Deliverable 5.5

Report on the “Direct Conditioning of Liquid Organic Waste” Route

28 June 2024 Version Final

Dissemination level: Public

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This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Project acronym PREDIS	**Project title** PRE-DISposal management of radioactive waste	**Grant agreement No.** 945098
Deliverable No. D5.5	**Deliverable title** Report on the “Direct Conditioning of Liquid Organic Waste” Route	**Version** Final
Type Report	**Dissemination level** Public	**Due date** M46
Lead beneficiary Galson Sciences Ltd., SOGIN, CVŘež		**WP No.** 5
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Abstract

Results of the technical, economic and environmental strengths and weaknesses of the direct conditioning routes for Radioactive Liquid Organic Waste (RLOW) studied in PREDIS WP5, based on Life Cycle Analysis (LCA), Life Cycle Costing (LCC) and value assessment are presented and analysed in this report, thus completing PREDIS WP5 task 5.5. Data transferred to Work Package 2 for the purpose of LCA and LCC is also included in this report.

Direct conditioning of contaminated oils and scintillation cocktails using Metakaolin (MK)-based, Blast Furnace Slag, or the MIX-based geopolymer formulations was found to result in better operational safety outcomes, compared with a current two-step cementation approach that is currently used for some oil wastes. The environmental impact of the overall geopolymer process is also lower, whilst reducing conditioning, storage and disposal costs. Several challenges were identified in the form of raw material procurement and purity. The need for further R&D to achieve a TRL of nine was also acknowledged and is reflected in the EURAD-2 proposals.

Direct conditioning of solvents using MK-based geopolymers was compared against a baseline comprising incineration followed by cementation. Geopolymer conditioning was found to result in improved safety and environmental outcomes. The same challenges to implementation as those highlighted above were identified. The economic impact of implementing this management route was not fully evaluated due to unavailability of cost data associated with incineration facilities. Current findings indicate, however, that disposal is likely to be more costly due to the relative reduction in waste loading compared with those achieved when thermal treatment is used.

Keywords
Radioactive liquid organic waste, technology selection, oils, solvents, scintillation cocktails, geopolymer, value assessment, predisposal, conditioning, treatment and processing, optimisation

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Notification

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Acknowledgement

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

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List of Acronyms

Al_2O_3	Aluminium (III) oxide
BFS	Blast furnace slag
CIEMAT	(Spanish) Center for Energy, Environmental and Technological Research
CEA	(French) Atomic Energy and Alternative Energies Commission
EC	European Commission
FA	Fly ash
H_2O	Water
ILW	Intermediate-level waste
KIPT	Kharkov Institute of Physics and Technology
KOH	Potassium hydroxide
K_2O	Potassium oxide
LCA	Lifecycle analysis
LCC	Lifecycle costing
LLW	Low-level waste
MK	Metakaolin
NaOH	Sodium hydroxide
NNL	(British) National Nuclear Laboratory
POLIMI	Polytechnic University of Milan
PREDIS	PRE-DISposal management of radioactive waste
RATEN	Autonomous Directorate of Technologies for Nuclear Energy
RLOW	Radioactive liquid organic waste
RSOW	Radioactive solid organic waste
SCK CEN	(Belgian) Nuclear Research Centre
SiO_2	Silicon dioxide
SOGIN	Italian Waste Management Organisation
TBP	Tributyl phosphate
TRL	Technology Readiness Level
WAC	Waste Acceptance Criteria
WP2	Work Package 2 (in PREDIS: Strategic Implementation)
WP5	Work Package 5 (in PREDIS: Innovations in liquid organic waste treatment and conditioning)

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 intermediate- and low-level (ILW/LLW) 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 five (WP5) of the PREDIS project was concerned with the treatment and conditioning of RLOW. In WP5, options for direct conditioning of RLOW using innovative geopolymers and related alkali activated materials were developed and investigated. The work package was divided into tasks focused on studying the direct conditioning process (T5.3), the conditioning matrix performances (T5.4), and on assessing the overall technical, economic and environmental performance of the direct conditioning route (T5.5). This report, deliverable D5.5, falls under T5.5.

1.1 Aims and Objectives

This deliverable (D5.5) is dedicated to the preliminary technical, economic and environmental analysis of the direct conditioning route of RLOW. 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 what the overall performance of the direct conditioning route would be. These results (summarised in Deliverables 5.2 and 5.3 [1] [2]) were compared with current waste management practices (summarised in Deliverable 5.1 [3]) to provide a comparison of how the novel direct conditioning route performs against current practices.

This report also provides a basic design description of the "direct conditioning route for RLOW" studied in WP5. A summary of data transferred to Work Package (WP2) and used for the purpose of lifecycle analysis (LCA), lifecycle costing (LCC) and value assessment is also provided. The value assessment described above helps to summarise its technical, economic, and environmental strengths and weaknesses when compared with current waste management practices for the waste types identified [4].

The overarching objective of this deliverable is to provide technology developers and end-users with an objective assessment of the novel waste management routes across the full waste management lifecycle (from treatment through to disposal) to support decision making and industrial application of direct encapsulation technologies for three types of RLOW: contaminated oils, solvents and scintillation cocktails.

1.2 Scope, Interfaces and Exclusions

Based on a review of the European inventory of RLOW, it was recommended in Deliverable 5.1 [3] that oils and contaminated organic solvents (e.g. tributyl phosphate (TBP), or TBP plus a diluent such as dodecane) should be studied in WP5. This recommendation was followed, with the further inclusion of scintillation cocktails. Therefore, the scope of this report is limited to the following three sub-groups of RLOW:

- Oils.
- Solvents.
- Scintillation cocktails.

Other RLOW types are excluded from the scope of this report.

A detailed description of these RLOW and of the process that led to the identification of reference formulations for WP5 is provided in D5.2 [1] and is not repeated herein.

The value assessment work undertaken in Task 5.5 draws on the LCA and LCC analyses undertaken under WP2. It also relies heavily on results from research activities undertaken during PREDIS and summarised in D5.2 [1] and D5.3 [2].

Tasks 5.4.9 and 5.5 have run in parallel; discussions and information exchange took place regularly to ensure good alignment between these tasks, and with Deliverable 5.4 [5].

Dedicated value assessment activities, including a workshop with research partners and end-users were also undertaken in preparation of this deliverable, and are summarised herein [6].

The outputs from Task 5.5 activities have fed into Deliverable D2.10.

1.3 Report Structure

This report is structured as follows:

- Section 2 describes the basic design for the direct conditioning routes studied within PREDIS WP5.
- Section 3 presents the value assessment methodology used in PREDIS (a common approach is used across Work Packages 4 to 7).
- Section 4 summarises the scenarios, attributes, life cycle stages and input data for the value assessment.
- Section 5 presents the technical, economic and environmental impacts of the direct conditioning route, summarising results from the value assessment workshops.
- Conclusions are presented in Section 6.
- Appendix 1 presents the value assessment workshop agenda and a list of attending organisations.
- Appendices 2 to 4 include the output tables from the value assessment workshop.

2 Basic Design Description of the Direct Conditioning Route

A blueprint for the direct conditioning routes developed in PREDIS WP5 is provided in this section; experimental results and optimisations have been accounted for, as far as is reasonably practicable. This basic design description draws from the results reported in D5.2 and D5.3 [1] [2] and serves as a point of reference for the value assessment; specific assessment scenarios are further defined and discussed in Section 4.1.

This section also presents a set of assumptions related to the direct conditioning route, for each of the five combinations of waste type and geopolymer formulations listed below. Such assumptions are, as far as is reasonably practicable, aligned with data selected for the purpose of the disposability assessment undertaken under T5.4.9 and reported in Deliverable 5.4 [5]. The five combinations of waste types and geopolymer formulations taken forward for the purpose of the disposability and value assessments are:

- Contaminated oils, encapsulated in:
    - A metakaolin (MK)-based geopolymer.
    - A blast furnace slag (BFS)-based geopolymer.
    - A geopolymer based on a mixture of different raw materials, including MK, BFS and fly ash (FA). This formulation is referred to as the MIX formulation.
- Contaminated solvents, represented by a mixture of TBP and Dodecane, in proportions of 30/70 %vol encapsulated in a MK-based geopolymer
- Scintillation cocktails represented by the commercial Instagel Plus, encapsulated in a MK-based geopolymer.

2.1 Waste Conditioning in MK-based Geopolymers

Three organisations (National Nuclear Laboratory (NNL), University of Shefield, and the Center for Energy, Environmental and Technological Research (CIEMAT)) participated in the optimisation and robustness studies for the MK-based formulations, results of which are reported in D5.2 [1]. Testing with real RLOW was carried out by UJV Řež, the Polytechnic University of Milan (POLIMI) and Nucleco. MK-based formulations have been studied and optimised for all three types of RLOW studied in PREDIS: contaminated oils, contaminated solvents, and scintillation cocktails.

From these results, an attempt at describing a "standardised" illustrative process has been made below. This was only achieved to the following extent:

- The conditioning matrix formulation is the same for all three waste types, with the exception of:
  - A surfactant (Tween 80) is used when conditioning contaminated solvents.
  - The mixing regime is the same for conditioning contaminated oils and scintillation cocktails but differs from that used for conditioning contaminated solvents.
  - Activator formulation and preparation regimes are the same for all three waste types.

Further variations are highlighted in the description below when necessary. Values were chosen to balance optimisation and conservatism and are based on experimental results reported in D5.2 [1] and D5.3 [2].

2.1.1 Metakaolin formulation and mixing regime

Experimental work concluded that the Metamax MK should be used instead of the Argicem product, due to the improved wasteform characteristics yielded by the former (Section 5 of [1]). The use of surfactant is not required for the conditioning of contaminated oils and scintillation cocktails but is necessary to achieve good incorporation of contaminated solvents. It has the added benefit of reducing the size and number of pores in the wasteform.

Therefore, the reference geopolymer formulation for this direct conditioning route uses Metamax MK and a potassium silicate activator (such as Betol or K120 (oils) or Betol K-5020T (cocktails)) enriched in potassium hydroxide (KOH) to achieve the desired potassium oxide (K_2O) concentration and ratios summarised in Table 1 (Section 5.1, [1]). The KOH pellets (85 to 90% purity) were added slowly to the mixture of water and Potassium silicate [1]. The mixture was stirred for four hours at 500 rounds per minute (r.p.m) and left to rest until the next day (nominal resting period: 24 hours) (Section 5.1 of [1], and [2]). This process is summarised in Figure 1. In this section, that activator is labelled "A".

Table 1: Mid-point molar formulation ratios for the MK-based geopolymer formulation

Silicon dioxide (SiO_2) : K_2O = 1.2
K_2O : aluminium (III) oxide (Al_2O_3) = 1.2
water (H_2O) : K_2O = 13

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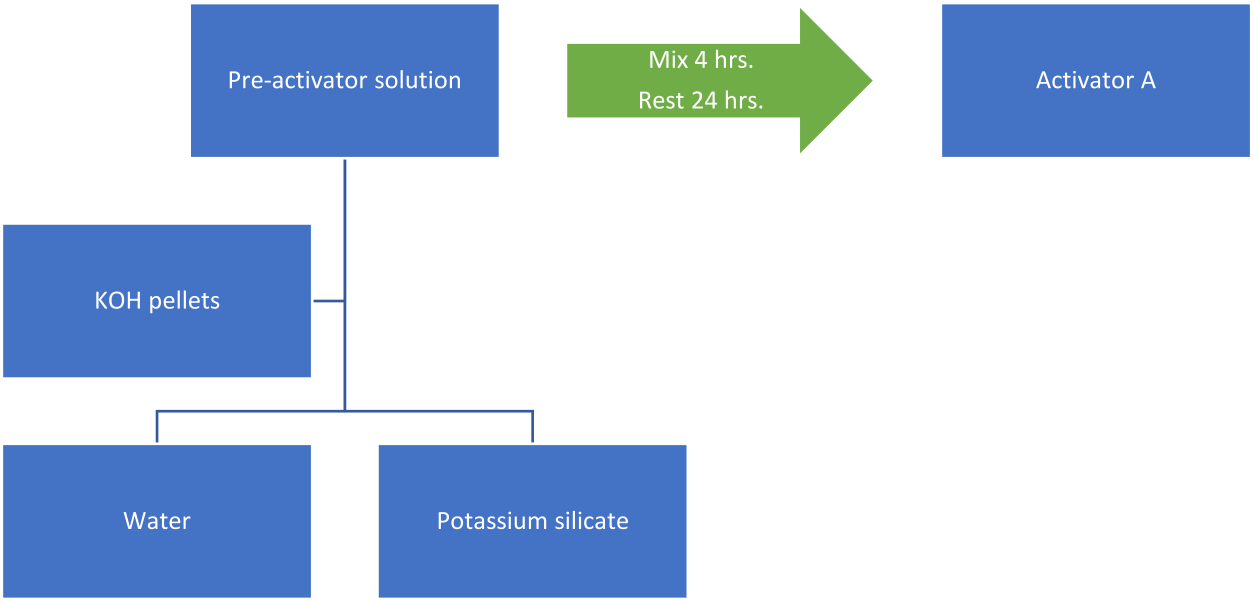
[1] In some cases, the alkali activator was purchased directly as a ready-made product from the supplier [16].

Figure 1: Activator preparation process summary



When conditioning contaminated oils and / or scintillation cocktails, metakaolin is added to the activator A and mixed for five minutes at low speed (a Hobart mixer was used during the PREDIS experiments).

This mixture is then transferred to a high-shear (high speed) mixer (a Silverson L5 mixer was used during the PREDIS experiments). Waste incorporation took place over approximately two minutes while mixing, followed by a further 13 minutes of mixing, before pouring the mix into the waste container or mould for setting and curing. The mixing method (low or high shear) was not found to significantly impact the characteristics of the wasteform for waste loadings up to, and including, 30%vol [3]. The high-shear method was followed and is illustrated in Figure 2.

Conditioning of contaminated solvents relies on the same preparation method for the activator A. However, the surfactant (Tween 80, between 3 to 5 wt.% relative to waste mass) is mixed at high speed for 10 to 13 minutes with the solvents prior to the addition of activator A. This mixture is mixed at low speed for two minutes (see Figure 3).

MK is then progressively added over five minutes, while mixing at low speed. This mixture is finally transferred to the high speed mixer and mixed for a further 13 minutes before being poured into the waste container or mould for setting and curing.

It was demonstrated through experimentation that curing conditions have a significant impact on the final wasteform properties. Curing under controlled conditions of temperature and humidity (nominal temperature of 20°C and saturated conditions of humidity (e.g. relative humidity >90%)) was found to prevent the appearance of cracks in the wasteform and is therefore assumed for the direct conditioning route basic design.

Based on experimental results, wasteforms with a waste loading of 20 to 30%vol achieve consistently good characteristics. A waste loading of 30%vol is assumed for the basic design of the direct conditioning of contaminated oils route. A waste loading of 20%vol is assumed for contaminated solvents and scintillation cocktails conditioning.

