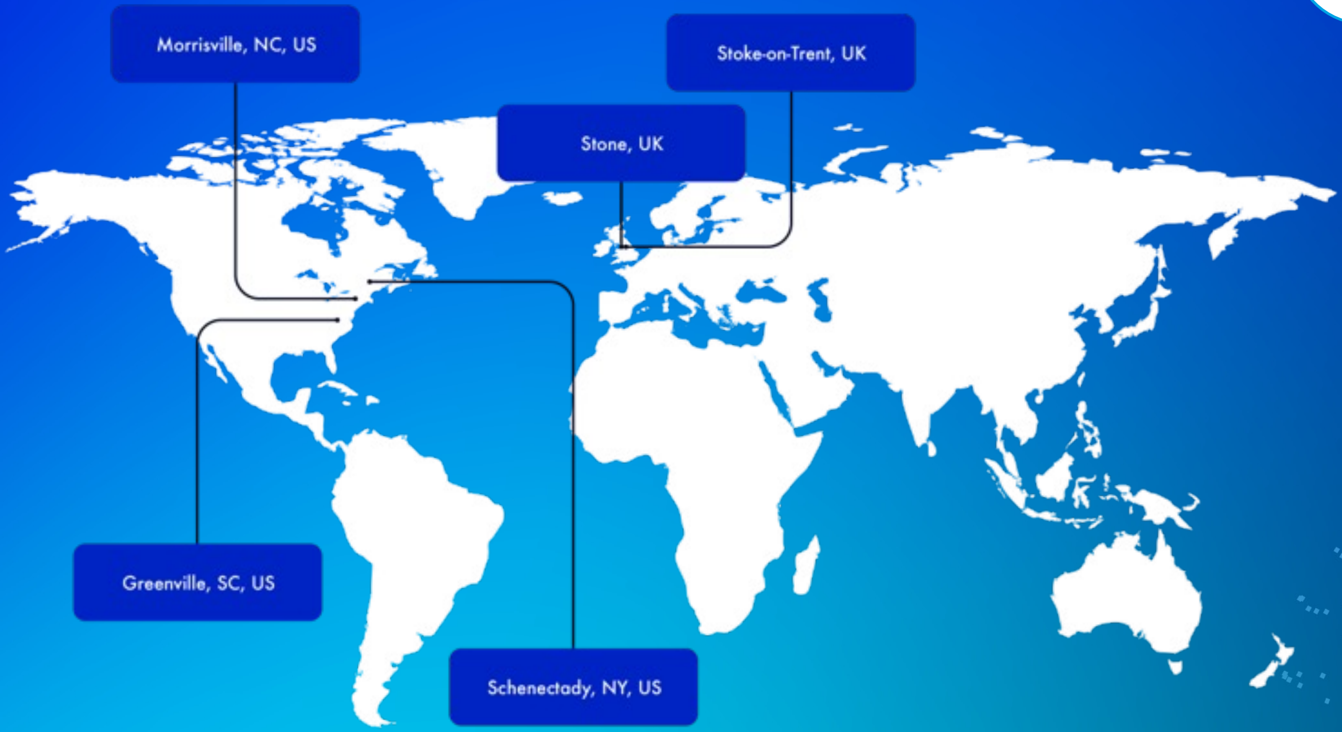
LUCIDEON
providing material solutions

Development of MALLET(™) for Radioactive Waste Encapsulation

Stuart MacLachlan and Marta Fedorciuc-Onisa



- International materials technology business with HQ in Stone, UK
- Materials R&D supported by wide range of testing & characterisation capabilities
- Advanced Materials & Processes supporting Manufacturing Innovation
- >240 Employees, >40 PhD's
- Proven track record supporting highly regulated industries
- Bridging the gap between academia and industry

Providing Material Solutions through Consultancy

Research & Development

Materials & Process Development
LLW/ILW Encapsulation (MIDAR®)
HLW Ceramic Encapsulation
Ceramics and Composites
Cement Formulation Development

Materials Consultancy

Materials for Harsh Environments
Materials Optioneering & Validation
Root Cause Failure Analysis
Process Optimisation
Computational Materials

Analysis & Evaluation

High Temperature to Cryogenic
Custom Complex Mechanical Testing
Complex Corrosion Testing (SCC)
Surface Science
Hydrogen Testing
Cement Testing
Drop Load/ Impact testing

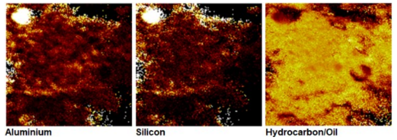
Geopolymers at Lucideon

Geopolymer Development Facilities

Scalable, consistent development of geopolymer cement — from laboratory recipes to validated demonstration evidence.

CAPABILITIES COVER

01	**Formulate**	Recipes for different applications and precursor combinations.
02	**Scale-up**	Controlled progression from lab trials to demonstration processing up to 1000L.
03	**Characterise**	Properties and durability checked against acceptance criteria and standards.



Microstructure

Strength testing

PROCESS & FORMULATION DEVELOPMENT / SUPPORT

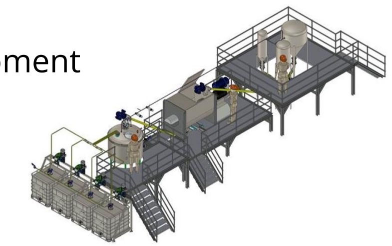
Lab scale → Stage 1 scale-up → Demo → Apply

Testing and characterisation runs across every stage

Acoustic Mixer

Stir Mixer

Pilot Equipment



Expanded facilities with £1.5m UK Government support through the Industries Sustainability Consortium (FISC).

Drivers for Geopolymer adoption

Adoption is driven by lower embodied carbon, circular feedstocks and durable performance in demanding applications.

