning present a similar set of conventional health and safety challenges.

Higher waste loadings achieved with incineration will result in fewer waste packages that need to be produced, but with comparatively higher specific activities. Whether the balance tilts in favour of the baseline or variant scenario could not be quantified during this task and will depend on facility-specific design and organisational arrangements.

The overall impact on safety of the incineration and geopolymer conditioning route was seen to be ***neutral to slightly negative****. The baseline management route is comparatively simpler and requires fewer processing steps and fewer facilities. However, this is offset by the volume reduction associated with thermal treatment meaning that much fewer packages will need to be manufactured.*

3.1.4.2 Environmental Impact

The global warming potential of the incineration and geopolymer encapsulation scenario is dominated by the incineration step, the global warming potential is more than double that of the baseline scenario.

Significant benefits are realised by using natural materials (tuff) and repurposing industrial by-products (BFS) to formulate the geopolymer. This was found to align with the principles of circular economy. In addition, the increased waste loadings result in a reduction in the number of waste containers required for final disposal, further lessening the environmental impact of materials required by the process. Alternative geopolymer formulations could also become available, should the environmental impact of the current formulation worsen due to changes in the supply chain.

Overall, based on evidence gathered during this task, the environmental impact of the incineration and geopolymer conditioning route is ***worse to slightly worse*** *than direct cementation.*

3.1.4.3 Disposability and Long-term Safety

Secondary waste volumes from the incineration step are reported in Section 3.1.1.3 and are in addition to housekeeping waste that will be generated during geopolymer conditioning. Secondary waste generation is evaluated negatively by the value assessment process, although management routes exist for those arising from incineration.

The compatibility of the primary waste product (incinerator ashes conditioned in geopolymer) with different disposal facilities was evaluated separately in Appendix 1. A number of disposability risks are removed in comparison to the baseline due to the elimination of organics. The main risks relate to the potential for activity concentration due to incineration to increase the radiological classification of waste packages. In addition, uncertainties remain around the long-term performance of geopolymer and, in particular, its compatibility with a cementitious backfill.

Overall, disposability and long-term safety are ***positively impacted*** *by the use of incineration and geopolymer conditioning, due primarily to the elimination of organics and the generally good properties of the geopolymer wasteform. Further work is required to address uncertainties around long the compatibility of geopolymer wasteforms with engineered barriers.*

3.1.4.4 Implementation

Implementation considerations for the IRIS process are reported in Section 3.1.1.4. For the encapsulation step there are no foreseeable barriers to the conditioning process being able to match the throughput of the incineration step. Scale-up experiments carried out in WP5 indicate that geopolymer conditioning can achieve throughputs similar to those achieved by cement encapsulation.

Tuff availability is location-dependent, and uncertainties around the future availability of BFS led to a negative assessment of material availability for the variant scenario.

A TRL of 3 to 4 was assigned to the geopolymer conditioning step. Although comparatively low, this TRL needs to be seen in the context of positive results with experimental near-scale encapsulation of RLOW in drums at CVŘež/UJV Řež [18]. The technological readiness of the process is further supported by the commercialisation of geopolymer encapsulation by companies such as Jacobs (SIAL®) [19] [20] [21]. SIAL is currently being used [22] for the management of radioactive sludge at the A-1 and V-2 Mochovce NPPs (Slovakia), and at the Dukovany NPP (Czech Republic). Workshop attendees agreed that, although the exact formulation may differ, mixing equipment and procedures are unlikely to differ significantly between the SIAL technology and the new formulations developed under PREDIS. The consensus was reached that, with adequate funding, moving up the TRL ladder would be relatively quick due to the absence of exotic equipment or processes. Fine powder storage, dosage, and in-drum mixing of cementitious materials are well-known processes and equipment is readily available off the shelf.

Overall, based on the activities undertaken during this task, implementation of geopolymer conditioning preceded by incineration was deemed to be ***slightly more challenging*** *that direct cementation. However, the former may benefit waste management strategies by opening a new waste management route for challenging waste streams. Continued Research and Development funding is necessary to bridge the TRL gap.*

3.1.4.5 Costs

Waste treatment and conditioning costs using incineration and geopolymer-conditioning are driven by facility's costs, which are much higher than under baseline assumptions. The exact extent of this increase cannot be quantified due to the lack of cost data related to the incineration plant.

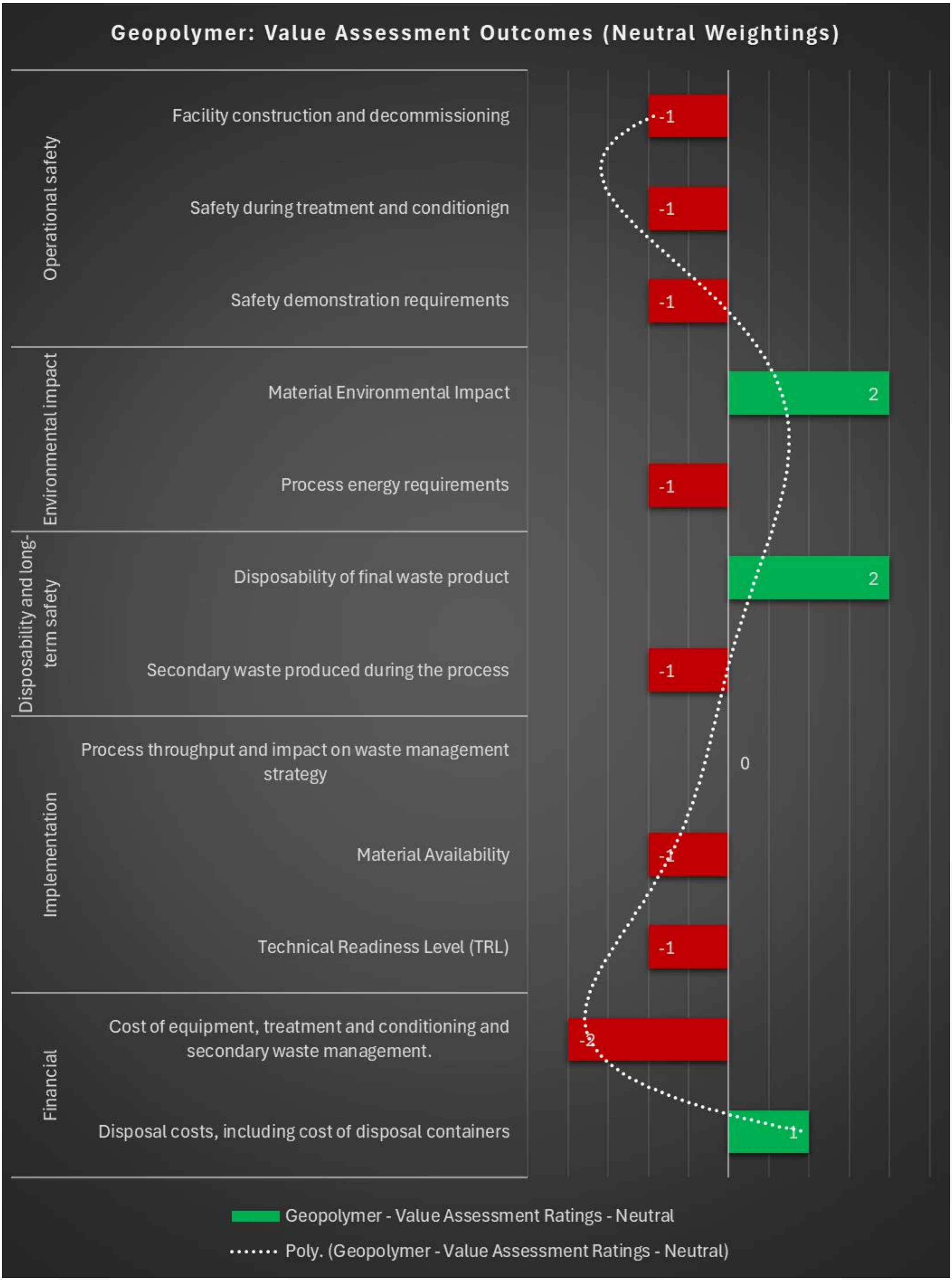
On the other hand, disposal costs are likely to decrease approximately twentyfold, in line with the assumptions on waste loading listed at the beginning of this section.

The overall economic impact of the novel treatment and conditioning route is difficult to quantify in the absence of facility-related cost data for the incineration step. Having regards to the balance between the need for additional facilities, and the reduction in the number of waste packages compared with the baseline route, the novel route is deemed to be ***neutral to slightly beneficial*** *in terms of cost. This conclusion should be revised if additional cost data becomes available to the user of these results.*

3.1.4.6 Summary

These results are illustrated in Figure 6.

Figure 6: Value assessment outcomes for the RSOW incineration and geopolymer conditioning route



3.2 MSO process

Treatment scenario 6.2.1 consists of the treatment of IERs with Molten salt oxidation (MSO) followed by the encapsulation of the spent salt in geopolymer. For consistency with previous evaluations, the impact of the thermal treatment step (MSO) is evaluated in Section 3.2.1, and the impact of the overall MSO and geopolymer encapsulation process is evaluated in Section 3.2.2.

3.2.1 Molten Salt Oxidation (MSO)

MSO entails oxidising waste within a vat of molten carbonate salts at temperatures between 400 and 900 °C. Air or oxygen is pumped into the salt bath and oxygen reacts with the carbonate to produce free peroxide and superoxide ions which then react with the waste. The organics are oxidised, and metals and inorganic residue are retained in the salt melt. The residue left behind by the waste builds up in the salt, reducing its fluidity and ability to absorb acidic gases; this necessitates the periodic discharge of salts. These spent salts are the primary waste product from the MSO process.

Scenario 6.2 considers MSO of spent IERs, with the properties of the process based on the MSO demonstrator rig at CV Řež in the Czech republic. A full charge of 95 kg of fresh salt (across two reactor vessels) is estimated to be able to process approximately 1,300 kg of IERs before discharge. The mass of discharged spent salts would be approximately 145 kg. The waste throughput of the demonstrator is 1-3kg waste /hr.

3.2.1.1 Operational Safety

Compared with the baseline scenario, the addition of the thermal treatment step increases construction (an additional facility is needed) and operational risks. Gaseous effluents (in the form NOx, water vapour, carbon dioxide and SO_3) could pose a hazard to operators if not properly managed. However, experience with the demonstrator suggests that these are easily managed.

MSO has been used to manage inactive waste, and trials were conducted in the USA, successfully treated a range of organic wastes, including IERs [23]. This experience is likely to support safety demonstrations and licensing activities.

3.2.1.2 Environmental Impact

Sodium carbonate production (required for the molten salt bed) has a lower environmental cost than Portland cement manufacture required in the baseline. Although MSO was excluded from the scope of LCA assessment, its energy consumption falls within the same order of magnitude as the IRIS process; it can therefore be expected that MSO process will have a higher global warming potential than the baseline cementation scenario.