Figure 2: Process flow diagram for the conditioning of contaminated oils and scintillation cocktails in MK-based geopolymers

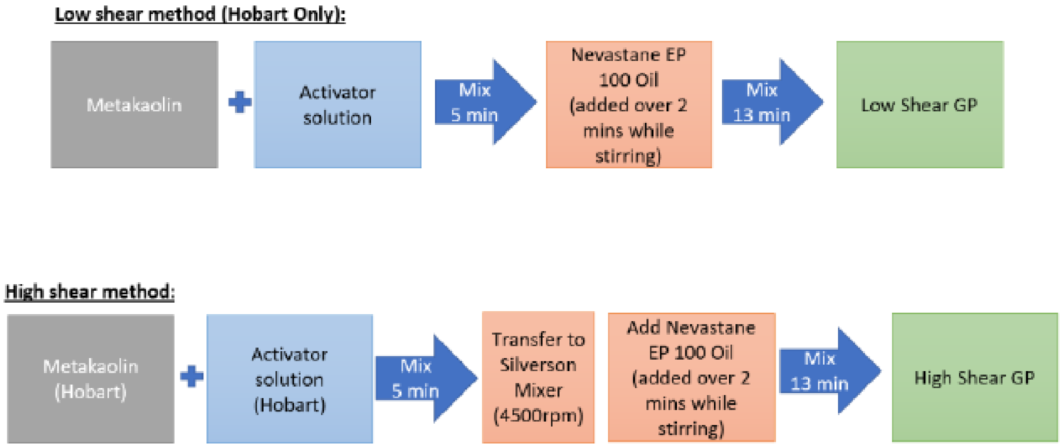
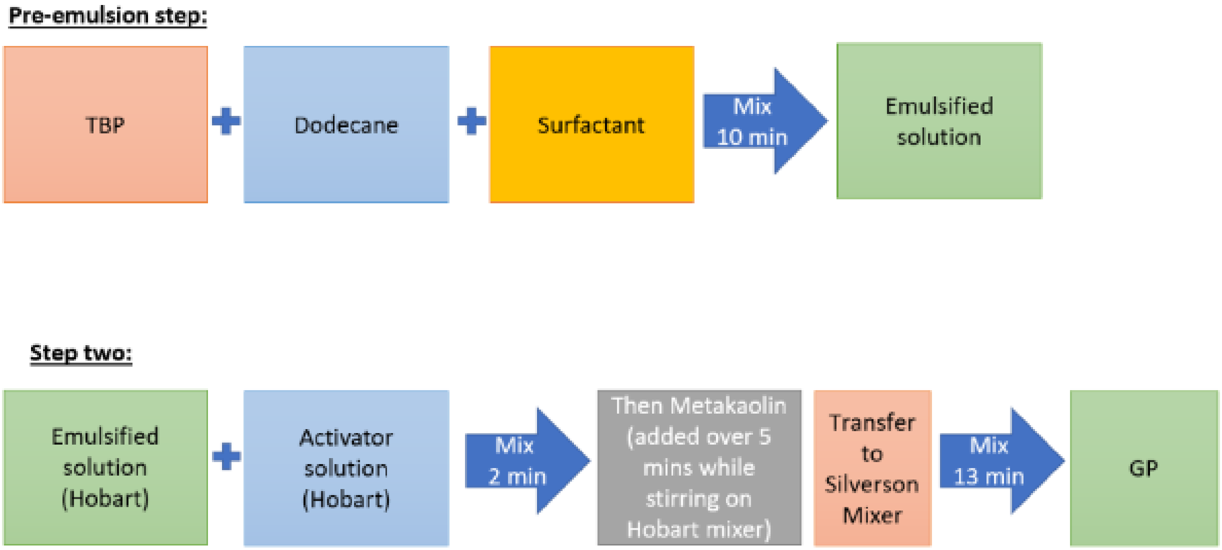


Figure 3: Process flow diagram for conditioning contaminated solvents in MK-based geopolymers



2.2 Oil encapsulation in BFS geopolymer

Two organisations (the Autonomous Directorate of Technologies for Nuclear Energy (RATEN) and the Nuclear Research Centre (SCK CEN)) participated in the optimisation and robustness studies for the BFS-based formulations, results of which are reported in D5.2 [1]. From these results, an illustrative process is described below, based on values chosen to balance optimisation and conservatism.

2.2.1 BFS geopolymer formulation and preparation regime

Experimental work demonstrated that a surfactant was needed to improve the incorporation of RLOW into BFS-based geopolymers. Tween 80 was shown to be the most effective surfactant [1].

The optimal geopolymer composition is reported in D5.2 and reproduced below for convenience. The alkaline activator, composed of sodium silicate in powder form mixed with sodium hydroxide (NaOH) (10M) pellets and additional water was prepared 24 hours prior to casting.

Wasteform casting followed the followings steps, illustrated below:

1. Mix oil plus Tween 80 for 5 minutes (mixture A)
2. Two minutes into step 1, in a separate container, mix the activating solution with BFS for 3 minutes at low speed (mixture B).
3. Pour A into B and mix for 8 minutes at high speed (mixture C).
4. Pour sand into the mix and mix for a further 2 minutes at high speed.

Samples were dried under standard temperature and saturated humidity conditions (20°C and relative humidity>95%) [7].

Based on experimental results, wasteforms with a waste loading of 20 to 30%vol achieve consistently good characteristics. A waste loading of 30%vol is conservatively assumed for the basic design of the direct conditioning route.

The water to binder ratio and BFS purity and particle size were found to play a significant role in the properties of the wasteform.

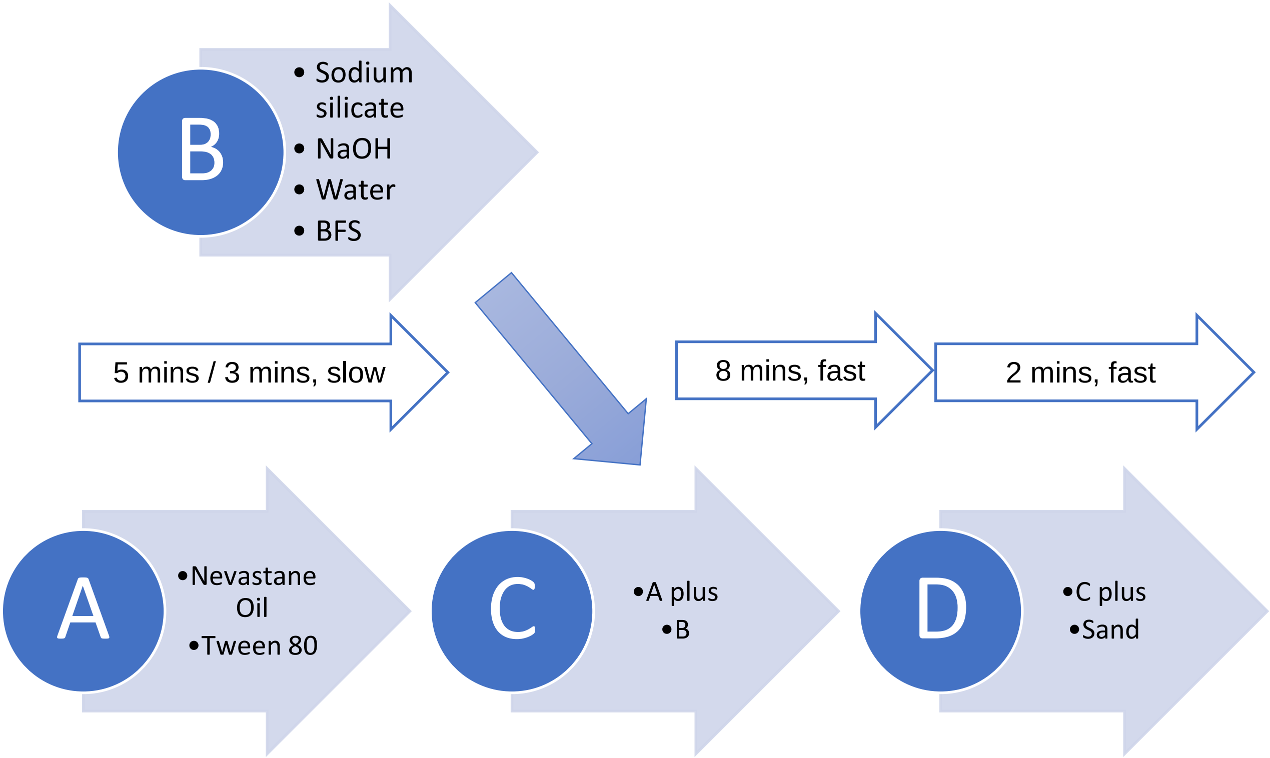


Table 2: Optimum BFS-based geopolymer formulation for conditioning of contaminated oils

Component	Quantities
BFS (Ecocem (1), Ecocem (2), RO_BFS #3)	42.9 wt.%
Sodium silicate solution (Water glass)	4.4 wt.%
NaOH 10M	8.6 wt.%
Water	7.5 wt.%
Sand	23.3 wt.%

Component	Quantities
Oil	30 vol.%
Tween 80	5 % of the oil volume
Water to binder	0.35

2.3 Oil encapsulation in composite MK/BFS/FA geopolymer

Four organisations, in three groups, (the Kharkov Institute of Physics and Technology (KIPT), Nucleco and SOGIN (Italian Waste Management Organisation) and the Atomic Energy and Alternative Energies Commission (CEA)) participated in the optimisation and robustness studies for the MIX-based formulations, results of which are reported in D5.2 [1].

Based on the experimental results, it was concluded that the MIX formulation requires further optimisation before it can be considered ready for direct conditioning of the RLOW types studied in PREDIS WP5. Some elements are repeated below for completeness.

The KIPT formulation using raw materials from Italy was deemed the most robust. The composition of the test samples prepared by POLIMI for T5.4 (results of which are reported in D5.3 [2]) is repeated in Table 3.

Basic design characteristics are similar to those used with the other formulations. Waste loadings up to 30 %vol are easily achieved with oil, and the addition of surfactant (0.5 wt.%) reduces the size and occurrence of pores. A process flow diagram for the mixing steps is provided in Figure 4. Raw material purity and finesse has a significant impact on the characteristics of the cast product. Once again, experimental results concluded that curing under room temperature and in saturated humidity conditions was necessary to prevent the apparition of cracks.

However, regardless of the formulation or raw materials used, wasteform characteristics did not permit further investigation, mainly due to excessive bleeding (Section 6.3 of [1]). Despite these hurdles, this formulation has been evaluated under the value and disposability assessment tasks for completeness.

Table 3: Wasteform composition of the samples prepared by POLIMI for T5.4

Material	Concentration (wt%)
FA (Italy)	0.32 – 0.34
BFS (Ecotrade/Ecocem, France)	0.19 – 0.20
MK (Metamax, BASF)	0.14
Betol K 5020 T	0.14 – 0.11
KOH	0.08 – 0.09
Water	0.144 – 0.12
Oil	10-40 (%vol)
Surfactant	Castament FW10

Figure 4: Process flow diagram for the preparation of a MIX-based wasteform

2.4 Direct Conditioning Route Basic Design

Table 4: Summary of the direct conditioning route formulations[1] provides a summary of the reference geopolymer formulations selected in PREDIS WP5 for direct conditioning of RLOW.

Table 4: Summary of the direct conditioning route formulations

Formulation	Raw Materials	Activating Solution	Formulation Parameters
MK based	Metamax	Betol K5020T H_2O KOH	Waste 19 wt% MK 26 wt% Betol 33 wt% KOH 8% Additional H_2O 14%
BFS	BFS from Ecocem (France) Sand	NaOH Sodium Silicate H_2O	Waste 11 wt% BFS 41 wt% Sand 25 wt% Sodium silicate 1.3 wt% Sodium hydroxide 6% Additional H_2O 16%
MIX (BFS/FA/MK) based	BFS from Buzzi (Italy) FA from Italy Metamax	Betol K5020T H_2O KOH	Waste 15 wt% BFS 17 wt% FA 28 wt% MK 12 wt% Betol 13 wt% KOH 7% Additional H_2O 8%

3 Value Assessment Methodology

Value Assessment is a form of multi-criteria cost benefit analysis that provides a methodology for assessing and comparing the technical, economic, and environmental performance of alternative waste management options. It was used to perform a strategic analysis of the performance of alternative waste management options studied under WP5.

The value assessment process is outlined in Figure 5 [8]. For WP5, 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 4.1.

Research work in WP5 focused on increasing the Technology Readiness Level (TRL) for the use of geopolymers for waste conditioning into a disposable matrix. Having identified representative scenarios, it was necessary to develop a list of technology attributes[2] covering areas that may differentiate the benefits of direct conditioning with geopolymers from the current waste management approaches of incineration and/or cementation. To make the analysis easier and more systematic, it was also necessary to identify and compare the various relevant stages in the waste management lifecycle[3]. These are discussed in Appendix 5.

The assessment was done on a comparative basis; with the direct conditioning method compared against its respective baseline, rather than each geopolymer type being compared against each other. A comparative evaluation also allowed simplification of the assessment process by excluding attributes and management steps for which there is no differentiation between the direct conditioning route and the baseline scenario. Such exclusions are presented and discussed in Table 6, together with the list of criteria retained for consideration.

A gap analysis of information available for each scenario[4], and related to each attribute, was carried out and resulted in the data request forms sent to project partners in January 2024. Information provided as a result [9] [10] [11] [12] [13] [14] [15] [16] was analysed and fed into an internal value assessment discussion. This iterative process resulted in further queries, and in an updated list of criteria.

