Final report

General information

The text in this report has been produced with assistance from a generative language model.

1. Project details

Project title	*Improving Geothermal System Performance Through Filter Technology Development – (PERFORM II)*
File no.	64022-5003
Name of the funding scheme	Joint Call 2021 - Accelerating the Heating and Cooling Transition
Project managing company / institution	Geological Survey of Denmark and Greenland (GEUS)
CVR number (central business register)	55145016
Project partners	GEUS
Submission date	05.12.2025

2. Summary

Project summary

The purpose of the project

Scaling and corrosion caused by trace metals in the geothermal brine can hinder the deployment of geothermal energy. PERFORM II aimed at developing an innovative filter technology to remove such metals, preventing scaling, corrosion, and reducing NORM waste volumes. The technology also has the potential to extract valuable metals if present.

Results, conclusions and perspective

The trans-European PERFORM II project advanced zeolite filter technology to TRL6 in specific cases. Synthetic zeolites (e.g., 4AK, 4ABFK) effectively removed problematic ions (e.g., lead, ~50% removal) from high-salinity, high-temperature brines at the Ammerlaan demonstration site. However, the technology's effectiveness was site-dependent, and not all zeolite types performed well under prevailing geothermal conditions. A main conclusion is that despite achieving TRL6 in certain contexts, the technology's application is highly site-

specific. Further development is essential to define precise boundary conditions for broad commercial implementation.

The Danish sub-project contributed to understanding copper/lead sorption mechanisms on zeolites, depending on zeolite type. This provided a foundation for generic filter design models. The overall trans-European project also developed guidelines and numerical models to optimize future filter designs.

Where effective, benefits include a reduced environmental footprint (less inhibitors), decreased downtime (scaling/corrosion prevention), and minimized NORM waste. Crucially, radioactive Pb-210 (and other Ra isotopes) was detected in filter material post-regeneration, creating an unexpected radioactive waste challenge. Addressing this complex NORM waste issue safely is paramount for future commercialization.

Projektresumé

Formålet med projektet

Udfældning og korrosion pga. af spormetaller i geotermisk formationsvand han hindre udnyttelse af geotermisk energi. PERFORM II tilstræbte at udvikle en innovativ filterteknologi til fjernelse af disse ioner for at reducere udfældning, korrosion og NORM affalds mængder. Teknologien har potentiale til at udvinde værdifulde metaller i formationsvand.

Resultater, konklusioner og perspektiv

PERFORM II-projektet hævede zeolitfilterteknologien fra TRL4 til TRL6 i visse tilfælde. Syntetiske zeolitter (f.eks. 4AK, 4ABFK) fjernede effektivt problematiske ioner (fx ca. 50% bly) fra saltholdigt, højtemperatur-formationsvand ved Ammerlaan. Effektiviteten var dog stedafhængig, og ikke alle zeolittyper fungerede optimalt under forskellige geotermiske forhold. Selvom TRL6 blev opnået i visse tilfælde, er projektets hovedkonklusion, at teknologiens anvendelse er meget stedsspecifik. Præcise tekniske begrænsninger skal defineres før bred kommercialisering forventes muligt.

Det danske delprojekt bidrog med grundlæggende forståelse af kobber/bly sorptionsmekanismer på zeolitter og udviklede generiske numeriske filterdesignmodeller. Det transeuropæiske projekt udviklede ligeledes retningslinjer og modeller til optimering af filterdesign.

Hvor teknologien er effektiv, kan den reducere miljøpåvirkning, nedetid og mængden af NORM-affald. Et opmærksomhedspunkt er fund af radioaktivt Pb-210 (og andre Ra-isotoper) i filtermaterialet efter regenerering – en uventet potentiel affaldsudfordring. Sikker løsning af dette NORM-problem er afgørende for eventuel fremtidig kommercialisering.