UP TO

80%

lower CO_2 emissions versus Portland cement

CORE DRIVERS

01 Lower-carbon

Up to 80% CO_2 reduction.
No high-temperature kilns.

02 Circular inputs

Uses fly ash and slag.
Supports circular economy.

03 Performance

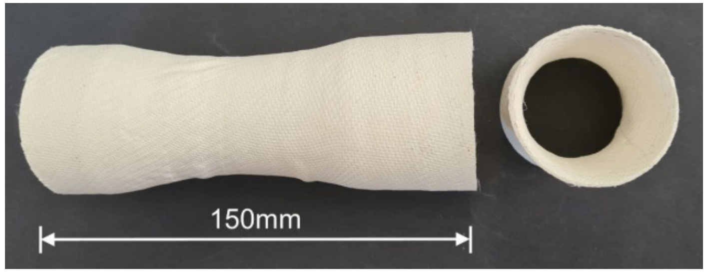
40–90 MPa compressive strength.
Excellent chemical resistance.

04 Fire & stability

600–800 °C standard systems.
Advanced up to 1,200–1,400 °C.

Development Areas

- **Low carbon, sustainable products** for the construction sector
- **Encapsulation of Intermediate Level Waste (ILW)** in the nuclear sector
- **Barrier structures** for nuclear applications
- **Geoceramic MIDAR® Composites (GMC)** for high-temperature environments, offering a lightweight alternative to metals and polymers, with service temperatures up to **1000 °C**
- **In-Situ Resource Utilization (ISRU)** for space applications.



Barriers faced

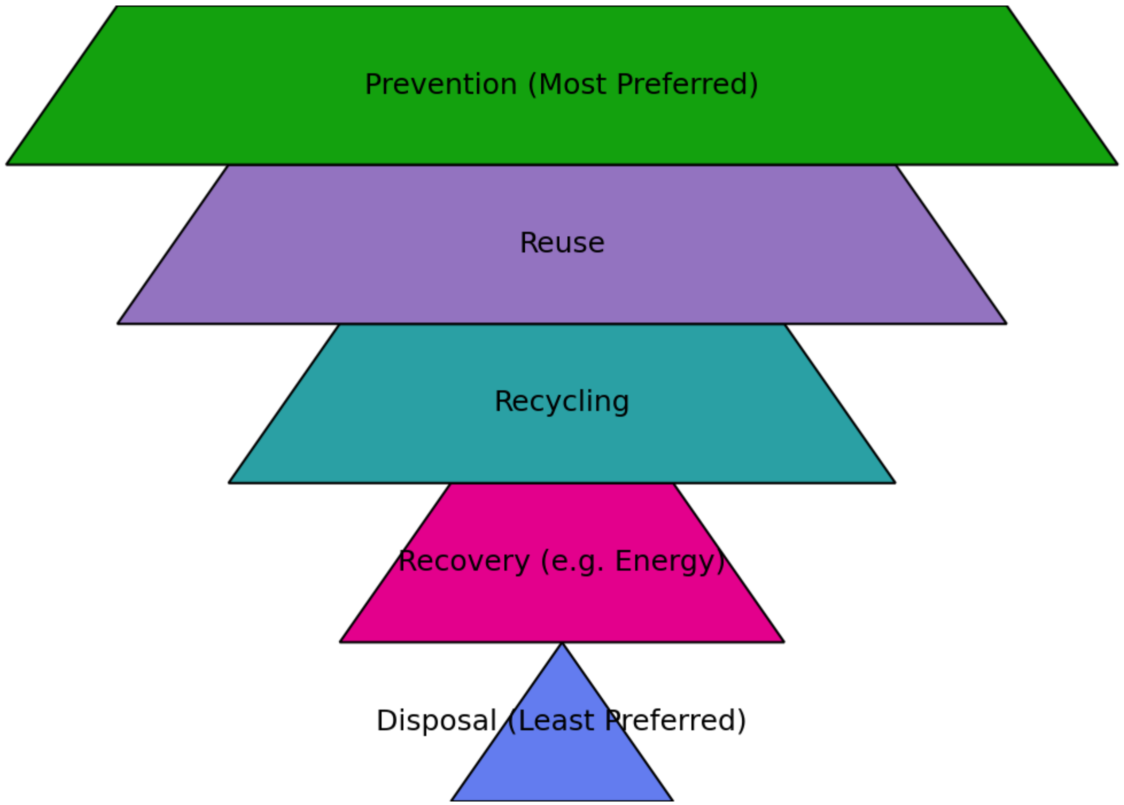
Key adoption barriers sit across standards, material variability, evidence maturity and regulated-market inertia.

BARRIER		WHAT IT MEANS FOR ADOPTION
01	**Design codes & standards** Existing standards are not globally harmonised.	Fragmented guidance increases qualification effort and slows acceptance.
02	**Feedstock variability** Performance depends heavily on source material characteristics.	Quality control and scalability require robust mix-design protocols.
03	**Long-term durability evidence** Limited field data from real-world applications.	More validation evidence is needed before broad specification.
04	**Conservative, regulated markets** Construction and nuclear sectors favour established materials and methods.	Adoption depends on demonstrable compliance and code alignment.

Waste Encapsulation

Managing Wastes

- Waste hierarchy classifies waste management approaches
- Prevention gives the greatest environmental benefit.
- Reuse, recycling and recovery retain value.
- Some wastes cannot be safely recovered
- Encapsulation supports safe disposal - locking contaminants into stable forms.



Encapsulation Applications

Encapsulation immobilises contaminants and improves handling across a range of mental waste streams.