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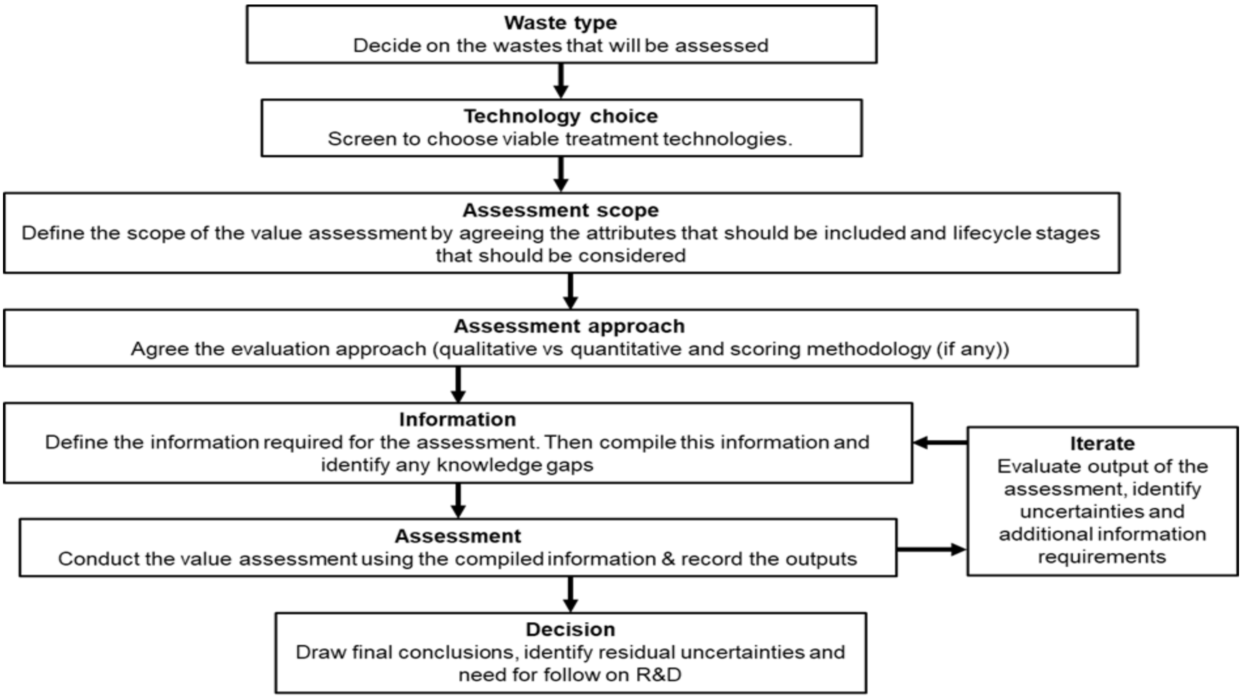
[2] In this report, the terms “attributes” and “criteria” are used interchangeably. “Attributes” refers to technology or geopolymer formulation properties and characteristics, whilst “criteria” refers to the evaluation of attributes for the purpose of value and disposability assessment.

[3] Comprising of planning, characterisation, transport, pre-treatment, treatment, conditioning, storage, disposal and waste management facility decommissioning.

[4] Sourced from data provided to support the LCA and LCC work undertaken by the University of Manchester, as well as from the summary of experimental data provided in Deliverable 5.2 [1].

Figure 5: Flow chart summary of the Value Assessment process



4 Value Assessment Scenarios, Attributes and Input Data for Value Assessment

4.1 Scenario Selection

Preliminary variant[5] scenario identification was based on a review of previous project outcomes, namely:

- Inventory data from Deliverable 5.1 produced under sub-task T5.2.1 [3].
- Case Study Inputs to LCA/LCC from Milestone 37 [17].
- Reference waste type/formulation combinations for further studies identified in Milestones 32 [18] and 34 [19].
- LCA/LCC scenarios discussed with the University of Manchester (UoM) during a workshop held on 27/09/2023 [20].

Waste type/technology combinations that have been modelled as part of the LCA/LCC were previously developed in consultation with individual WP Partners and have been included in the value assessment. Those combinations align with the first three combinations (modelling direct conditioning of contaminated oil) selected in MS34.

Scenarios studying the conditioning of solvents and scintillation cocktails are not modelled in the LCA/LCC but were included in the list of reference formulations presented in MS34. Therefore, two additional scenarios, based on the combinations presented in Table 5 of MS34, have been selected for value assessment.

It is assumed that in all variant scenarios the final waste product can be disposed of in a near-surface disposal facility.

These RLOW types, their origin, and, where available, their representative inventory datasheet from [3] are presented in Table 5. These combinations of RLOW types and geopolymer formulations were

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[5] As opposed to baseline scenarios.

presented at the autumn WP5 meeting held in Prague in December 2023, where it was agreed that a standard 200 L drum would be used as the common waste container for the value assessment [8].

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

- The first number refers to the Work Package (WP5).
- The second number refers to waste type.
- The third number refers to geopolymer formulation.
- Scenarios with the label “B” represent the baseline for waste type “x”. For example, scenario 5.1.B is the baseline scenario for the waste type “oil”.

The selection of baseline scenarios is discussed in the following sub-section.

4.1.1 Baseline Scenarios Selection

Baseline scenarios were selected for each waste type, thus enabling comparison of the direct geopolymer encapsulation routes for each waste type against a consistent baseline. Information was sourced from the same references as those that helped to select the scenarios above (i.e. LCA/LCC inputs and workshop, and MS32 and MS34). The main factors used in determining the baselines were:

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

Each baseline is discussed in more detail in the following sub-sections. The main characteristics of each baseline are summarised in Table 5.

4.1.1.1 Oils

Nevastane oil was chosen as the representative waste for the “oily waste” baseline, in line with MS34. Polymer absorption (e.g. Nochar+ or Experlite) followed by cement encapsulation of pump oils is currently used in several countries, including the Czech Republic (UJV Řež), Italy (SOGIN), Ukraine (KIPT) and Romania (RATEN) [3] [17]. This is consistent with the baseline scenario modelled in the LCA/LCC [20]. Data provided by CVŘež/UJV Řež to support LCA/LCC [17] and furthered via the value assessment data request [13] [9] [12] was deemed representative. Baseline scenario 5.1.B is therefore based on data received from CVŘež, and complemented, where necessary, with data from SOGIN [11].

Disposal in a near-surface disposal facility is assumed for this baseline scenario.

4.1.1.2 Solvents

A 30/70 mix of TBP and Dodecane was selected as the representative waste for the “organic solvents” baseline, in line with MS34[6]. This is representative of waste streams found, for instance, at Sellafield in the UK, in Italy, and at the CEA in France as described in the waste stream datasheets in Tables 2, 8 and 22 of [3], respectively. For consistency, and based on the nature of the waste, it has been assumed for the baseline that these waste streams arose from the “PUREX” spent fuel reprocessing process and are therefore similar in nature.

Incineration followed by ashes cementation was reported as the current management route in Italy for Ion Exchange Resins and contaminated solvents ([3] and Section I.2 of [21]). Incineration is carried out at the TSU RAO facility in Slovakia. In Romania, solvents are also sent abroad for incineration, and ashes are returned to Romania. They are currently stored pending identification of

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[6] Note that the proportions of TBP and dodecane reported in MS34 are incorrect, with the proportions reversed.

a conditioning method. Incineration has been assumed to be in an IRIS-type incinerator[7]. This allows for data sharing with WP6 where the IRIS process is also included as part of a baseline, and conditioning of ashes produced through incineration via this process is studied in greater detail.

Direct conditioning was reported as being an option explored by the CEA. However, this option was not considered representative of other countries, and was therefore not selected as the baseline for organic solvents.

Based on these considerations, and on the decision made during the autumn WP5 meeting [8], the baseline treatment route for organic solvents is a two-step process, consisting of:

- Incineration in an IRIS-type incinerator.
- Cement encapsulation of ashes in 200 L drums.

This is consistent with the second baseline scenario modelled in LCA/LCC.

Disposal in a near-surface disposal facility is assumed for this baseline scenario.

4.1.1.3 Scintillation Cocktails

The Instagel Plus scintillation cocktail was selected as the representative waste for the “scintillation cocktails” baseline, in line with MS34. Although no exact information on the type of scintillation cocktail was provided in the inventory datasheets [3], Instagel Plus was selected as it was deemed representative during the formulation exercise reported in MS34 [19]. Scintillation cocktails were mentioned in the inventories provided by CV Řež and UJV Řež (Czech Republic), RATEN and Cernavoda (Romania), and the CEA (France).

Polymer absorption (e.g. Nochar+ or Experlite) followed by cement encapsulation of scintillation cocktails is currently used in several countries, including the Czech Republic (UJV Řež) and Romania (RATEN). Other potential routes such as Molten Salt Oxidation (MSO) or incineration were reported in the inventory report [3], but it was judged that they are not sufficiently developed to form a credible baseline. MSO was included in the WP6 value assessment [22].

Data provided by CVŘež/UJV Řež to support LCA/LCC [17] and further expanded via the value assessment data request [13] [9] [12] were deemed representative. A baseline similar to that selected for oily waste was therefore deemed representative and is based on data received from CVŘež and complemented, where necessary, with data from SOGIN.

Disposal in a near-surface disposal facility is assumed for this baseline scenario.

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[7] IRIS is a CEA pilot solid incineration unit - presenting two processing steps: the removal of corrosive materials such as chlorine and organic load combustion. It has been chosen as the baseline incinerator in this assessment as it is a facility that can handle the wastes considered and data on the facility has already been collected for WP6.

Table 5: Waste type / formulation selected as scenarios for value assessment

Waste Type	**Scenario ID**	**Formulation / process description**	**Waste**	**Radiological classification**	**Value assessment tables**	**Waste unit/ container in LCA/LCC data**	**Waste container for value assessment**	**Disposal route**
Oil	5.1.1	Encapsulation in metakaolin (Metamax) geopolymer	Nevastane oil	LLW	Appendix 2	500 L drum	200 L drum	Near-surface disposal
	5.1.2	Encapsulation in composite metakaolin (Metamax), blast furnace slag (Ecocem), fly ash (Italy) geopolymer	Nevastane oil		Appendix 2	200 L drum		
	5.1.3	Encapsulation in blast furnace slag geopolymer	Nevastane oil		Appendix 2	50 L drum		
	5.1.B	Two-step process: Step 1: absorption onto Experlite and transfer to a 115 L drum. The sorbent is then encapsulated with cement. Step 2: 115 L is placed into a 216 L drum. Cement is used to fill void between the two drums. Cement assumed to be ordinary Portland cement.	Nevastane oil		Baseline origin: LCA/LCC, MS34, D5.1 CVŘež and SOGIN	216 L drum		

Waste Type	Scenario ID	Formulation / process description	Waste	Radiological classification	Value assessment tables	Waste unit/ container in LCA/LCC data	Waste container for value assessment	Disposal route
Solvents (TBP-Dodecane)	5.2.1	Encapsulation in metakaolin (Metamax) geopolymer	TBP-Dodecane (30/70)	LLW and ILW suitable for near-surface disposal[8]	Appendix 3	500 L drum		
	5.2.B	Step 1: transport to, and incineration at an incinerator using the IRIS process (assumption: at the CEA in France) Step 2: cement encapsulation of ashes in 200 L drum (assumption: collocated with incinerator).	Solvents (incl. TBP-dodecane 30/70) used in the PUREX process (spent fuel reprocessing).		Baseline origin: D5.1, WP6 LCA/LCC CEA	1 kg of feed material		
Scintillation Cocktails	5.3.1	Encapsulation in metakaolin (Metamax) geopolymer	INSTAGEL Plus	LLW	Appendix 4	220 L drum		

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[8] Based on the activity values used in active experiments, as reported in D5.2 (38 GBq/t Ni-63/C-14).

Waste Type	Scenario ID	Formulation / process description	Waste	Radiological classification	Value assessment tables	Waste unit/ container in LCA/LCC data	Waste container for value assessment	Disposal route
	5.3.B	Two-step process: Step 1: absorption onto Experlite and transfer to a 115 L drum. The sorbent is then encapsulated with cement. Step 2: 115 L is placed into a 216 L drum. Cement is used to fill void between the two drums. Cement assumed to be ordinary Portland cement.	Scintillation cocktails in drums with or without stabilisation, conditioned or unconditioned, modelled for value assessment by INSTAGEL Plus		Baseline origin MS34, D5.1, WP5 LCA/LCC CVŘež	216 L drum		

4.2 Attributes and Life Cycle Stage Selection

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

The attributes presented in Appendix 3 of [8] were used as the starting point of this exercise. Discussions with the University of Manchester [20] 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, the value assessment process can consider a wider set of attributes because it can account for qualitative as well as quantitative evaluations, and is based on a relative assessment against the baseline scenario. Therefore, value assessment outputs only need to determine if the geopolymer direct encapsulation route has benefits in comparison with the baseline, which represents conventional practice. A summary table of attributes is presented in Table 6. Full justification for the inclusion or exclusion of criteria is presented in Appendix 5.

For each attribute, a number of quantitative or qualitative metrics are also suggested within Table 6. This ensures that the assessment is proportionate and targeted, and that attributes are 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.

Table 6: Summary of Value Assessment criteria

Area	Criterion	Metric examples
Cross-cutting	Waste loading	Number of packages /m^3 of waste. Waste loadings (%vol).
Operational safety	Facility construction and decommissioning	Size of the facility. Recorded H&S accidents during construction. Judgement on facility complexity.
	Safety during pre-treatment operations	Shielding requirements. Operator dose rates. Sorting and segregation requirements.
	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).
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.
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.
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).
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.

Area	Criterion	Metric examples
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.
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).
	Material availability	Known and/or anticipated issues in sourcing materials, including considerations of material purity and consistency. Waste loading / number of waste packages.
	Technical Readiness Level (TRL)	TRL (1-9).
Financial	Cost of facility and of treatment and conditioning	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed. Waste loading.
	Material costs	Calculated cost of materials (LCC).
	Cost of secondary waste management	Cost of secondary waste management per m^3 of waste.
	Disposal costs, including cost of disposal containers	Cost of disposal containers. Total volume of waste to be disposed of (waste loading).

4.3 Value Assessment Workshop Evaluation Approach

The value assessment workshop agenda and list of attending organisations is presented in Appendix 1.

In practical terms, draft assessment tables [6] were used to support discussions and record the results of the workshop held on 15-16 February 2024. For each evaluation, each criterion was considered in turn and the strengths and weaknesses of the variant scenario in comparison with the baseline scenario were discussed, identified and recorded. For each criterion, the panel was asked to agree on an outcome[9], or rating (geopolymer direct encapsulation vs. baseline), on a scale of -2 (much worse) to 2 (much better), via -1 (worse), 0 (neutral), and 1 (better).

Workshop attendees did not challenge the baseline and variant scenarios and criteria chosen for the value assessment; it was agreed that they were representative and suitably developed to be assessed.

5 Technical, Economic and Environmental Impact of Direct Conditioning of RLOW with Geopolymers

The following sub-sections are structured around the two treatment and conditioning routes identified as baselines (i.e. current RLOW management practices) for the purpose of this report. The technical, economic and environmental impacts, or performance, of geopolymer encapsulation compared to

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[9] The evaluation approach recommended for this exercise is based on five comparative levels: much worse, worse, neutral, better, and much better. There is some subjectivity around the applicability of such descriptors: such variations were limited by having the same GSL staff at every workshop, thus maintaining consistency across the assessments. It is suggested that an evaluation of a much better or much worse outcome is only used where such a score is suitably substantiated and evidenced by quantitative or semi-quantitative metrics.

these management options are listed in Appendices 2 to 4; conclusions for each assessment area are drawn below.

The following set of common assumptions was agreed during discussions of the cross-cutting criterion (waste loading):

- For the purpose of value assessment, costs expressed in Euros are considered to be broadly similar to those expressed in Pound Sterling.
- Downgrading the disposal requirements and the waste category results in an indicative ten-fold reduction in disposal price. For instance, near-surface disposal of borderline ILW/LLW would cost ten times less than deep geological disposal of the same waste. Conversely, disposing of the same waste as VLLW to a surface facility would cost ten times less than near-surface disposal (and hence cost one hundred times less than disposal to a geological disposal facility).

The initial assessment carried out prior to the workshop did not include the weighting of criteria. Such weighing depends on the priorities of each individual Waste Management Organisation. Therefore, the conclusions drawn below are “weighting neutral”. An example of weighted results is provided for illustration purposes in 5.3.