3.2.1.3 Disposability and Long-term Safety

The secondary wastes associated with MSO will consist primarily of wastes from off-gas management. The experimental rig does not have active off-gas handling and there is therefore not a reliable estimate of the volumes of these wastes. Furthermore, the aggressive nature of the salt melt means that the reactor vessel will need periodic replacement. It is not expected that any of the secondary wastes will pose excessive disposability challenges.

3.2.1.4 Implementation

The throughput of the existing rig is approximately 1-3 kg/hr; this is less than the throughput of the IRIS process and would also be significantly below the throughput of a typical cementation plant. However, this apparent weakness is mitigated by the potential for the technology to be scaled-up; its TRL is currently 4-6, and improvements in throughput and treatment capacity are expected to be possible.

In terms of material availability, availability of salts was reported as good, and is not expect to pose an issue.

3.2.1.5 Costs

Waste treatment cost for MSO are driven by facility's construction and licencing costs, which are much higher than under baseline assumptions. The exact extent of this increase cannot be quantified due to the lack of cost data related to the MSO plant.

3.2.2 Scenario 6.2.1 – MSO and Geopolymer Encapsulation

Scenario 6.2.1 consists of the thermal treatment of RSOW using MSO and the encapsulation of the spent salts in a geopolymer. Geopolymer encapsulation of MSO salts has been investigated by a number of partners in PREDIS, although this assessment considers the process developed at CV Řež. The final package is a 200 L drum of geopolymer with a total mass of 366.7 kg and a salt loading of 52 kg (14 wt%). Each 200 L drum of geopolymer encapsulates the ashes of 475 kg of raw waste.

An alternative approach identified in PREDIS consists of converting a fraction of the spent salt to $CaCO_3$, to improve the properties of the geopolymer [5], this approach is not considered here.

3.2.2.1 Operational Safety

The main safety considerations for the scenario are associated with the MSO step reported in Section 3.2.1.1. In addition, the use of alkali activators in geopolymers adds a chemical hazard that is not present in a cementation plant. Apart from this chemical hazard, cementation and geopolymer conditioning present a similar set of conventional health and safety challenges.

Higher waste loadings achieved MSO will result in fewer waste packages that need to be produced, but with comparatively higher specific activities. Whether the balance tilts in favour of the baseline of variant scenario could not be quantified during this task and will depend on facility-specific design and organisational arrangements.

The overall impact on safety of the MSO and geopolymer conditioning route was seen to be ***negative****. The baseline management route is comparatively simpler and requires fewer processing steps and fewer facilities.*

3.2.2.2 Environmental Impact

The metakaolin-based geopolymer was evaluated to have a smaller environmental impact than Portland cement manufacture. In conjunction with the increase in waste loading, this contributes to significantly reducing the environmental burden placed by manufacture of the process materials.

As discussed in Section 3.2.1.2, the energy consumption from the MSO is likely to be comparable to that of the IRIS process and can therefore be expected to dominate the overall environmental impact, and will likely exceed the negative impact of the baseline scenario.

Overall, based on the evidence assembled during the value assessment process, MSO of RSOW followed by geopolymer encapsulation has a ***higher*** *climate change potential than the baseline of compaction and cementation.*

3.2.2.3 Disposability and Long-term Safety

The scenario will inherit the secondary wastes produced by the MSO process identified in Section 3.2.1.3.

The disposability risks associated with the geopolymerised drum are discussed in Appendix 1. The main disposability risks associated with MSO salts in geopolymer relate to the issues with cracking, sodium leaching and salt blooming observed in the experimental part of PREDIS. While the pretreatment of the salt can mitigate a number of these issues, there remains a large amount of uncertainty in the disposability of the salts.

*Overall, the disposability of geopolymer encapsulation of MSO salts is assessed as **worse** compared to the baseline. Disposability risks associated with untreated IERs are removed by the thermal treatment step, but substantial residual uncertainty in the performance of the wasteform under saturated conditions remains.*

3.2.2.4 Implementation

Conditioning of organic waste in geopolymer achieves throughput rates similar to those of cement encapsulation (see Section 3.1.4.4). The main scaling challenge is therefore expected to be associated with the MSO process itself, discussed in Section 3.2.1.4.

*The main strength of the MSO and geopolymer route resides in the reduction in raw material quantities required per kilogram of waste treated. Good material availability was reported. The route's throughput is lower than under baseline assumptions, but this weakness is linked with the lower TRL, and is expected to be easily overcome upon system and process scale-up. Implementation of the novel route is **slightly more difficult** to neutral compared to the baseline.*

3.2.2.5 Costs

Waste treatment and conditioning costs using MSO followed by geopolymer-conditioning are driven by facility costs, which are much higher than under baseline assumptions. The exact extent of this increase cannot be quantified due to the lack of cost data related to the incineration plant.

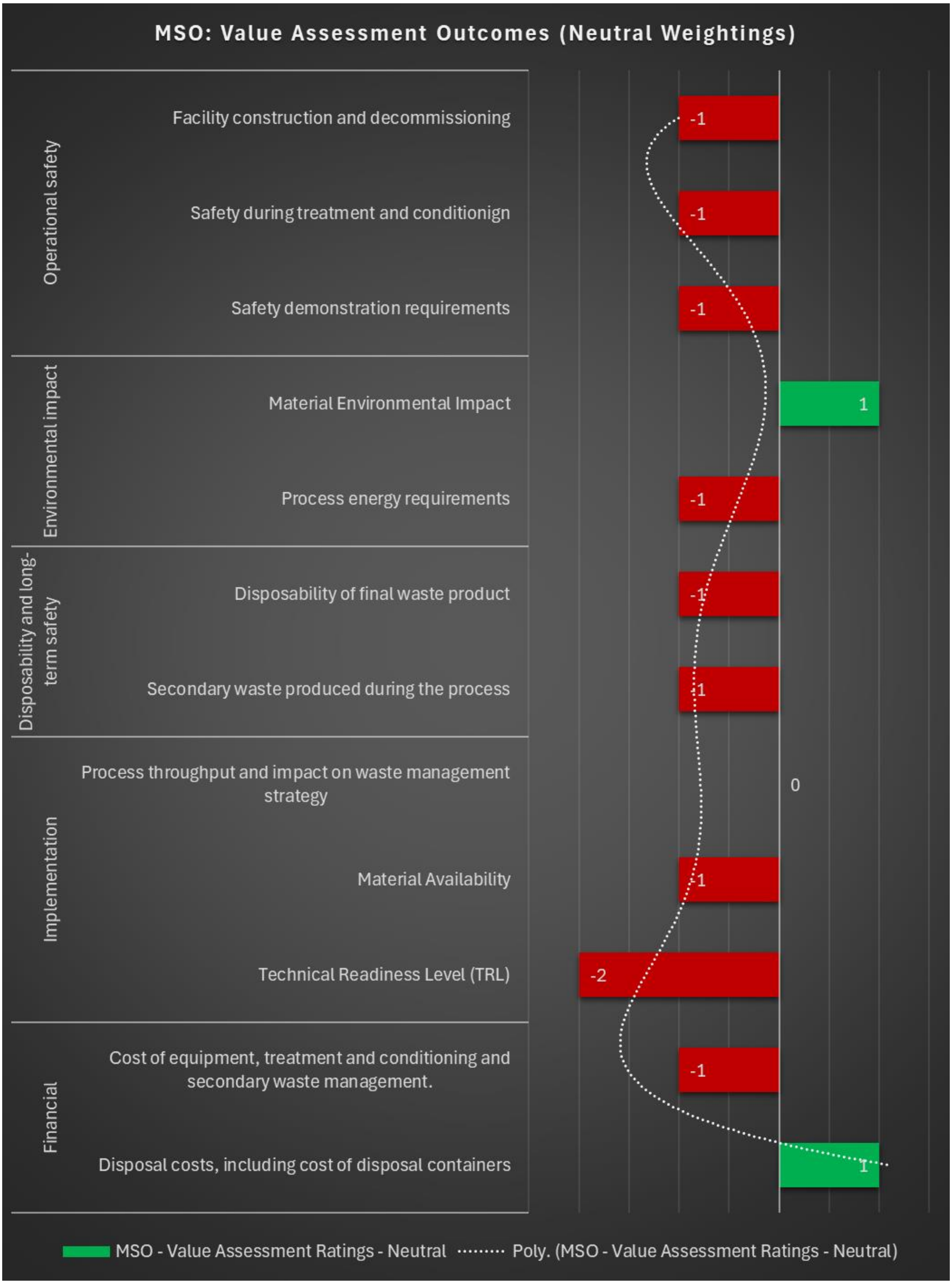
On the other hand, disposal costs are likely to decrease due to the volume reduction associated with the process. In the baseline process, it is estimated that 45 kg of (wet) IER resin is encapsulated per 200 L drum, while the encapsulation of MSO salts in geopolymer results in the production of one 200 L drum per 475 kg of resin.

*The overall economic impact of the novel treatment and conditioning route is difficult to quantify in the absence of facility-related cost data for the MSO step. Having regards to the balance between the need for additional facilities, and the reduction in the number of waste packages compared with the baseline route, the novel route is deemed to be **neutral to slightly beneficial** in terms of cost. This conclusion should be revised if additional cost data becomes available.*

3.2.2.6 Summary

The value assessment results are illustrated in Figure 7.

Figure 7: Value assessment outcomes for the RSOW MSO route



4 Conclusions

An analysis of the economic environmental and disposability impacts of the novel treatment technologies has been undertaken, focusing on a subset of the technologies investigated in PREDIS WP6. The following thermal treatment scenarios were considered:

- **Scenario 6.1.1:** Incineration of mixed organic waste and IERs, HIP of the ashes and consolidation and cementation of the HIPped cans.
- **Scenario 6.1.2: :** Incineration of mixed organic waste and IERs, compaction of the ashes and consolidation and cementation of the pellets.
- **Scenario 6.1.3:** Incineration of mixed organic waste and IERs and encapsulation of the ashes in geopolymer.
- **Scenario 6.2.1:** Molten Salt Oxidation (MSO) of IERs with encapsulation of the spent salts in geopolymer.

Each of these treatment scenarios was considered to produce a 200 L drum suitable for disposal. The value assessment considered the performance of each of these scenarios across a number of criteria in comparison with a baseline consisting of compaction and cementation of mixed waste and direct cementation of IERs.

Overall, it is found that the novel treatment technologies typically provide benefits in terms of material environmental impact, package disposability and the disposal and storage costs for the product drums. This is offset however by the safety and cost impacts of the additional facilities as well as the uncertainties associated with a novel technology. Further development of the new technologies to the point where operating TRL 9 versions of these treatment facilities are available would remove or lessen many of the negatives or uncertainties, in which case they could in future become more sustainable, less costly alternatives. Which technology will perform ‘best’ in any situation will be highly dependent on the context and the priorities driving waste management. The unweighted outcomes presented here may be used at the basis for more specific, context specific evaluations.

