PNNL-39067

SELF-HEALING CEMENTS WITH IMPROVED TOUGHNESS AT CASING AND FORMATION INTERFACES FOR SUBSURFACE APPLICATIONS (CRADA 530)

February 2026

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date: 2/28/2026

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement:

Hotrock Energy Research Organization (HERO)

Resource Cementing

CRADA number: 530

CRADA Title: SELF-HEALING CEMENTS WITH IMPROVED TOUGHNESS AT CAISING AND FORMATION INTERFACES FOR SUBSURFACE APPLICATIONS

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Sponsoring DOE Program Office(s): Technology Commercialization Funds – Geothermal Technology Office and Fossil Energy and Carbon Management Office

Joint Work Statement Funding Table showing DOE funding commitment:

	Funding Amounts			
CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
Resource Cementing			$200,000	$200,000
Hotrock Energy Research Organization (HERO)			$450,844	$450,844
DOE Funding to PNNL	$1,487,600	N/A	N/A	$1,487,600
Total of all Contributions	$1,487,600		$650,844	$2,134,444

Cost share updates/details provided in Appendix A.

List of publications, conference papers, or other public releases of results, developed under this CRADA:

Publications

1. Zihao Li, Robert G. Felsted, Trenton R. Graham, Mark A. Rhodes, Yuntian Teng, C. Heath Stanfield, Harshvardhan Chopra, Jian Liu, Chao Zeng, Lan Li, Quin R. S. Miller, **Carlos A. Fernandez*** A High-temperature Self-healing Cement Based on Molecular Velcro Technology. 2026. *Under review.*
2. C. Zeng, Z. Li, L. Li, **C. A. Fernandez*** A Molecular Velcro Self-healing Cement *Nature Communications* **2026** *Accepted for publication.*
3. **Carlos A. Fernandez,*** Zihao Li, Chao Zeng, Guoqing Jian, and Cheng Chen *Geothermal Energy Engineering - Technology Transfer with the Oil and Gas Industry*. Editors Silviu Livescu, Birol Dindoruk **2025** Elsevier, *Chapter 8 - Stimulation in enhanced geothermal systems* 221-254.
4. Manh-Thuong Nguyen and **Carlos A. Fernandez*** et al Toward Self-Healing Concrete Infrastructure: Review of Experiments and Simulations across Scales. *Chemical Reviews*, Articles ASAP (2023). Impact Factor 72.3
5. Li, Z., Zeng, C., **Fernandez**, C.A et.al. 2023. " Self-healing Cements for Low- and High- temperature Applications." In *Proceedings of the 48th Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Workshop, February 10-12, 2023, Stanford, CA*, Paper No. SGP-TR-223. Stanford, California:Stanford University.

6. **Fernandez**, C.A; Li, Z.; Zeng, C. 2023. " Fit-for-Purpose Self-Healing Cements" In *Proceedings of the International Congress on the Chemistry of Cement 2023, Bangkok. Thailand, September 18-22.*

Presentations

7. **Fernandez, C. A**. Self-Repairing Polymer-Modified Cements for Subsurface Applications and Beyond. Presentation to U.S. Army's ERDC. 2025
8. **Fernandez, C. A**. PNNL's Self-Repairing Cements. Presentation to the U.S. Navy. Richland 2025
9. **Fernandez C. A.** World's First Molecular Velcro Cement Technology for Subsurface Applications. DARPA Concrete Workshop 2024
10. **Fernandez, C. A**. Stimuli-responsive Materials for Fossil and Geothermal Energy Recovery. Presentation at the University of Idaho. 2023. Invited Talk
11. **Fernandez, C. A**. PNNL's Self-Repairing Cements. Presentation to the U.S. Air Force. Richland 2023
12. **Fernandez, C. A**. Molecular Velcro Cement Technology for Subsurface Applications. *American Geological Union.* 2023
13. **Fernandez, C. A**. Self-Repairing Polymer-Modified Cements for Subsurface Applications and Beyond. Presentation to Baker Hughes. 2023
14. **Fernandez, C. A.** Self-Healing Cements for Geothermal Wellbore Applications SPE/GRC Workshop, Englewood, Co, Colorado, 2023. Invited talk.
15. **Fernandez, C. A. Molecular Velcro Cement Technology for Subsurface Applications** AGU 2023, San Francisco, CA. Invited talk.
16. **Fernandez, C. A.** Stimuli-responsive Materials for Fossil and Geothermal Energy Recovery. University of Idaho, April 2023
17. **Li, Z., Fernandez, C. A.** Self-healing Cements for Low- and High-temperature Applications. Presentation 48th Workshop on Geothermal Reservoir Engineering Stanford University, 2023
18. **Fernandez, C. A.** The 16th International Congress on the Chemistry of Cement 2023 (ICCC2023) "Further Reduction of CO2 -Emissions and Circularity in the Cement and Concrete Industry" September 18–22, 2023, Bangkok, Thailand
19. **Fernandez, C. A.** Self-Repairing Polymer-Modified Cements for Subsurface Applications and Beyond University of Austin, TX, 2022. Invited talk.

Media Releases

20. https://www.energy.gov/technologycommercialization/articles/doe-announces-186-million-three-national-lab-led-projects

21. https://www.pnnl.gov/projects/advanced-cement-and-concrete-technologies

22. https://volumeconcrete.com/the-concrete-that-fights-back-a-game-changer-or-a-global-gamble

23. https://www.pnnl.gov/available-technologies/self-healing-cement

24. https://www.pnnl.gov/publications/toward-future-self-healing-cement
25. https://www.pnnl.gov/sites/default/files/media/file/DDST_0063_Brochure_v15_web_opt.pdf
26. https://www.pnnl.gov/publications/pnnl-turns-algae-fuel-and-cement
27. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32903.pdf

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

28. **C. A. Fernandez**. U.S. Patent Application 17/955,030, "Self-Healing Polymer-Modified Cements for Ambient Temperature Applications", US Patent application 2023/0109371 A1, **2023**
29. **Fernandez, C. A.** Provisional License agreement on a self-healing cement formulation (bPEI-cement) for underwater applications. **2025**

Executive Summary of CRADA Work

Over the three-year CRADA, Pacific Northwest National Laboratory (PNNL) advanced **PaNaCEM™, (PaNa** is originated from the Latin/English word "panacea" or "heal all" as well as Pacific Northwest Lab**) a new class of self-healing wellbore cements** with autonomous repair that resembles the known Velcro^{TM} technology. PaNaCEM^{TM} was designed to improve the long-term integrity of wells used for **geothermal energy production** and **carbon storage**. Conventional wellbore cement can crack due to repeated mechanical loading, temperature swings, and exposure to aggressive subsurface fluids. Once cracks form, they can create leakage pathways, drive expensive remediation ("workovers"), and in extreme cases shorten well life. This project addressed that problem by developing polymer-modified cement systems that can **autonomously re-seal cracks** and better tolerate the extreme conditions experienced in subsurface wells, while remaining compatible with practical cementing operations.

How the research advanced understanding

The work expanded scientific and engineering understanding of how "self-healing" can be engineered into cement by embedding carefully selected polymers that interact with cement hydration products and, upon cracking, can re-adhere across fracture faces and restore load-bearing capacity. The project demonstrated that self-healing behavior can be achieved across **both high-temperature geothermal conditions** and **lower-temperature carbon storage conditions**, providing a clearer materials-design basis for tailoring polymer chemistry, loading, and slurry formulation to downhole temperature and fluid regimes.

Technical effectiveness demonstrated

The project achieved a sequence of lab-to-field readiness outcomes:

- **Field-relevant deployment was executed**: cement specimens were fabricated and deployed downhole in an operating geothermal well (Newberry Well 55-29).
- Although the deployment itself was successfully completed, the team was **unable to retrieve the samples after three attempts** due to wellbore conditions, and the samples were ultimately lost.
- To avoid delaying technical validation, the project formally **modified Milestone 8 and Go/No-Go #2** to evaluate **thermal shock resistance**, a critical stressor during geothermal stimulation and cyclic power plant operations. The revised testing demonstrated that polymer-modified self-healing cements **tolerate extreme thermal cycling**, and that **healing performance was not measurably degraded by thermal shock** (no statistically significant differences in recovery before vs. after thermal shock for the tested self-healing formulations).
- Microstructural evidence supported improved damage tolerance: after thermal shock, the best-performing self-healing formulation (ISOX4-cement) exhibited **substantially fewer fractures** than the control cement, consistent with improved ductility and crack tolerance.

Collectively, these results demonstrate that the technology can be prepared and handled in practical workflows, withstand aggressive geothermal stress conditions, and maintain its self-healing function under repeated thermal cycling.

Economic feasibility and commercialization relevance

A rigorous **40-year lifetime cost modeling framework** was developed to quantify how reduced cracking and fewer interventions translate to total cost reductions. The analysis integrated intervention types and costs, time-dependent failure probability, and laboratory healing performance. A representative case showed that a self-healing formulation could reduce lifetime costs by **~$9M (73.8%)** compared to conventional cement assumptions, while meeting cost/performance thresholds for multiple formulations.
In parallel, the Tech-to-Market (T2M) plan was updated to reflect validated technical performance and field execution experience. The team conducted broad stakeholder outreach across the cement value chain (admixture suppliers, chemical suppliers, cement producers, and service providers), contacting **60+ organizations**, and defined a staged pathway with **HERO and Resource Cementing** for follow-on pilot deployment and licensing discussions.

Benefit to the public

If deployed at scale, self-healing wellbore cements could reduce the frequency of costly interventions and unplanned outages, improve well integrity, and lower leakage risks—directly supporting reliable geothermal power and safer carbon storage operations. Reduced workovers also decrease operational disruption and associated emissions from remediation activities. By improving the durability of the cement sheath that provides zonal isolation in wells, the technology contributes to **energy reliability**, **public and environmental safety**, and **lower total cost of clean energy and decarbonization infrastructure**.

Summary of Research Results

1.1 Project Overview

Over three years, this project advanced PNNL's **PaNaCEM™** self-healing cement platform from formulation development through field execution, extreme-condition validation, techno-economic quantification, and commercialization planning for geothermal and carbon storage wellbores. The work demonstrated autonomous crack repair, improved damage tolerance, and scale-up readiness, and it quantified substantial modeled lifetime cost reductions (≥40–75%) for geothermal wellbores using a probabilistic 40-year intervention framework.

A downhole deployment was completed at Newberry well 55-29; however, **field-exposed specimens could not be recovered after three retrieval attempts** and were lost.

In response, the project formally **replaced the original post-retrieval Milestone 8 / Go-No-Go #2** with a revised milestone focused on **thermal shock resistance**, a critical property for geothermal stimulation and cyclic operations. The revised Milestone 8 and Go-No-Go #2 were met, demonstrating that self-healing cement systems tolerate severe thermal cycling and retain healing capability, with ISOX4-cement showing superior mechanical resilience and supportive microstructural evidence (reduced cracking after thermal shock).