COMMON DRIVERS Addressing release pathways – leaching, dust or fibre release, radionuclide migration

PRIMARY WASTE STREAMS

01 Nuclear industry

Low/intermediate-level radioactive waste, sludges and resins

02 Oil & gas

Drill cuttings, contaminated soils and NORM scale

03 Mining & minerals

Tailings, acid mine drainage sludge and metal residues

04 Water & wastewater

Sewage sludge ash and treatment sludges

INDUSTRIAL & EMERGING USES

05 Battery, EfW & chemical

Pb/Cd/Ni/Li residues; ash and APC residues; acidic/alkaline sludges

06 Remediation & construction

Contaminated soils, hydrocarbons, tar residues and concrete fines

07 Defence & hazardous waste

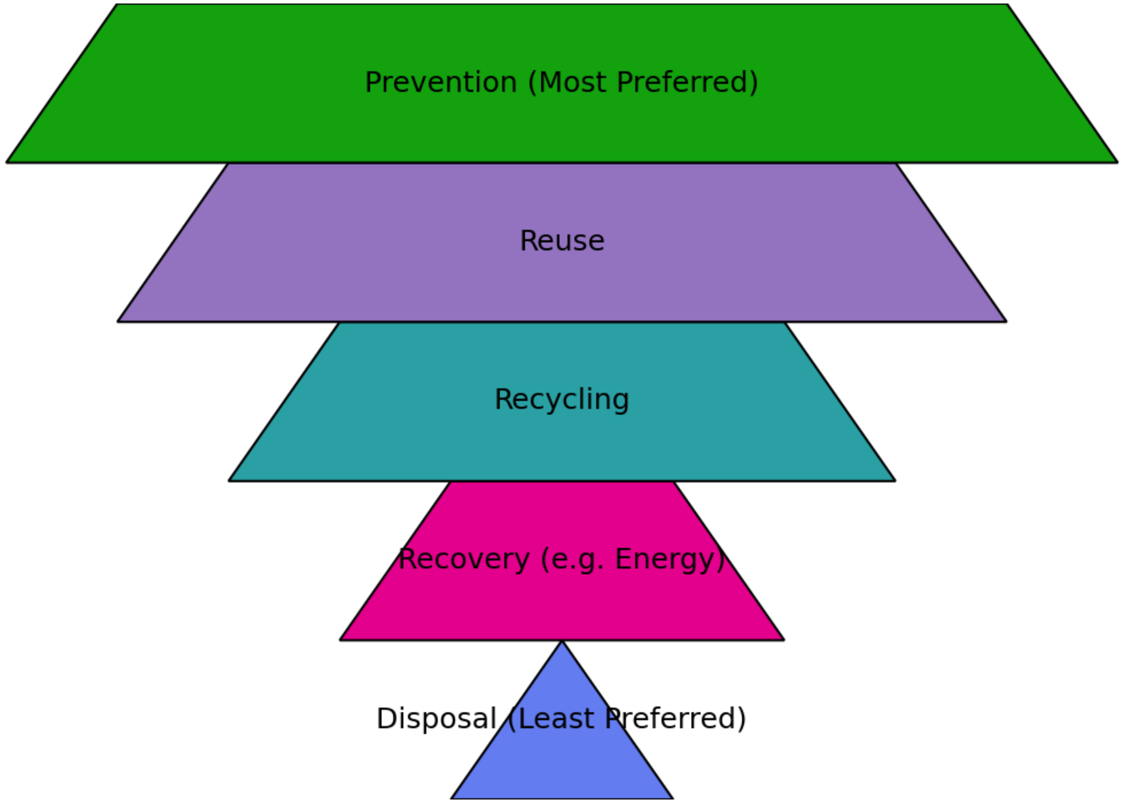
Energetic residues, salts and decontamination/stabilisation residues

08 Emerging uses

Carbon capture residues; microplastic composites; specialist hazardous solids

Orphan Wastes

- Disposal is the least preferred waste-management option.
- “Orphan wastes” lack a clear treatment or disposal route.
- They block systems ,e.g. decommissioning, retrieval, packaging and store emptying.
- Treatment and encapsulation turn them into disposable wasteforms.



Problematic Waste Treatment – Nuclear

Radioactive problematic waste remains a persistent treatment challenge — demanding routes that are practical, lower volume and lower carbon.

CORE ISSUE

Reduce risk, disposal burden and carbon intensity.

Intermediate-level wastes sit above low-level activity limits, require shielding and do not produce enough heat for active cooling.

Driven by disposal cost, volume reduction and the shift away from OPC baselines.

DRIVERS

01 Long-standing challenge

A persistent issue in the nuclear sector.

02 ILW treatment target

Above low-level waste limits; shielding required, but active cooling is not.

03 Cost and volume pressure

Innovative routes can reduce high storage and disposal costs.

04 Lower-carbon imperative

Options are increasingly favoured over carbon-intensive OPC baselines.

OPC = ordinary Portland cement; ILW = intermediate-level waste

Problematic Waste Treatment – Nuclear

High treatment volumes, high disposal cost and the need for better encapsulation define the nuclear waste opportunity.

FORECAST TOTAL

82,744.6 m^3

problematic UK LLW / ILW requiring treatment

WHAT THIS MEANS

Big waste challenge: 82,700+ m^3 needs treatment.

Disposal is expensive: storage and disposal drive cost.

OPC has limits: some wastes need better routes.

Potential value: higher loading can cut packages and lifecycle cost.

Forecast Problematic Waste Arisings

Waste Type (m^3)	ILW (m^3)	LLW (m^3)	Total (m^3)
Oils	234.3	373.3	607.6
Graphite	58,069.5	17,945.1	76,014.6
Ion Exchange Materials	662.0	45.2	707.2
Sludges	3,550.1	1,865.1	5,415.2
Total	**62,515.9**	**20,228.7**	**82,744.6**

Source: 2019 UK Radioactive Waste Inventory

Graphite dominates the forecast volume

At 76,014.6 m^3, graphite represents ~92% of the total arisings — making treatment efficiency and waste loading central to value creation.