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Appendix 1: Assessment of disposability related risks

Scenario 6.1.B – Supercompaction of mixed organics		
Assessment area		**Identified disposability risks**
Physical form		**Concept dependant disposability risk (NS1-2):** Potential negative impact on disposability to shallow near surface as compacted drum or contents may be considered a discrete object within cemented waste package. **Otherwise, no risk:** Cemented drum will be solid.
Mechanical stability		**No risk identified:** Drum and cement have adequate mechanical stability.
Homogeneity		**General disposability risk:** Compacted wasteform is not homogeneous, although this may not be required for this type of wasteform is some disposal concepts.
Dose-rate		**No risk identified:** Annular grouted wasteform provides some shielding. Activity concentration will be comparable to initial waste.
Surface contamination		**No risk identified:** Low potential for external contamination of outer drum.
Specific activity		**No risk identified:** Activity concentration (per kg) slightly lower than that of initial waste.
Radiation, thermal and chemical stability		**General disposability risk:** Organic components of waste in the pucks can undergo degradation under thermal, biological, chemical and radiological processes. Fire performance of the compacted waste itself would be expected to be poor (having the potential to combust and/or melt); the concept relies on containment provided by annular grouted drum (which will have good stability and fire performance).
Package		**No risk identified:** Standard package may be used. Significant confidence in package compatibility with wasteform and performance under impact accidents.
Physically hazardous materials		**Waste dependant disposability risk:** Waste will have to be segregated to remove unacceptable hazardous material. Reactive chemical species (such as combustible gases, acids) may evolve within the package due to degradation of some organic wastes.
Putrescible, fermenting, or infectious material		**Waste dependant disposability risk:** Waste may contain quantities of biodegradable organic material which are unacceptable for some disposal facilities.
Void space		**Waste dependant disposability risk:** Degradation of organic components of waste may result in evolution of void space into package in long term.
Gas generation		**Waste dependant disposability risk:** Degradation of organic components of waste may result of evolution of gases into package in long term. Separation of waste and cement mitigates radiolytic gas generation to an extent. This is less of a concern in concept DG3 as dry conditions are likely to inhibit degradation of organic waste.
Radiological gas generation		**Waste dependant disposability risk:** Potential for gas generation due to degradation of organic waste (releasing C-14 or tritium) in addition to release of radioactive volatiles.
Organic content		**General disposability risk:** Organic components remain in wasteform. Compacted wasteform will be unacceptable to disposal facilities which do not accept organic materials.
Swelling/ shrinkage		**Waste dependant disposability risk:** Some waste constituents may shrink or swell; these constituents may need to be excluded from the package.
Free liquids		**Waste dependant disposability risk:** Some wastes may contain free liquids or evolve them under disposal conditions.
Chelating/ complexing agent		**Waste dependant disposability risk:** The large fraction of cellulose in some mixed organic waste streams can pose an unacceptable disposability risk in some disposal concepts due to the risk of the evolution of chelating agents. These may be a particular problem for near-surface disposal concepts (NS1-3) and DGRs in high strength rock (GD1) where

Scenario 6.1.B – Supercompaction of mixed organics		
Assessment area	**Identified disposability risks**	
		significant migration of radionuclides in groundwater is expected to occur.
Leaching		**General disposability risk:** RSOW is not itself chemically stable, reliance is placed on the barrier provided by the annular grouted drum. **Waste dependant disposability risk:** Evolution of HCl by PVC in mixed organic waste can locally reduce pH and damage or reduce the chemical buffering function of cement. Not a concern for concept DG3 due to dry conditions.
Overall disposability outlook: The primary disposability risks for compacted mixed organic waste arises from the presence of significant untreated organics; depending on the nature of the organics and the assumed disposal conditions, the degradation of these organics can pose a disposability risk in a number of areas. The potential for the compacted drum to be considered a discrete object poses a concept specific disposability risk for concepts NS1 and NS2.		

Scenario 6.1.B – Cement encapsulation of Ion Exchange Resins		
Assessment area		**Identified disposability risks**
Physical form		**No risk identified:** Cementation of IERs results in solid monolithic wasteform.
Mechanical stability		**General disposability risk:** Chemical and physical properties of IERs can adversely impact cement performance. This needs to be managed in wasteform design (waste loading, mixing).
Homogeneity		**No risk identified:** Good mixing between grout and IERs can be achieved by proper process design (e.g. mixing with lost paddles).
Dose-rate		**No risk identified:** Activity concentration will be slightly lower than initial waste due to dilution, however shielding likely to be required for spent IERs.
Surface contamination		**No risk identified:** Expected that process may be designed to mitigate potential for surface contamination.
Specific activity		**No risk identified:** Activity concentration (per kg) slightly lower than that of initial waste.
Radiation, thermal and chemical stability		**General disposability risk:** Radiolytic and biological degradation of IERs in matrix may occur which will adversely impact stability of wasteform. Untreated IERs can also have poor chemical compatibility with OPCs; for example, resins that contain boric acid (arising from PWR primary circuit purification) will adversely affect the setting of cement. Fire performance of IERs themselves is expected to be poor; the concept relies on stability and containment provided by cement matrix.
Package		**No risk identified:** Standard package may be used. Significant confidence in package compatibility with wasteform and performance under impact accidents.
Physically hazardous materials		**General disposability risk:** Combustible gases and acids may evolve within package due to degradation of organic IERs.
Putrescible, fermenting, or infectious material		**No risk identified:** Biological degradation expected to be a component of degradation process for IERs but not a specific issue in itself.
Void space		**General disposability risk:** Degradation of IERs may result of evolution of void space into package in long term.
Gas generation		**General disposability risk:** Degradation of IERs may result of evolution of gases into package in long term. Permeability of waste matrix may be expected to mitigate pressurisation hazard. Less of a concern in concept DG3 as dry conditions are likely to inhibit degradation of organic waste.
Radiological gas generation		**Waste dependant disposability risk:** Potential for gas generation due to degradation of organic resin constituents (releasing C-14 or tritium) in addition to release of radioactive volatiles.
Organic content		**General disposability risk:** Organic components remain in wasteform. Cemented wasteform will be unacceptable to disposal facilities which do not accept organic materials.
Swelling/ shrinkage		**General disposability risk:** Dehydration and rehydration of ion exchange resins and associated shrinking and swelling can potentially result in disintegration of wasteform.
Free liquids		**General disposability risk:** IERs arise wet, requiring dewatering prior to management. Free liquids may be evolved by degradation of IERs.
Chelating/ complexing agent		**Waste dependant disposability risk:** Some IER waste streams contain chelating agents (such as EDTA). There is also the potential for the degradation of IERs to produce chelating agents. These may be a particular problem for near-surface disposal concepts (NS1-3) and DGRs in high strength rock (GD1) where significant migration of radionuclides in groundwater is expected to occur.

Scenario 6.1.B – Cement encapsulation of Ion Exchange Resins		
Assessment area	**Identified disposability risks**	
Leaching		**General disposability risk:** Radionuclides may be leached from IERs due to the presence of more favourable ions in contacting water (e.g. calcium, sodium) or degradation (chemical, biological, radiolytic). There is also the potential for the evolution of acids which can locally reduce pH and reduce the chemical buffering function of cement. Not a concern for concept DG3 due to dry conditions.
Overall disposability outlook: The primary disposability risks for cemented IERs relate to the presence of untreated IERs in the wasteform which poses a disposability risk in a number of areas. Key concerns include the incompatibility of IERs with the cement wasteform as well as the long-term evolution of the IERs in contact with water.		

Scenario 6.1.1 – Incineration, HIP of ashes and cementation		
Assessment area		**Identified disposability risks**
Physical form		**Concept dependant disposability risk (NS1-2):** Potential negative impact on disposability to shallow near surface as HIPped can may be considered a discrete object within the cemented waste package. **Otherwise, no risk:** HIP product expected to be homogeneous monolith, with no loose powders.
Mechanical stability		**No risk identified:** HIPped can itself is a compacted product, expected to have good load-bearing capacity. Issues might arise from can/grout interactions or cracking
Homogeneity		**No risk identified:** Phase separation is not a concern given HIP is a powder process (no liquids present).
Dose-rate		**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification. The annular grouted drum into which the HIPped cans are consolidated will provide several cm of concrete shielding.
Surface contamination		**No risk identified:** HIP cans provide good containment of waste once sealed. Surface contamination is not expected to be an issue.
Specific activity		**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification.
Radiation, thermal and chemical stability		**Risk to disposability due to uncertainty:** The properties of the product are very contingent on the properties of the wastestream, although the HIPped product is likely to have good radiation, thermal and chemical stability. There may be poor compatibility with the high pH conditions associated with cementitious porewater. There is uncertainty in the long-term stability of the HIPped product; this risk is most acute for concepts ID1 and GD1-2 due to the need for long term stability under saturated conditions.
Package		**Risk to disposability due to uncertainty:** It is assumed HIP cans will be consolidated into a standard package (e.g. 200 L drum) and grouted. The consolidation and grouting process would have to be developed to mitigate the risk of the grout cracking around HIPped cans. **Otherwise, no risk:** No issues with size, weight, or impact accidents anticipated.
Physically hazardous materials		**No risk identified:** Thermal treatment expected to destroy most physically hazardous (flammable, explosive, corrosive) materials. The HIP can may pressurise during treatment if moisture is not removed from ashes prior to treatment; this risk can be eliminated in process design (e.g. vacuum drying prior to HIP).
Putrescible, fermenting, or infectious material		**No risk identified:** Thermal treatment expected to destroy any biological material.
Void space		**No risk identified:** Wasteform is not compressible, components likely to degrade will have been destroyed by thermal treatment. Voidage in package will be comparable to that in cementation of bulk solid waste.
Gas generation		**No risk identified:** Gas generation will be waste dependant, although it is expected that waste components likely to evolve gases will have been removed by thermal treatment so there will only be a small component of radiolytic gas generation. HIP can will present barrier to gas migration, although this is not expected to present a pressurisation risk given the relatively low gas volumes which would be generated.
Radiological gas generation		**Waste dependant disposability risk:** Radiological gas generation will be waste dependant, although it is expected waste with large quantities of tritium, C-14 or radioactive volatiles are likely to be unsuitable for thermal treatment.
Organic content		**No risk identified:** Organic content of waste destroyed by the thermal treatment step.
Swelling/ shrinkage		**General disposability risk:** Radiation damage could cause ceramic swelling, expansive corrosion of the metal HIP can is also possible. These effects could result in cracking of

Scenario 6.1.1 – Incineration, HIP of ashes and cementation		
Assessment area	**Identified disposability risks**	
		wasteform.
Free liquids		**No risk identified:** Free liquids in waste eliminated by thermal treatment. Conditioning process not expected to create significant free liquids.
Chelating/ complexing agent		**No risk identified:** Organic chelating or complexing agents will be destroyed by the thermal treatment step.
Leaching		**No risk identified:** PREDIS has demonstrated low leach rates and no water-soluble species would be expected to be present.
Overall disposability outlook: The main disposability risks relating to ashes in HIP relate to the potential increase in waste package classification (due to concentration of activity) and uncertainty in the long-term performance of the disposal package. The potential for the HIPped can to be considered a discrete object poses a concept specific disposability risk for concepts NS1 and NS2. Overall HIPping is given a Value Assessment rating of +2 as compared to the baseline due to the mitigation of a number of the risks associated with untreated organics. **Value Assessment Rating:** +2		