Technology Readiness Level (DOE TRL) assessment: Based on successful field deployment (installation), extensive laboratory validation under relevant geothermal conditions, and completion of extreme-condition validation supporting field readiness, the technology is best assessed as **TRL 6 (prototype demonstrated in a relevant environment)**, with advancement toward TRL 7–8 contingent on a full-scale annular cementing pilot and verification via in-well performance data and/or recoverable post-exposure qualification samples.

1.1.1 Project Objectives

- Develop self-healing cement systems for **high-temperature geothermal** and **low-temperature carbon storage** environments.
- Validate **pumpability/workability**, setting behavior, mechanical integrity, and scalability needed for practical cementing workflows.
- Demonstrate **autonomous crack healing** and retention of healing performance under relevant stressors, including **thermal shock** representative of geothermal operations.
- Execute field-relevant deployment activities and integrate lessons learned (including retrieval limitations) into a strengthened validation and deployment pathway.
- Quantify lifetime economic benefit using probabilistic modeling to support commercialization decisions and partner adoption.
- Establish commercialization readiness via an updated T2M plan, stakeholder engagement, and a staged pilot/licensing pathway with service partners.

1.2 Year 1 – Formulation Development & Laboratory Validation

During Year 1, the project successfully advanced PNNL's patented PaNaCEM™ self-healing cement technology through formulation development, rheological testing, setting behavior evaluation, mechanical characterization, scalability validation, and autonomous healing assessment under conditions relevant to geothermal and carbon storage wellbore environments. The majority of planned technical milestones were achieved, establishing a robust technical foundation for field deployment and commercialization.

1.2.0. Project kickoff.

M1 Status: **Met.**

1.2.1. Self-Healing Cement Formulation Development

Multiple polymer-modified cement systems were synthesized for both low-temperature carbon storage and high-temperature geothermal environments. Low-temperature formulations included MBA-BDA polymer-modified cement systems based on dynamic reversible polymer–cement interactions. High-temperature systems included EPS25-based and Zn-salt polymer-modified cements optimized for extreme geothermal conditions.

These (PaNaCEM™) formulations constitute the world's first self-healing cement platform capable of multiple autonomous sealing (like the Velcro$^{\text{TM}}$ technology) under harsh subsurface conditions. Successful down-selection of candidate systems completed Milestone 1.

1.2.2. Milestone 2 – Cement Slurry Consistency

Description: Identify at least one polymer-modified cement formulation for carbon storage applications and one polymer-modified cement formulation for EGS applications with similar or improved workability to conventional wellbore cement

Criteria: FE Office: Consistency values below 1,000 mPa•s for 90 min at 25°C, and/or 70°C
GT Office: Consistency values below 1,000 mPa•s for 90 min at 70°C, and/or 120°C

Rheological measurements demonstrated that:

- Low-temperature self-healing MBA-BDA-cement maintained pumpable viscosity for over 150 minutes at 25°C with plastic viscosity in the 1,000–1,300 mPa·s range and at 70°C, with plastic viscosity below 1,000 mPa·s.
- High-temperature self-healing EPS25-cement exhibited pumpable consistency at 70 °C without dispersant additives outperforming conventional Class H cement in workability. However, EPS25-cement does require a superplasticizer at 120°C for pumping times above 60 min.
- Water-to-cement ratio adjustments provided controlled viscosity tuning without mechanical compromise.
- Figure 1 shows the results of undisturbed yield stress, dynamic yield stress, and consistency (in the form of plastic viscosity) for two self-healing wellbore cements and control cement G at 70C.

These results met Milestone 2 criteria requiring slurry consistency below 1,000 mPa·s for at least 90 minutes across operational temperatures.

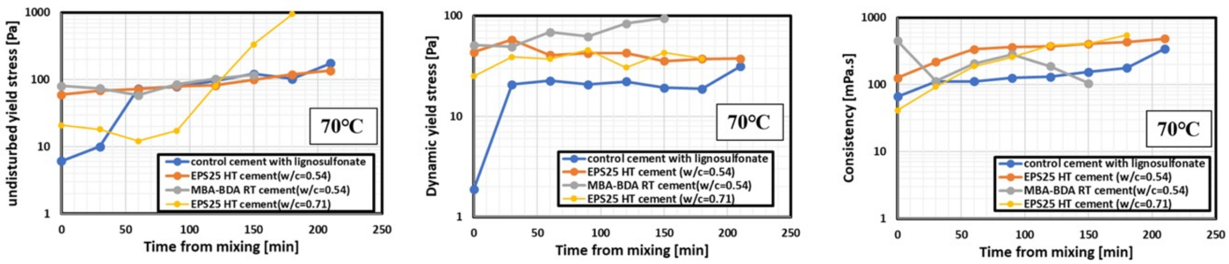


Figure 1: Workability of wellbore MBA-BDA-cement and EPS25-cement for low-T and high-T applications, respectively and as compared to conventional wellbore cement (control).

M2 Status: **Met.**

1.2.3. Milestone 3 - Setting Time and Density Performance

Description: Measure setting times and density at 25°C using vicat needle and mud balance, respectively.
Criteria: (1) Initial and final setting times similar to or longer than conventional wellbore cement at 25°C (carbon storage)
(2) Slurry density similar (within 10%) to conventional wellbore cement at 25°C (carbon storage).

Setting and density measurements confirmed:

- Initial and final setting times of polymer-modified cements comparable to or longer than conventional cement, supporting controlled placement.
- Slurry densities maintained within ±10% of conventional cement formulations.

These results fully satisfied Fossil Energy Office Milestone 3 criteria.

M3 Status: **Met.**

1.2.4. Milestone 4 - Scalability Assessment

Description: Demonstrated material’s scalability when going from (previously studied) 1” diameter × 2” long cylinders to 2” diameter × 4” long cylindrical monoliths (~8X greater mass)

Criteria: Polymer-modified cements show:

(1) homogeneous distribution of polymer per X-ray microtomography;

(2) similar (within 10%) compressive strength (2,500 psi) and Young’s modulus (70% lower than conventional cement) to previously reported (smaller) monoliths.

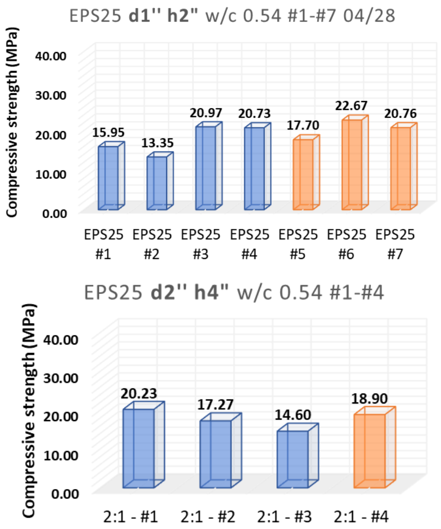


Figure 2: Compressive strength of 1” diameter by 2” long high-T EPS25-cements was within +/-1% of the compressive strength of 2” diameter by 4” long EPS25-cement monoliths.

Compressive Strength

- EPS25- (specialized epoxidized polysulfide resin) and Zn-salt- [Poly(ethylene-co-acrylic acid) zinc salt] polymer-modified cements exceeded the minimum 1,000 psi wellbore strength requirement after high-temperature curing (200–300°C).
- EPS25-cement achieved average compressive strengths of ~17–18 MPa under geothermal conditions.
- Confinement during curing increased compressive strength by 8–45%, reflecting in situ wellbore stress benefits (additional work, not part of milestone).

Scalability

- EPS25-cement maintained compressive strength within 1% when scaled from 1-inch to 2-inch diameter monoliths (8× mass increase) **meeting** scale equivalence criterium. (Figure 2).
- Zn-salt cement showed larger variability and **did not meet** strict scale equivalence criteria.
- Control cement G **did not meet** strict scale equivalence criteria.

X-ray microtomography (XMT) confirmed homogeneous polymer distribution within cement matrices for both Zn salt-cement and EPS25-cement (XMT for Zn salt-cement shown in Figure 3). Optical microscopy confirmed polymer migration to crack surfaces and pore wall coating. BET and powder XRD spectroscopy confirmed stable phase evolution and microstructural modification at 300 °C for Zn salt-cement.

Figure 3: XMT micrograph of Zn salt-cement showing homogeneous polymer distribution (in magenta).

Enhanced Ductility

Young’s modulus measurements showed self-healing EPS25-cement was **2X - 3X (!) more ductile** than conventional Class H cement, substantially reducing brittleness and improving crack tolerance. However, Zn salt-cement was only 23%-35% more ductile than conventional cement H. EPS25-cement **met criteria 2** of M4 while Zn salt cement **did not.**

M4 Status: **Met.** EPS25-cement (partially by Zn salt-cement).

Autonomous Healing and Fracture Sealing – Additional work, not part of Milestone

- High-temperature self-healing EPS25-cement demonstrated early recovery levels of 103–113%.
- Although Zn salt-cement did not meet the strict scale equivalence criteria, it did show multiple self-healing capability as follow:
    - Zn-salt-cement initial CS ≈ 14.0 MPa (> 6.9 MPa requirement) for d1” (1” diameter x 2” long) samples
    - D1” Zn-salt-cement 1st cycle recovery: 93.3% (vs. 27.6% for control cement).
    - Zn-salt-cement sustained measurable strength through 6 cycles.
    - Zn-salt-cement initial CS ≈ 16.7 MPa for d2″ (2” diameter x 4” long; 8× mass scale) samples (Figure 4).
    - D2” Zn-salt-cement showed a 45.7% first-cycle recovery of CS.
    - Control cement H with either showed no recovery past the first damage/healing cycle independently of samples dimensions (Figure 4).

1.2.5 Publications

Deliverable 2: Publication #1.

- **Fernandez**, C.A; Li, Z.; Zeng, C. 2023. " Fit-for-Purpose Self-Healing Cements” In *Proceedings of the International Congress on the Chemistry of Cement 2023, Bangkok. Thailand, September 18-22.*

D2 status: **Met**

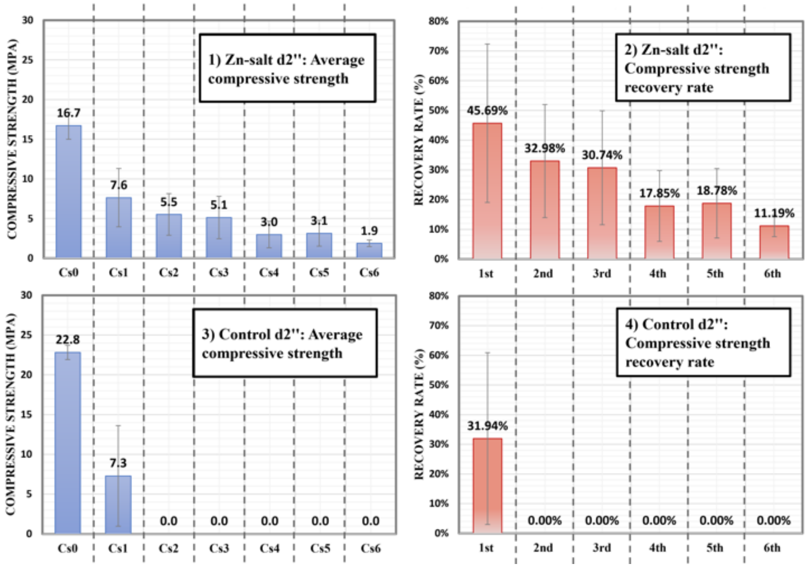


Figure 4: Average compressive strength and compressive strength recovery ratio for of D2” Zn salt-modified cement (top) as compared to control cement H (bottom) over six damage-healing cycles.