3. Project objectives

The overarching objective of the trans-European PERFORM II project was to support the green transition by addressing key technological and operational barriers in geothermal energy production. To obtain this, the project aimed at developing and demonstrating an innovative filter technology that could support cost-effective and climate-neutral operation of geothermal heat production facilities.

Specifically, the trans-European project aimed to:

- Mitigate the prevalent issues of scaling, corrosion, and NORM accumulation in geothermal plants, which lead to significant operational disruptions and high maintenance costs.
- Advance the existing zeolite filter technology, which was at TRL4 after the precursor PERFORM project, to TRL6. This involved refining the filter materials and processes to function effectively in the challenging environment of highly saline and hot geothermal brines.
- Validate the new filter technology through rigorous laboratory testing, pilot-scale mini-plant operations, and real-world field trials at active geothermal sites. This demonstration aimed to understand the filter's efficiency in removing problematic ions and its stability under different operational conditions.
- Support the competitiveness and growth of European companies in the geothermal sector by providing a reliable and cost-effective solution, thereby contributing to geothermal energy's role as a secure, sustainable, and affordable energy source.

The Danish sub-project funded by EUDP focused mainly on the initial steps of the filter technology development i.e., on understanding the fundamentals of trace metal sorption to zeolites with the purpose to include these insights in numerical models that may be used for future filter design purposes.

4. Project implementation

The trans-European PERFORM II project was structured into several Work Packages (WPs), each contributing to the overall goal of advancing the geothermal filter technology of the project. The implementation involved a systematic approach from defining requirements and criteria, through material characterization and mini-plant design, to pilot testing and field trials, and finally, project management and dissemination. The major focus of the Danish sub-project was to contribute to the basic understanding of sorption processes and support numerical modelling (WP2). However, for completeness the entire trans-European project is described below with the Danish sub-project mentioned where relevant.

The project's evolution was dynamic, adapting to scientific findings and technical challenges encountered. Initially, building on the precursor PERFORM project, the focus included natural zeolites. However, during the project (WP2), it became evident that natural zeolites (clinoptilolite) performed poorly in real geothermal brines due to their mineral complexity, heterogeneous composition, and low surface area. This necessitated a significant re-orientation of research efforts towards identifying and developing synthetic zeolites. This critical pivot on one hand ensured that the project pursued the most viable technological path for the demanding geothermal environment. However, the relatively late discovery of certain synthetic zeolites being superior to others also hindered a thorough investigation of sorption mechanisms related to the most promising zeolites. Thus, there is still need for further investigations if the results from the demonstration cases need to be understood fully.

Detailed Implementation by Work Package:

Work Package 1: Defining Filter Requirements and Criteria The goal of WP1 was to establish a comprehensive set of requirements for fit-for-purpose filtration systems in geothermal plants.

- **Task 1.1: Data Compilation:** This task involved gathering data through surveys of geothermal plant operators, literature reviews, and existing data repositories. Information included plant layout, brine and gas composition, and historical scaling and corrosion issues. Operators and filter suppliers were interviewed to understand operational challenges, NORM practices, and suggestions for filter operation.
- **Task 1.2: Criteria for Filter Requirements:** Based on the compiled data, criteria were classified according to brine composition, operating conditions, desired separation efficiency, and economic

considerations. Operational guidelines for temperature-corrected backwashing and NORM handling were developed. An initial recommendation favored durable, heat-resistant clinoptilolite zeolite materials, though subsequent experimental work in WP2 revealed its unsuitability. Two key deliverables, D1.1 (report on literature review and drinking water filtration experience) and D1.2 (report on criteria for filter requirements), were combined into a single final report. The Danish contribution was secured through inclusion of Danish operator Innargi in the operator interviews and through having GEUS commenting on the WP deliverable before finalizing it.

Work Package 2: Characterization and Demonstration of the Adsorption/Desorption Performance of Filter Materials under Conditions of Geothermal Application WP2 focused on understanding the sorption and desorption mechanisms of metals (specifically Cu (copper) and Pb (lead)) on zeolites using experimental and numerical methods, aiming to advance the TRL of the filter material.