Scenario 6.1.2 – Incineration, compaction of ashes and cementation	
Assessment area	**Identified disposability risks**
Physical form	**Concept dependant disposability risk (NS1-2):** Potential negative impact on disposability to shallow near surface as compacted pellets may be considered discrete objects within the cemented waste package. **Otherwise, no risk:** Compacted pellets are solid.
Mechanical stability	**Risk to disposability due to uncertainty:** Will be a need to demonstrate compacted ashes will not revert to a powder form over time or under stress and otherwise meet mechanical requirements. Drum and grout may be relied upon to provide some structural strength.
Homogeneity	**No risk identified:** Mixing and grinding ensures good homogeneity prior to compaction. Phase separation is not a concern given compaction is a powder process.
Dose-rate	**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification. The annular grouted drum into which the pellets are consolidated will provide several cm of concrete shielding.
Surface contamination	**No risk identified:** Ash/dust dissemination hazard following thermal treatment may contribute to potential surface contamination, although this is expected to be handled in process design.
Specific activity	**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification.
Radiation, thermal and chemical stability	**Risk to disposability due to uncertainty:** Stability is expected to be good, however there is outstanding risk due to lack of long-term stability tests for this wasteform. This risk is most acute for concepts ID1 and GD1-2 due to the need for long term stability under saturated conditions.
Package	**Risk to disposability due to uncertainty:** It is assumed pellets will be consolidated into a standard package (e.g. 200 L drum) and grouted. The consolidation and grouting process would have to be developed to mitigate the risk of the grout cracking around pellets. **Otherwise, no risk:** No issues with size, weight, or impact accidents anticipated.
Physically hazardous materials	**No risk identified:** Thermal treatment expected to destroy most physically hazardous (flammable, explosive, corrosive) materials.
Putrescible, fermenting, or infectious material	**No risk identified:** Thermal treatment expected to destroy organic materials no risk in this category.
Void space	**No risk identified:** Wasteform is not compressible, components likely to degrade will have been destroyed by thermal treatment. Voidage in package will be comparable to that in cementation of bulk solid waste.
Gas generation	**No risk identified:** Gas generation will be waste dependant, although it is expected that waste components likely to evolve gases will have been removed by thermal treatment so there will only be a small component of radiolytic gas generation. Wasteform matrix expected to be gas permeable and this will mitigate the pressurisation hazard.
Radiological gas generation	**Waste dependant disposability risk:** Radiological gas generation will be waste dependant, although it is expected waste with large quantities of tritium, C-14 or radioactive volatiles are likely to be unsuitable for thermal treatment.
Organic content	**No risk identified:** Organic content of waste destroyed by the thermal treatment step.
Swelling/ shrinkage	**No risk identified:** No swelling or shrinking issues are anticipated.

Scenario 6.1.2 – Incineration, compaction of ashes and cementation		
Assessment area	**Identified disposability risks**	
Free liquids		**No risk identified:** Free liquids in waste eliminated by thermal treatment. Conditioning process not expected to create significant free liquids.
Chelating/ complexing agent		**No risk identified:** Organic chelating or complexing agents will be destroyed by the thermal treatment step.
Leaching		**Risk to disposability due to uncertainty:** It is expected that the leaching rate would be relatively low for typical ashes as these are expected to be composed primarily of oxides (noting no chemical alterations occur during compaction). However, leaching tests have not been undertaken in PREDIS on this wasteform. This is not a concern for concept DG3 due to dry conditions.
Overall disposability outlook: The main disposability risks relating to compaction of incinerations ashes relate to the potential increase in waste package classification (due to concentration of activity) and uncertainty in the long-term performance of the wasteform. The potential for the pellets to be considered discrete objects poses a concept specific disposability risk for concepts NS1 and NS2. Overall compaction is given a Value Assessment rating of +1 as compared to the baseline due to the mitigation of a number of the risks associated with untreated organics offset by the relatively large uncertainty about the long-term performance. **Value Assessment Rating:** +1		

Scenario 6.1.3 – Incineration and conditioning of ashes in geopolymer	
Assessment area	**Identified disposability risks**
Physical form	**No risk identified:** Geopolymer encapsulation produces a solid monolith.
Mechanical stability	**No risk identified:** Geopolymers have been shown to have adequate compressive strength and to have good performance under thermal cycling.
Homogeneity	**No risk identified:** Achievable homogeneity is dependent on the waste type and particle size, good homogeneity has been achieved for ashes in PREDIS.
Dose-rate	**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification. Wasteform provides a small amount of self-shielding.
Surface contamination	**No risk identified:** Ash/dust created following thermal treatment may contribute to potential surface contamination. Expected that process may be designed to mitigate this.
Specific activity	**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification.
Radiation, thermal and chemical stability	**Risk to disposability due to uncertainty:** There may be some compatibility issues with geopolymers and standard Portland type cements and there is a lack of evidence supporting the long-term stability of geopolymers under disposal conditions. This risk is most acute for concepts ID1 and GD1-2 due to the need for long term stability under saturated conditions. **Otherwise, no risk:** Geopolymer demonstrated to have good stability, including for alkaline conditions, under thermal cycling and for fire scenarios.
Package	**Risk to disposability due to uncertainty:** Further development work expected to be required for these geopolymer formulations to demonstrate that there are no adverse wasteform/container interactions or cracking during curing. **Otherwise, no risk:** Process for filling of a standard package (e.g. 200 L drum) with geopolymer expected to be comparable to standard cementation processes. No issues with size, weight, or impact accidents anticipated.
Physically hazardous materials	**No risk identified:** Thermal treatment expected to destroy most physically hazardous (flammable, explosive, corrosive) materials.
Putrescible, fermenting, or infectious material	**No risk identified:** Thermal treatment expected to destroy any biological material.
Void space	**No risk identified:** Wasteform is not compressible, components likely to degrade will have been destroyed by thermal treatment. Voidage in package will be comparable to that in normal cementation (i.e. expect only some nominal ullage space).
Gas generation	**No risk identified:** Gas generation will be waste dependant, although it is expected that waste components likely to evolve gases will have been removed by thermal treatment so there will only be a small component of radiolytic gas generation. Geopolymers are gas permeable and this will mitigate the pressurisation hazard.
Radiological gas generation	**Waste dependant disposability risk:** Radiological gas generation will be waste dependant, although it is expected waste with large quantities of tritium, C-14 or radioactive volatiles are likely to be unsuitable for thermal treatment.
Organic content	**No risk identified:** Organic content of waste will be destroyed by the thermal treatment step. Trace organics would be present in precursor powders, although not in sufficient quantities to be of concern.
Swelling/ shrinkage	**No risk identified:** No swelling or shrinking issues observed with geopolymer encapsulated ashes. No long-term issues anticipated.
Free liquids	**No risk identified:** Free liquids in the waste stream are removed by thermal treatment. Geopolymer should not create free liquids (e.g. "bleed water") during curing if properly

Scenario 6.1.3 – Incineration and conditioning of ashes in geopolymer		
Assessment area	**Identified disposability risks**	
		formulated.
Chelating/ complexing agent		**No risk identified:** Organic chelating or complexing agents will be destroyed by the thermal treatment step. No potential chelating or complexing agents (e.g. surfactants) need to be used in geopolymer formulations targeting ashes.
Leaching		**No risk identified:** Expect geopolymer to provide good containment of radionuclides; work within PREDIS has demonstrated low leach rates. Some leaching of sodium (one of the main matrix constituents) observed, analogous to behaviour of calcium in OPCs; this is expected not to be a concern.
Overall disposability outlook: The main disposability risks relating to the conditioning of ashes in geopolymer relate to the potential increase in waste package classification (due to concentration of activity) and uncertainty in the long-term performance of the disposable package (although less uncertainty as compared to compaction of ashes due to the tests undertaken in PREDIS). Overall Geopolymer encapsulation is given a Value Assessment rating of +2 for disposability as compared to the baseline due to the mitigation of a number of the risks associated with untreated organics. **Value Assessment Rating: +2**		

Scenario 6.2.1 – MSO and encapsulation of spent salts in geopolymer		
Assessment area		**Identified disposability risks**
Physical form		**No risk identified:** Geopolymer encapsulation produces a solid monolith.
Mechanical stability		**No risk identified:** Work within PREDIS has demonstrated that adequate compressive strength is achievable for geopolymer encapsulated spent MSO salts.
Homogeneity		**No risk identified:** Achievable homogeneity is dependent on the waste type and particle size, good homogeneity has been achieved for MSO salt in PREDIS.
Dose-rate		**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification. Wasteform provides a small amount of self shielding.
Surface contamination		**No risk identified:** Expected that process may be designed to mitigate potential for surface contamination.
Specific activity		**General disposability risk:** Thermal treatment will result in activity concentration and potentially higher classification.
Radiation, thermal and chemical stability		**Risk to disposability due to uncertainty:** Geopolymers generally have good stability under thermal cycling and for fire scenarios. There may however be some compatibility issues with standard Portland type cements and there is a lack of evidence supporting the long-term stability of geopolymers under disposal conditions. Chemical stability for MSO salts (Na_2CO_3) in geopolymer may not be good in an aqueous environment; work in PREDIS has shown issues with mechanical stability and confinement of the MSO salts (although some of these issues may be mitigated by pretreatment of the salt). The disposability risk is most acute for concepts ID1 and GD1-2 due to the need for long term stability under saturated conditions.
Package		**Risk to disposability due to uncertainty:** Process for filling of standard package (e.g. 200 L drum) with geopolymer would be consistent with cement. No issues with size, weight, or impact accidents anticipated. Further development work expected to be required for these geopolymer formulations to demonstrate that there are no adverse wasteform/container interactions or cracking during curing.
Physically hazardous materials		**No risk identified:** Thermal treatment expected to destroy most physically hazardous (flammable, explosive, corrosive) materials.
Putrescible, fermenting, or infectious material		**No risk identified:** Thermal treatment expected to destroy any biological material.
Void space		**No risk identified:** Wasteform is not compressible, components likely to degrade will have been destroyed by thermal treatment. Voidage in package will be comparable to that in normal cementation (i.e. expect only some nominal ullage space).
Gas generation		**No risk identified:** Gas generation will be waste dependant, although it is expected that waste components likely to evolve gases will have been removed by thermal treatment so there will only be a small component of radiolytic gas generation. Geopolymers are gas permeable and this will mitigate any pressurisation hazard.
Radiological gas generation		**Waste dependant disposability risk:** Radiological gas generation will be waste dependant, although it is expected waste with large quantities of tritium, C-14 or radioactive volatiles are likely to be unsuitable for thermal treatment.
Organic content		**No risk identified:** Organic content of waste will be destroyed by the thermal treatment step. Trace organics would be present in precursor powders, although not in sufficient quantities to be of concern.
Swelling/ shrinkage		**General disposability risk:** The carbonate salts in the wasteform swell when hydrated, which can result in cracking of the wasteform, this can be mitigated to an extent by pre-