Year 1 - Key achievements:

- Developed self-healing EPS25-cement and Zn-salt-cement for 200–300°C environments
- Developed MBA-BDA-cement for low-temperature applications
- Demonstrated pumpability under geothermal conditions (<1,000 mPa·s for >90 min)
- Achieved setting time and density compatibility with conventional cement
- Validated scalability to 8× mass monoliths (EPS25-cement)
- Achieved 2X – 3X (!) improved ductility (EPS25-cement) relative to Class H cement
- Demonstrated autonomous compressive strength recovery for all self-healing cement formulations.

1.3 Year 2 – Field Deployment, Commercial Validation & Carbon Storage Performance

During Year 2, the project advanced from laboratory validation to field deployment, techno-economic validation, commercialization planning, and statistically validated mechanical and healing performance under both high-temperature geothermal and low-temperature carbon storage conditions. All Year-2 milestones and deliverables were met with exception of M7 which was partially met.

1.3.1 Milestone 5 – Field Deployment (GTO)

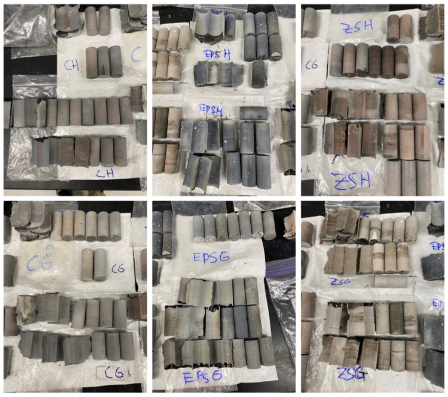


Figure 5: 90 samples shipped to deploy in wellbore 55-29 at Newberry for one year.

Field deployment was successfully completed at Newberry Geothermal Well 55-29 on July 11, 2023.

- 90 fractured cement monoliths deployed (EPS25-H, EPS25-G, Zn-salt-H, Zn-salt-G, Control-H, Control-G; see Figure 5).
- Samples placed at ~9,950 ft depth.
- Exposure conditions: ~300 °C for one year.
- Deployment supervised by AltaRock Energy and Resource Cementing.

Both criteria were met:

1. Samples fractured and shipped.
2. Successful underground deployment.

This represented a major advancement from laboratory validation to in situ evaluation.

M5 Status: **Met.**

1.3.2 Deliverable 3 – Cost/Benefit Analysis (TEA) – Part 1

Criteria: The techno-economic assessment demonstrated:

- Cost per pound ≤ 2× conventional geothermal cement for all formulations.
- Three out of four formulations projected ≥30% lifetime cost savings.

D3 status: **Met.** Savings driven by reduced intervention frequency and extended well life.

1.3.3 Deliverable 4 – Tech-to-Market (T2M)

A comprehensive commercialization strategy was developed, including:

- Licensing pathway to cement and operating companies.
- Market identification (geothermal, carbon storage, high-temperature wells).

- Value proposition definition.
- Early adopters identified: Resource Cementing and AltaRock Energy.
- Supply chain and precursor risk analysis.
- See Appendix B

D4 status: **Met**

1.3.4 Milestone 6 – Carbon Storage Cement Mechanical Validation (FE)

Description: A polymer-modified cement formulation with similar compressive strength to conventional cement and superior tensile strength.

Criteria: similar (within 10%) compressive strength (2,500 psi) after 7 days and 30% higher *flexural* strength as compared to conventional wellbore cement.

Results: A new low-temperature branched polyethylenimine (bPEI)-modified cement type I/II system achieved:

- Compressive strength statistically similar (within 10%) to control (>2,500 psi).
- Flexural strength **29%** higher than control.
- Tensile strength statistically similar to control.
- Cyclic healing performance:
    - CS recovery: 40–65% (vs. 30% → 0% for control)
    - FS recovery: up to 50% (vs. 0% control)
    - TS recovery: 25–58% (vs. ~0% control)
- Direct tensile test method developed to isolate tensile healing behavior.
- Healing initiated within hours; crack aperture reduced >95% within days.
- Polymer loading: only 0.15 wt%.

M6 status: **Met**

1.3.5 Deliverable 5 - Publication

Publication #2 submitted and accepted.

- Manh-Thuong Nguyen and **Carlos A. Fernandez*** et al Toward Self-Healing Concrete Infrastructure: Review of Experiments and Simulations across Scales. *Chemical Reviews*, Articles ASAP (2023). Impact Factor 72.3

D5 status: **Met**

1.3.6 Milestone 7 - Cement self-healing at low temperature (carbon storage applications (FE)

Description: Demonstrate recovery of structural and mechanical integrity after damage/healing events compared to conventional cement.

Criteria: A low-temperature self-healing cement with >80% recovery of compressive strength after (minimum) two damage/healing events at a relevant temperature and pressure.

Results:

- Low temperature MBA-BDA-cement exhibited consistent compressive strength recovery across multiple damage cycles, in a range of 35-72% over six damage/healing cycles (Figure 6). MBA-BDA is defined as N, N-methylene-bis-acrylamide (MBA) and 1,4-butanediamine (BDA) copolymer.

M7 status: **Not met.** **72% (instead of 80%) max recovery of CS.** Nevertheless, self-healing cement showed self-healing capability over six damage/healing cycles

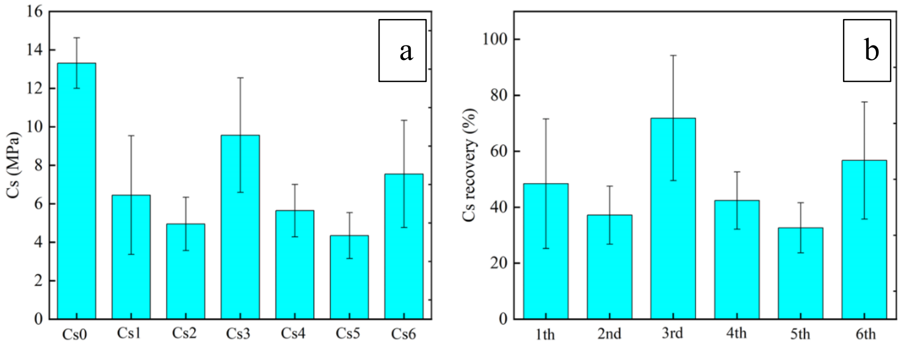


Figure 6: (a) Average compressive strength of MBA-BDA-modified cement, (b) compressive strength recovery ratio of MBA-BDA-modified cement over six damage-healing cycles.

1.3.7 Old - 8 and Go/No-Go – Superior structural and mechanical integrity of exposed self-healing cement (after approximately 1-year exposure) compared to conventional cement

M8 and Go/No-go was cancelled due to accessing the samples at the wellbore resulted to be impossible after three attempts.

M8 status: **Not met.** Samples lost in the wellbore.

1.3.8 New Milestone 8 and Go/No-Go – Resistance to thermal shock for self-healing cements for geothermal wellbore applications (GTO)

Description: Demonstrate superior mechanical integrity after exposing self-healing cements to five thermal shock cycles as compared to conventional cements.

Criteria #1: Self-healing cement samples must maintain compressive strength within 10% of unexposed samples after six thermal shock cycles.

Criteria #2: Self-healing cement must maintain healing capability after at least two damage/healing cycles, with CS recovery within 10% of unexposed samples.

The new Milestone 8 evaluated the mechanical integrity and self-healing capability of high-temperature (300 °C) self-healing cement formulations following six severe thermal shock exposure (25C & 300C) representative of geothermal wellbore conditions. This milestone served as the technical basis for Go/No-Go #2 for geothermal wellbore cement deployment.

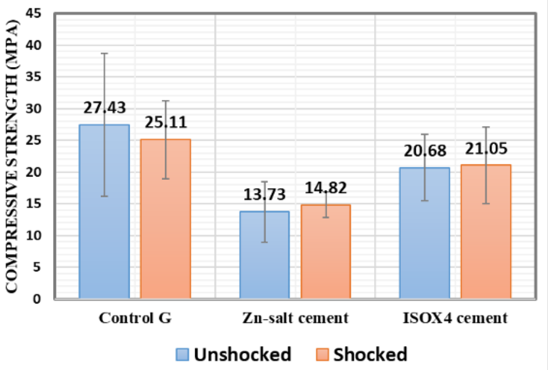


Figure 7: (a) Average compressive strength of cements before and after thermal shock.

- Six thermal shock cycles (modified ASTM C1171-16) applied to 28-day cured (300 °C) samples via exposure to dry heat at 300C and rapid quenching protocol (15 min at 300 °C dry heat followed by 15 min immersion in 10-gal 25C water).
- Compressive strength (CS) retention analysis post-six thermal shock cycles.
- Cyclic damage–healing performance under uniaxial compression.
- Statistical comparison of exposed vs. unexposed samples (paired t-tests).
- Microstructural evaluation via X-ray microtomography.
- Polymer stability assessment in polymer-cement samples via CP-NMR.
- A new thermally resilient polymer additive was synthesized, oxazolidone-based thermoset or ISOX4 to determine whether self-healing capability can be brought to cement.

Results:

1. Compressive Strength Retention After Thermal Shock (Figure 7)

- **ISOX4-cement**: Slight increase in CS after thermal shock; retained ≥90% original CS
- **PAA-Zn cement**: Slight increase in CS after thermal shock; retained ≥90% original CS
- **Control Cement (G, silica flour 6:4)**: ~8.5% CS reduction after six thermal shock cycles but statistically similar to pre-thermal shock due to high data variability.

Both polymer-modified formulations met the requirement of maintaining compressive strength within 10% of unexposed samples, so did control cement.

2. Self-Healing Capability After Thermal Shock (Figures 8 and 9)

Cyclic damage–healing tests were conducted under uniaxial compression (minimum triplicate samples per cycle; 5 days healing at 300 °C between cycles).