- **Task 2.1: Binding Structures/Processes of Cu and Pb on Zeolites:** This task, which was performed by GEUS and constituted the major part of the Danish sub-project, investigated the molecular-scale interactions of Cu and Pb with two zeolites: natural clinoptilolite and synthetic faujasite. Employing aqueous measurements and synchrotron-based X-ray methods after reaction in both low- and high-salinity brines, the research revealed that synthetic faujasite was generally more effective for Cu and Pb uptake and exhibited faster sorption kinetics. However, natural clinoptilolite demonstrated superior Cu removal in the presence of high Ca concentrations and showed greater structural stability during regeneration with HCl. Regeneration was typically effective with 0.01 M HCl for faujasite and 0.1 M HCl for clinoptilolite, though higher acid concentrations could compromise the stability of synthetic faujasite. The study provided crucial molecular-scale insights for improving filter design and led the project in the direction of looking for other synthetic zeolites as best candidates for the filter material.

- **Task 2.2: Adsorption of Pb^{2+} and Cu^{2+} with Synthetic Zeolites in Near-Geothermal Brines:** This task was part of the German sub-project and specifically investigated zeolite sorption performance in real geothermal fluids obtained from deep wells in Heemskerk (Netherlands), Spandau (Germany), and Insheim (Germany). These brines are characterized by high salinity (100 to 270 g/l TDS) and complex chemical compositions. Initial tests confirmed that natural zeolites and chitosan were largely ineffective in these challenging environments. Consequently and in line with the findings of Task 2.1, the research shifted to synthetic zeolites. Types like 4AK and 4ABFK demonstrated high lead uptake (up to 50% after 6 hours) in Insheim-type near-geothermal brines and proved to be stable against mechanical stress, making them promising for large-scale geothermal applications. However, not all laboratory experiments showed evenly promising results, and therefore the results were also a first indication of zeolite filters working well only under certain conditions.

- **Task 2.3: Desorption Properties and Recyclability of Filter Materials:** This task focused on evaluating the sustainability and reusability of the filter materials through multi-cycle adsorption-desorption experiments. These tests were conducted using natural fluids from Insheim, Berlin-Spandau, and Heemskerk. The synthetic zeolite 4ABFK showed particular promise for Pb adsorption/desorption from Insheim-type fluids, with nearly complete regeneration achieved over at least 10 cycles using 2 M NaCl. Observations indicated that NaMSXK granules were mechanically unstable under agitation, disintegrating into powder, leading to the selection of 4AK for further experiments. The study also highlighted that proper oxygen exclusion is crucial to prevent precipitation of iron and manganese oxides.

- **Task 2.4: Numerical Simulation of Adsorption/Desorption Process:** This task with a joint effort between the Danish and the Dutch sub-projects aimed to develop numerical models for Pb and Cu sorption onto zeolites to aid in optimizing zeolite-based filter units. Ion-exchange models were fitted to experimental data, providing valuable insights into the cation exchange capacity, equilibrium constants, and temperature dependencies of the zeolites. Two different modeling softwares, PHREEQC (main effort from the Danish sub-project) and ORCHESTRA (Dutch sub-project), were used, yielding similar optimal model parameters. Key achievements included improved model descriptions for Pb

sorption on both natural clinoptilolite and synthetic faujasite, as well as a new model for Pb desorption using HCl solutions, incorporating a proton-exchange reaction. These modeling results are useful for guiding the future design of optimal filter systems.

Work Package 3: Mini-Plant Design, Construction and Commissioning in Laboratory Environments WP3 focused on designing, building, and testing a mini-plant for filter validation. The contribution from the Danish sub-project in this WP was mainly through participation in meetings and workshop and providing scientific input to designs based on findings in WP2.