Scenario 6.2.1 – MSO and encapsulation of spent salts in geopolymer		
Assessment area	**Identified disposability risks**	
		treatment of the salt. This would not be of concern for the dry environment in concept GD3.
Free liquids		**No risk identified:** Free liquids in the waste stream are removed by thermal treatment. Geopolymer should not create free liquids ("bleed water") during curing if properly formulated.
Chelating/ complexing agent		**General disposability risk:** Organic chelating/complexing agents or components which may evolve them (such as cellulose) are likely to have been destroyed by thermal treatment but carbonate (from MSO salts) can act as a complexing agent for elements such as uranium. This would not be of concern for the dry environment in concept GD3.
Leaching		**General disposability risk:** Significant leaching of sodium was observed in lab tests resulting in the deterioration of the wasteform (this may be mitigated to an extent by pretreatment of the salt). This would not be of concern for the dry environment in concept GD3.
Overall disposability outlook: The primary disposability risks associated with MSO salts in geopolymer relate to the issues with cracking, sodium leaching and salt blooming observed in the experimental part of PREDIS. Overall Geopolymer encapsulation of MSO salts is given a Value Assessment rating of -1 for disposability compared to the baseline due to the significant outstanding risks associated with the long term performance of the wasteform in an aqueous environment. Work within PREDIS has demonstrated that a number of disposability risks may be mitigated by the pretreatment of the salt, which may improve this rating given further development. **Value Assessment Rating: -1**		

APPENDIX 2: VALUE ASSESSMENT CRITERIA: BOUNDARIES, EXCLUSIONS AND RATIONALE

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
Cross-cutting	Impact of incineration stage	Volume of secondary waste (m^3) Volume reduction factors Operational safety risks	IRIS process used as representative incineration facility. Co-located with facilities for further treatment and conditioning.	The safety, environmental, and cost impact of adding an incineration stage compared to the baseline was deemed complex and there was a risk that discussions would be repeated or that an inconsistent approach would be used across the assessment. This is therefore included as a cross-cutting criterion. It is included here for discussion (no rating) and to agree on the scale of the impacts and on any additional boundaries and exclusions. Discussing this incineration stage at the beginning and in one go should enable the panel to easily identify which criteria are affected, and the scale of the impact throughout the assessment. This cross-cutting criterion provides a unique point of reference that ensures consistency across the assessment. In line with the assumption made in WP5 (which is relatively consistent with the assumed distance of 100 km made in the LCA/LCC models), the incineration facility is assumed to be co-located with the processes studied in WP6.	All.

[6] Considerations around the impact on planning activities are included within the respective waste management steps and are not detailed separately. Treatment and conditioning are considered together (unless otherwise stated) to allow comparison between one and two-step processes: considering treatment and conditioning provides comparable entry and exit points into the assessment of a given criterion.

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
	Waste loading	Number of packages /m^3 of waste. Waste loadings (%vol).	From raw waste to waste package ready for disposal (assumption: standard 200 L drum). Excluding any overpack used in the disposal concept.	Waste loading is one of the main differentiators between compaction and direct cementation and incineration and further treatment and conditioning. The resulting change in package numbers has the potential to impact all the other areas. Disposal concepts vary between countries, with varying needs for and designs of overpacks. This is therefore excluded from this criterion to remove country-specific dependencies.	All.
Operational safety	Facility construction and decommissioning	Size of the facility. Recorded H&S accidents during construction. Judgement on facility complexity.	Excluded from this assessment.	Facilities for absorption and cementation, and facilities used for direct conditioning of RLOW are similar in nature and size and involve similar processes and equipment. Facilities for incineration are not novel in nature, and there is extensive operational experience. Their construction and decommissioning are therefore anticipated to result in similar health and safety risk levels compared to the direct encapsulation route. Therefore, this criterion was not judged to be a differentiator.	NA
	Safety during pre-treatment operations	Shielding requirements. Operator dose rates. Sorting and segregation requirements.	Excluded from this assessment.	Since the baseline scenario is constructed around a one step process, including this criterion would result in a de facto negative rating. Thus, the pre-treatment step of the variant scenario (incineration) would not be compared against the baseline, but against itself. It is therefore proposed that this criterion is excluded, and that operational safety be assessed as a whole, considering the treatment and conditioning steps together.	NA

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
	Safety during treatment and conditioning	Shielding requirements. Operator dose rates. Known or anticipated operational issues. Number of treatment and conditioning steps. Number of packages (waste loading).	Includes radiological and conventional safety. Includes transport impact.	Issues such a conventional safety, concentration of radionuclide activity, and radiation protection are relevant and differentiating between the baseline and variant processes. Anticipated differences in the number of process steps and in waste loading support this conclusion.	Treatment and conditioning.
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.	Excludes disposability considerations (dedicated set of criteria below). Includes impact of transboundary transport.	Regulatory requirements in terms of permitting and/or licensing play a significant role in the emergence and implementation of novel technologies. The ability of the variant scenarios to meet regulatory requirements, and the ability of facility operators to assemble the safety demonstration are therefore deemed differentiating. Such demonstrations are necessary for new facilities and processes and are therefore relevant to this assessment. The impact of transboundary waste transport to a centrally locally incinerator is included in the assessment of this criterion (e.g. ease of obtaining transboundary transport permits).	Treatment and conditioning.

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
Environmental impacts	Material Environmental Impact	Known environmental impact of material excavation (qualitative). Calculated in LCA. Calculated (LCA) energy requirements for material manufacture and/or excavation. Number of waste packages (waste loading). Material requirements of alternative treatment options.	Includes the environmental impact (incl. energy use) of material manufacture, for all materials feeding into the process (e.g. HIP can, geopolymer)	The environmental impact of material manufacture is calculated in the LCA and is a differentiator of particular relevance when considering the potential benefits or weaknesses of the variant scenarios.	Treatment and conditioning.
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Including impact of transboundary transport.	Process energy requirements are calculated in the LCA and are a differentiator of particular relevance when considering the potential benefits or weaknesses of the variant scenarios. The impact of transporting waste to a centralised incineration facility is included.	Treatment and conditioning.
Disposability / long-term safety	Secondary waste produced during the process	Type and quantity of secondary waste. Known and/or existing management routes for secondary waste, including its disposability.	Includes interim management, existing disposability assessments and regulatory approvals.	The ease of and technological readiness for managing secondary waste is an important factor in evaluating the viability of any new waste management technology. This is therefore included in the assessment.	Treatment and conditioning. Disposal
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.	For discussion only. Disposability is considered in the disposability assessment part of D6.3.	Disposability of the final waste product is a significant factor in evaluating any new waste management technology. The disposability assessment is running in parallel to value assessment.	Disposal

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
Implementation	Process throughput and impact on waste management strategy	Full-scale facility throughput (m^3 of waste processed per unit time). Experimental facility throughput and estimated ease of scale-up. Inventory of waste for treatment and conditioning. Other implementation considerations (e.g. anticipated issues during scale-up, throughput-limiting steps).	Includes transboundary transport impact. Excludes TRL considerations (accounted for in dedicated criterion).	Depending on the waste inventory for treatment and conditioning, process throughput may play a significant role in this evaluation. Identification of the rate-limiting step is an important part of process optimisation and scale-up and will inform the choice of technology and waste management strategy adopted for a particular RSOW type. Scaling-up variant processes from laboratory to industrial scale usually comes with a number of challenges. Based on this set of considerations, this criterion is considered to be differentiating and is included for evaluation.	Treatment and conditioning.
	Material availability	Known and/or anticipated issues in sourcing materials, including considerations of material purity and consistency. Waste loading / number of waste packages.	Excluding financial considerations (dedicated criterion below).	The availability of raw materials and/or systems and components needed for the variant processes and facilities is an important factor in evaluating process viability. It may also impact on the facility's throughput if material availability becomes the limiting factor. This criterion is therefore included for evaluation. Note that it is excluded from the scope of the HIP evaluation.	Treatment and conditioning.
	Technical Readiness Level (TRL)	TRL (1-9).	Incineration process assumed to have TRL 9.	TRL is an internationally recognised and accepted way of measuring the technical readiness of a technology. TRL levels are well documented and are used within EC-projects to evaluate technologies and progress in research and development activities. This criterion is therefore included for evaluation.	Treatment and conditioning.

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[6]
Financial	Cost of facility and of treatment and conditioning.	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed. Waste loading.	Including construction and decommissioning costs if available. Including costs HIP cans or any sacrificial containers. Includes transboundary transport impact (if provided by LCC).	The cost of building, decommissioning, and operating facilities is a significant driver in implementing technical changes. Material and process costs are added to yield the cost of waste processing, per unit volume or mass. Such cost reductions are of particular importance to member states and to the End-Users and are calculated by the LCC. This criterion is therefore included for evaluation.	Treatment and conditioning.
	Material costs	Calculated cost of materials (LCC).	Including costs HIP cans or any sacrificial containers. Includes transboundary transport impact (if provided by LCC).	Material costs are accounted for under the criterion above and are therefore not evaluated separately to prevent double counting. This criterion is therefore excluded from the assessment but is accounted for under “cost of facility and of treatment and conditioning”.	NA
	Cost of secondary waste management	Cost of secondary waste management per m^3 of waste.	Including treatment, conditioning, and disposal. Excluding transport. Excluding storage.	Secondary waste management costs will impact final waste management costs and are therefore included for consideration in this evaluation. This criterion will be evaluated together with facility, treatment, and conditioning costs because secondary waste management is an integral part of the treatment and conditioning process: cost data provided by project partners is often inclusive of all the stages of treatment and conditioning, including secondary waste management (or, if excluded, the data provided pointed towards the same degree of difference against the baseline). This prevents double-counting financial benefits.	Treatment and conditioning (considered as one). Disposal
	Disposal costs, including cost of disposal containers	Cost of disposal containers. Total volume of waste to be disposed of (waste loading).	Excluding transport. Excluding storage.	Disposal costs, and the cost of associated facilities play an important role in decision making related to waste management strategies. This is calculated by the LCC. This criterion is therefore included for evaluation.	Disposal

Appendix 3: Value Assessment Tables

HIP

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Cross cutting	Impact of initial thermal treatment step	No thermal treatment step	IRIS process [8]: • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. • Primary waste consists of ashes and dust. Factor of 30 reduction in mass compared to raw waste. • Secondary wastes - liquid effluents, HEPA filters, kiln metal bar[7].	Volume reduction – positive impacts on storage and conditioning costs, raw material requirements for subsequent steps (drums, cement, etc).	Volume reduction reduces disposal costs. Destruction of organics may have positive impact on disposability (waste stream dependant).	Additional design construction and decommissioning of treatment facility. Additional secondary wastes requiring management. Additional process step adds to safety demonstration burden. Additional exposures due to additional process steps. Waste product (ashes) presents particulate dissemination risk.	None	Crosscutting: no rating assigned.