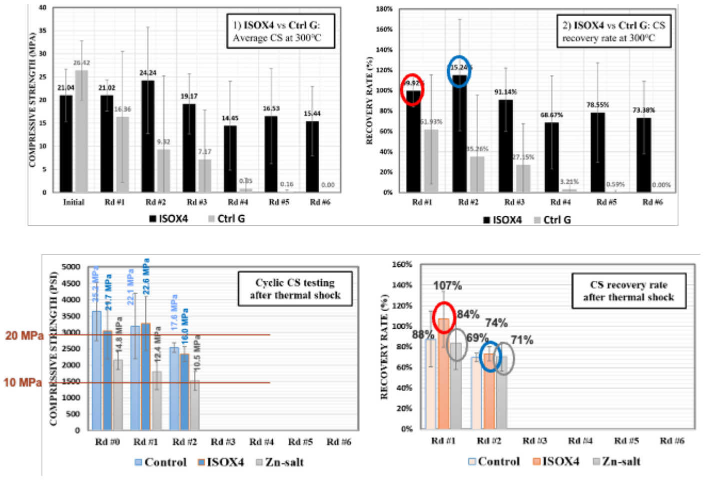


Figure 8: Self-healing of ISOX4-cement over multiple damage/healing events as compared to control cement before (top plots) and after (bottom plots) thermal shock.

Recovery Rate – First Damage/Healing Cycle (Rd#1):

- ISOX4-cement: ~105% recovery (indicating full restoration + autogenous contribution)
- Control cement: ~95% recovery
- PAA-Zn cement: ~85% recovery

ISOX4-cement demonstrated superior first-cycle healing performance relative to both control and PAA-Zn cement. However, all three cements showed similar recovery on the second cycle.

Statistical Validation (Thermal Shocked cements vs. unexposed cements):

Paired t-tests comparing recovery rates with and without thermal shock showed:

- ISOX4-cement: p = 0.6161 (>0.05)
- PAA-Zn-cement: p = 0.080 (>0.05)

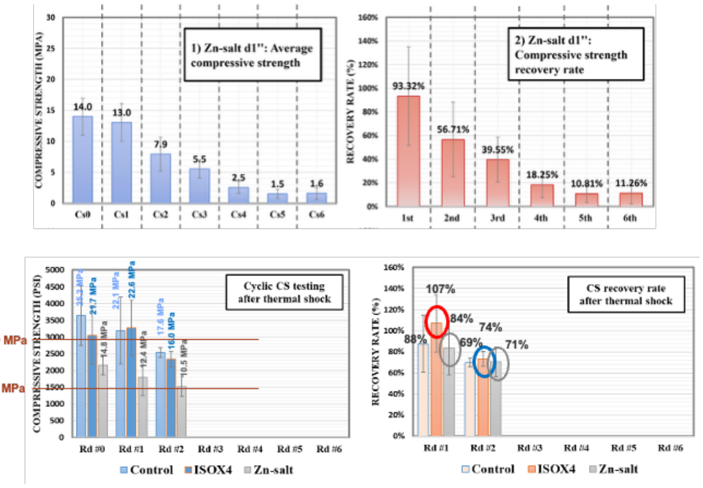


Figure 9: Self-healing of Zn salt-cement over multiple damage/healing events as compared to control cement before (top plots) and after (bottom plots) thermal shock.

No statistically significant difference (95% confidence) was observed in healing performance before and after thermal shock. Similarly, control cement did not show statistical difference in healing performance but due primarily to the significantly large data variability in compressive strength of the original samples.

Conclusion: Thermal shock did not measurably degrade self-healing capability on both self-healing cements as well as in control cement.

3. Microstructural Evidence (X-ray Microtomography) on control cement and best performing self-healing cement, ISOX4-cement.

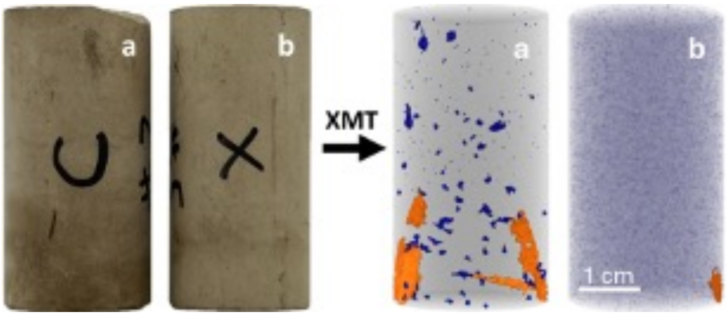


Figure 10: XMT 3D structures show distributions of fractures (orange) and pores (blue) in the cement samples after thermal shock test. *Left-hand side*: cement samples. *Right-hand side*: the corresponding 3D model from XMT. **(a)** Control cement sample, which generated four fractures after thermal shock. **(b)** ISOX4 cement sample generated only one fracture after thermal shock.

Post-shock imaging (25 µm resolution) revealed (Figure 10):

Control Cement:
- *Four visible fractures*
- Nearly no porosity
- Unreacted silica present

ISOX4-cement:
- *Only one edge fracture*
- Reduced unreacted silica
- Higher porosity associated with polymer domains.

These findings correlate enhanced ductility and damage tolerance with polymer distribution.

Polymer Thermal Stability (13C MAS-NMR) ISOX4 polymer analysis:
- Stable between 80–300 °C
- 28 days at 300 °C: peak broadening indicates amorphization but no degradation
- Polymer embedded in cement: no degradation after 28 days at 300 °C.

4. Overall Technical Significance

New Milestone 8 – Go/No-go #2 demonstrated that:

- Self-healing cement systems tolerate extreme thermal shock representative of geothermal wells
- Healing capability is not compromised by thermal cycling
- ISOX4-cement formulation exhibits superior mechanical resilience
- Polymer remains thermally stable when embedded in cement matrix
- Mechanical and microstructural data consistently favor polymer-modified systems over conventional cement. Control cement did not show significant decrease of compressive strength or healing ability though data variability of compressive strength pre-thermal shock was significantly larger than self-healing cements.

New M8 status: **Met**

This milestone provides strong technical validation supporting geothermal field deployment and commercialization readiness.

Year 2 - Key achievements:

- Successful deployment of 90 fractured cement monoliths in Newberry Geothermal Well 55-29 at ~9,950 ft (~300°C)

- Validated multi-cycle healing for EPS25-cement, Zn-salt cement at 300°C
- Demonstrated homogeneous polymer distribution via XMT and microscopy
- Completed TEA Part 1 showing ≥30% lifetime cost savings
- Delivered Tech-to-Market commercialization strategy
- Demonstrated a new carbon storage cement formulation, branched polyethylenimine (bPEI)-modified cement type I/II with:
    - Similar compressive strength
    - 29% higher flexural strength
    - 25–58% tensile strength recovery
    - Rapid crack healing at only 0.15 wt% polymer loading based on dry mass of cementitious materials
- Both high-temperature self-healing Zn salt- and ISOX4-cements tolerate extreme thermal shock representative of geothermal wells by maintaining compressive strength.
- Self-healing capability for high-temperature self-healing Zn salt- and ISOX4-cements are not compromised by thermal cycling.

1.4 Year 3 – Lifetime Economic Modeling, Thermal Shock Evaluation, & Carbonation Durability Assessment

During Year 3, the project focused on advanced techno-economic validation of self-healing cement systems for geothermal applications and durability performance under carbon storage carbonation conditions. Major accomplishments included completion of a comprehensive lifetime cost/benefit analysis (TEA – Part 2) incorporating probabilistic failure modeling and experimental performance data, as well as systematic evaluation of low-temperature self-healing cement resistance to carbonated brines under representative pressure and temperature conditions. All but one milestone (M9) and deliverables were met.

1.4.1 Milestone 9 – Carbonation Resistance of Low-Temperature Self-Healing Cement

Low-temperature polymer-modified self-healing cement was evaluated under CO_2-rich brine environments representative of carbon storage wellbores.

Milestone 9 Criteria: Maintain compressive and tensile strength within ~10% of original values after carbonation exposure.

Test Conditions

- 25°C and 90°C
- 2,500 psi CO_2
- 10 wt% NaCl brine
- 28-day exposure

Mechanical Integrity Results

At 25°C:

- Self-healing cement:
  - Compressive strength decreased by ~30%
  - Tensile strength remained essentially unchanged
- Control cement:
  - Compressive strength remained constant
  - Tensile strength decreased by ~19%

At 90°C:

- Both control and self-healing cement experienced:
  - ~30% compressive strength loss
  - ~20% tensile strength loss

M9 status: **Not met**. Post-exposure compressive strengths of self-healing cement remained significantly above minimum wellbore requirements (~2,700 psi).

1.4.2 Milestone 10 – Techno-Economic Analysis (TEA) Part 2: Lifetime Cost Modeling

Description: Updated TEA analysis with component sensitivity analysis and lifetime cost reduction.
Criteria: (1) Cost/pound ≤ 1.3× the cost of conventional geothermal wellbore cement and (2) estimated (minimum) 40% lifetime cost savings with respect to a conventional well cement (based on cement unit cost reduction).

Results:
A rigorous 40-year geothermal wellbore lifetime cost framework was developed integrating:

- Four escalating intervention types: clam shell, scab liner, milling, and liner installation
- Time-dependent failure probability modeled using Weibull distributions
- Three operational scenarios: conservative, baseline, and harsh conditions
- Laboratory damage-healing performance of high-temperature self-healing cements

Intervention frequency for conventional cement was modeled at approximately once every 10 years, while self-healing cements demonstrated a **2× extension of service life before intervention** based on cyclic mechanical testing.

Key Findings

- Lifetime intervention costs for conventional cement were dominated by repeated high-cost repairs and production losses.
- Self-healing cement formulations significantly reduced the number of required interventions over 40 years.
- Four out of five polymer-modified cement systems met economic performance thresholds.

Quantified Impact (Newly formulated ISOX4-cement)

- Unit cost of ISOX4 self-healing cement: **$0.11/lb**
- Material cost for a 1.5 km wellbore: **~$1.18M**
- Conventional cement lifetime cost: **~$12.26M**
- Self-healing cement lifetime cost: **~$3.21M** reduced by **~$9M (73.8% !)**

Milestone 10 Performance Criteria

- Cost per pound ≤ **1.3×** conventional geothermal cement
- ≥ **40% lifetime cost savings**

M10 status: Met. Four out of five formulations accomplished both milestone’s criteria.

Sensitivity Analysis of Intervention Severity

Sensitivity studies confirmed:

- Lifetime cost advantages persisted across easy, standard, and harsh operating scenarios.
- Economic benefits were only weakly sensitive to variation in intervention difficulty.
- Real-world intervention costs are likely higher than modeled, further strengthening the business case.
- This analysis robustly validated commercialization viability of the self-healing cement platform.

Please refer to Appendix B for the detailed analysis.

1.4.3 Deliverable 6 – T2M for self-healing geothermal wellbore cement – Part 2

Description: Deliver updated T2M plan

Criteria: Produce a report summarizing identified stakeholder and details on a potential field deployment and commercialization agreement and any remaining commercialization barriers to be addressed, including a plan to this end.