Geopolymer Encapsulation

Geopolymers compete with established nuclear wasteforms when durability, waste loading and lower-carbon processing matter.

HOW THE MATRIX WORKS

01 Physical containment

Low-permeability matrices trap particles and limit water movement.

02 Chemical immobilisation

Metals can be bound, adsorbed or converted into less soluble forms.

03 Radionuclide retention

Caesium, strontium and cobalt can be held within the matrix structure.

04 Long-term durability

Chemical, thermal and sulfate resistance supports stable disposal.

Positioning: low-temperature, tunable binders for problematic LLW / ILW where OPC is constrained.

RIVAL ENCAPSULATION TECHNOLOGIES

OPC / cementitious grout

incumbent LLW / ILW baseline; proven, low-cost and simple to deploy

Borosilicate glass vitrification

high-durability wasteform for high-activity streams; energy- and capex-intensive

Ceramics / Synroc

crystalline host phases for specific radionuclides; strong but complex to qualify

Bitumen / polymer matrices

legacy organic encapsulants; useful niches but fire, ageing and radiolysis concerns

Phosphate / magnesia cements

specialist binders for difficult chemistries; feedstock- and case-dependent

Sources: World Nuclear Association (2024); Frontiers in Materials review (2023).

Intermediate Level Waste Encapsulation

Innovate UK feasibility study

A focused programme on geopolymer encapsulation can safely process nuclear waste simulants and create a route for wider hazardous-waste applications…. Collaboration with NUVIA supported by Innovate UK.

STUDY AIM

Prove practical, lower-carbon encapsulation routes.

The study looked to determine whether the formulation, processing window and composite properties are credible for nuclear-sector use.

FEASIBILITY WORKSTREAMS

01 **Develop geopolymer technology**
Formulate and process nuclear waste simulants.

02 **Prove sector suitability**
Demonstrate safe, practical use in waste management.

03 **Maximise encapsulation efficiency**
Increase simulant volume contained in the matrix.

04 **Characterise composite properties**
Confirm performance and regulatory readiness.

05 **Evaluate future applications**
Assess wider hazardous-waste encapsulation routes.

Targets - MALLET™

1	2	3	4
Explore encapsulation of radiologically contaminated problematic wastes using MALLET geopolymer	Maximise simulant quantity encapsulated within geopolymer	Minimise environmental impact and cost of encapsulation	Characterise properties to indicate disposal requirements compliance

Graphite
Oil (60%v/v)
Magnox Sludge 70wt.%
Zeolite 60 wt.%

- Matrix stability (90 days)
- Structural integrity after immersion in a range of liquids & irradiation
- Container compatibility during storage period
- Leachability tests review & specified
    - ANSI/ANS-16.1 2019 & WAC criteria

Project Success Criteria... Waste Acceptance Criteria

Essential

- Low viscosity slurry formed
- Product fully set and crack free
- Leach resistant
- Compressive strength > 0.4MPa
- Dimensionally and physically stable
- Controlled homogeneity

Desirable

- Measure the exotherm (if present)
- Measurements of permeability to waste and gases and water under pressure would be useful if possible (ideal encapsulant releases gases, but prevents ingress/release of water).

Nice to Have (Future Work)

- Fire/high temperature testing, in line with Nuclear Waste Services requirements
- Determine the fluidity/viscosity of the encapsulant during mixing pouring
- Irradiation trials to determine long-term stability in Geological Disposal Facility.

Magnox sludge encapsulation

A focus has been on the encapsulation of Magnesium Hydroxide sludges, with simulant materials provided by Sellafield Ltd.

Over 5,400 m^3 of MgOH based sludges require treatment and disposal, with 61% of this inventory at Sellafield

Baseline plan is for sludge to be retrieved from legacy plants and stored in 3 m^3 boxes or storage vessels awaiting final grouting

Problems with sludge encapsulation in OPC

High storage and disposal costs

- Disposal packages are 3.3 times the volume of raw sludge volumes
- Sludge incorporation into final matrix only up to 30% = 70% is OPC cement

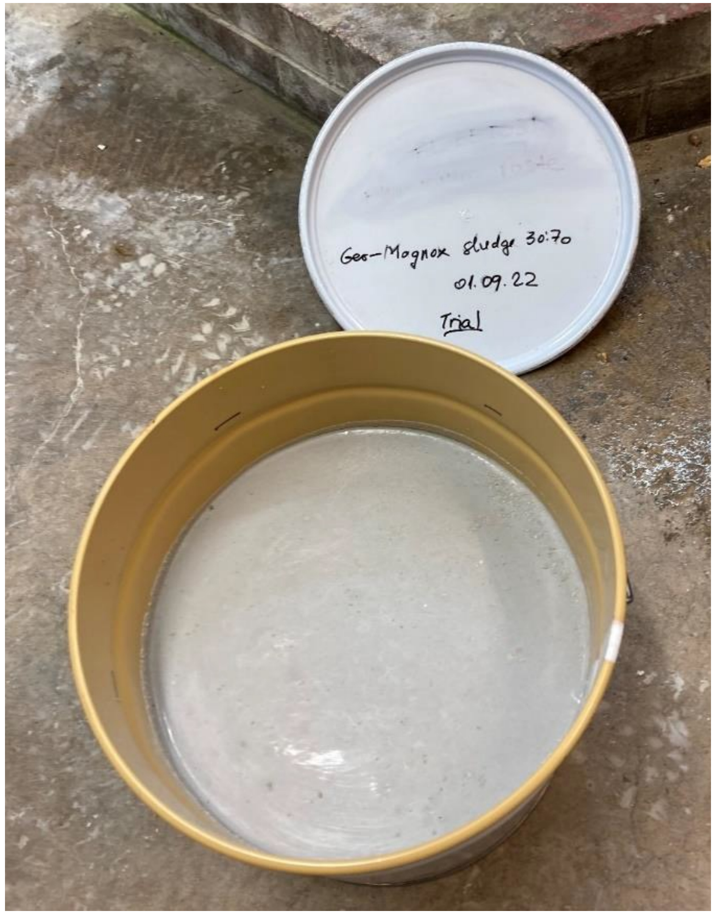
Difficulties in processing

- High yield stress = difficult to mix with sludge
- Homogeneous matrices are difficult to achieve