[7] See “secondary waste” criterion for detailed secondary waste quantities.

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
	Waste loading	IRIS equivalent package[8] (1/3 IXR, 2/3 Mixed waste): • 107 kg/drum (26 %wt) • 414 l/drum	Waste loading per drum- Ash[9]: • 52 kg/drum (11 %wt) • 260 l/drum (uncompacted) Raw waste*: • 1316 kg/drum • 5084 l/drum *IRIS process results in a factor 30 mass reduction compared to raw waste. Neglect secondary waste.	Thermal treatment results in significant volume reduction relative to baseline. Largest benefits realised for IXR which have low waste loading in baseline.		None	None	Crosscutting: no rating assigned.
Operational safety	Facility construction and decommissioning	Cementation plant	IRIS • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. HIP • Can-packing station • Bakeout oven • Welding station • HIP rig. • Cementation facilities	Volume reduction due to thermal treatment means smaller scale conditioning facilities required. HIP rig & cementation facilities likely to remain relatively clean as HIP provides containment.	NA	Additional facilities required. Dust dissemination hazard may require process steps to be undertaken in containment (gloveboxes). There is scope for HIP rig and cementation facility to be outside containment (requiring HIP can to fulfil containment function). Potential for HIP can failure (low probability) needs to be accounted for in safety demonstration and facility design.	Larger volume of decommissioning wastes (due to more facilities). Dust dissemination may mean equipment has higher radiological classification than decommissioning waste from baseline.	-2

[8] Data based on IXR and mixed waste loading for 200 L drums from *OPERA-PG-COV023* and *OPERA-PU-NRG1112B*. Derivation in spreadsheet *VA_baseline_values_derivation_Issue_1.xlsx*

[9] Data based on the values provided for LCA and VA. Derivation in spreadsheet *WP6_LCA_Inputs_VA_workshop_values.xlsx*

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Safety during treatment and conditioning	Shielding can be used by operators if necessary (for waste with high dose rates). Criticality risk (PCM).	(IRIS and HIP) Particulate dispersion risk– must be managed by classical static & dynamic confinement. In principle ashes can be received to HIP directly following IRIS. Criticality risk (PCM). [UoS] – Currently handled manually. HIP cans can be procured directly.	Higher waste loading per package cancels out for this category; less packages but correspondingly higher dose.	NA	Additional exposure opportunities due to additional process steps. Particulate dispersion risk during and following IRIS. Dispersion risk mitigated once ashes are sealed in HIP can. [UoS] - Additional risks linked to pressurised equipment and welding and asphyxiation (argon).	NA	-1
	Safety demonstration requirements	Safety cases and necessary regulatory approvals are in place for existing and operating facilities.	Safety cases and necessary regulatory approvals in place for IRIS type process. Safety case for an industrial-scale HIP facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed.	The Active Furnace Isolation Chamber (AFIC) system is used when HIPing in an active environment. Mitigates risk associated with can failure. => UoS to provide additional details on AFIC.	NA	(IRIS) Additional burden due to the existence of several steps. (HIP) The process will require a safety demonstration, with associated time and effort requirements. To date no HIP facility has been built for radioactive waste consolidation. Activity concentration may lead to upgrade in waste categorisation.	NA	-1

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Environmental impact	Material Environmental Impact	Material inputs consist of cement and 200 l drums.	Material inputs consist of HIP cans, 200 l drums, cement and glass former (optional ~5 wt% of ash).	Volume reduction due to thermal treatment results in significantly less cement per unit waste.	NA	Further environmental impact data will become available upon completion of the LCA. Steel production feeding into HIP cans has a significant impact.	NA	-2 (doesn't account for thermal treatment step).
	Process energy requirements	Awaiting LCA results.	(IRIS) Expect significantly higher process energy requirements compared to baseline. (HIP) higher energy use compared to baseline.		NA	(IRIS +HIP) Expect significantly higher process energy requirements compared to baseline. => confirmed by preliminary LCA results. Argon production is energy intensive.	NA	-2

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Disposability and long-term safety	Secondary waste produced during the process	Housekeeping waste	(IRIS) •1 m^3 of liquid effluents (sodium-contaminated liquids) are generated for every 200 kg of waste incinerated. •The IRIS incinerator has one HEPA filter, changed every 1000 kg of waste incinerated. •The rotary kiln metal bar (Inconel), weighing approx. 10kg, is changed for every 4000 kg of waste incinerated [17]. (HIP) Housekeeping waste. Small volume of (inactive) argon gas escapes from recycling system.	N/A		(IRIS) More secondary waste produced as compared to baseline. (HIP) Expect lower relative volume of housekeeping waste for conditioning process due to reduced number of drums. [Note] – Argon gas is insulated from activity (only used to apply pressure).		0
	Disposability of final waste product	For discussion only.	For discussion only.	NA	Awaiting disposability assessment results. HIP Can can be considered as a disposal container in itself.	NA	Awaiting disposability assessment results	(Discussed)

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Implementation	Process throughput and impact on waste management strategy	Assume throughput to be limited by waste availability.	(IRIS) continuous process 4-7kg/hr. It has to be operated in 2x8 or 3x8 shifts. (HIP) Current pilot rig (at NNL) expected to be large enough to manage IRIS throughput.	[NNL] – Belief is that HIP throughput will be able to match that of the incineration step. Majority of supporting equipment is standard (welding, can production). Only potential challenge to scale-up is the HIP process itself. Opens up new treatment and conditioning avenues. Versality of HIP process (also applicable to PCM treatment and conditioning) needs to be taken into account: facility may be used for a variety of waste streams, reducing relative capital cost.	NA	NA	NA	0
	Technical Readiness Level (TRL)	9	(IRIS-mixed waste) 9 (IRIS-IXR) 8 (HIP) 4-6	HIP facility being built in Australia is another step up (scale up) compared to NNL/UoS facility	NA	Low TRL (4-6) compared to baseline (9).	NA	-1

6.1.1 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Financial	Cost of facility and of treatment and conditioning and cost of secondary waste management.	Construction of conditioning facility. Cost per package for waste loading of 14vol% (IXR) 44vol% (mixed waste).	Construction of thermal treatment, effluent treatment and HIP facilities. Cost per package for waste loading 14 wt% ashes.	There will be fewer waste packages produced due to the increased waste loading, leading to a reduction in cost directly proportional to the waste loading difference.	NA	Additional plant (with associated construction and decommissioning costs) required compared to baseline due to additional process steps. Additional secondary waste management required.	NA	-2 (pending discussion with NNL re: facility cost).
	Disposal costs, including cost of disposal containers	IXR (wet): 14 %wt (14%vol) Mixed organics: 34 %wt (44%vol)	Ash: Waste loading up to 14 %wt (IRIS process results in a factor 30 mass reduction compared to raw waste).	NA	Disposal cost will be reduced in line with the increase in waste loading between scenario 6.1 and the baseline. Direct use of HIP can as disposal container may further reduce disposal cost.	NA	Potential increased in radiological classification.	+1

Compaction

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Cross cutting	Impact of initial thermal treatment step	No thermal treatment step.	IRIS process: • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. • Primary waste consists of ashes and dust. Factor of 30 reduction in mass compared to raw waste. • Secondary wastes - liquid effluents, HEPA filters, kiln metal bar.	Volume reduction – positive impacts on storage and conditioning costs, raw material requirements for subsequent steps (drums, cement, etc).	Volume reduction reduces disposal costs. (waste stream dependant) Destruction of organics may have positive impact on disposability.	Additional design, construction and decommissioning of treatment facility. Additional secondary wastes requiring management. Additional process step adds to safety demonstration burden. Additional exposures due to additional process steps. Waste product (ashes) presents particulate dissemination risk. Cost of licencing a thermal treatment facility.		Cross cutting. No rating assigned.
	Waste loading	IRIS equivalent package[10] (1/3 IXR, 2/3 Mixed waste): • 107 kg/drum (26 %wt) • 415 l/drum	Waste loading per drum- Ash[11]: • 160 kg/drum (39 %wt) • 800 l/drum (uncompacted) Raw waste equivalent*: • 4054 kg/drum	Thermal treatment results in significant volume reduction relative to baseline. Largest benefits realised for IXR which have low waste loading in baseline.		None	None	Cross cutting. No rating assigned.

[10] Data based on IXR and mixed waste loading for 200 L drums from *OPERA-PG-COV023* and *OPERA-PU-NRG1112B*. Derivation in spreadsheet *VA_baseline_values_derivation_Issue_1.xlsx*

[11] Data based on the values provided for LCA and VA. Derivation in spreadsheet *WP6_LCA_Inputs_VA_workshop_values.xlsx*

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
			(993%wt) • 15655 l/drum *IRIS process results in a factor 30 mass reduction compared to raw waste. Neglect secondary waste.					
Operational safety	Facility construction and decommissioning	Cementation plant	IRIS • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. Compaction • Mixing (expect drum scale vessel to be sufficient) • Pellet press (equipment ~m scale) • Cementation facility – comparable to baseline	Volume reduction due to thermal treatment means smaller scale conditioning facilities required.	NA	Additional facilities required. Dust dissemination hazard may require some or all process steps to be undertaken in containment (gloveboxes).	Larger volume of decommissioning wastes (due to more facilities). Dust dissemination may mean equipment has higher radiological classification than decommissioning waste from baseline.	-1 Dust management incurs additional engineering and requirements and increases decommissioning complexity
	Safety during treatment and conditioning	Shielding can be used by operators if necessary (for waste with high dose rates). Criticality risk (Plutonium Contaminated	Particulate dispersion risk (IRIS and compaction) – must be managed by classical static & dynamic confinement. Note higher activity concentration in ashes compared to	Higher waste loading per package cancels out for this category; less packages but correspondingly higher dose. However, waste loading might be limited by limits (per package) placed	NA	Additional exposure opportunities due to additional process steps. Particulate dispersion risk during and following thermal treatment.	NA	-1

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
		Material (PCM)).	waste. Criticality risk (PCM).	upon specific radionuclides.				
	Safety demonstration requirements	Safety cases and necessary regulatory approvals are in place for existing and operating facilities.	Safety cases and necessary regulatory approvals in place for IRIS type process. Safety case for an industrial-scale compaction facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed. Not safety related but need to capture regulatory requirements and issues with transport via third countries and potential stakeholder objections.	None	NA	The process will require a safety demonstration, as well as an environmental permit with associated time and effort requirements. No single step is particularly novel so expect fairly low barrier. Additional burden due to the existence of several steps. Treatment of fissile materials (with required criticality safety assessment and management of contamination) raises an additional barrier; regulatory scrutiny / burden associated with criticality risk tends to be comprehensive / high. Classification of facility will depend on the feed. [Spain] – One of the main issues is dealing with the exhaust gases and their environmental impact.	NA	-1 Compaction has been demonstrated before. Regulatory burden associated with incineration accounted for under “crosscutting”.
Environmental impact	Material Environmental Impact	Material inputs consist of cement and 200 L drums.	Material inputs consist of cement, binder and 200 L drums.	Volume reduction due to thermal treatment results in significantly less cement and fewer	NA	Further environmental impact data will become available upon completion of the LCA.	NA	+1 Higher waste loading leads to less conditioning