Results – Updated Commercialization Strategy and Deployment Readiness
Deliverable 6 Part 2 updated the Technology-to-Market (T2M) strategy to reflect validated technical performance, expanded industry engagement, and a revised but strengthened field-readiness pathway following modification of Milestone 8 and Go/No-Go #2.
Building on the Part 1 T2M framework—which defined the commercial product as a **self-healing cement formulation combined with standardized slurry preparation and deployment protocols** designed for seamless integration into existing cementing operations—the updated plan incorporates both field execution experience and extreme-condition performance validation.

1. **Stakeholder Identification and Market Engagement**

A structured industry socialization campaign was executed across the geothermal cement value chain, including:
- Cement admixture manufacturers
- Chemical suppliers supporting polymer additives
- Cement producers
- Resource Cementing as a well cementing service provider.

More than **60 targeted organizations** were contacted through direct outreach, meetings, and technical showcases, establishing an active commercialization funnel and early-adopter interest base. Engagement tracking documented responses, follow-ups, and ongoing discussions supporting licensing and pilot deployment planning.

2. **Field Deployment Pathway and Revised Validation Strategy**

Initial commercialization execution successfully demonstrated:
- Preparation of field-scale cement monoliths
- Integration with cementing service workflows
- Underground deployment in an operating geothermal well (Newberry Well 55-29)

Despite three retrieval attempts, field-exposed samples could not be recovered due to solids accumulation above the cement baskets, ultimately resulting in loss of the deployed samples. Rather than delaying commercialization readiness, this operational outcome informed a **formal modification of Milestone 8 and Go/No-Go #2**, shifting performance validation toward **thermal shock resistance**, a more severe and directly relevant stress condition for geothermal stimulation and cyclic power plant operation.

3. Strengthened Commercial Validation Through Thermal Shock Testing

The revised Milestone 8 and Go/No-Go #2 conclusively demonstrated that:

- Self-healing cement systems tolerate extreme geothermal thermal shock conditions
- Healing capability are maintained after repeated temperature cycling
- ISOX4-cement exhibits superior mechanical resilience
- Polymer remains thermally stable when embedded in cement
- Polymer-modified systems show greater mechanical reliability than conventional cement

Both new Milestone 8 criteria and the revised Go/No-Go #2 were fully met.

This outcome provides **stronger commercialization confidence** than post-retrieval testing alone by validating cement performance under the most aggressive thermo-mechanical stress scenarios encountered in geothermal operations.

4. Updated Commercialization Agreement Pathway

The revised T2M plan formalizes a staged commercialization approach with **HERO and Resource Cementing** as deployment partners:

a. Licensing of self-healing cement formulations and QC specifications
b. Joint pilot cementing operations in geothermal wells using service-company blending and pumping workflows
c. Performance-based expansion agreements tied to intervention reduction and well integrity metrics

This structure de-risks early deployment while enabling rapid scaling upon successful pilot demonstrations.

5. Remaining Commercialization Barriers and Mitigation Plan

Barrier 1 – Full-scale annular placement visualization and bonding validation still needed
Mitigation: Development of controlled intermediate-scale annulus demonstration systems (transparent concentric casing testbeds) to visualize placement, gap formation, and post-mortem bonding quality.

Barrier 2 – First-of-kind deployment risk perception by operators
Mitigation: Use thermal-shock-validated performance envelopes, probabilistic TEA results, and staged pilot agreements to limit operator exposure.

Barrier 3 – Supply chain readiness for polymer additives
Mitigation: Standardize polymer packaging, blending procedures, QC ranges, and service-company compatible workflows.

6. Commercial Readiness Level (CRL)

Based on:

- Completion of multi-year laboratory validation
- Thermal shock validation under extreme geothermal conditions
- Comprehensive TEA demonstrating 40–75% lifetime cost reduction
- Active engagement with >60 industry stakeholders
- Defined licensing and pilot deployment pathway with HERO and Resource Cementing

The self-healing geothermal cement technology is assessed at: **CRL 5–6** (Pre-commercial pilot readiness stage)
CRL 5: Commercial feasibility validated with quantified economic advantage
CRL 6: Identified early adopters and defined pilot deployment agreements
The technology has advanced beyond concept validation and is positioned for structured pilot commercialization with defined licensing pathways.

7. Adoption Readiness Level (ARL)

From an operator perspective:
- Compatible with existing cementing workflows
- No new pumping hardware required
- Polymer loading minimal and operationally manageable
- Clear performance metrics defined (CS retention, healing recovery, thermal shock resistance)
- Economic value proposition validated

Adoption readiness is assessed at: **ARL 4–5** (Validated pilot integration stage)
Operators require one successful pilot annular deployment under commercial pumping conditions before broad adoption.

8. Technology Readiness Level (TRL)

Based on:
- Successful geothermal well deployment (installation)
- Successful extreme-condition (thermal shock) validation
- Demonstrated multi-cycle healing under 300 °C
- Comprehensive TEA and commercialization pathway

The technology is assessed at: **TRL 5-6**. Although the technology was not demonstrated in an operational geothermal environment (installation), performance has been validated under severe relevant stress conditions. Advancement to **TRL 7** requires successful pilot annular cementing operation with documented in-well performance metrics or successful retrieval-based qualification.

Deliverable 6 Performance Criteria Assessment
Criteria:
Updated T2M plan including:
- Identified stakeholders
- Deployment and commercialization agreement pathway
- Remaining barriers
- Mitigation plan

D6 Status: Met. The revised T2M strategy integrates real field execution experience, extreme-condition validation (thermal shock), active stakeholder engagement, and a structured licensing/deployment roadmap, positioning the self-healing cement platform for near-term commercialization.

1.4.4 Deliverable 7 – Publication

Criteria: A third publication

C. Zeng, Z. Li, L. Li, **C. A. Fernandez*** A Molecular Velcro Self-healing Cement *Nature Communications* **2026** *Accepted for publication.*

D7 satus: **Met**

1.4.5 Deliverable 8 – Publication

Criteria: A fourth publication

Zihao Li, Robert G. Felsted, Trenton R. Graham, Mark A. Rhodes, Yuntian Teng, C. Heath Stanfield, Harshvardhan Chopra, Jian Liu, Chao Zeng, Lan Li, Quin R. S. Miller, **Carlos A. Fernandez**[*] A High-temperature Self-healing Cement Based on Molecular Velcro Technology. 2026. *Under review.*

D8 status: Partially Met. Above manuscript is under review but not yet published.

Year 3 - Key achievements:

- Developed probabilistic Weibull-based 40-year lifetime cost model
- Incorporated laboratory healing performance into intervention frequency reduction
- Demonstrated 2× extension in service life before intervention
- Achieved ≥40–75% lifetime cost savings for four self-healing formulations
- Confirmed economic robustness across conservative to harsh scenarios
- Carbonation testing revealed:
    - Low-T self-healing cement experienced 30% CS reduction under CO_2 brine exposure
    - Performance remained above minimum wellbore strength thresholds
    - Durability targets (±10% retention) were not met — guiding next-phase formulation optimization
- Executed updated Technology-to-Market (T2M) plan including:
    - Engagement of 60+ stakeholders across cement, admixture, chemical, and a service-provider
    - Defined staged licensing and pilot deployment pathway with HERO and Resource Cementing
- Integrated extreme-condition validation (thermal shock resistance) into commercialization readiness following field retrieval limitations, strengthening operator confidence for geothermal deployment.

Comprehensive Milestones & Deliverables Compliance Table

Year	Milestone / Deliverable	Description	Passing Criteria	Status
Y1	M1	Formulation development & kickoff	≥1 LT + ≥1 HT formulation	Met
Y1	M2	Rheology	<1,000 mPa·s ≥90 min	Met
Y1	M3-FE	Setting & density	Similar setting; ±10% density	Met
Y1	M4-GTO	Scalability & ductility	CS within ±10%; YM ≥70% lower	Met
Y1	D1	Field test apparatus	Built + wells identified	Met
Y1	D2	Publication #1	Accepted	Met
Y1	**Go/No-go #1**	**Based on (1) workability & (2) scalability assessments**	**(1) similar workability to conventional wellbore cement & scalability to 8X based on mass with no impact on mechanical properties**	**Met**
Y2	D3	TEA Part 1	≤2× cost; ≥30% savings	Met
Y2	M5	Field deployment	Ship samples and underground placement	Met
Y2	D4	T2M plan	Market & licensing strategy	Met
Y2	M6	Carbon storage cement strength	CS ±10%; FS ≥30% higher	Met
Y2	D5	Publication #2	Submitted/accepted	Met
Y2	M7	Cement self-healing at low temperature carbon storage applications (FE)	A low-temperature self-healing cement with **>80%** recovery of compressive strength after (minimum) two damage/healing events	**Partial met (72%** recovery and self-healing over 6 damage cycles)
~~Y2~~	~~M8~~	~~Cement self-healing for geothermal wellbore applications – evaluation post-wellbore retrieval (GTO)~~	~~Self-healing cement samples are the only ones that show: (1) an absence of tensile fractures and (2) similar (within 10%) compressive strength and Young's modulus to unexposed samples~~	Samples lost in wellbore even after 3 attempts to retrieve them.
Y2	**New M8 & Go/No-go #2**	**Resistance to six thermal shock (25C & 300C) for self-healing cements for geothermal wellbore applications (GTO)**	**Self-healing cement samples show (1) similar (within 10%) compressive strength to unexposed samples and (2) show self-healing capability after (minimum) two damage/healing events.**	**Both criteria met.**
Y3	M9	Carbonation durability	CS & TS within ±10% after carbonation exposure as compared to the original CS and TS.	**Not Met** CS within ±30% & TS within ±20%.
Y3	M10	TEA Part 2	≤1.3× cost; ≥40% savings	Met
Y3	D6	T2M for self-healing geothermal wellbore cement – Part 2	Deliver updated T2M plan summarizing identified stakeholder and details on a potential field deployment and commercialization agreement.	Met
Y3	D7	Publication #3	Accepted	Met

Year	Milestone / Deliverable	Description	Passing Criteria	Status
Y3	D8	Publication #4	Under review	**Partially met**
Y3	D9	Final report	A report submitted to GTO and FECM	Met