5.1 Geopolymer encapsulation vs. absorption and cement encapsulation (oils and scintillation cocktails)

Waste loading, or the ability of a conditioning method to incorporate waste, is a significant factor when evaluating waste packaging options. Solidification with a Nochar-type polymer followed by cementation of contaminated oils or scintillation cocktails can achieve waste loadings of up to 10%vol [9] [23]. By comparison, waste loadings of up to 40%vol could be achieved when using direct geopolymer encapsulation for the same RLOW.

Such a high waste loading value is unlikely to always be (if at all) achievable outside of research and development activities [24]. Research results and discussions concluded that wasteform performance is highly dependent upon waste loading (amongst other parameters). During the value assessment workshop, attendees agreed that a range of 15 to 30% would best describe waste loadings that are most likely to result in compliant waste forms and waste packages.

5.1.1 Operational Safety Considerations

Treatment and conditioning under baseline assumptions rely on two distinctive process steps: absorption onto a Nochar-type polymer followed by cement-encapsulation. Geopolymer encapsulation, on the other hand, is a one-step process. Fewer handling operations will result in lower health and safety risks. The increased waste loading, resulting in fewer waste packages that must be produced, will further this trend. The overall risk reduction is difficult to quantify with precision, but it can be noted that tripling the waste loading and halving the number of treatment steps is likely to, at least, halve the risk levels associated with conditioning of the RLOW studied in this work package.

Geopolymer encapsulation requires the handling of strong alkali activators, introducing new chemical hazards to operators. The potentially finer powders found in Metakaolin might increase air filtration requirements. Whilst recognising this difference with absorption onto Nochar-type polymers followed by cement encapsulation, workshop attendees noted that it was not of significant concern. The need to obtain regulatory approval for the novel treatment and conditioning method was also factored into the evaluation, although the relative simplicity of the process might limit the negative impact of such activities.

Overall, implementation of the direct conditioning route using geopolymers results in ***improvements*** *in operational safety compared with absorption onto a Nochar-type polymer followed by cement encapsulation. Most of the improvements are made possible by the simplification of the process and reduction in the number of waste packages that will need to be produced.*

5.1.2 Environmental Impact

Discussions around the environmental impact of the direct encapsulation route focused on material requirements. Process energy requirements are similar between the baseline and geopolymer encapsulation because both routes use a similar process (mixing with a cementitious matrix), on a similar scale.

There are pros and cons to both options in terms of material environmental impact. The need to use an inner drum is removed by direct geopolymer encapsulation, thus reducing the amount of steel required by the conditioning process. On the other hand, strong hydroxides are used for direct geopolymer encapsulation, the production of which is considered to have a detrimental environmental impact. However, on balance the LCA concluded that:

Overall, a significant reduction in environmental impacts can be achieved through the utilisation of geopolymer encapsulation as opposed to cementation when climate change potential is concerned. Other geopolymer environmental impacts are dominated by the use of KOH as a precursor. However, this does not change the conclusion that the direct conditioning route using geopolymers is ***better*** *than the baseline in terms of environmental impact.*

5.1.3 Disposability and Long-term Safety

No significant differences were observed between the potential disposability of the baseline option (adsorption and cementation) and the variant scenarios. Disposability assessment of geopolymer wasteforms is described in the D5.4.9 report [5]. The results are promising; however, the surfactants used in some formulations need to be evaluated as they may behave as a complexing agent, which is usually prohibited in disposal facilities. Moreover, some formulations do not yet present conclusive results regarding the mechanical strength and the homogeneity of the waste form. Some disposability assessment criteria were not evaluated in [5] owing to the absence of information regarding the waste package and its activity, for example. Such criteria will have to be assessed for application of geopolymer wasteforms in real disposal scenarios. More experiments are needed in order to evaluate these additional criteria more thoroughly.

Overall, the disposability and long-term safety of geopolymer wasteforms are difficult to evaluate as more disposability criteria need to be assessed than is currently possible with current data at laboratory scale.

5.1.4 Implementation

A typical throughput for the process of polymer absorption followed by cement encapsulation is approximately eight standard 220L drums per day, or 160 L of RLOW treated. Both the baseline and geopolymer processes require a dedicated on-site drying area, whilst wasteform mixing and pouring require up to one hour for both processes. It was confirmed during the value assessment workshop that these values apply equally to the baseline and geopolymer routes. Furthermore, experimental rigs at CVŘež/UJV Řež have achieved near-industrial scale by using 115L drums for geopolymer mixing, without meeting significant issues during the implementation of the process.

The availability of, and consistency in the purity of materials required for geopolymer manufacture were reported as problematic in some cases, which impacted on the reproducibility of experimental results. Obtaining a consistent source material was reported as difficult in the case of MK, BFS, and fly ash.

A TRL of 4 to 6 was assigned to direct RLOW encapsulation with geopolymers. The Metamax (MK) and BFS formulations were assigned a TRL of 5 to 6, based on the achievement of oil encapsulation in near-scale drums at CVŘež/UJV Řež [15], and further supported by the commercialisation of geopolymer encapsulation by companies such as Jacobs (SIAL®) [12] [25] [26]. SIAL is currently being used [27] 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 this represented adequate technology demonstration in a relevant environment (TRL 6) [28].

The mixed formulation (MK, BFS and FA) has not been tested in near-scale drums, but the same arguments in terms of overall mixing and industrial equipment applies. It was therefore agreed that a TRL of 5 to 6 could be assigned.

When compared with a TRL of 9 for the baseline, such figures may seem low or could be considered to pose a significant disadvantage. However, workshop attendees agreed 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, implementation of the direct conditioning route is **slightly more challenging** than the baseline. Whilst process throughputs have already been demonstrated to be similar, sourcing consistently pure source materials was reported to be sometimes challenging, and additional research is required to fully demonstrate and qualify the RLOW direct conditioning routes studied in PREDIS at the system level.*

5.1.5 Cost

During the workshop, the panel agreed that costs associated with secondary waste management were likely to be of the same order of magnitude between the baseline and variant scenarios. The processes are of a similar nature, with similar health and safety requirements and personal protective equipment needs.

Based on figures obtained from the Czech Republic [9] [13] and attendees feedback, it was concluded that per-drum production costs were of a similar order of magnitude between the baseline and the direct encapsulation route, taking into account costs associated with facility construction, operations, maintenance, and decommissioning.

However, the overall cost associated with the management of a particular waste stream will be reduced by a factor proportional with the increase in waste loading. Based on the conservative assumption that waste loadings using direct geopolymer encapsulation are three times as high as those observed under baseline assumptions, waste package production and disposal costs are likely to be a third of those required with the baseline.

*Overall, the costs of implementing the direct conditioning route are **much lower** than those associated with the baseline. Whilst precise quantification of the financial gains is country-dependent, it can be assumed that management costs are likely to be halved when compared with the baseline.*

5.2 Geopolymer Encapsulation vs. Incineration Followed by Cementation (solvents)

Direct conditioning of contaminated solvents using MK-based geopolymers was assessed against a different baseline, as justified in Section 4. Incineration at a central facility followed by immobilisation of the resulting ashes in cement in a standard 200 L drum, at a facility co-located with the incinerator was the baseline chosen for this value assessment.

Waste loadings for solvents were debated in a similar way to that reported in Section 5.1 for oils, recognising that a trade-off needed to be found between increased waste loading and wasteform performance. Based on figures provided by research partners [29] [30] [11], the waste loading achieved by incineration is typically around 100%vol. The waste loading achieved by geopolymer encapsulation is similar to that reached with other RLOW, e.g. in the range [15-30]%vol. Therefore, the assumption that geopolymer encapsulation results in a fivefold increase in the number of waste packages compared to incineration was accepted for this exercise.

5.2.1 Operational safety

During the value assessment workshop, attendees identified two significant strengths when comparing direct geopolymer conditioning with incineration and cementation.

Preparing the waste for (transboundary) transport and incineration incurs significant time and human effort, thus increasing health and safety risks, compared with the simple one-step process used for direct geopolymer conditioning. Health and safety risks associated with the direct conditioning route are further reduced by removing the need for transport to an incineration facility. Such a reduction is significant due to the statistically high risk levels associated with road transport. This reduction in hazard is partially offset by the chemical hazard posed by the presence of strong alkali activators in the geopolymer formulation.

Removing the need for (transboundary) transport also reduces the regulatory and administrative burden on waste producers, by removing the need for permit applications, and reducing exposure to geopolitical risks. On the other hand, direct conditioning with geopolymer is a novel waste management practice and will require regulatory approvals, the burden of which is country dependent. Workshop attendees agreed that such a burden was likely to be reduced by the simplicity of the process, and that experience from any first-of-a-kind facility could be used by other countries to substantiate their safety demonstrations (see Sections 5.1.4 and 5.2.4).

Overall, implementation of the direct conditioning route with geopolymers was deemed to be ***safer than the baseline****. This is substantiated by the reduction in the number of steps and activities required for waste management, by the removal of the need for transport and the associated regulatory burden. Such advantages will be partly counter-balanced by the increase in the number of waste packages and the slight increase in chemical risks.*

5.2.2 Environmental impact

The environmental impact of the two management routes was evaluated against the environmental impact of the materials required by the process, and its energy requirements.

The material environmental impact of cement production is comparable with that of geopolymer production, albeit with a slightly higher marine and freshwater ecotoxicity cost for the latter (LCA results to be published – see PREDIS D2.9).

The main difference comes from the removal of the transport step, resulting in a significant reduction in the environmental cost of geopolymer conditioning compared with incineration. Such improvements in terms of climate change potential are confirmed by the LCA calculations, which indicate that the carbon dioxide equivalent is halved when shifting from incineration to direct geopolymer encapsulation.

Overall, the environmental impact of direct conditioning of contaminated solvents with geopolymer is ***neutral to slightly better*** *than that of incineration followed by cementation. Whilst energy requirements are lower for geopolymer encapsulation, mining of the minerals incurs an environmental cost in terms of water ecotoxicity.*

5.2.3 Disposability and long-term safety

The geopolymer management route is much better than the baseline IRIS incineration process in terms of producing much less secondary wastes. In terms of disposability, the baseline has fewer uncertainties because it involves the destruction of all organic liquid, but several important disposability criteria were not evaluated owing to the absence of data at waste package scale.

Disposability assessment of geopolymer wasteforms is described in the D5.4 report [5]. The results are promising; however, the surfactants used in some formulations need to be evaluated as they may behave as a complexing agent, which is usually prohibited in disposal facilities. Moreover, some formulations do not yet present conclusive results regarding the mechanical strength and the homogeneity of the waste form. Some disposability assessment criteria were not evaluated in [5] owing to the absence of information regarding the waste package and its activity, for example. Such criteria will have to be assessed for application of geopolymer wasteforms in real disposal scenarios. More experiments are needed in order to evaluate these additional criteria more thoroughly.

Overall, the disposability and long-term safety of geopolymer wasteforms are difficult to evaluate as more disposability criteria need to be assessed than is currently possible with current data at laboratory scale.

5.2.4 Implementation

Workshop attendees agreed that, based on information provided by the CEA [29], the incineration step throughput was likely to be the limiting step under baseline assumptions. Discussions around the throughput of the direct geopolymer conditioning route reached the same conclusion as that reported in Section 5.1.4: cementation and geopolymer encapsulation are comparable in terms of production rate. The impact of the rate-limiting incineration step was deemed negligible, since the quantities and arising rates of RLOW intended for these processes are low. However, removing the need for (transboundary) transport was seen as a significant strength of the geopolymer route.

Issues related to the purity and consistency of MK and other reagents were reported. Discussions around TRL were similar to those reported in Section 5.1.4 and reached the same conclusions.

*Overall, implementation of the direct geopolymer conditioning route for contaminated solvents was seen as being of a **similar** complexity level compared with the baseline. Process simplification is counter-balanced by issues with source materials purity and the need for further development to reach a TRL of 9.*

5.2.5 Cost

Cost data related to incineration of contaminated solvents was not available at the time of the assessment and at the time of writing: meeting participants agreed not to draw any conclusions related to the cost of treatment and conditioning.

The cost of waste disposal following geopolymer encapsulation is likely to be up to five times higher than that associated with disposal of cemented ashes, in line with differences in waste loadings between the two options.

*Overall, the cost impact of managing contaminated solvents via direct geopolymer encapsulation is **worse** than under baseline assumptions. Such a conclusion is substantiated by the decrease in waste loading between the two routes but is subject to change if treatment and conditioning costs for the baseline become available.*

5.3 Further Considerations

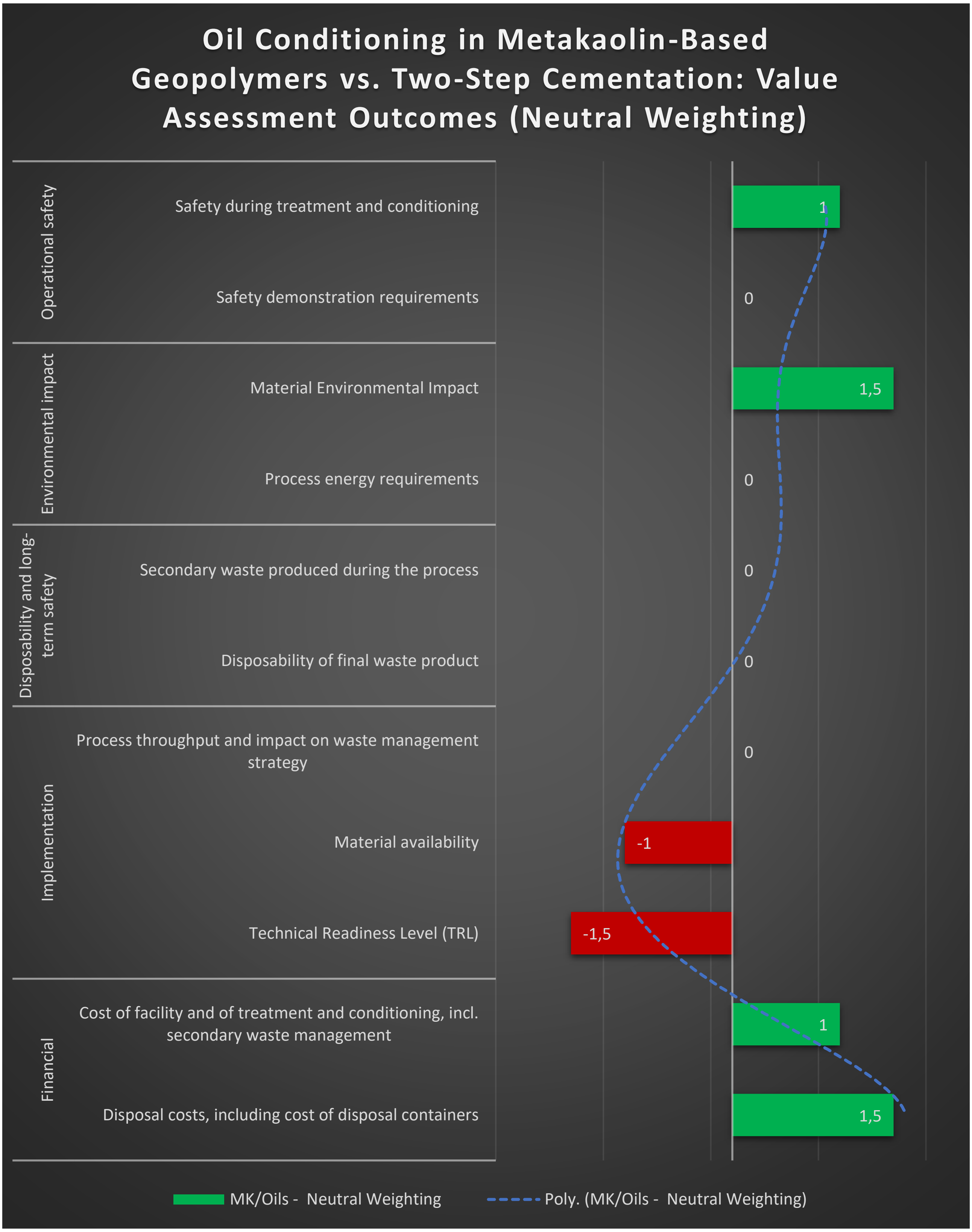
The above discussions are summarised by attribute and by life cycle stage, and no overall rating has been attributed, recognising that waste owners may need to apply their own analysis based on their own national waste management context. In this respect, each organisation and / or End-User is invited to consider customising the results by applying weighting factors to each attribute that reflect national priorities.