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
				drums per unit of raw waste.				and packaging material.
	Process energy requirements	Awaiting LCA results.	Awaiting LCA results.		NA	(IRIS) Expect significantly higher process energy requirements compared to baseline. (Compaction) Energy to run pellet press on top of cementation process which will be comparable to baseline.	NA	-1 Higher process energy requirements associated with incineration.
Disposability and long-term safety	Secondary waste produced during the process	Housekeeping waste	(IRIS) •1 m^3 of liquid effluents (sodium-contaminated liquids) are generated for every 200 kg of waste incinerated. •The IRIS incinerator has one HEPA filter, changed every 1000 kg of waste incinerated. •The rotary kiln metal bar (Inconel), weighing approx. 10kg, is changed for every 4000 kg of waste incinerated. (compaction) •Housekeeping waste.	N/A		(IRIS) More secondary waste produced as compared to baseline. Gaseous emissions (CO2, air, potentially some NOx). [fr] lijquids handled by evaporation facility.p . Will provide additional info by email Country dependent. (Compaction) Expect similar volume of housekeeping waste per drum to baseline.	Is there an existing and well established disposal route for the secondary waste?	-1
	Disposability of final waste product	For discussion only.	For discussion only.	NA	Awaiting disposability assessment results.	NA	Awaiting disposability assessment results. Increased waste loading leads to	0

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
							activity concentration and higher dose rates (issue with transport and disposal). Potential to exceed radionuclide-specific limits, depending on disposal concept and design (country dependent). [cea] – THERAMIN assumption was vitrification of ashes. (ashes are mineral in nature). Don't anticipate any negative interactions with cement. Vitrification: managed to reach 50% waste loading (pellet vitrification). => Remain within envelope of PREDIS experimental work, i.e stick with cement.	
Implementation	Process throughput and impact on waste management strategy	Assume throughput to be limited by waste availability.	(IRIS) continuous process 4-7kg/hr. It has to be operated in 2x8 or 3x8 shifts. (Compaction) So far only lab scale studies. The operations may be	(Compaction) Compaction throughput only has to be scaled to that of the output of IRIS process. Scale-up anticipated to be relatively easy, might be able to use	NA	(IRIS) Incinerator may have very strict WAC. (Compaction) Process scale-up is still experimental and has not been demonstrated in an industrial	NA	0 Neutral in terms of scale up, slightly positive in terms of waste management strategy, but too early to tilt toward

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
			automated for industrial applications. Use of international facility avoids the need to develop national infrastructure.	pharmaceutical processes (compaction of powders already implemented in that field). Opens up new waste management route (e.g. SL thermal treatment programme). May allow current disposability issues to be addressed/bypassed.		environment.		+1
	Material availability	Material inputs consist of cement and 200 l drums.	Material inputs consist of cement, binder and 200 L drums.	(Compaction) Lower volume of cement required per unit raw waste due to fewer packages.	NA	NA	NA	0
	Technical Readiness Level (TRL)	9	(IRIS-mixed waste) 9 (IRIS-IXR) 8 (Compaction) 1-2	None	NA	Low TRL (1-2) compared to baseline (9).	NA	-2
Financial	Cost of facility and of treatment and conditioning and cost of secondary waste management.	Construction of conditioning facility. Cost per package for waste loading of 14vol% (IXR) 44vol% (mixed waste).	Construction of thermal treatment, effluent treatment, compaction, and conditioning facilities. Cost per package for waste loading 40 vol% ashes.	There will be fewer waste packages produced due to the increased waste loading, leading to a reduction in cost directly proportional to the waste loading difference.	NA	Additional plant (with associated construction and decommissioning costs) required compared to baseline due to additional process steps. More secondary waste requiring management. Cost of licensing of incineration facility might be quite high, depending on the nature of waste treated	NA	-2

6.1.2 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
						(fissile materials will lead to higher licensing costs).		
	Disposal costs, including cost of disposal containers	IXR (wet): 14 %wt (14%vol) Mixed organics: 34 %wt (44%vol)	Ash: Waste loading up to 35 %wt (40 %vol) (IRIS process results in a factor 30 mass reduction compared to raw waste).	NA	Disposal cost will be reduced in line with the increase in waste loading between scenario 6.1.2 and the baseline. This benefit is mitigated by potentially higher handling and disposal costs.	NA	None.	+2 (strongly context dependent, depends on current disposal route for IERs).

Geopolymer Conditioning

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Cross cutting	Impact of initial thermal treatment step	No thermal treatment step	IRIS process: • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. • Primary waste consists of ashes and dust. Factor of 25 reduction in mass compared to raw waste. • Secondary wastes -liquid effluents, HEPA filters, kiln metal bar.	Volume reduction – positive impacts on storage and conditioning costs, raw material requirements for subsequent steps (drums, cement, etc).	Volume reduction improves disposal costs. (waste stream dependant) Destruction of organics may have positive impact on disposability.	Additional design construction and decommissioning of treatment facility. Additional secondary wastes requiring management. Additional process step adds to safety demonstration burden. Additional exposures due to additional process steps. Waste product (ashes) presents particulate dissemination risk.		

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Waste loading	IRIS equivalent package[12] (1/3 IXR, 2/3 Mixed waste): • 107 kg/drum (26 %wt) • 414 l/drum	Waste loading per drum-Ash[13]: • 80 kg/drum (19 %wt) • 400 l/drum (uncompacted) Raw waste*: • 2025 kg/drum • 7821 l/drum *IRIS process results in a factor 30 mass reduction compared to raw waste. Neglect secondary waste.	Thermal treatment results in significant volume reduction relative to baseline. Largest benefits realised for IXRs which have low waste loading in baseline.		None	None	
Operational safety	Facility construction and decommissioning	Cementation plant	IRIS • Equipment is set up in gloveboxes in a 3 floor building. IRIS prototype has a footprint of 9 m x 5 m x 8 m. Geopolymer • Grinding (equipment ~m scale) • Geopolymer facility – comparable to baseline.	Volume reduction due to thermal treatment means smaller scale conditioning facilities required.	NA	Additional facilities required. Dust dissemination hazard may require some or all process steps to be undertaken in containment (gloveboxes).	Larger volume of decommissioning wastes (due to more facilities). Dust dissemination may mean equipment has higher radiological classification than decommissioning waste from baseline.	0 – neutral Reproduce comments from 6.1.2 re: thermal treatment.

[12] Data based on IXR and mixed waste loading for 200 L drums from *OPERA-PG-COV023* and *OPERA-PU-NRG1112B*. Derivation in spreadsheet *VA_baseline_values_derivation_Issue_1.xlsx*

[13] Data based on the values provided for LCA and VA. Derivation in spreadsheet *WP6_LCA_Inputs_VA_workshop_values.xlsx*

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Safety during treatment and conditioning	Shielding can be used by operators if necessary (for waste with high dose rates). Criticality risk (PCM).	(IRIS and encapsulation) Particulate dispersion risk– must be managed by classical static & dynamic confinement. Note higher activity concentration in ashes compared to waste. Criticality risk (PCM). Alkali activators used in the process present a chemical hazard requiring the use of PPE – covered by requirements for radiation protection.	Higher waste loading per package cancels out for this category; less packages but correspondingly higher dose.	NA	Additional exposure opportunities due to additional process steps. Particulate dispersion risk following thermal treatment.	NA	0 – Reproduce thermal treatment comments from 6.1.2
	Safety demonstration requirements	Safety cases and necessary regulatory approvals are in place for existing and operating facilities.	Safety cases and necessary regulatory approvals in place for IRIS type process. Safety case for an industrial-scale geopolymer facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed.	There is a geopolymer production plant in Italy, comparable to cementation plant	NA	(IRIS) Additional burden due to the existence of several steps. (Geopolymer) The process will require a safety demonstration, with associated time and effort requirements. No step is particularly novel so expect fairly low barrier. This weakness only applies to the first-of-a-kind facility. Subsequent safety demonstrations can be substantiated with operational experience.	NA	0 (context dependent, but existing plants and SIAL provide operational experience)

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Environmental impact	Material Environmental Impact	Material inputs consist of cement and 200 l drums.	Geopolymer: • fly ash (14 wt%), • BFS (14 wt%) • Zeolitic Tuff (9 wt%) • Sodium hydroxide (activator, sourced directly) (7 wt%) • Aluminium oxide (6 wt%) 200 l drum	Volume reduction due to thermal treatment results in significantly fewer drums per unit of raw waste. Process repurposes industrial by-products (fly ash, BFS) and the uses of natural materials (tuff). Tuff is widely available and POLIMI didn't have issues procuring it. Alternative geopolymer formulations may be available and, depending on formulation, will be impacted by cost and availability of MK and sodium silicate (activator). No issues with raw material changes and consistency. Good numbers (LCA) when only considering conditioning (excl. thermal treatment).	NA	Further environmental impact data will become available upon completion of the LCA.	NA	+2

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
	Process energy requirements	Awaiting LCA results.	(Geopolymer) expect energy use per drum to be comparable to cementation process. Results from WP5 indicate that this is the case.		NA	(IRIS) Expect significantly higher process energy requirements compared to baseline. (confirmed by preliminary LCA results, outweighs benefits of higher waste loading). (Geopolymer) Less energy per unit waste due to volume reduction.	NA	-1
Disposability and long-term safety	Secondary waste produced during the process	Housekeeping waste	(IRIS) IRIS) •1 m^3 of liquid effluents (sodium-contaminated liquids) are generated for every 200 kg of waste incinerated. •The IRIS incinerator has one HEPA filter, changed every 1000 kg of waste incinerated. •The rotary kiln metal bar (Inconel), weighing approx. 10kg, is changed for every 4000 kg of waste incinerated. (Geopolymer) Housekeeping waste.	N/A		(IRIS) More secondary waste produced as compared to baseline. (Geopolymer) Expect lower relative volume of housekeeping waste for conditioning process due to reduced number of drums.	Curing conditions need to be well controlled. Any additional / bleeding can be incorprorated in the next batch.	-1 due to incineration

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Disposability of final waste product	No free liquid should be observed.	~~BFS (high sulphide content, which increases corrosion rates and microbial multiplication).~~ ~~Material purity will thus impact disposability.~~ No free liquid was observed.	NA	Good incorporation. Thermal treatment allows disposal of previously problematic waste.	NA	The presence of BFS may increase corrosion rates and microbial growth, resulting in higher rates of gas generation and package corrosion.	0
Implementation	Process throughput and impact on waste management strategy	Assume throughput to be limited by waste availability. Usually approx. 8 drums / day (based on operational data provided by CVŘež under WP5).	(IRIS) continuous process 4-7kg/hr. It has to be operated in 2x8 or 3x8 shifts. (Geopolymer) Expect process is as easy to scale up as any cementation/concrete production process. Experimental data provided by CVŘež indicates that process scale up is well underway and that throughputs similar to those reached with cement can be achieved.	(Geopolymer) Throughput only has to be scaled to that of the output of IRIS process.	NA	(Geopolymer) Process scale-up is still experimental and has not been demonstrated in an industrial environment. This is mitigated by good experimental results and feedback from research partners who report that throughputs close to those of the baseline scenario (30 to 60 minutes per drum / 8 drums/day) is achievable. Lab scale, mixing by hand.	NA	0