Appendix A

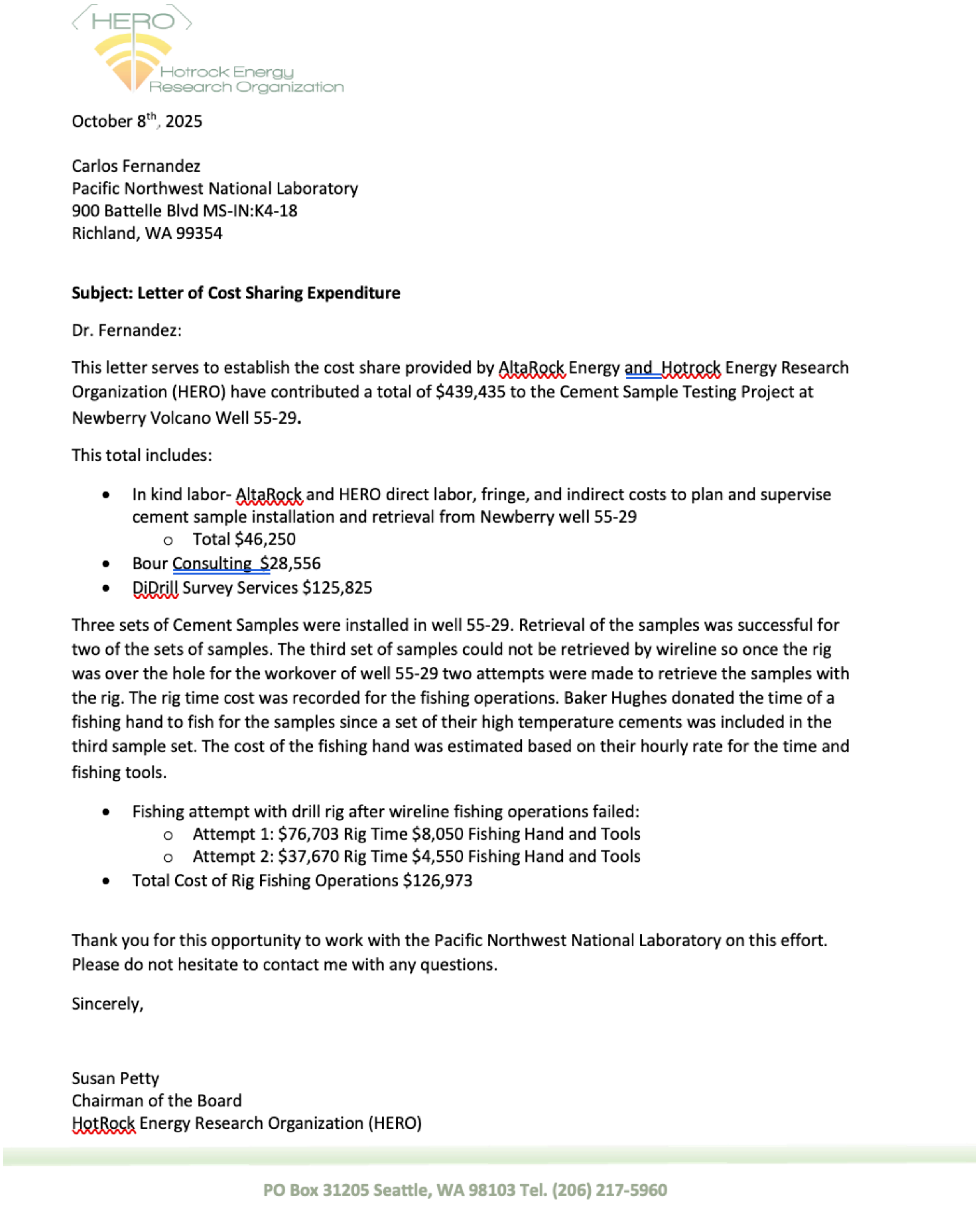
Project Cost and Cost Share

- Project funds allocated: **$1,487,600**
- Project cost from kickoff on February 28, 2021: **$1,487,370**
- Project's remaining balance: **$230**

- RC original cost share: **$200,000**
- RC cost share provided to project this far (as of 10/07/2025): **$110,150**
- Difference is related to the decision of not performing a scab liner cementing job in phase 3 of the project in agreement with GTO/FE

RC's in-kind contribution		**Year 1**	**Year 2**	**Year 3**
A.	Personnel	$20,000	$13,000	$10,000
B.	Travel	$4,500.00	$0.00	$0.00
C.	Equipment	$27,000.00	$27,000.00	$0.00
D.	Supplies	$2,250.00	$3,200.00	$3,200.00
E.	Contractual	$0.00	$0.00	$0.00
F.	Other			
Total Direct Charges		$53,750.00	$43,200.00	$13,200.00
Indirect Charges				
TOTAL		**$110,150**		

- HERO original cost share: **$1,352,600**
- HERO cost share provided to project this far (as of 10/07/2025): **$439,435**
- **Difference is related to the decision of not performing a scab liner cementing job in phase 3 of the project in agreement with GTO/FE**



HERO
Hotrock Energy
Research Organization

October 8th, 2025

Carlos Fernandez
Pacific Northwest National Laboratory
900 Battelle Blvd MS-IN:K4-18
Richland, WA 99354

Subject: Letter of Cost Sharing Expenditure

Dr. Fernandez:

This letter serves to establish the cost share provided by AltaRock Energy and Hotrock Energy Research Organization (HERO) have contributed a total of $439,435 to the Cement Sample Testing Project at Newberry Volcano Well 55-29**.**

This total includes:

- In kind labor- AltaRock and HERO direct labor, fringe, and indirect costs to plan and supervise cement sample installation and retrieval from Newberry well 55-29
    - Total $46,250
- Bour Consulting $28,556
- DiDrill Survey Services $125,825

Three sets of Cement Samples were installed in well 55-29. Retrieval of the samples was successful for two of the sets of samples. The third set of samples could not be retrieved by wireline so once the rig was over the hole for the workover of well 55-29 two attempts were made to retrieve the samples with the rig. The rig time cost was recorded for the fishing operations. Baker Hughes donated the time of a fishing hand to fish for the samples since a set of their high temperature cements was included in the third sample set. The cost of the fishing hand was estimated based on their hourly rate for the time and fishing tools.

- Fishing attempt with drill rig after wireline fishing operations failed:
    - Attempt 1: $76,703 Rig Time $8,050 Fishing Hand and Tools
    - Attempt 2: $37,670 Rig Time $4,550 Fishing Hand and Tools
- Total Cost of Rig Fishing Operations $126,973

Thank you for this opportunity to work with the Pacific Northwest National Laboratory on this effort. Please do not hesitate to contact me with any questions.

Sincerely,

Susan Petty
Chairman of the Board
HotRock Energy Research Organization (HERO)

PO Box 31205 Seattle, WA 98103 Tel. (206) 217-5960

APPENDIX B

Milestone 4. T2M – Part 1.

A) What is the product, process, or technology the team intends to develop and commercialize?

We will provide the stakeholders with self-healing cement formulation/s in the form of precursors composition and proportions, a method to prepare a slurry of such self-healing cement, and a method to deploy such slurry in a wellbore. Such formulation and method/s will (1) require minimum (if any) additional training to prepare, and (2) attain a self-healing cement product with reproducible and predictable rheological and mechanical properties.

B) What specifics can be provided regarding your concept of the product features and benefits, and what information was used to develop this concept?

Technology value proposition:

1. Self-healing cement formulation (HT and RT) may not need a retarder depending on P/T conditions
2. Self-healing cement (HT and RT) may not need a superplasticizer depending on P/T conditions
3. Self-healing cements for Carbon Storage will have flexural strength 30% higher than commercial wellbore cement
4. Self-healing cements for Carbon Storage will have similar tensile strength to commercial wellbore cement
5. Self-healing cements for Carbon Storage will have similar (or lower) compressive strength to commercial wellbore cement
6. Self-healing cements for Carbon Storage will have similar or lower Young's modulus to commercial wellbore cement
7. Self-healing cements for Carbon Storage will have self-healing capability over multiple damage/healing events as demonstrated by the recovery of TS (rate 25-58%) and CS (rate 40-65%) over (minimum) four cycles as compared to conventional wellbore cement showing no recovery of TS and recovery of 30% of CS only after the first damage. No recovery of CS after.
8. Self-healing cements for EGS were designed for temperatures of up to 200C (formulation #1 and up to 300C (formulation #2)
9. Self-healing cements for EGS will have statistically similar tensile strength to commercial wellbore cement

10. Self-healing cements for EGS will have 25-40% lower compressive strength to commercial wellbore cement but significantly above 1000 psi
11. Self-healing cements for EGS will have 40-70% lower Young's modulus (more ductile than) to commercial wellbore cement.
12. Self-healing cements for EGS will have self-healing capability over multiple damage/healing events as demonstrated by:
    Formulation 1 (200C): 107% and 113% in the first two damage/healing cycles (versus 30% and then negligible recovery of commercial cement).
13. *Formulation 2 (300C):* recovery of CS of 93% (versus 27% of control) and a recovery rate decreasing from 93% to 11% over the next six cycles. Conventional cement is irreversibly damaged over (minimum) four cycles as compared to conventional wellbore cement showing no recovery of TS and recovery of 30% of CS only after the first damage. For comparison, conventional cement show irreversible damage with no recovery of any CS after the first damage/healing cycle.
14. *Cost:* three out of the four cement formulations will have a 30% lifetime cost savings as compared to commercial cement provided by RC.

C) How do you expect this technology to transition from lab to market? Do you expect to form a company, license the technology, sell the technology, etc.? How will this be done?

PNNL anticipates licensing the formulation and methods for preparation and deployment to cement companies, operators or cement admixtures companies

D) What experiences do the team members have with moving technology from lab to market, and can examples of prior successes be described?

Resource Cementing has a long track record of wellbore cement formulation design, preparation and, deployment in geothermal and carbon storage wells.

E) What factors will influence your approach to moving this technology from lab towards market and why?

- Cost and availability of polymer precursors
    - ✓ Need to get manufacturing volumes of precursors and turnaround time
- Material's performance matches or exceeds target metrics
- TEA shows a more inexpensive and better performing material and/or shows lifetime cost savings associated to reduction of inspection, maintenance and repair as well as longer lasting concrete structures.

F) What partners are currently involved in, or expected to be involved in, the transition of the technology from lab to market, including name, position title, company, description of relationship and value provided?

Currently Resource Cementing and AltaRock Energy Inc. are involved in the transition of these cement technologies to market.

G) What characteristics will you look for in partnering organizations and why?

- Cement companies.
- Additive manufacturing companies.
- Wellbore operating companies.

H) What is your expected time to commercialization, including major steps and timing for each major step?

It will highly depend on the results from our first cementing job. In conversations with Resource Cementing and HERO.

I) Current risk levels and mitigation methods for each of the following as they relate to commercialization:

- Materials and supply chain risks: price stability, precursors availability and location (U.S. or foreign)
- People/ talent
- Understanding cement performance variance between that in controlled lab environment and that in the field. We will know some more about the HT self-healing cements after retrieving them in July next year.

Report on Milestone 10: Cost/benefit analysis for self-healing geothermal wellbore cement-Part 2.

Geothermal wellbore repair cost over 40 years

The lifetime cost of geothermal wellbore cement is strongly influenced by the frequency and type of wellbore interventions required. Because interventions depend on construction quality, operating conditions, and maintenance practices, we modeled three scenarios to capture a range of outcomes:

1. **Conservative scenario** – excellent construction and proactive monitoring.
2. **Baseline scenario** – average construction and monitoring practices.
3. **Harsh scenario** – aggressive chemical environment and severe operating conditions.

Intervention Types and Costs

Discussions with industry partners (Resource Cementing and HERO) identified four major types of interventions, ranked from least to most expensive:

1. **Clam shell** – approximately **$200K**
2. **Scab liner – $750K–$1.0M** (occasionally up to $1.5M)
3. **Milling – $1.5M–$2.0M**
4. **Run a (Production or Drilling) liner – $4.5M–$7.0M**

Please see the Definitions Section for a description of each intervention operations.