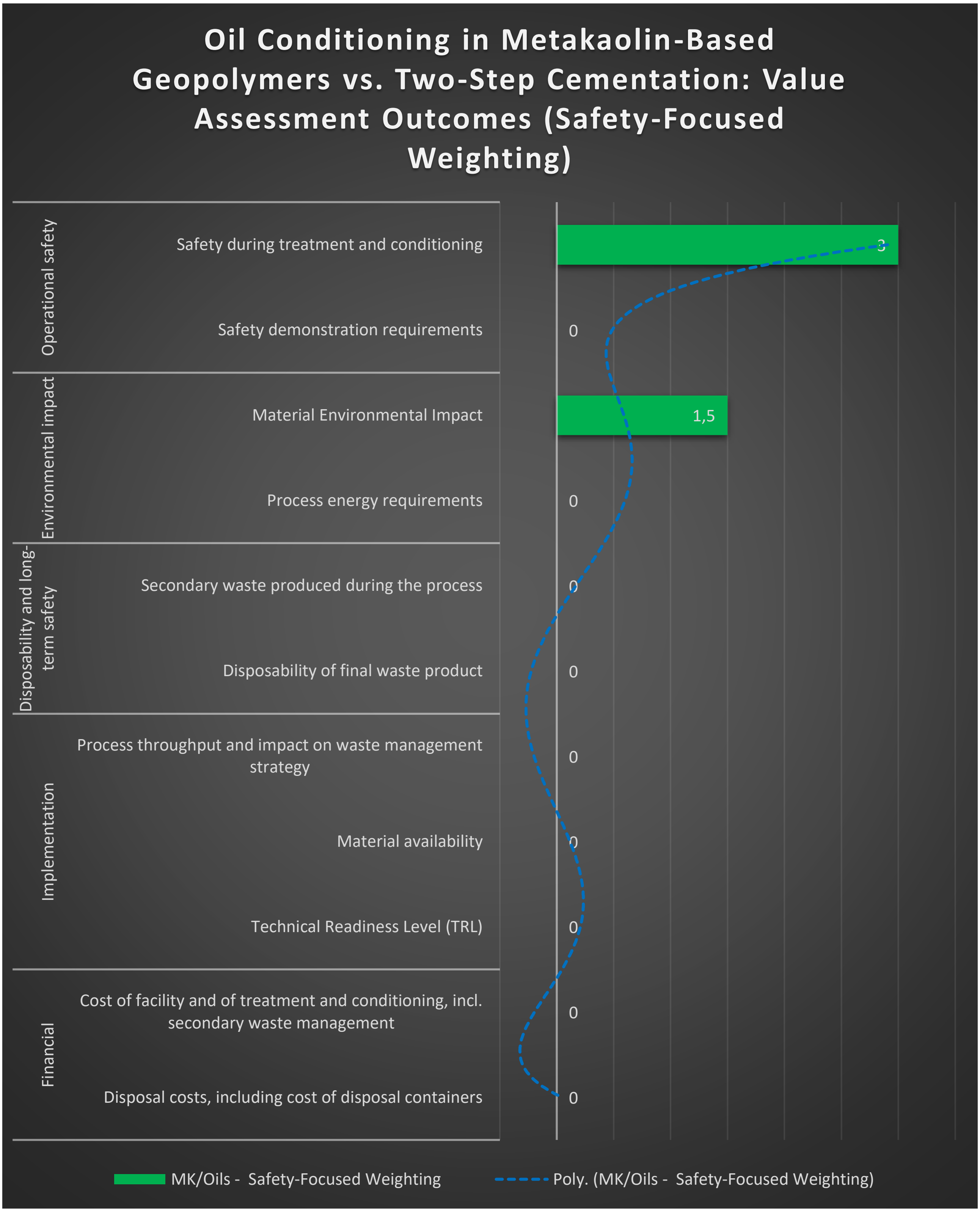
Results from the assessment of the direct conditioning of oils and scintillation cocktails using MK-based geopolymers route vs. two-step cementation are illustrated in the figures below. Note that these results are also applicable to the BFS and MIX formulations (noting that disposability considerations are not formally rated - see D5.4).

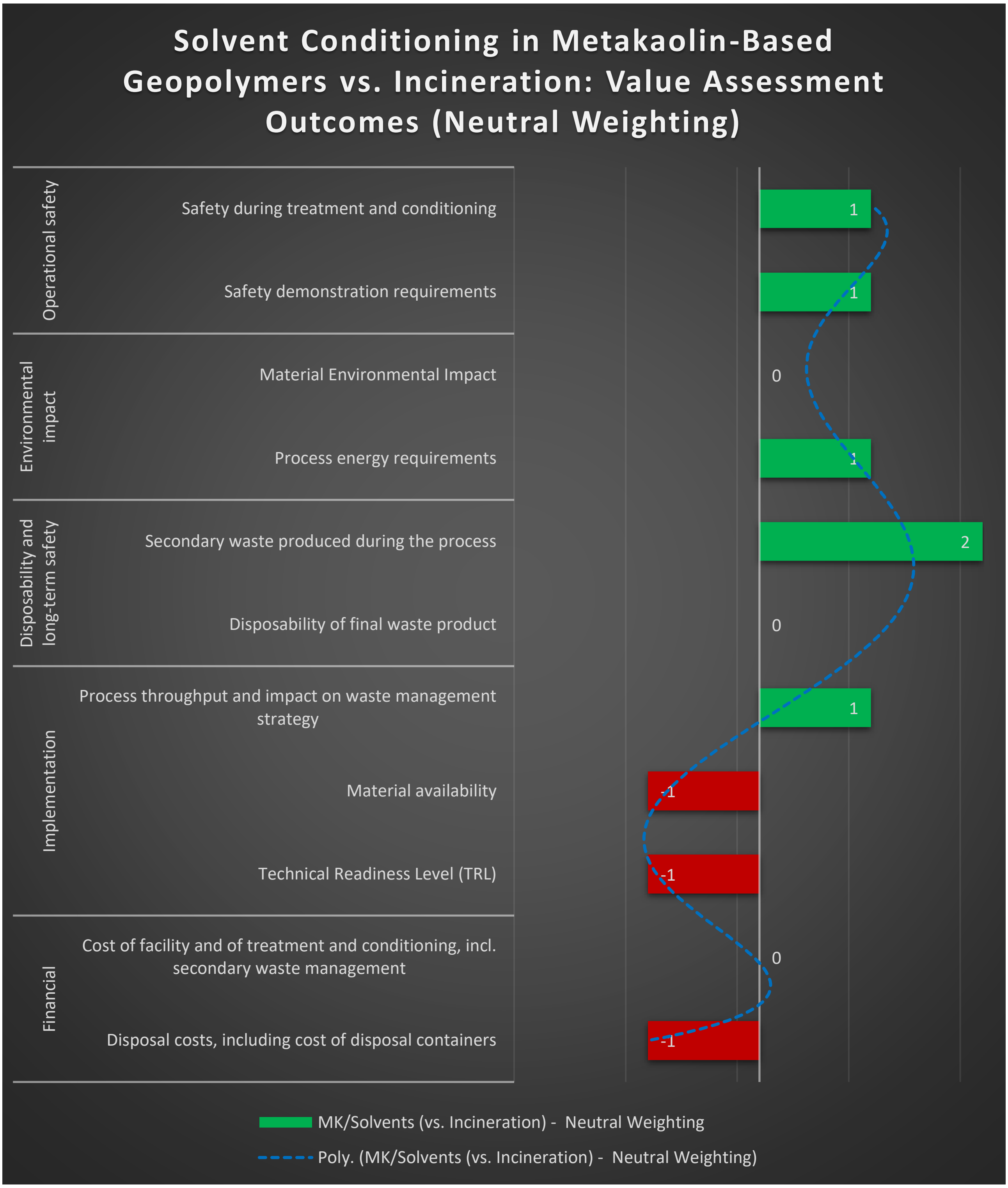
Results from the assessment of the direct conditioning contaminated solvents using MK-based geopolymers route vs. incineration followed by cementation are illustrated in the figures below.

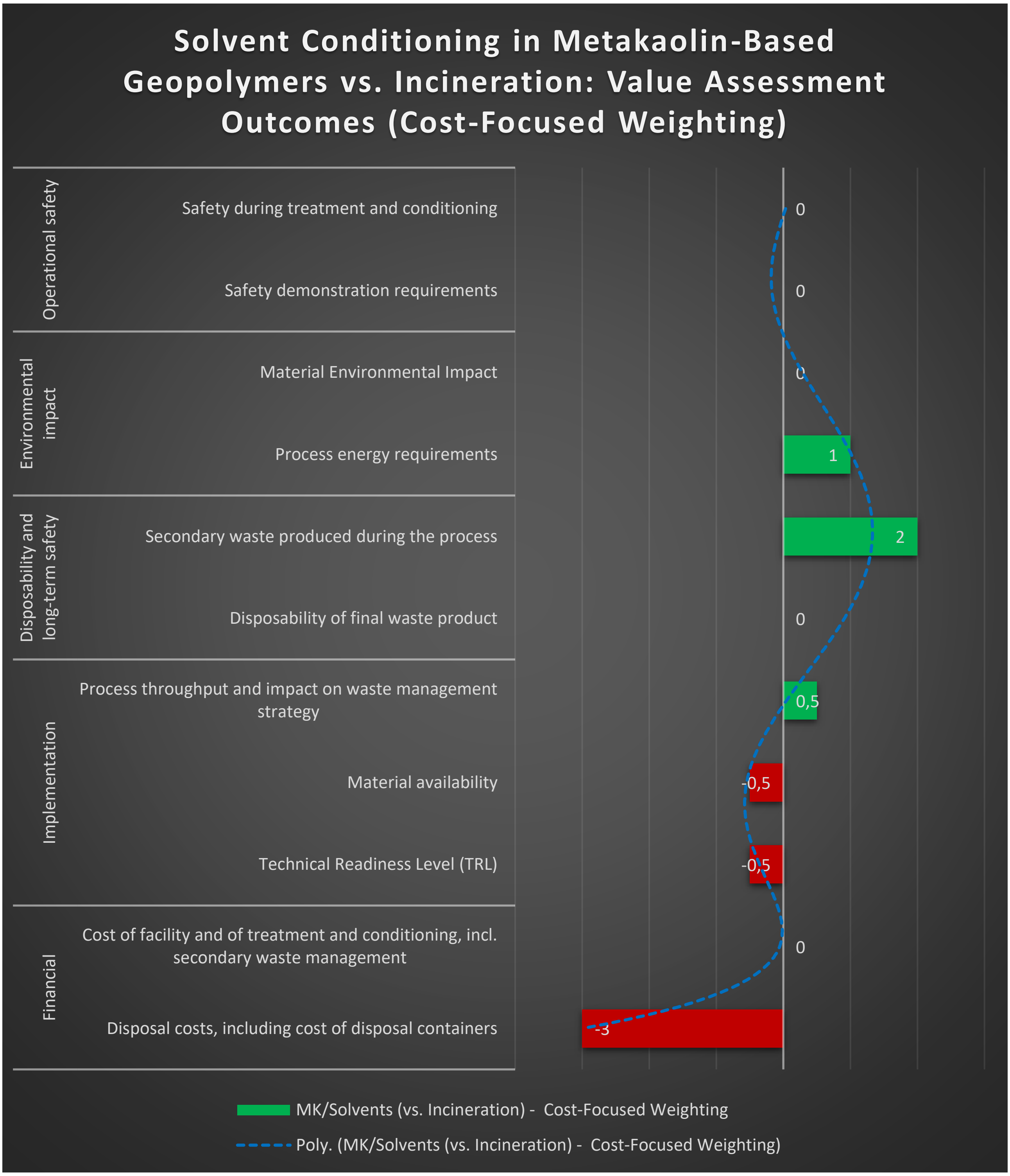
Similar graphs can be obtained for the BFS and MIX formulations but are not included in this report for conciseness.

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




Oil Conditioning in Metakaolin-Based Geopolymers vs. Two-Step Cementation: Value Assessment Outcomes (Safety-Focused Weighting)
Operational safety
Safety during treatment and conditioning
3
Safety demonstration requirements
0
Environmental impact
Material Environmental Impact
1,5
Process energy requirements
0
Disposability and long-term safety
Secondary waste produced during the process
0
Disposability of final waste product
0
Implementation
Process throughput and impact on waste management strategy
0
Material availability
0
Technical Readiness Level (TRL)
0
Financial
Cost of facility and of treatment and conditioning, incl. secondary waste management
0
Disposal costs, including cost of disposal containers
0
MK/Oils - Safety-Focused Weighting
Poly. (MK/Oils - Safety-Focused Weighting)


Solvent Conditioning in Metakaolin-Based Geopolymers vs. Incineration: Value Assessment Outcomes (Neutral Weighting)
Operational safety
Safety during treatment and conditioning
1
Safety demonstration requirements
1
Environmental impact
Material Environmental Impact
0
Process energy requirements
1
Disposability and long-term safety
Secondary waste produced during the process
2
Disposability of final waste product
0
Implementation
Process throughput and impact on waste management strategy
1
Material availability
-1
Technical Readiness Level (TRL)
-1
Financial
Cost of facility and of treatment and conditioning, incl. secondary waste management
0
Disposal costs, including cost of disposal containers
-1
MK/Solvents (vs. Incineration) - Neutral Weighting
Poly. (MK/Solvents (vs. Incineration) - Neutral Weighting)


Solvent Conditioning in Metakaolin-Based Geopolymers vs. Incineration: Value Assessment Outcomes (Cost-Focused Weighting)
Operational safety
Safety during treatment and conditioning
0
Safety demonstration requirements
0
Environmental impact
Material Environmental Impact
0
Process energy requirements
1
Disposability and long-term safety
Secondary waste produced during the process
2
Disposability of final waste product
0
Implementation
Process throughput and impact on waste management strategy
0,5
Material availability
-0,5
Technical Readiness Level (TRL)
-0,5
Financial
Cost of facility and of treatment and conditioning, incl. secondary waste management
0
Disposal costs, including cost of disposal containers
-3
MK/Solvents (vs. Incineration) - Cost-Focused Weighting
Poly. (MK/Solvents (vs. Incineration) - Cost-Focused Weighting)

6 Conclusions

In WP5, options for direct conditioning of RLOW using innovative geopolymers and related alkali activated materials were developed and investigated. The work package was divided into tasks focused on studying the direct conditioning process (T5.3), the conditioning matrix performances (T5.4), and on assessing the overall technical, economic and environmental performance of the direct conditioning route (T5.5). This report, deliverable D5.5, falls under T5.5.