Each 1 m^3 of MgOH costs £165,000 to dispose if OPC encapsulation methods are used

Total Disposal Cost = £891M

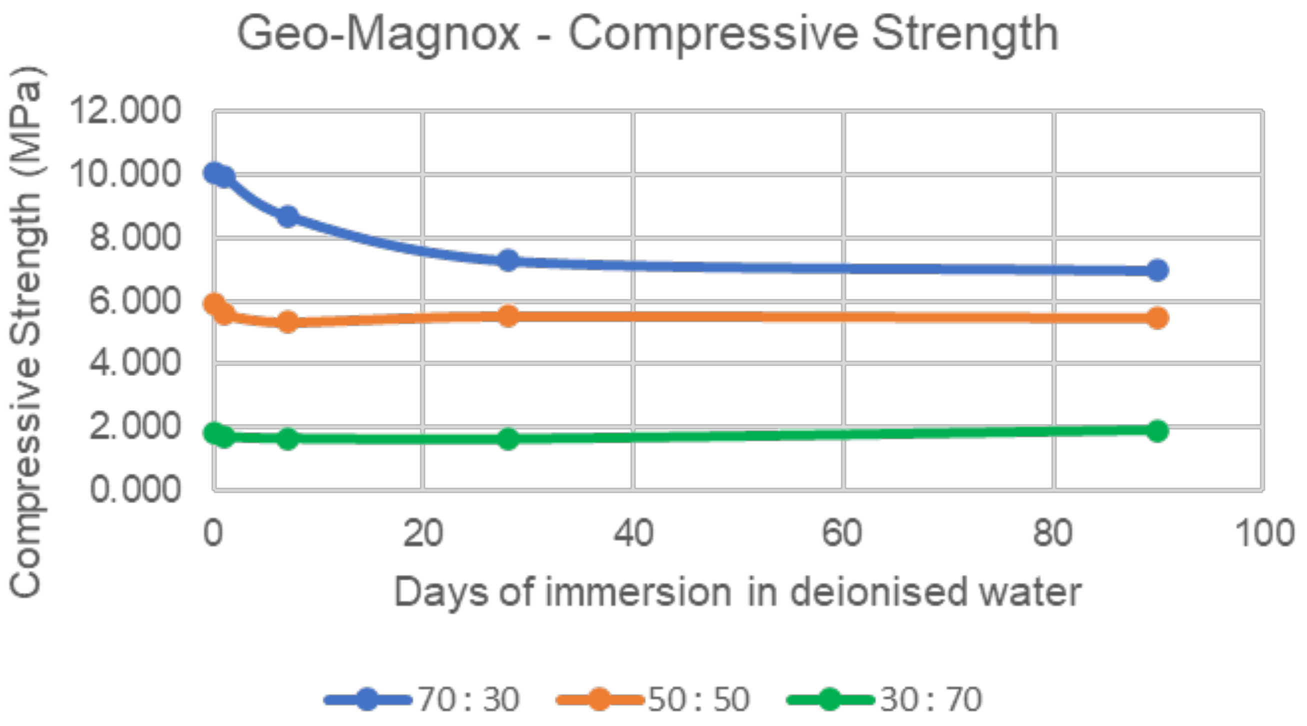
MALLET™ disperses sludge in a simple batch mixing process



Compressive strength and leach testing of Magnox sludge matrices

Encapsulation effective in leach testing in deionised water for up to 90 days

- No Sr^{+2} detected in leaching solution
- Cs^{+} remained encapsulated in matrix after 90 days is 99.97%
- No cracking
- Compressive strength continues to exceed WAC level



MALLET™ Magnox sludge matrices.. Scale-up to 12kg

Process size increased easily from 1 kg to 12 kg

Showed a 40% increase in the volume of sludge simulant encapsulated compared to OPC

Potential cost saving of £95k per $1m^3$ of raw sludge

Scale-up – 12 kg sample section of Magnox sludge matrix

Scale-up to 100 L

OBJECTIVE

Increase process scale to demonstration level using 100 L batches of Magnox sludge encapsulated in geopolymer.

SCALE-UP CONDITIONS

01	**Batch scale**	100 L demonstration batches
02	**Waste feed**	Magnox sludge (~150 kg)
03	**Formulation**	Geopolymer at 70:30 and 50:50 ratios

Mixer 60–200 L capacity

Scale-up

01 100 L slurry in 200 L reactor

02 Slurry added to Magnox sludge paste

03 Final blend shows low viscosity

The 100 L scale-up route produced a pumpable Magnox–geopolymer blend without visible process instability.

Scale-up

SCALE-UP RESULT

100 L

scale-up achieved

Lab formulation transferred directly to demonstration scale without chemistry or process changes.

WHAT THE TRIAL PROVED

01 Magnox sludge compatible

70:30 and 50:50 blends both successful.

02 Process proved robust

Stable temperature profile, no segregation and retained castable / pumpable behaviour.