These interventions follow an "escalation ladder," where the cost and complexity increase from (1) to (4). On average, conventional geothermal wellbore cement requires an intervention approximately every 10 years.

Time-Dependent Probability of Interventions

As service time increases, cement degrades due to thermal, chemical, and mechanical stresses. Consequently, the probability of requiring **larger, more costly interventions rises over time**, while the likelihood of smaller interventions decreases.
To model this behavior, a **parametric Weibull time-to-event model** was applied:

$$F(t) = 1 - exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

Where:

- t = service time (years)
- β = shape parameter (failure rate behavior)
- η = scale parameter (characteristic life).

The Weibull distribution captures the "bathtub curve" behavior of wellbore failure: low-to-moderate risk early, a flat mid-life period, and an increasing hazard rate in later years.
Three sets of parameters were used for sensitivity analysis:

- **Conservative**: $\beta = 1.5$, $\eta = 38$
- **Baseline**: $\beta = 1.9$, $\eta = 32$
- **Harsh**: $\beta = 2.3$, $\eta = 26$

Calculation Framework

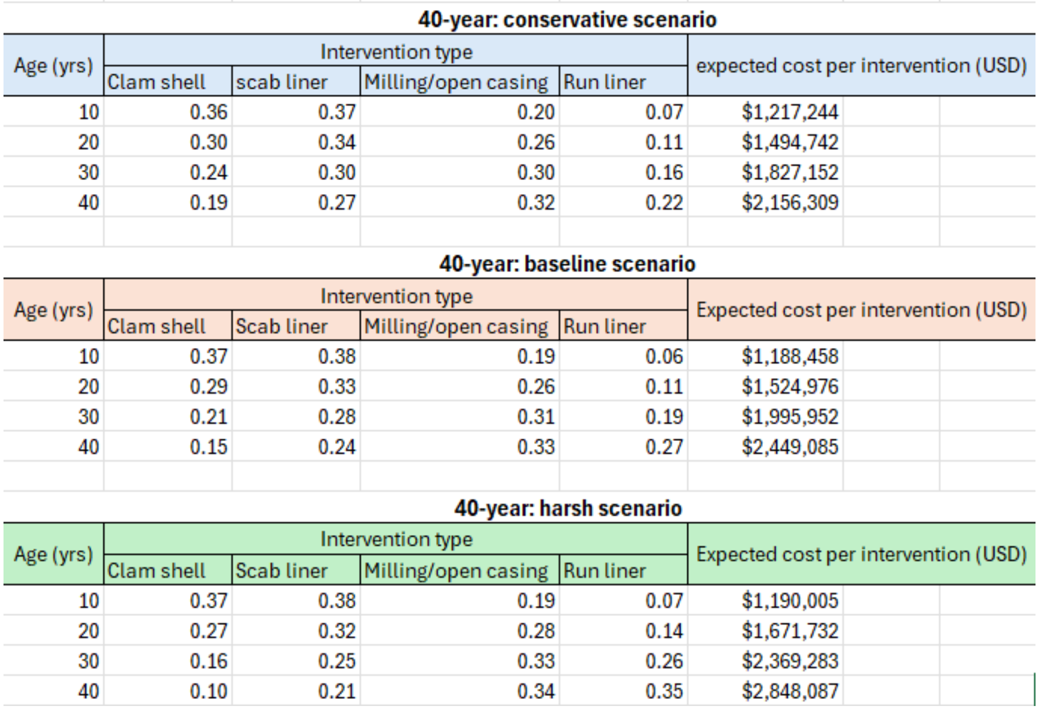
Table 1 shows the intervention costs in a geothermal wellbore over its 40-year lifetime. The total intervention cost over 40 years was calculated by combining:

- Intervention cost ranges,
- Time-dependent intervention probabilities, and
- Cement performance data from laboratory testing.

The reference geothermal wellbore was defined as:

- Temperature = **300°C**
- Wellbore length = **1.5 km**
- Cement = **Class G**
- Casing = **Carbon steel**

Table A1. Intervention costs of a geothermal wellbore over a service time of 40 years.



40-year: conservative scenario

Age (yrs)	Intervention type				expected cost per intervention (USD)
	Clam shell	scab liner	Milling/open casing	Run liner	
10	0.36	0.37	0.20	0.07	$1,217,244
20	0.30	0.34	0.26	0.11	$1,494,742
30	0.24	0.30	0.30	0.16	$1,827,152
40	0.19	0.27	0.32	0.22	$2,156,309

40-year: baseline scenario

Age (yrs)	Intervention type				Expected cost per intervention (USD)
	Clam shell	Scab liner	Milling/open casing	Run liner	
10	0.37	0.38	0.19	0.06	$1,188,458
20	0.29	0.33	0.26	0.11	$1,524,976
30	0.21	0.28	0.31	0.19	$1,995,952
40	0.15	0.24	0.33	0.27	$2,449,085

40-year: harsh scenario

Age (yrs)	Intervention type				Expected cost per intervention (USD)
	Clam shell	Scab liner	Milling/open casing	Run liner	
10	0.37	0.38	0.19	0.07	$1,190,005
20	0.27	0.32	0.28	0.14	$1,671,732
30	0.16	0.25	0.33	0.26	$2,369,283
40	0.10	0.21	0.34	0.35	$2,848,087

Intervention Trigger Criterion

According to federal regulations for casing and cementing requirements, a **minimum compressive strength of 500 psi (3.45 MPa)** is required for wellbore cement to remain effective. Falling below this threshold triggers intervention.

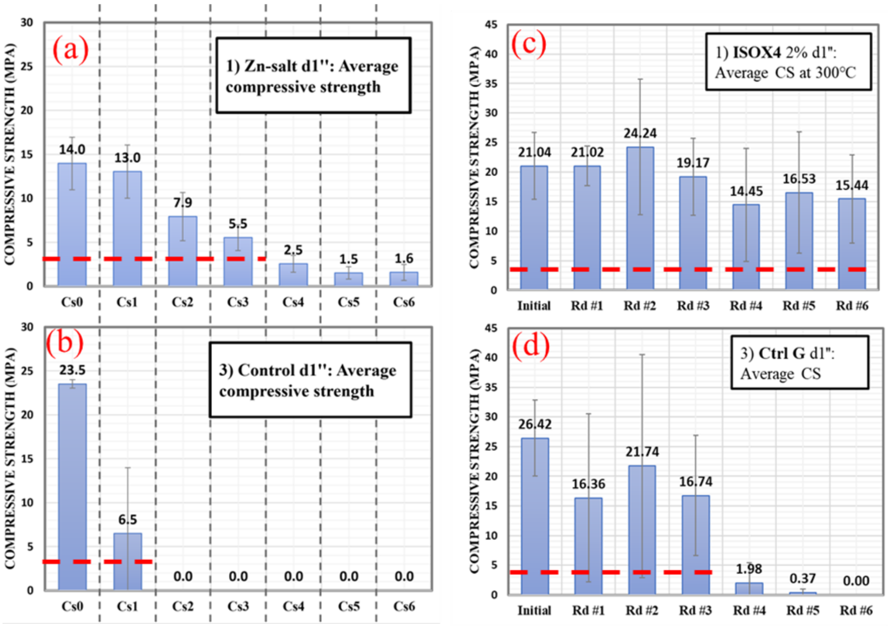


Figure A1. Cyclic compressive damage-healing tests on self-healing cement and control cement samples by minimm triplicate. (a) Zn-salt cement, (b) corresponding control cement, (c) ISOX4 cement, (d) corresponding control cement.

Incorporation of Self-Healing Cement Performance

Laboratory data were used to compare the mechanical performance, as measured by multiple damage/healing cycles, of conventional cement with two high-temperature self-healing formulations:

- **Zn-salt modified cement**: intervention required at **cycle 4**, versus **cycle 2** for control cement → **2× lifetime extension**.
- **Isox4 modified cement**: intervention required at **cycle 6**, versus **cycle 3** for control cement → **2× lifetime extension**.

Thus, both self-healing systems demonstrated **a doubling of service time before intervention** compared to conventional cement. This extension factor was applied in the TEA analysis to quantify cost savings.

Summary

The 40-year repair cost analysis incorporates:

- Four intervention types with associated cost ranges,
- Time-dependent degradation modeled with Weibull functions,
- Three scenarios (conservative, baseline, harsh), and
- Laboratory performance data for self-healing cements.

Results demonstrate that **self-healing cements could significantly reduce intervention frequency**, leading to large lifetime cost savings compared to conventional wellbore cements.

1.1 Cost/benefit analysis

The self-healing polymer-modified cements developed in this work consist of Class G cement and silica fume at a 60:40 mass ratio, water (w/c = 0.54), and a single proprietary high-temperature resistant polymer admixture/additive. These include:

- (A) polyethylene-co-acrylic acid zinc salt (10 wt%),
- (B) a self-healing thermoplastic elastomer based on oxazolidone (ISOX4, 2 wt%), or
- (C) a self-healing thermoset epoxy (EPS25, 8 wt%),
- (D) For carbon storage wellbore applications, type I/II cement with silica fume (60:40 ratio, w/c = 0.54) was also tested with alternative self-healing polymers:
  1. a self-healing ternary polymeric complex based on branched poly(ethylenimine) (bPEI, 0.15 wt%), and
  2. a self-healing hyperbranched polymer based on N,N'-methylene diacrylamide and 1,4-butanediamine (MBA-BDA, 10 wt%).

This techno-economic analysis evaluates the cost benefits of the above self-healing cements relative to conventional geothermal cement in a 50 MW geothermal power plant. Lifetime costs were estimated as the sum of material costs and maintenance costs, which include intervention operations and production losses. Intervention cost and frequency were determined from literature and experimental data (see previous section). Unit cement cost was calculated based on additive price and dosage; an additional 5% was added during pre-mixing and before injection.

Evaluation criteria for Milestone 10 were:

1. Cost per pound ≤ 1.3× that of conventional geothermal wellbore cement.
2. At least 40% lifetime cost savings compared with conventional wellbore cement.

Example calculation – ISOX4-cement:

The unit cost of ISOX4-modified self-healing wellbore cement is \$0.11/lb. For a 1.5 km wellbore requiring ~2,588 yd^3 (10.44 million lbs), the material cost is ~\$1.18M. Conventional geothermal cement, by contrast, is more expensive due to special polymer additives, including a proprietary latex, used by our industry partner, Resource Cementing. Additionally, conventional wellbores require on average three interventions (years 10, 20, 30) during a 40-year lifetime. Each intervention costs ~\$1.19M (base case) plus production losses, resulting in a total lifetime cost of ~\$12.26M.