- **Task 3.1: Simulation of Geothermal Fluids in Adsorber:** A one-dimensional numerical model was developed to simulate the adsorption of lead ions onto zeolites in a fixed-bed adsorber. This model was validated against data from the precursor PERFORM project and mini-plant experiments at Ammerlaan. It considered mass transport and fluid-solid interactions along the column axis, assuming uniform variable distribution within each control volume. The model helped in understanding the adsorption process under flow conditions.

- **Task 3.2: Design, Construction and Commissioning of a Mini-plant under Laboratory Conditions:** A corrosion-resistant mini-plant was designed to align with sorption experiment needs and the boundary conditions of geothermal sites. It incorporated features for measuring flow rate, temperature, pressure, pH, and redox potential. A heated internal circuit for backwashing and an electric flow-through heater for regeneration (up to 80°C) were integrated. A 3D CAD model facilitated proper assembly, and a risk assessment (PAAG/HAZOP equivalent) was conducted to ensure safety. The miniplant was successfully placed in a bypass at Ammerlaan.

- **Task 3.3: Technology Assessment and Design Guidelines:** This task utilized information from the entire project to elaborate design guidelines for industrial application. Field tests at the Amerlaan site showed satisfactory Pb adsorption from high-salinity brines using synthetic zeolites, emphasizing the crucial role of residence time (e.g., 1 minute, requiring a significant filterbed volume). Field tests at the Insheim site did not show similar promising results, again emphasizing that the zeolite filters have very different efficiency depending on local physico-chemical conditions at specific geothermal sites. Further experiments indicated that fixed-bed reactors are preferable to stirred vessels to minimize mechanical stress on the zeolite. For continuous operation, a system with at least two vessels operating in parallel (one for adsorption, one for regeneration/maintenance) was recommended to avoid downtime.

Work Package 4: Pilot Testing and Field Trials WP4 scaled up sorption and desorption tests to conditions closer to final applications, involving fixed-bed cation-exchange filters. The contribution from the Danish sub-project in this WP was mainly through participation in meetings and workshop and providing scientific input to designs based on findings in WP2.

- **Task 4.1: Piloting of the Filter Materials:** Experiments were conducted using a High Temperature and Salinity (HTS) flow loop at TNO (Dutch partner), which was modified to test filter materials in a fixed-bed configuration. Artificial brines containing $PbCl_2$ and NaCl were used, heated to 70°C. Initially, clinoptilolite was tested, but based on WP2 findings, synthetic zeolites (4AK, NaMSXK) were subsequently evaluated due to clinoptilolite's limited suitability for real geothermal brines. Baseline tests with synthetic zeolites showed a high Pb(II) uptake of 50-70% at low background salinity and medium residence times. The importance of residence time, grain size, and background salinity was assessed, and showed – as expected from WP2 results – much less sorption at higher salinities.

- **Task 4.2: Demonstration on the Sites:** Field tests were carried out at two geothermal sites: Ammerlaan Geothermie B.V. (Netherlands) and V-NI - Vulcan in Insheim (Germany). At Ammerlaan, the miniplant, connected at the fine filter downstream of a gas separator, demonstrated an average lead decrease of over 50% using synthetic 4AK zeolite similar to what is already mentioned for WP3. Regeneration showed limited Pb recovery, likely due to incomplete saturation. At VNI, the test aimed for breakthrough behavior, but complications such as fluid cooling, degassing, pH decrease, and carbonate scaling interfered with results, making Pb and Cu uptake interpretations complex.