This deliverable was dedicated to the preliminary technical, economic and environmental analysis of the direct conditioning route developed in PREDIS WP5 for three types of RLOW: contaminated oils, solvents and scintillation cocktails. This analysis, also termed value assessment, brought together research results in terms of waste loading, conditioning matrix performance, process cost, and product disposability to capture the overall performance of the direct conditioning route. These results were compared with current waste management practices to provide a comparison of how the novel direct conditioning route performs against current practices over a range of criteria.

This report also provides a basic design description of this “direct conditioning route for RLOW” as well as a summary of data transferred to WP2 and used for the purpose of LCA, LCC and value assessment.

Direct conditioning of contaminated oils and scintillation cocktails using Metakaolin-based, Blast Furnace Slag, or the MIX-based geopolymer formulations was found to result in better operational safety outcomes, compared with the current two-step cementation approach. The environmental impact of the overall process is also lower, whilst significantly reducing conditioning, storage and disposal costs. Several challenges were identified in the form of raw material procurement and purity. The need for further research and development to achieve a TRL of nine was also acknowledged and is reflected in the EURAD-2 proposals.

Direct conditioning of solvents using MK-based geopolymers was compared against a baseline comprising incineration followed by cementation. Geopolymer conditioning was found to result in improved safety and environmental outcomes. The same challenges to implementation as those highlighted above were identified. The economic impact of implementing this management route was not fully evaluated due to unavailability of cost data associated with incineration facilities. Current findings indicate, however, that disposal is likely to be more costly due to the relatively lower geopolymer waste loading compared with the loading achieved when thermal treatment is used.

Disposability considerations are evaluated separately in another deliverable (D5.4) and have not been discussed in detail in this report.

Overall, direct conditioning of RLOW using the geopolymer formulations developed in PREDIS WP5 was found to result in positive economic, safety, and environmental outcomes.

7 References

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[4] European Commission, “PREDIS: Pre-disposal Management of Radioactive Waste, Annex 3 (detailed implementation plan associated with Section 3).,” September 2019.

[5] D. Alby et al. (GSL), “Deliverable 5.4: Disposability Assessment Report for Direct Conditioning,” April 2024.

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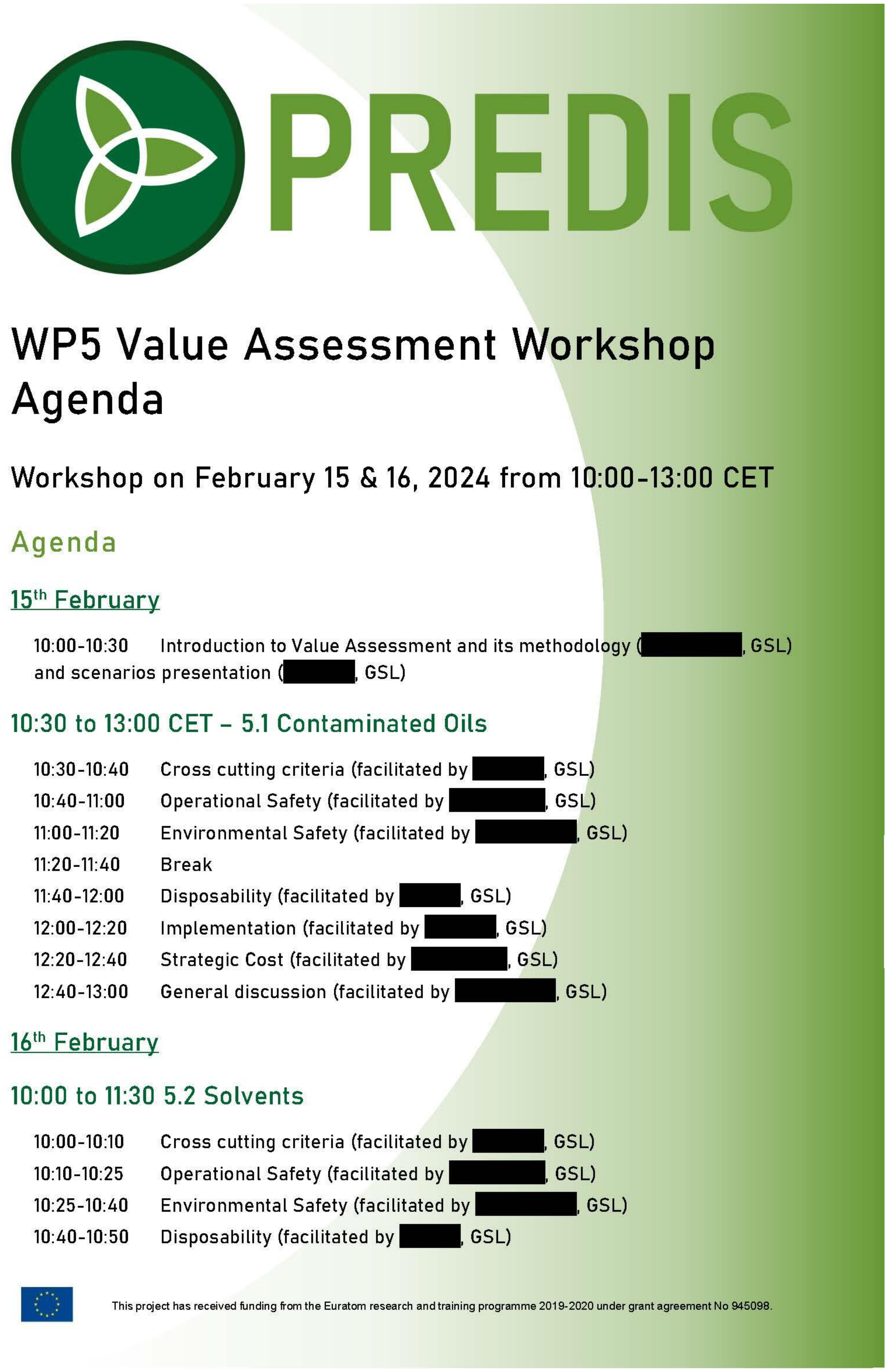
Appendix 1: Value Assessment Workshop Agenda and Attendance



WP5 Value Assessment Workshop Agenda

Workshop on February 15 & 16, 2024 from 10:00-13:00 CET

Agenda

15th February

10:00-10:30	Introduction to Value Assessment and its methodology ([redacted], GSL) and scenarios presentation ([redacted], GSL)

10:30 to 13:00 CET – 5.1 Contaminated Oils

10:30-10:40	Cross cutting criteria (facilitated by [redacted], GSL)
10:40-11:00	Operational Safety (facilitated by [redacted], GSL)
11:00-11:20	Environmental Safety (facilitated by [redacted], GSL)
11:20-11:40	Break
11:40-12:00	Disposability (facilitated by [redacted], GSL)
12:00-12:20	Implementation (facilitated by [redacted], GSL)
12:20-12:40	Strategic Cost (facilitated by [redacted], GSL)
12:40-13:00	General discussion (facilitated by [redacted], GSL)

16th February

10:00 to 11:30 5.2 Solvents

10:00-10:10	Cross cutting criteria (facilitated by [redacted], GSL)
10:10-10:25	Operational Safety (facilitated by [redacted], GSL)
10:25-10:40	Environmental Safety (facilitated by [redacted], GSL)
10:40-10:50	Disposability (facilitated by [redacted], GSL)

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

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WP5 Value Assessment Workshop Agenda

10:50-11:00	Implementation (facilitated by [redacted], GSL)
11:00-11:10	Strategic Cost (facilitated by [redacted], GSL)
11:10-11:20	General discussion (facilitated by [redacted], GSL)
11:20-11:40	Break

11:40 to 12:50 5.3 Scintillation Cocktails

11:40-11:50	Cross cutting criteria (facilitated by [redacted], GSL)
1:50-12:00	Operational Safety (facilitated by [redacted], GSL)
12:00-12:10	Environmental Safety (facilitated by [redacted], GSL)
12:10-12:20	Disposability (facilitated by [redacted], GSL)
12:20-12:30	Implementation (facilitated by [redacted], GSL)
12:30-12:40	Strategic Cost (facilitated by [redacted], GSL)
12:40-12:50	General discussion (facilitated by [redacted], GSL)

12:50-13:00 Wrap up & Closure

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Name	Organisation	Email address	Role
[redacted]	GSL	[redacted]	Facilitation team lead
[redacted]	GSL	[redacted]	Facilitation team
[redacted]	GSL	[redacted]	Facilitation team
[redacted]	GSL	[redacted]	Facilitation team
[redacted]	CEA	[redacted]	WP5 Lead
[redacted]	CEA	[redacted]	WP5 Lead
[redacted]	University of Manchester	[redacted]	LCA/LCC input
[redacted]	University of Manchester	[redacted]	LCA/LCC input
[redacted]	University of Manchester	[redacted]	LCA/LCC input
[redacted]	SOGIN	[redacted]	Technical input
[redacted]	SOGIN	[redacted]	Technical input
[redacted]	SOGIN	[redacted]	Technical input
[redacted]	CVŘež	[redacted]	Technical input
[redacted]	PSI	[redacted]	Technical input
[redacted]	Romania Institute of Nuclear Research	[redacted]	Technical input
[redacted]	NNL	[redacted]	Technical input
[redacted]	NNL	[redacted]	Technical input
[redacted]	SCK CEN	[redacted]	Technical input
[redacted]	UJV Řež	[redacted]	Technical input
[redacted]	UniPi	[redacted]	Technical input
[redacted]	UniPi	[redacted]	Technical input

APPENDIX 2: VALUE ASSESSMENT RESULTS (OILS)

Waste Type	Scenario ID	Formulation / process description	Waste	Radiological classification	Scenario origin and source organisation	Waste unit/container in LCA/LCC data	Waste container for value assessment	Disposal route
Oil	5.1.1	Encapsulation in metakaolin (Metamax) geopolymer	Nevastane oil	LLW	LCA/LCC and MS34 NNL	500 L drum	200 L drum	Near-surface disposal
	5.1.2	Encapsulation in composite metakaolin (Metamax), blast furnace slag (Ecocem), fly ash (Italy) geopolymer	Nevastane oil		LCA/LCC and MS34 NSC KIPT	200 L drum		
	5.1.3	Encapsulation in blast furnace slag (BFS) geopolymer	Nevastane oil		LCA/LCC and MS34 CVŘež	50 L drum		
	5.1.B	Two-step process: Step 1: absorption onto Experlite and transfer to a 115 L drum. The sorbent is then encapsulated with cement. Step 2: 115 L is placed into a 216 L drum. Cement is used to fill void between the two drums. Cement assumed to be ordinary Portland cement.	Nevastane oil		LCA/LCC, MS34, D5.1 CVŘež	216 L drum		

5.1.x vs 5.1.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		**Overall scenario rating versus baseline**
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	
Cross cutting	Waste loading	Number of packages /m^3 of waste. Waste loading (%vol). *Consistency in measurement approach is required*	From raw waste to waste package ready for disposal (assumption: standard 200 L drum). Excluding any overpack used in the disposal concept.	Waste loadings from 5%vol. (Czech Republic) and up to 10%vol. (Romania).	Waste loading up to 40%vol. to 50%vol. (NNL) Performance (durability and strength) decline with increasing waste loading – realistic achievable waste loading of 15-30%vol. *Hard to give a specific value, so a range is given instead.*	Waste loadings during direct conditioning with the geopolymer formulations used in scenarios 5.1.x are significantly higher than that of the baseline. Even if the upper value of 40%vol. is not achieved, a loading of 20%vol. would represent a significant improvement, with positive impacts across the whole waste management lifecycle.		None		No rating assigned.
Operational safety	Safety during treatment and conditioning	Shielding requirements. Operator dose rates and cumulative dose (man Sieverts). Known or anticipated operational issues. Number of treatment and conditioning steps. Number of packages (waste loading).	Includes radiological and conventional safety.	Shielding can be used by operators if necessary (for waste with high dose rates). The operational impact can be mitigated by preparing the outer drum and concrete annulus ahead of inner drum placement.	Alkali activators used in the process present a chemical hazard requiring the use of PPE. CVŘež/UJV Řež reported that they did not encounter or expect any additional health and safety risks.	The number of process steps is reduced to one, with the expected benefit of fewer handling operations, resulting in potentially lower dose rates and health and safety risks. The increased waste loading in scenarios 5.1.x tilts the balance in its favour: fewer waste packages to be produced will result in a proportional reduction in risk. The baseline involves an extra handling step (noting that RATEN cementation is a one-step process).	NA	The presence of alkali activators adds a chemical hazard to the process and requires the use of PPE. Requirement for strong alkali solution is recipe dependent. However, differences are minor compared with safety handling issues for cement in baseline. Safety can be easily managed with standard procedures.	NA	+1
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.	Excludes disposability considerations (dedicated set of criteria below).	Safety cases and necessary regulatory approvals are in place for existing and operating facilities.	The safety case of an industrial-scale facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed. Potentially finer powder (MK only) but likely not a significant enough difference to require different standards.	None	NA	The novelty of the formulation and process will require a safety demonstration, with associated time and effort requirements. Delays in obtaining regulatory approvals may occur. However, this only applies to the first such treatment facility. Subsequent safety demonstrations can be substantiated with operational experience. May need more air filtration to manage dust levels. More silos for storage of raw materials needed.	NA	No significant differences (weaknesses highlighted herein were deemed minor).