Laboratory performance predicts that ISOX4-cement could reduces the number of interventions to only one over 40 years, cutting total lifetime cost by ~\$9M (73.8%). Similar calculations for the other four self-healing cements (Figure A1) show that four out of five meet the criteria and are cheaper than conventional wellbore cement, with >40% lifetime cost savings. Only MBA-BDA-cement failed to meet the threshold. Thus, the requirements for Milestone 10 were successfully achieved.

Sensitivity analysis

We also conducted a sensitivity analysis of intervention cost, illustrated for ISOX4-cement in Figure A1a. Results show that lifetime cost of the self-healing cement is only weakly affected by variation in intervention difficulty (easy, standard, harsh downhole conditions). Notably, our intervention cost estimates are conservative. In practice, interventions are often more expensive, and in some cases costs are prohibitive enough to necessitate wellbore abandonment.

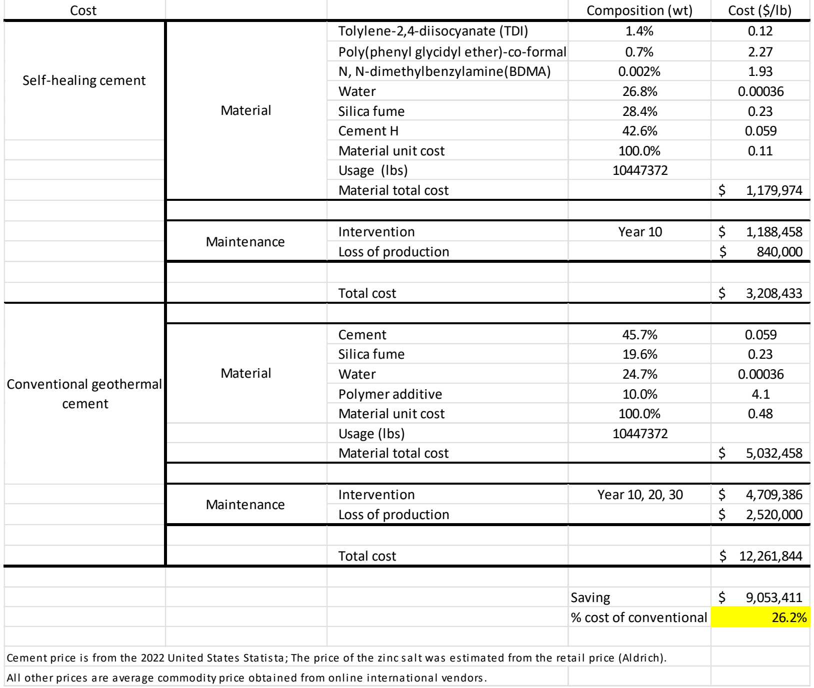
Summary

The cost/benefit analysis evaluates five self-healing polymer-modified cement formulations for geothermal and carbon storage wellbores. The analysis includes:

- Material cost estimates incorporating polymer dosage and pre-mixing overhead.
- Lifetime cost modeling that combines material cost with intervention frequency and production loss.
- Benchmark comparison against conventional geothermal cement in a 50 MW power plant.
- Evaluation against Milestone 10 criteria: cost per pound ≤ 1.3× conventional cement and ≥40% lifetime cost savings.
- Example calculations (ISOX4-cement) showing ~$9M (73.8%) lifetime savings over 40 years.
- Sensitivity analysis confirming that cost advantages persist across easy, standard, and harsh intervention conditions.

Results show that **four out of five self-healing cements meet the milestone requirements**, achieving substantial cost reductions relative to conventional cement (Figure A2). Only MBA-BDA-cement did not pass the threshold.

Table 2. Comparison of lifetime cost of ISOX4-modified self-healing cement and conventional geothermal cement for geothermal energy applications.



Cost			Composition (wt)	Cost ($/lb)
Self-healing cement	Material	Tolylene-2,4-diisocyanate (TDI)	1.4%	0.12
		Poly(phenyl glycidyl ether)-co-formal	0.7%	2.27
		N, N-dimethylbenzylamine(BDMA)	0.002%	1.93
		Water	26.8%	0.00036
		Silica fume	28.4%	0.23
		Cement H	42.6%	0.059
		Material unit cost	100.0%	0.11
		Usage (lbs)	10447372	
		Material total cost		$ 1,179,974
	Maintenance	Intervention	Year 10	$ 1,188,458
		Loss of production		$ 840,000
		Total cost		$ 3,208,433
Conventional geothermal cement				
	Material	Cement	45.7%	0.059
		Silica fume	19.6%	0.23
		Water	24.7%	0.00036
		Polymer additive	10.0%	4.1
		Material unit cost	100.0%	0.48
		Usage (lbs)	10447372	
		Material total cost		$ 5,032,458
	Maintenance	Intervention	Year 10, 20, 30	$ 4,709,386
		Loss of production		$ 2,520,000
		Total cost		$ 12,261,844
			Saving	$ 9,053,411
			% cost of conventional	26.2%

Cement price is from the 2022 United States Statista; The price of the zinc salt was estimated from the retail price (Aldrich).
All other prices are average commodity price obtained from online international vendors.

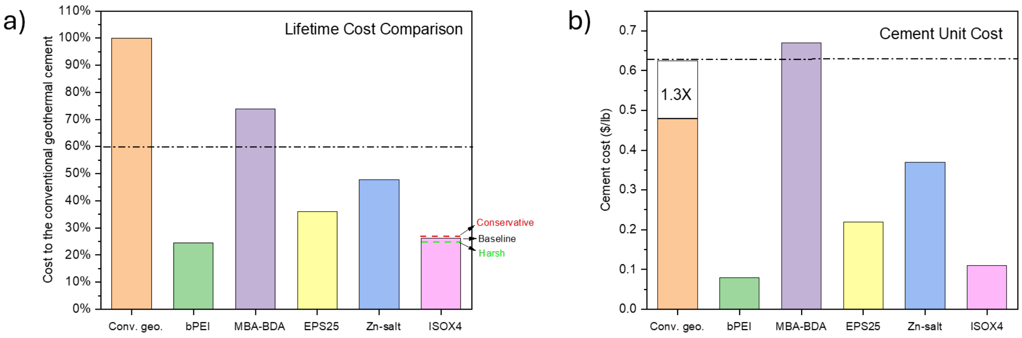


Figure A2. Lifetime cost and unit cost comparison of self-healing cement and conventional geothermal cement. a) Lifetime cost; b) Unit cost of cement.

Definitions

Scab Liner Description

- **Purpose**: Its primary function is to repair existing damaged casing, isolate leaks or unwanted perforations, or strengthen a weak section of the wellbore. It is often used as a more economical workover technique compared to replacing a full string of casing.
- **Installation method**: A scab liner is run and sealed inside a previously installed casing string. For many systems, it is sealed using packers at the top and bottom of the liner. It can also be cemented in place.
- **Isolation**: By sealing off a specific zone, the scab liner allows for continued production or injection in other areas of the well.
- **Reduced diameter**: Because it is installed inside existing casing, a scab liner reduces the internal diameter of the wellbore. While this reduction may not be a significant issue for some completions, it could affect the ability to use certain equipment or procedures further down the well.
- **Configuration**: Some versions, like the Scab Liner Packer (SLP), consist of a liner connected by upper and lower packer assemblies that can be set in place using a running tool.

Production or Drilling Liner Description

- **Liner** is a casing string that does not extend back to the wellhead but instead is hung from another casing string. Liners are used instead of full casing strings to reduce cost, improve hydraulic performance when drilling deeper, allow the use of larger tubing above the liner top, and not represent a tension limitation for a rig. Liners can be either an intermediate or a production string. Liners are typically cemented over their entire length.

- **Location:** The liner is set across the reservoir or productive interval, with its top terminating inside the bottom section of the final production casing.
- **Purpose:** Its primary function is to provide isolation across the production or injection zones and protect the wellbore's structural integrity.
- **Cost-efficiency:** By not extending to the surface, a production liner offers a significant cost-saving advantage over running a full casing string. Liners are often selected when the adjacent formation can not support a column of cement back to surface.
- **Design considerations:** The liner is an integral part of the well's completion. It must be robust enough to withstand reservoir stimulation and compatible with the produced or injected fluids it will be exposed to.
- **Cementing:** Liners are typically cemented in place for their entire length to provide zonal isolation. However, special versions like slotted or predrilled liners may use alternative sealing methods like swell packers.

Clam Shell Description

- **Purpose:** The clam shell repair is a localized remedial operation designed to seal small leaks, corrosion pits, or minor cracks in the well casing without requiring extensive milling or liner installation. It is used when damage is confined to a limited section and pressure integrity can be restored with an external clamp or patch.
- **Installation method:** The clam shell consists of two semi-circular steel shells (halves) that are mechanically clamped around the damaged section of casing. The interior is often lined or filled with sealing compounds (such as elastomers, epoxy, or metal-based sealants) to restore pressure containment. The system can be deployed using a workover rig or, for shallower depths, via wireline or coiled tubing-assisted tools.
- **Operation:** Once positioned, the clam shell halves are closed and torqued together using hydraulic or mechanical actuators, compressing the sealant against the casing wall to form a pressure-tight seal. The installation requires precise alignment and may include pressure testing to confirm sealing integrity.
- **Advantages:** This approach avoids pulling the casing or performing cemented liner runs, providing a rapid, lower-cost alternative when access and geometry permit. It is particularly suited for wells where continued production is needed and downtime must be minimized.
- **Limitations:** The repair is localized and not suitable for extensive corrosion or deformation. Temperature and chemical resistance of the sealing material are critical considerations in geothermal applications where thermal cycling and brine chemistry can degrade elastomers over time.

Milling Operation Description

- **Purpose:** Milling is performed to remove damaged, corroded, or obstructed casing sections, scale buildup, or cement plugs that prevent normal well operations. In geothermal wells, milling is also used to prepare the borehole for subsequent liner or patch installations after severe casing damage or collapse.
- **Method and Tools:** A milling assembly—typically comprising a heavy-duty drill string, stabilizers, and a rotating mill bit (flat-bottom, watermelon, or taper mill)—is deployed to mechanically grind through metal or cement. The process is conducted using a workover rig equipped with rotary drive or coiled-tubing units. Continuous circulation of high-temperature drilling fluid removes cuttings from the wellbore.
- **Applications:** Common scenarios include removing scale or debris in high-temperature zones, re-establishing full-bore access through collapsed sections, or cleaning cement from casing shoes before installing new liners.
- **Operational Considerations:** Milling requires careful torque and weight-on-bit control to prevent tool damage and minimize casing eccentricity. Real-time monitoring of torque and pressure ensures efficient removal and helps avoid stuck pipe or excessive vibration.
- **Post-Milling Procedures:** After the operation, caliper or video logging is often conducted to verify the borehole condition before running a liner or patch. In geothermal environments, additional cleaning and temperature stabilization are performed prior to cementing or lining operations.
- **Cost and Duration:** Due to high energy demand, specialized tools, and extended rig time, milling is among the most expensive intervention options, typically ranging from \$1.5–\$2.0 million depending on depth, casing thickness, and material hardness.

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