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Material availability	Material inputs consist of cement and 200 l drums.	Geopolymer: • fly ash (14 wt%), • BFS (14 wt%) • Zeolitic Tuff (9 wt%) • Sodium hydroxide (7 wt%) • Aluminium oxide (6 wt%) 200 l drum	Significantly less raw material required following thermal treatment, allowing for higher material costs.	NA	Availability of Tuff may be geographically dependant. Potential for issues with consistency. Future availability of fly ash is uncertain. BFS (cost) might increase in the near future. (POLIMI): main concern is with BFS rather than fly ash.	NA	-1
	Technical Readiness Level (TRL)	9	(IRIS-mixed waste) 9 (IRIS-IXR) 8 (Geopolymer) 3-4 Note that geopolymers are already used in an industrial environment (e.g. SIAL). Although this does not increase the TRL, it increases confidence that the industrialisation steps will be easily and quickly achieved.	None	NA	Low TRL (3-4) compared to baseline (9).	NA	-1

6.1.3 vs 6.1.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Financial	Cost of facility and of treatment and conditioning and cost of secondary waste management.	Construction of conditioning facility. Cost per package for waste loading of 14vol% (IXR) 44vol% (mixed waste). In the area of €3000/drum.	Construction of thermal treatment, effluent treatment and geopolymer conditioning facilities. Cost per package for waste loading 20 wt% ashes. In the area of €3000/drum.	There will be fewer waste packages produced due to the increased waste loading, leading to a reduction in cost directly proportional to the waste loading difference.	NA	Additional plant (with associated construction and decommissioning costs) required compared to baseline due to additional process steps. Additional secondary waste requiring management.	NA	-2
	Disposal costs, including cost of disposal containers	IXR (wet): 14 %wt (14%vol) Mixed organics: 34 %wt (44%vol)	Ash: Waste loading up to 20 %wt (IRIS process results in a factor 30 mass reduction compared to raw waste).	NA	Disposal cost will be reduced in line with the increase in waste loading between scenario 6.3 and the baseline.	NA	None.	+1 (similar to compaction, country and context dependent).

Molten Salt Oxidation

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Cross cutting	Impact of initial thermal treatment step	No thermal treatment step	MSO: Flameless thermal treatments with decomposition under the surface of the molten salt. Two-stage reactor for total organic decomposition to CO_2 and H_2O. Radionuclides and heavy metals are captured within the molten salt.	Volume reduction – positive impacts on storage and conditioning costs, raw material requirements for subsequent steps (drums, cement, etc).	Volume reduction improves disposal costs. (waste stream dependant) Destruction of organics may have positive impact on disposability.	Additional design construction and decommissioning of treatment facility. Additional secondary wastes requiring management. Additional process step adds to safety demonstration burden. Additional exposures due to additional process steps. Waste product (salts) may be more challenging to immobilise.		

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
	Waste loading	Waste loading per drum-IXR package[14]: • 45 kg/drum (wet) (14 wt%) • 27 l/drum	Salts: 5-25 wt% salts. (MSO process results in at least a factor 10 mass reduction compared to raw waste). (Geopolymer) Waste loading in geopolymers usually falls within a range. Panel discussion is invited on what represents an achievable and reasonable (in terms of compliance and physical properties) waste loading.	Thermal treatment results in significant volume reduction relative to baseline. Largest benefits realised for IXR which have low waste loading in baseline. If samples exposed to air, then 25% waste loading achievable in MK-based geopolymer. Curing in high moisture environment (above 20%) makes it difficult to avoid cracking. Slow curing in a dry environment improves final matrix properties. [5-15]% led to good characteristics. [For disposability area: host rock may have an impact (evaporatites?)].		None	Salt immobilisation in geopolymer was challenging.	
Operational safety	Facility construction and decommissioning	Cementation plant	(MSO) Panel discussion is invited on the complexity and hazards associated with construction of a MSO reactor. (Geopolymers) Technologies and components are similar to those used for cementation.	MSO process is quite clean.	NA	Vapors need to be processed / treated by gas abatment, but small quantities.	NA	-1 (due to addition of a process step)

[14] Data based on IXR and mixed waste loading for 200 L drums from *OPERA-PG-COV023* and *OPERA-PU-NRG1112B*. Derivation in spreadsheet *VA_baseline_values_derivation_Issue_1.xlsx*

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Safety during treatment and conditioning	Shielding can be used by operators if necessary (for waste with high dose rates).	(MSO) Standard PPE. (Geopolymers) Alkali activators used in the process present a chemical hazard requiring the use of PPE – covered by requirements for radiation protection.	Vapours are well controlled and easily processed. Stainless steel reactor ensures good containment.	NA	No experiment in active environment.	NA	-1 (due to addition of a process step)

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Safety demonstration requirements	Safety cases and necessary regulatory approvals are in place for existing and operating facilities.	Safety case for an industrial-scale MSO facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed.	None	NA	(MSO) Additional burden due to the existence of several steps. The process will require a safety demonstration, with associated time and effort requirements. There are examples of MSO implementation for radioactive waste to draw from. [Corrosion resistance, energy requirements and difficulty of processing the salts are barriers to industrial implementation (Geopolymer) The process will require a safety demonstration, with associated time and effort requirements. No step is particularly novel so expect fairly low barrier. This weakness only applies to the first-of-a-kind facility. Subsequent safety demonstrations can be substantiated with operational experience.	NA	-1

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Environmental impact	Material Environmental Impact	Material inputs consist of cement and 200 l drums.	Material inputs consist of: • MSO salts (carbonate salts) • Metakaolin • Activator solution • 200 L drums	Volume reduction due to thermal treatment results in significantly fewer drums per unit of raw waste. (Geopolymer) Use of commercial MK and activator. Can use byproducts from industry. (geopolymer usually 3x better than cement in terms of environment). Cement production is environmentally intensive.	NA	Some Co2 release (small amounts). Process to manufacture geopolymers is more environmentally costly than baseline. [LCA rough results] – Per kg of sodium salt, 300g of Co2 200g of Co2 per kg of MK 700g of Co2 per kg of Portland cement	NA	+1
	Process energy requirements	Pull from other LCA results.	(MSO) Expect higher process energy requirements for MSO compared to baseline. Geopolymer process expected to be comparable to baseline on a per-drum basis.	(Geopolymers) The increase in waste loading leads to a reduction in the number of waste packages. Some level of self-sustaining heat generation in first reactor. Second reactor requires heating. => look at data provided in data request form	NA	(MSO) Expect higher process energy requirements compared to baseline.	NA	-1

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall scenario rating versus baseline**
Disposability and long-term safety	Secondary waste produced during the process	Housekeeping waste	(MSO) Liquid effluent from gas system requiring further processing in effluent treatment plant. (Geopolymer) Housekeeping waste.	N/A	NA	(MSO) Liquid effluent requires treatment. Some water vapor For 1t of IER, there could be 2t of steam (50-60% can be captured and reprocessed). Salt discharged from reactor is then put into a water tank to cool down (diluted sodium carbonate in tank). Can be partially evaporated. Small amounts of gaseous waste. Effluent management is likely to be facility-dependent.		0 (secondary waste is primarily managed / feeds into primary)

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Disposability of final waste product	For discussion only.	For discussion only.	NA	Awaiting disposability assessment results. Change to calcium carbonate would make it easier to condition.	NA	(Geopolymer) The presence of BFS may increase corrosion rates and microbial growth, resulting in higher rates of gas generation and package corrosion. (carry previous comment forward).	Indicative -1 (noting ongoing work and early stages of disposability considerations).

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Implementation	Process throughput and impact on waste management strategy	Assume throughput to be limited by waste availability. Usually approx. 8 drums / day (based on operational data provided by CVŘež under WP5).	(MSO) Batch replacement of salts. (Geopolymer) Expect process is as easy to scale up as any cementation/concrete production process. Experimental data provided by CVŘež indicates that process scale up is well underway and that throughputs similar to those reached with cement can be achieved.	NA	NA	(Geopolymer) Process scale-up is still experimental and has not been demonstrated in an industrial environment. This is mitigated by good experimental results and feedback from research partners who report that throughputs close to those of the baseline scenario (30 to 60 minutes per drum / 8 drums/day) is achievable. (MSO) Best case scenario is 1t of IER can be processed with 25 kg of salt. Second reactor can keep going, only first reactor needs to be stopped for reloading. Current dosing rate is 1 to 3kg/hr. Constrained by manpower and regulatory / HSE. Re-use WP5 results.	NA	0 (scale up constrinaed by operational barriers rather than technical).

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
	Material availability	Material inputs consist of cement and 200 l drums.	Material inputs consist of: • MSO salts (carbonate salts) • Metakaolin • Activator solution 200 L drums (Geopolymer) Consistency in the purity of BFS and of the reagent have been reported to lead to issues with repeatability (WP5).	(Geopolymer) Significantly lower volume of raw material (drums, etc) required compared to cementation. Salts are easy to procure.	NA	(Geopolymer) Consistency issues, and potential issues with material availability. High corrosion environment requires “regular” reactor replacement (Inconel 600). Timely availability of material could be an issue.	NA	-1
	Technical Readiness Level (TRL)	9	(MSO) 4-6 (Geopolymer) 3-4 Note that geopolymers are already used in an industrial environment (e.g. SIAL). Although this does not increase the TRL, it increases confidence that the industrialisation steps will be easily and quickly achieved.	None Potential for tecnhology cross over from GEN IV MSR and led cooled / Na cooled.	NA	Low TRL (4-6) compared to baseline (9).	NA	-2 -1 (check NAAREA website).

6.2.1 vs 6.2.B		Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall scenario rating versus baseline
Financial	Cost of facility and of treatment and conditioning and cost of secondary waste management.	Construction of conditioning facility. Cost per package for waste loading of 14vol% (IXR).	Construction of thermal treatment and effluent treatment facilities. Cost per package for waste loading 5-25 wt% salts.	There will be fewer waste packages produced due to the increased waste loading, leading to a reduction in cost directly proportional to the waste loading difference.	NA	Additional plant (with associated construction and decommissioning costs) required compared to baseline due to additional process steps. Maintenance costs (reactor corrosion and replacement).	NA	-1
	Disposal costs, including cost of disposal containers	IXR (wet): 14 %wt (14%vol)	Salts: Waste loading up to 5-25 wt% (MSO process results in a factor 10 mass reduction compared to raw waste).	NA	Disposal cost will be reduced in line with the increase in waste loading between scenario 6.2 and the baseline.	NA	None. Potential for rad category to go up, albeit less likely that incineration because volume reduction is smaller.	+1