03 Simple in-drum route demonstrated

Slurry mixed effectively with thick sludge using basic manual mixing.

04 Clear scale-up case

Evidence supports pilot validation and plant-ready production planning.

MALLET™ encapsulation of oil

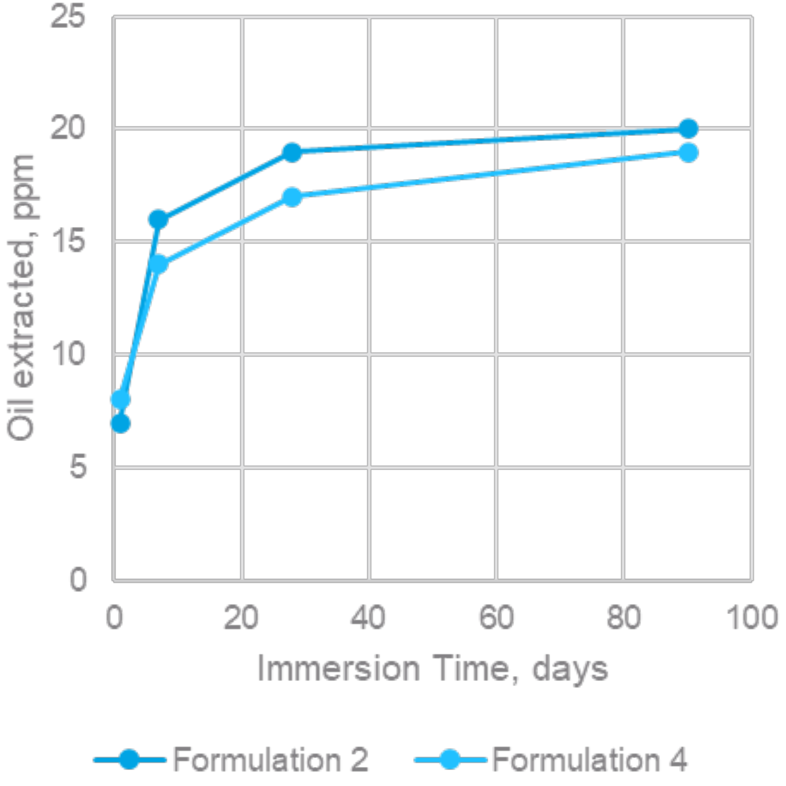
Simulant: Mobil 1 5W-30 motor oil

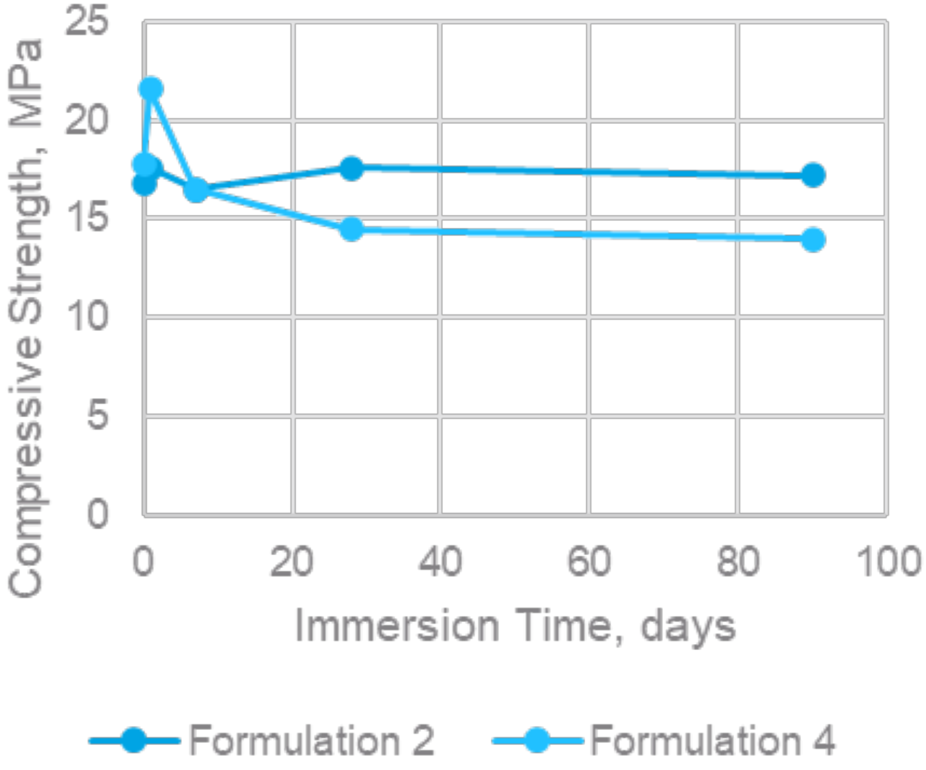
Amount encapsulated: Up to 60% v/v

Characteristics:

- Low viscosity slurry formed
- Product fully set and crack free
- Leach resistant in water, organic liquid and alkaline liquid to pH11 up to 90 days
- Compressive strength > 0.4MPa
- Oils not released
- Dimensionally and physically stable
- No porosity, voids and homogeneity
- Minimal exotherm on setting