5.1.x vs 5.1.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		**Overall scenario rating versus baseline**
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	
Environmental impact	Material Environmental Impact	Known environmental impact of material excavation (qualitative). Calculated (LCA) material requirements for manufacture and/or excavation. Number of waste packages (waste loading). Material requirements of alternative treatment and conditioning option.	Includes the environmental impact (including energy use) of material manufacture, for all materials feeding into the process (e.g. inner drum, encapsulant).	An inner drum is usually required for this process.	No inner drum is needed. The scale of the difference has been calculated in the LCA model.	Direct conditioning with geopolymers removes the need to use an inner drum, thus reducing the amount of steel required by the overall process. Quantitative environmental data (such as the mass of steel required) will become available upon completion of the LCA. BFS represents reuse of material. Cement requires v. high temperatures to precursors (MK also requires calcining but not to the same temperatures).	NA	Further environmental impact data will become available upon completion of the LCA (see PREDIS D2.9 – in preparation) Use of strong hydroxides (Na or K).	NA	+1.5 *Differences between geopolymer formulations but not sufficient to change overall rating* *Incorporates preliminary LCA findings.* *Includes energy requirements of packaging material requirements.*
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Excluding transport.	Awaiting LCA results - see PREDIS D2.9 – in preparation.	Awaiting LCA results - see PREDIS D2.9 – in preparation.	Quantitative energy use data (such as the total energy requirement for the two options) will become available upon completion of the LCA process. However, the processes are similar in nature (mixing with a cementitious matrix): major variations are not expected.	NA	Further energy use data will become available upon completion of the LCA process. However, the processes are similar in nature (mixing with a cementitious matrix): major variations are not expected.	NA	No significant difference
Disposability and 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.	No specific information.	Residual bleed has been observed in experiments, and rinsing water will arise (unless in-drum mixing is used). Where present, bleed was recorded at a maximum of 1.25 vol%. at 48 hours. Research partners reported that residual bleed is treated via the same route, and rinsing water can be used as mixing water for the next batch. Note that CVŘež did not observe bleeding with this formulation (waste loadings up to 30 %vol). Bleed is not a secondary waste as it cannot be removed – if significant amounts of bleed (<1%) are observed then the process is typically considered to have failed.	None. Residual bleed and rinsing water will arise in both processes. Residual bleed from direct encapsulation with geopolymers can be re-incorporated into the next batch. The use of in-drum mixing with a sacrificial paddle would remove the need for rinsing water. The lack of a disposability assessment for the resulting waste is compensated for by the advantage provided by the reduction in waste package numbers resulting from the increased waste loading. Experimental results reported in D5.2 [1] show acceptable amounts of residual bleed for the waste loadings considered in this value assessment.				No significant difference

5.1.x vs 5.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.	For discussion only. Disposability is considered separately in the disposability assessment (D5.4 [5]). Exclude packaging Exclude radioactivity	For discussion only.	There is the potential for some of the oil to exist as free organic liquid in pores within the geopolymer matrix. Due to the polycondensation reaction of the geopolymer system it expels water over time. Bleed was recorded at maximum of 1.25 vol% of product for all formulations at 48 h.	NA	See D5.4 [5].	The criteria evaluated are promising and similar to the baseline, however, for the CIEMAT formulation, a few criteria were not conclusive such as the mechanical strength, the homogeneity and the use of surfactant, which could potentially be problematic for disposal		No rating assigned.
Implementation	Process throughput and impact on waste management strategy[10].	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).	Excludes transport considerations. Excludes TRL considerations (accounted for in dedicated criterion).	Fully implemented. The rate of waste generation is the limiting factor. 30-60 minutes per 115 L drum (then placed in a 200 L drum). =>8 drums/day Section of plant needed for first 24h of curing. Throughput very dependent on facility	Geopolymers and cements have similar forms and mixing properties. CVŘež/UJV Řež reported that waste and geopolymer mixing took approximately 45 minutes, and that a rate of 7-8 drums/day was achievable. Section of plant needed for first 24h of curing.	The increased waste loading reduces the impact of process throughput on the overall waste management strategy.	NA	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 [1].	NA	No significant difference
	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).	Potential issues with the availability of Experlite were reported.	MK availability may be an issue. Consistency in the purity of the reagent may also be an issue. The alkali activator is premixed by the supplier (Potassium silicate 35 wt.% solution). BFS availability also a concern for relevant cases.	Direct conditioning with this geopolymer formulation removes the need to use Experlite, for which availability issues have been reported. Can be difficult to source correct grade of cement.	NA	MK availability, and consistency in the purity of the reagent were reported as slightly problematic. BFS availability (for BFS and MIX formulations).	NA	-1 *Differences between formulations aren't sufficient to alter overall conclusion*
	Technical Readiness Level (TRL)	TRL (1-9).	NA	9	4	Radioactive waste conditioning using geopolymers is already implemented in an industrial environment for other waste types (see Section 5.1.4, e.g. SIAL®). Therefore, there is a good chance that equipment will be available off-the-shelf, and that industrial experience can be transferred across.	NA	TRL of 4 vs. 9.	NA	-1.5 *The difference in TRL is mitigated by the existence of a similar process used for different waste types.*

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[10] Because of relatively small waste volumes, process throughput may be of a lesser importance when considering RLOW, compared to other waste types with significantly bigger inventories.

5.1.x vs 5.1.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		Overall scenario rating versus baseline
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	
Financial[11]	Cost of facility and of treatment and conditioning and cost of secondary waste management.	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed. Waste loading. Cost of secondary waste management per m^3 of waste.	Including construction and decommissioning costs if available. Including treatment, conditioning, and disposal of secondary waste. Excluding transport. Excluding storage.	Cost data per drum and per litre liquid organic waste to be published – see PREDIS D2.9 Drum in drum (two drums required).	Cost data per drum to be published – see PREDIS D2.9 Numbers might be inaccurate – Italian drums cost near this amount and costs are dependent on facility size (facility cost vs per drum cost). Better to conduct a qualitative comparison. Special (more expensive) design of drum may be required to delay/decrease corrosion. Stainless steel drums are suitable.	Production costs are similar between the baseline and scenarios 5.1.x [13] [16]. 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	None	NA	+1
	Disposal costs, including cost of disposal containers	Cost of disposal containers. Total volume of waste to be disposed of (waste loading).	Excluding transport.. Excluding storage.	Waste loading up to 10%vol. Cost of disposal.	Waste loading up to 30%vol. Cost of disposal.	NA	Disposal cost will be reduced in line with the increase in waste loading. It is assumed for this exercise that the waste loading is multiplied by 3.	NA	None.	+1.5

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[11] The construction cost of the baseline facility and its decommissioning costs are to be published – see PREDIS D2.9. It is assumed that the production costs include the construction, operational, and decommissioning costs, in line with normal accountancy practices. Production costs are calculated on the operational assumption that between 8 and 12 L of RLOW can be incorporated into a single 200 L drum.

APPENDIX 3: VALUE ASSESSMENT RESULTS (SOLVENTS)

Waste Type	Scenario ID	Formulation / process description	Waste	Radiological classification	Scenario origin and source organisation	Waste unit/container in LCA/LCC data	Waste container for value assessment	Disposal route
Contaminated solvents	5.2.1	Encapsulation in metakaolin (Metamax) geopolymer.	TBP-Dodecane (30/70).	LLW and ILW suitable for near-surface disposal[12]	MS34 NNL	500 L drum	200 L drum	Near-surface disposal
	5.2.B	Step 1: transport to, and incineration at an incinerator using the IRIS process (assumption: at the CEA in France). Step 2: cement encapsulation of ashes in 200 L drum (assumption: collocated with incinerator).	Solvents (incl. TBP-dodecane 30/70) used in the PUREX process (spent fuel reprocessing).		D5.1, WP6 LCA/LCC CEA	1 kg of feed material		

5.2.1 vs 5.2.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
Cross cutting	Waste loading	Number of packages /m^3 of waste. Waste loading (%vol). *Consistency in measurement approach is required.*	From raw waste to waste package ready for disposal (assumption: standard 200 L drum). Excluding any overpack used in the disposal concept.	[71.5-143]%vol.[13] This waste loading doesn't include secondary waste. *Secondary waste will be included in consideration below*	Waste loading up to 20%vol. (30%vol. reported by NNL) Performance (durability and strength) decline with increasing waste loading – realistic achievable waste loading of 15-30%vol. *Hard to give a specific value so range given instead*	None		The waste loading of the direct conditioning route in this scenario is four to seven times lower than that of the baseline.		No rating assigned.
Operational safety	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 safety impact of incineration step (baseline). **Includes (transboundary) transport impact.**	Some amount of waste treatment/management required before transport (special containers or treatment). Potentially higher dose rates due to two-step process. The cementation plant is assumed to be co-sited with the incinerator. Depending on waste composition, sorting and segregation may be required (although this is unlikely with RLOW). Contamination is the main risk associated with transport and incineration [29]. Radioactive solid powder generated.	Alkali activators used in the process present a chemical hazard requiring the use of PPE – covered by requirements for radiation protection CVŘež/UJV Řež reported that they did not encounter or expect any additional health and safety risks. Potentially finer powder (MK only) but likely not a significant enough difference to require different standards.	The number of process steps are cut down to one, with the expected benefit of fewer handling operations, resulting in potentially lower dose rates and H&S risks. Removing the need for transboundary transport for incineration is a significant advantage of the direct conditioning route. H&S risks associated with transport are statistically significant. Avoids generation of radioactive powders On-site management before export to incinerator increases number of steps	NA	The presence of alkali activators adds a chemical hazard to the process and requires the use of PPE. The decreased waste loading compared to the baseline will result in additional processing rounds, thus increasing the health and safety risk.	NA	+1

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[12] Based on the activity values used in active experiments, as reported in D5.2 [1] (38 GBq/t Ni-63/C-14).

[13] Calculated from data provided by the CEA and SOGIN. [80-90]%vol reduction at the incineration stage, and 7.5%wt. loading of ashes in final disposal container. Based on assumed densities of 1440 kg.m^{-3} for cement, and 700 kg.m^{-3} for ashes.

5.2.1 vs 5.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.	Excludes disposability considerations (dedicated set of criteria below). **Includes (transboundary) transport impacts.**	Safety cases and necessary regulatory approvals are in place for existing and operating facilities Not safety related but need to capture regulatory requirements and issues with transport via third countries and potential stakeholder objections	The safety case of an industrial-scale facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed. Potentially finer powder (MK only) but likely not a significant enough difference to require different standards	Removing the need for transboundary transport removes the need to obtain transport permits and to go through the associated regulatory approvals.	NA	The novelty of the formulation and process will require a safety demonstration, with associated time and effort requirements. Delays in obtaining regulatory approvals may occur. However, this only applies to the first-of-a-kind facility. Subsequent safety demonstrations can be substantiated with operational experience. May need more air filtration to manage dust levels. More silos for storage of raw materials needed.	NA	+1
Environmental impact	Material Environmental Impact	Known environmental impact of material excavation (qualitative). Calculated (LCA) material requirements for manufacture and/or excavation. Number of waste packages (waste loading). Material requirements of alternative treatment and conditioning option.	Includes the environmental impact (incl. energy use) of material manufacture, for all materials feeding into the process (e.g. inner drum, encapsulant).	Based on 4kg/hr of waste treated, material inputs are [29]: - 0.6 Nm^3/h nitrogen - 1560 Nm^3/h air - 0.6 Nm^3/h oxygen. Material outputs: 111 g/h of ashes (waste). Greater material demands associated with facility. Drums used for transport may or may not be reused. (Sogin: weren't reused for solid waste, planned use of plastic drums for liquid waste which are incinerated with waste). Cement environmental impact.	LCA results will quantify the environmental impact of material production.	Quantitative environmental data (such as the mass of steel required) will become available upon completion of the LCA. Cement requires v. high temperatures to precursors (MK also requires calcining but not to the same temps).	NA	Further environmental impact data will become available upon publication of LCA – see PREDIS D2.9. Contrary to scenarios 5.1.x, ashes are here directly encapsulated with cement: there is no inner drum. Use of strong hydroxides (Na or K)	NA	*Without quantitative data on secondary waste generated by baseline process it is difficult to give a rating with full confidence*
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. **Includes transboundary transport impact.**	120 kWh/hour of processing [29].	0.3255 kWh for mixing of a 4L sample. Scaling data: awaiting WP6 data request responses.	Removing the need for transboundary transport and for incineration (which is an energy intensive process) is a strength of this scenario.	NA	Further energy use data will become available upon completion of the LCA process. However, the processes are similar in nature (mixing with a cementitious matrix): major variations are not expected. The decreased waste loading potentially counters the benefits of removing the incineration and transport steps. The extent of the energy differences will become clear upon reception of the LCA results.	NA	+1 *Possibly up to +2 if quantitative data can be obtained*

5.2.1 vs 5.2.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
Disposability and 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.	47 g/h of dust composed mainly of phosphorus and zinc. Increased facility/PPE waste for multistep process. Sodium-contaminated liquid (used to neutralise acidic gases): 1m^3/200 kg of waste incinerated. One HEPA filter every 1000 kg of waste incinerated. One rotary kiln metallic bar (10 kg of Inconel) every 4000 kg of waste incinerated. [30]	Residual bleed has been observed in experiments, and rinsing water will arise (unless in-drum mixing is used). Research partners reported that residual bleed is treated via the same route, and rinsing water can be used as mixing water for the next batch. Where present, bleed was recorded at a maximum of 1.75 vol% at 48 hours. Bleed is not a secondary waste as it cannot be removed – if significant amounts of bleed (<1% [31]) are observed then the process is typically considered to have failed. Assumes in-drum mixing.	Residual bleed from direct encapsulation with geopolymers can be re-incorporated into the next batch. The use of in-drum mixing with a sacrificial paddle would remove the need for rinsing water. Much less secondary wastes than incineration (Secondary wastes produced by the incineration step (filters, gaseous emissions, etc)	None		The lack of a disposability assessment for the waste resulting from this scenario is a weakness, compounded by the reduction in waste loading which is likely to result in additional secondary waste compared to the baseline.	+2 *Tbc when final disposability assessment outputs are available*
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.	For discussion only. Disposability is considered separately in the disposability assessment (D5.4 [5]). Exclude packaging Exclude radioactivity	For discussion only.	Due to the polycondensation reaction of the geopolymer system it expels water over time. Bleed was recorded at maximum of 1.75 vol% of product for all formulations at 48 h.	NA		Potential for free liquid in the form of TBP, dodecane (70:30) and 1-3 vol % of Tween 80 (surfactant) to TBP/dodecane in the pores of the geopolymer matrix TBP and dodecane are toxic chemicals. Dodecane is flammable, with explosive limits of 0.5 vol% - 4 vol% No evidence to indicate that these materials are destroyed in the process, but this has not been assessed. Incorporation of TBP/dodecane in geopolymer formulation, it has not been assessed if held within the pores or encapsulated into the matrix. Use of a surfactant which can behave as a complexing agent, which is usually prohibited in disposal facility waste acceptance criteria (WAC). A verification needs to be done.		No rating assigned.