Leach testing and compressive strength of oil matrices





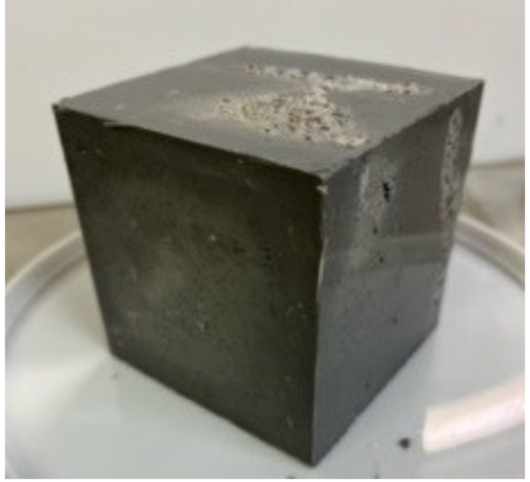
MALLET™ encapsulation of zeolite

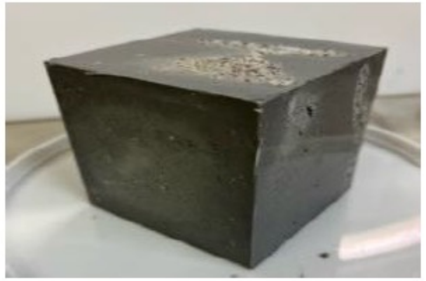
Pretreated AW500 zeolite with Caesium and Strontium

Add geopolymer slurry on top of pretreated AW500 and shake/vibrate for 5 minutes→ pour-on technique

Cs^{+} remained encapsulated in matrix after 90 days is 99.35%

Sr^{+2} remained encapsulated in matrix after 90 days is 99.95%



After curing and immersion in DI	
AW500 $Cs^{+1}/Sr^{+2}/NaOH$ Before immersion in DI	AW500 $Cs^{+1}/Sr^{+2}/NaOH$ After 90 days immersion in DI
750x750 mm	750x750 mm
	

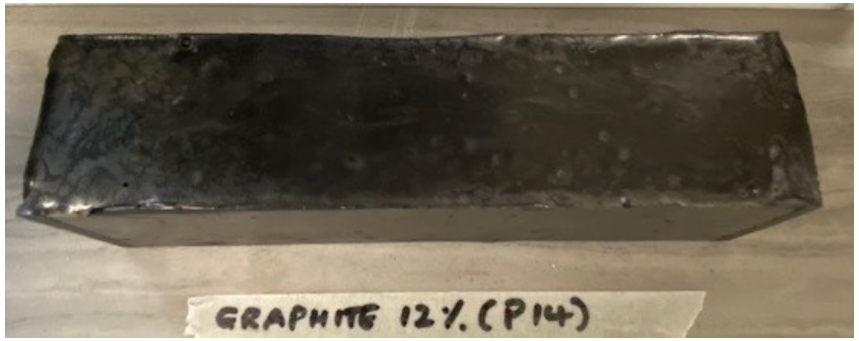
MALLET™ encapsulation of graphite

Slurry geopolymer with graphite powder 12% w/w

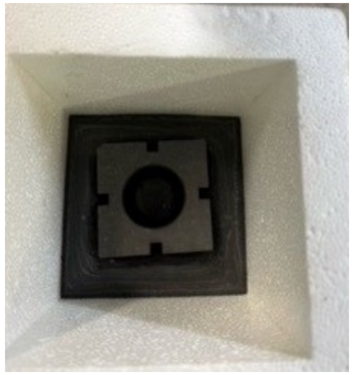
Graphite block from Magnox (designated M2): 57×57 mm square with 32 mm diameter hole

Pour graphite-loaded slurry onto the block

The block effectively encapsulated



Compressive strength after curing at RT for 24 hrs = 17.1 MPa



Graphite block (M2) in mould

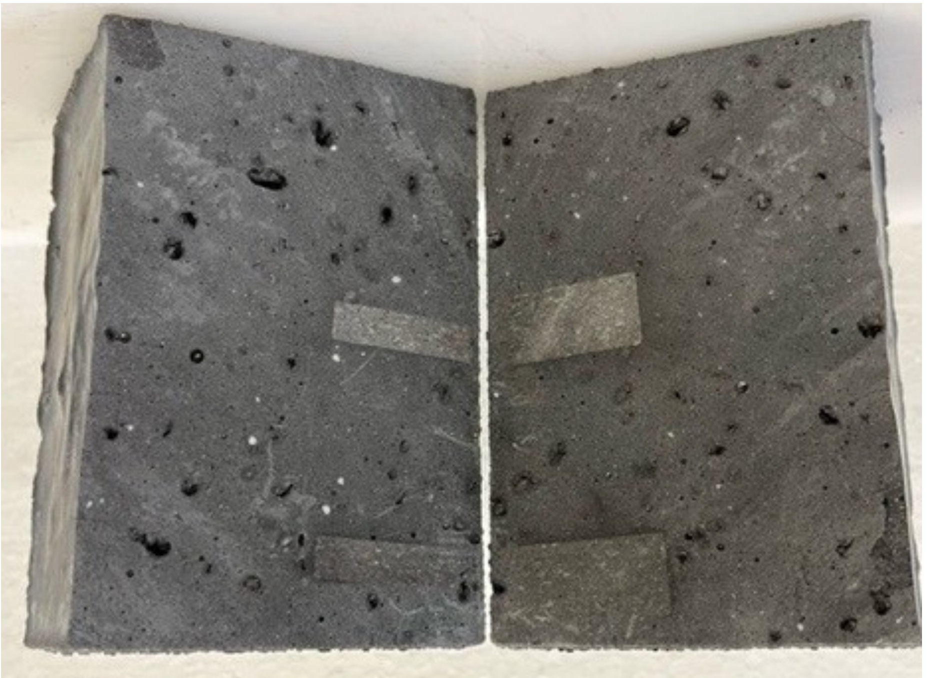
MALLET™ encapsulation of graphite – Graphite block encapsulation

Cross-sectioned encapsulated block (M2) encapsulated in geopolymer with 12%w/w powder after immersion in de-ionised water at room temperature for 7 months

The block and powder graphite well wetted

Geopolymer is crack free

No signs of attack by the water



MALLET™ encapsulation of graphite

Mixing the graphite/geopolymer slurry

Project success criteria met

Essential

- Low viscosity slurry formed
- Product fully set and crack free
- Leach resistant
- Compressive strength > 0.4M Pa
- Dimensionally and physically stable
- Controlled homogeneity

Desirable

- Measure the exotherm (if present)
- Measurements of permeability to waste and gases and water under pressure would be useful if possible (ideal encapsulant releases gases, but prevents ingress/release of water).

Nice to Have (Future Work)

- Fire/high temperature testing, in line with Nuclear Waste Services requirements
- Determine the fluidity/viscosity of the encapsulant during mixing pouring
- Irradiation trials to determine long-term stability in Geological Disposal Facility.

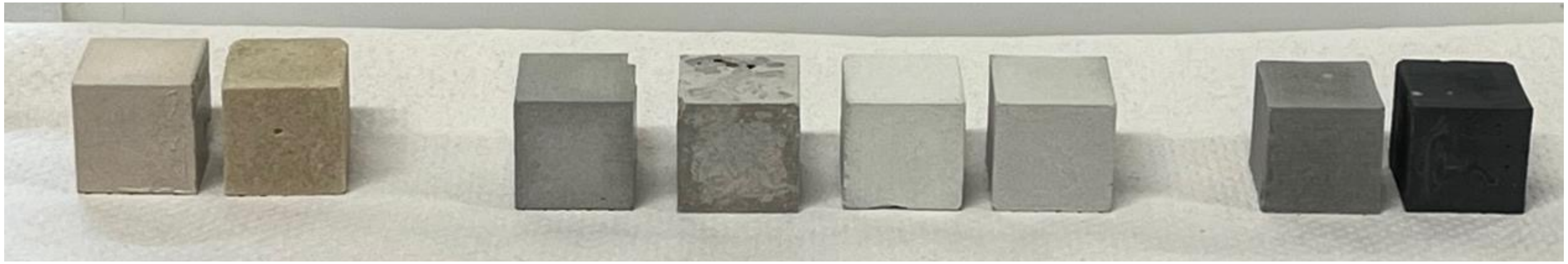
MALLET™ - Initial irradiation testing

Early-stage work

8 x 20 mm sided cubes containing each of the waste types

Received 1 MGy total absorbed dose of gamma radiation from Co-60 at Dalton Cumbrian Facility, University of Manchester

Visually unaffected, remaining integral

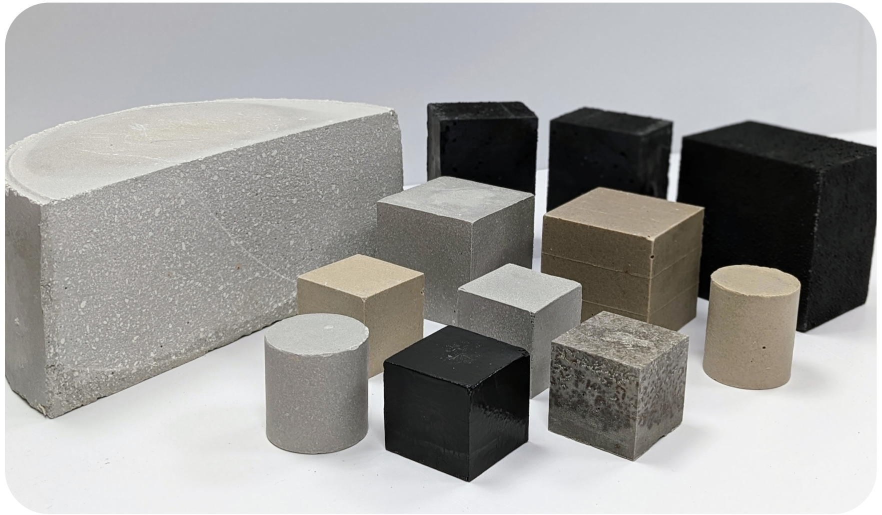


Hazardous Waste Encapsulation - MALLET™

MIDAR® **A**ugmented **L**ow-cost **L**ow-carbon **E**ncapsulation **T**echnique

Proprietary technology platform

- Unique formulations and people expertise
- Robust solid inorganic material with chemical stability and high strength



Encapsulate problematic wastes:

- Ion exchange resins
- Sludges
- Oils
- Graphite

Enabling technology for nuclear waste owners

- Process waste into passive waste matrix
- Maximises waste loading
- Smaller waste disposal volume
- Scalable
- Low carbon footprint

MALLET™

FISC

Conclusion

MALLET™ turns difficult wastes into lower-burden disposal packages.

The value is reducing storage pressure, disposal volume, lifecycle cost and carbon intensity for nuclear waste owners.

WHY THIS MATTERS

01 Market pull

High-pressure streams need safer, lower-volume treatment routes.

02 Technical edge

Low-temperature geopolymer route with chemical stability and waste-loading potential.

03 Commercial path

Target-stream qualification and partner trials create the scale-up path.

Conclusion — path to implementation

MALLET™ is at TRL 4/5 — now it needs a focused route to implementation.

The next phases are to create a qualified, deployable waste-treatment evidence for nuclear waste owners.

TRL 4 → IMPLEMENTATION

TRL 4 — **Lab validation**
Formulation and wasteform performance proven in controlled conditions.

TRL 5/6 — **Pilot evidence**
Trials, scale-up batches and operating envelope.

TRL 7/8 — **Implementation**
Qualification pack, compliance case and site-trial readiness.

Thank you

Contact:

Stuart MacLachlan

E: stuart.maclachlan@uk.lucideon.com

Marta Fedorciuc-Onisa

E: marta.fedorciuc-onisa@uk.lucideon.com

LUCIDEON