5.2.1 vs 5.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
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).	The throughput is limited by that of the IRIS process: 111 g/h. [29] Input 4kg/hr of waste. Use of international facility avoids the need to develop national infrastructure	Geopolymers and cement have similar forms and mixing properties. CVŘež/UJV Řež reported that waste and geopolymer mixing took approximately 45 minutes, and that a rate of 7-8 drums/day was achievable. Section of plant needed for first 24h of curing Throughput v. dependent on facility	Removing the need for transboundary transport increases process reliability and predictability. The relatively small volume arisings of RLOW reduce the negative impact of the rate-limiting incineration step: however, the variant scenario still benefits from being a single-step process. Section of plant needed for first 24h of curing Throughput very dependent on facility Incinerator may have very strict WAC (and thus not accept all RLOW).	NA	Need to build a geopolymer facility	NA	+1
	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)	Ordinary Portland Cement: no availability issues.	MK availability may be an issue. Consistency in the purity of the reagent may also be an issue	None.	NA	MK availability, and consistency in the purity of the reagent were reported as slightly problematic.	NA	-1
	Technical Readiness Level (TRL)	TRL (1-9).	NA	[9-6]. IRIS process TRL: 6 for RLOW [29].	4 Moving up the TRL ladder will be facilitated by existing experience as discussed in Sections 5.1.4 and 5.2.4.	None	NA	TRL of 4 vs. [9-6].	NA	-1 *Based on incineration TRL and on existing industrial experience with geopolymer encapsulation.*
Financial	Cost of facility and of treatment and conditioning and of secondary waste management	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed. Waste loading. Cost of secondary waste management per m3 of waste.	Including construction and decommissioning costs if available. **Includes transboundary transport impact (if provided by LCC).** Including treatment, conditioning, and disposal. Excluding transport. Excluding storage.	Detailed financial data was not made available due to commercial restrictions. Avoids need to develop a facility. Secondary waste costs. Transport costs.	Numbers might be inaccurate – Italian drums cost near this amount and costs are dependent on size facility (facility cost vs per drum cost). Better to conduct a qualitative comparison. Special (more expensive) design of drum may be required to delay/decrease corrosion. Stainless steel drums are suitable	Removing the need for transboundary transport may lead in a reduction in waste management costs	NA		NA	*No rating given – more data on baseline required.*

5.2.1 vs 5.2.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	Criterion	Metric examples	Boundaries and exclusions	Baseline	Variant	Treatment and conditioning	Disposal	Treatment and conditioning	Disposal	Overall rating
	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.	80-90% volume reduction, c.a 7.5% waste loading of ashes Large amounts of secondary waste but still outweighed by higher waste loading	Waste loading up to 20%vol	NA	None	NA	Reduced waste loadings compared to the baseline will lead to a proportional increase in disposal costs.	-1

APPENDIX 4: VALUE ASSESSMENT RESULTS (SCINTILLATION COCKTAILS)

Waste Type	Scenario ID	Formulation / process description	Waste	Radiological classification	Scenario origin and source organisation	Waste unit/container in LCA/LCC data	Waste container for value assessment	Disposal route
Scintillation cocktails	5.3.1	Encapsulation in metakaolin (Metamax) geopolymer	INSTAGEL Plus	LLW	MS34 CIEMAT, UJV, Polimi	220 L drum	200 L drum	Near-surface disposal
	5.3.B	Two-step process: Step 1: absorption onto Experlite and transfer to a 115 L drum. The sorbent is then encapsulated with cement. Step 2: 115 L is placed into a 216 L drum. Cement is used to fill void between the two drums. Cement assumed to be Ordinary Portland Cement.	Scintillation cocktails in drums with or without stabilisation, conditioned or unconditioned, modelled for VA by INSTAGEL Plus		MS34, D5.1, WP5 LCA/LCC CVŘež	216 L drum		

5.3.1 vs 5.3.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
Cross cutting	Waste loading	Number of packages /m^3 of waste Waste loading (%vol)	From raw waste to waste package ready for disposal (assumption: standard 200 L drum). Excluding any overpack used in the disposal concept.	Waste loadings from 5%vol. (Czech Republic) and up to 10%vol. (Romania).	Waste loading up to 20%vol (30%vol reported by POLIMI in the disposability assessment response form). Performance (durability and strength) decline with increasing waste loading – realistic achievable waste loading of 15-30% *Hard to give a specific value so range given instead*	Waste loading using direct conditioning with the geopolymer formulation used in this scenario is significantly higher than that of the baseline. Even if the upper value of 30%vol is not achieved, a loading of 20%vol would represent a significant improvement, with positive impact across the whole waste management lifecycle.		None		No rating assigned.
Operational safety	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.	Shielding can be used by operators if necessary (for waste with high dose rates). The operational impact can be mitigated by preparing the outer drum and concrete annulus ahead of inner drum placement.	Alkali activators used in the process present a chemical hazard requiring the use of PPE. – minor hazard only PPE requirement is captured by standard for handling rad materials CVŘež/UJV Řež reported that they did not encounter or expect any additional health and safety risks. Potentially finer powder (MK only) but likely not a significant enough difference to require different standards	The number of process steps are cut down to one, with the expected benefit of fewer handling operations, resulting in potentially lower dose rates and H&S risks. The increased waste loading in this scenario tilts the balance in its favour: fewer waste packages to be produced will result in a proportional reduction in risk.	NA	The presence of alkali activators adds a chemical hazard to the process and requires the use of PPE. May need more air filtration to manage dust levels. More silos for storage of raw materials needed.	NA	+1 *Reliant on being a one step rather than a two step process*

5.3.1 vs 5.3.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.	Excludes disposability considerations (dedicated set of criteria below).	Safety cases and necessary regulatory approvals are in place for existing and operating facilities	The safety case of an industrial-scale facility requires development, and necessary regulatory approvals can only be obtained once an industrial-scale facility is proposed. Potentially finer powder (MK only) but likely not a significant enough difference to require different standards	None	NA	The novelty of the formulation and process will require a safety demonstration, with associated time and effort requirements. Delays in obtaining regulatory approvals may occur. However, this only applies to the first-of-a-kind facility. Subsequent safety demonstrations can be substantiated with operational experience.	NA	No significant difference
Environmental impact	Material Environmental Impact	Known environmental impact of material excavation (qualitative). Calculated (LCA) material requirements for manufacture and/or excavation. Number of waste packages (waste loading). Material requirements of alternative treatment and conditioning option.	Includes the environmental impact (incl. energy use) of material manufacture, for all materials feeding into the process (e.g. inner drum, encapsulant).	An inner drum is usually required for this process.	No inner drum is needed. The scale of the difference will come from the LCA results.	Direct conditioning with geopolymers removes the need to use an inner drum, thus reducing the amount of steel required by the overall process. Quantitative environmental data (such as the mass of steel required) will become available upon completion of the LCA. Cement requires v. high temperatures to precursors (MK also requires calcining but not to the same temps).	NA	Further environmental impact data will become available upon completion of the LCA. Use of strong hydroxides (Na or K)	NA	+1 to +2
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Excluding transport.	Awaiting LCA results. Indicative value of 10 kWh/150L of conditioned scintillation cocktail.	Awaiting LCA results. Indicative value of 8 kWh per 50L drum	Quantitative energy use data (such as the total energy requirement for the two options) will become available upon completion of the LCA process. However, the processes are similar in nature (mixing with a cementitious matrix): major variations are not expected.	NA	Further energy use data will become available upon completion of the LCA process. However, the processes are similar in nature (mixing with a cementitious matrix): major variations are not expected.	NA	No significant difference

5.3.1 vs 5.3.B				**Input metric values**		**Strengths vs baseline**		**Weaknesses vs. baseline**		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
Disposability and 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.	No specific information.	Wasteforms bleed an amount of water <1% of the total wasteform volume during curing. Afterwards, no additional bleeding was observed (observation time of 6 months after casting) (POLIMI). Rinsing water will arise (unless in-drum mixing is used). Research partners reported that residual bleed is treated via the same route, and rinsing water can be used as mixing water for the next batch. Bleed is not a secondary waste as it cannot be removed – if significant amounts of bleed (<1%) are observed then process can be considered to have failed.					No significant difference
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.	For discussion only. Disposability is considered separately in the disposability assessment (D5.4). Exclude packaging Exclude radioactivity	For discussion only.	No additional bleeding was observed after the initial curing stage.	NA		The criteria evaluated are promising but, in function of the formulation the criteria are not all conclusive (mechanical strength, homogeneity)		
Implementation	Process throughput and impact on waste management strategy10	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).	Excludes transport considerations. Excludes TRL considerations (accounted for in dedicated criterion).	Fully implemented. The rate of waste generation is the limiting factor. 30-60 minutes per 115 L drum (then placed in a 200 L drum). =>8 drums/day Section of plant needed for first 24h of curing Throughput v. dependent on facility	Geopolymers and cement have similar forms and mixing properties. CVŘež/UJV Řež reported that waste and geopolymer mixing took approximately 45 minutes, and that a rate of 7-8 drums/day was achievable. Section of plant needed for first 24h of curing Throughput v. dependent on facility Scintillation cocktails are initially similar, but the waste is very variable depending upon what the cocktail is mixed with. This can increase the difficulty of scale up as waste streams are highly heterogenous.	The increased waste loading means that the process throughput could potentially be higher.	NA	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) are achievable.	NA	No significant difference

5.3.1 vs 5.3.B				Input metric values		Strengths vs baseline		Weaknesses vs. baseline		
Area	**Criterion**	**Metric examples**	**Boundaries and exclusions**	**Baseline**	**Variant**	**Treatment and conditioning**	**Disposal**	**Treatment and conditioning**	**Disposal**	**Overall rating**
	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)	Potential issues with the availability of Experlite were reported. => discuss	MK availability may be an issue. Consistency in the purity of the reagent may also be an issue. Most of the geopolymer products contain 2%wt. surfactants (higher amounts are used for TBP/dodecane, c.a. 5%wt.).	Direct conditioning with this geopolymer formulation removes the need to use Experlite, for which availability issues have been reported. Can be difficult to source correct grade of cement	NA	MK availability, and consistency in the purity of the reagent were reported as slightly problematic.	NA	-1
	Technical Readiness Level (TRL)	TRL (1-9).	NA	9	4 TRL to be reviewed	None	NA	TRL of 4 vs. 9.	NA	-2 *provisional*
Financial11	Cost of facility and of treatment and conditioning and of secondary waste management.	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed. Waste loading. Cost of secondary waste management per m3 of waste.	Including construction and decommissioning costs if available. Including treatment, conditioning, and disposal. Excluding transport. Excluding storage.	Drum in drum (two drums required)	Numbers might be inaccurate – Italian drums cost near this amount and costs are dependent on size facility (facility cost vs per drum cost). Better to conduct a qualitative comparison. Cocktails may contain significant amount of chlorides which may impact drum choice – high chloride often means a lower waste loading is required in order to meet WAC limits on chloride content per package Special (more expensive) design of drum may be required to delay/decrease corrosion. Stainless steel drums are suitable	Production costs are similar between the baseline and this scenario. 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	Production costs are similar between the baseline and this scenario.	NA	+1
	Disposal costs, including cost of disposal containers	Cost of disposal containers Total volume of waste to be disposed of (waste loading)	Excluding transport. Excluding storage.	5%vol	Waste loading up to 20%vol	NA	Disposal cost will be reduced in line with the increase in waste loading between scenario 5.3.1 and the baseline.	NA	None.	+1
Overall rating										

APPENDIX 5: VALUE ASSESSMENT CRITERIA

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[14]
Cross-cutting	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 cement and geopolymer encapsulation. 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.	Pre-treatment requirements are the same for cement and geopolymer encapsulation. Information on pre-treatment requirements for incineration has been requested under WP6. Although the baseline scenarios are based on two-step processes, it was assumed that the facilities are located on the same site, thus reducing the health and safety impact of the first step. Any further differences have been	NA

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[14] Considerations around the impact on planning activities are included within the respective waste management steps and are not detailed separately. Treatment and conditioning are considered as one to allow comparison between the baselines' two-step processes, and the direct conditioning route studied in the variant scenarios.

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[14]
				accounted for under the "safety during treatment and conditioning" criterion. Therefore, this criterion was not judged to be a differentiator.	
	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.	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 (considered as one).
	Safety demonstration requirements	Availability of safety case. Existing safety demonstrations / regulatory approvals.	Excludes disposability considerations (dedicated set of criteria below).	Regulatory requirements in terms of permitting and/or licensing play a significant role in the emergence and implementation of novel technologies. The ability of the variant scenarios to meet regulatory requirements, and the ability of facility operators to assemble the safety demonstration are therefore deemed differentiating. Such demonstrations are necessary for new facilities and processes and are therefore relevant to this assessment.	Treatment and conditioning (considered as one).
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).	Includes the environmental impact (incl. energy use) of material manufacture, for all materials feeding into the process (e.g. inner drum, encapsulant)	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 (considered as one).

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[14]
		Material requirements of alternative treatment options.			
	Process energy requirements	Calculated (LCA) process energy requirements. Number of waste packages (waste loading).	Limited to the energy requirements of the process only. Excluding transport.	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. Transport is excluded to remove any dependency related to facility location.	Treatment and conditioning (considered as one).
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 (considered as one). Disposal
	Disposability of final waste product	Existing disposability assessments. Known or anticipated issues with waste product characteristics.	For discussion only. Disposability is considered separately in the disposability assessment (D5.4).	Disposability of the final waste product is a significant factor in evaluating any new waste management technology. However scientific knowledge and experimental data may not be sufficient to draw definitive conclusions. In addition, delivery of the WP5 disposability assessment under task T5.4.9 runs in parallel to this technical, economic, and environmental analysis, which prevents full discussion of its results in the Value Assessment. As a result, this topic is included for discussion only at this stage. It will be included in the final evaluation if and only if results from the disposability assessment are available ahead of schedule.	Disposal
Implementation	Process throughput and impact on waste management strategy	Full-scale facility throughput (m^3 of waste processed per unit time).	Excludes transport considerations.	Depending on the waste inventory for treatment and conditioning, process throughput may play a significant role in this evaluation. Significant waste volumes may require high facility throughputs in the case of legacy waste (without new arisings) which may be found in high quantities. Routine volume arisings of RLOW tend to be	Treatment and conditioning (considered as one).

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[14]
		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).	Excludes TRL considerations (accounted for in dedicated criterion).	relatively low (of the order of magnitude of 10-100 m^3/year). 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 RLOW type. Scaling-up variant processes from laboratory to industrial scale usually comes with a number of challenges. Some of these challenges were encountered by PREDIS partners. Based on this set of considerations, this criterion is considered to be differentiating and is included for evaluation.	
	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.	Treatment and conditioning (considered as one).
	Technical Readiness Level (TRL)	TRL (1-9).		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 (considered as one).
Financial	Cost of facility and of treatment and conditioning	Construction cost. Design cost. Decommissioning cost. Cost per m^3 of waste processed.	Including construction and decommiss-ioning costs if available.	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 (considered as one).

Area	Criterion	Metric examples	Boundaries and exclusions	Justification	Relevant lifecycle stages[14]
		Waste loading.			
	Material costs	Calculated cost of materials (LCC).	Including costs of sacrificial drums. Excluding transport costs.	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.	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