- **Task 4.3: Analysis and Recommended Practice for Filter Implementation:** This task involved analyzing samples from the field tests (where zeolite 4AK was used) using ICP-OES for elemental composition and gamma spectroscopy for naturally occurring radionuclides. Key results include:
    - **Efficient Ion Uptake:** The synthetic 4AK zeolite efficiently took up various elements such as Ba, Fe, Pb , and Sr. Ion-exchange was confirmed by the opposing trends of Na and Ca concentrations in filter samples.
    - **Radioactive Waste Generation:** A critical finding from the second field test was the detection of radioactive Pb-210 in concentrations exceeding 1 Bq/g after regeneration with 0.01 M HCl. Low levels of Ra-224, Ra-226, and Ra-228 were also detected in site-specific ratios. Although the presence of radioactive elements in the filter likely reflect that regeneration did not work as intended, it shows that the technology generates radioactive waste – if radioactive components are present in the original brine - that requires specific management.
    - **Geochemical Modelling Validation:** Kinetic models, fitted to experimental data from lab and field tests, showed that significantly higher kinetic rates were required for field conditions compared to lab tests, consistent with the higher specific surface area of synthetic 4AK.
    - **Guidelines and Future Research:** The task concluded with an overview of lessons learned and provided guidelines and recommendations for filter implementation in practice, emphasizing the need to address remaining research questions to increase TRL and provide specific best practices if the technology should develop to commercially viable technology.

Work Package 5: LCA Work Package 5, focusing on Life Cycle Assessment, was not awarded and therefore scoped out from the project.

Work Package 6: Project Management and Coordination WP6 ensured the smooth implementation and execution of the project, with TNO as the responsible partner. This work package was crucial for maintaining cohesion and progress across the diverse international consortium.

- **Task 6.1: Legal Matters:** This task encompassed the finalization and signing of the Consortium Agreement by all partners, as well as an annex to include new partners (Vulcan Energy Resources and SCK-CEN). It also involved processing change requests and requests for project extensions (e.g., a 3-month extension, shifting the end date to November 30, 2025). Specifically for the Danish sub-project, there has been four change requests:
    - **Change request #1:** Due to strategic reasons, Danish commercial partner Ramboll unfortunately had to withdraw from the project in 2023. This change request adjusted the project plan for the Danish sub-project to fit this decision without loosing value of the project.
    - **Change request #2:** Minor allocations of budget from scientific staff to technical staff at GEUS.
    - **Change request #3:** Allocation of budget from travel costs to salary at GEUS.
    - **Change request #4:** Extension of project duration for a period of 3 months.
- **Task 6.2: Financial Accounting:** This task involved fulfilling financial reporting requirements set by the Geothermica Call Secretariat and national funding agencies. This included submitting 6-monthly "traffic light reports" and annual reports to various national bodies (e.g., RVO in the Netherlands, PTJ in Germany, EUDP in Denmark). All financial progress followed planned activities.
- **Task 6.3: Administrative Issues:** Continuous administrative support was provided to project partners throughout the project. This included managing changes in the timeline, facilitating communication among partners and funding agencies, and overseeing the creation and maintenance of the project website (planned to be functional by the end of 2024).

- **Task 6.4: General Assembly, Project Management and other related meetings:** Regular meetings were a cornerstone of the project's coordination. Monthly Online Project Management Team (PMT) meetings, attended by WP leaders and national coordinators, ensured continuous alignment. General Assembly (GA) meetings were held periodically (e.g., 14th November 2022, 21st June 2023, 23rd-24th May 2024, 30th-31st January 2025, 25th-26th September 2025), often in hybrid formats or combined with site visits, ensuring close collaboration and technical discussions. Extraordinary meetings were convened when needed, and specific work package meetings were also conducted remotely.

Risks associated with conducting the project: Risks included the potential for filter materials (like natural zeolites) to perform inadequately in complex geothermal brines, challenges in scaling up laboratory findings to pilot and field conditions, managing the extreme conditions of high temperature and salinity, and the effective handling of NORM. All of these challenge the commercial viability and regulatory acceptance of the technology. During the project some of these risks were handled e.g., by introducing specific synthetic zeolites that seemed promising for certain field applications. However, the sum of risks and challenges encountered during the project also means that the development of a universally applicable filter technology fit-for-purpose in all types of geothermal plants is not the result of the project. We have rather gained insights that forms the knowledge basis for future development of filter-based technologies under specific conditions. The project results also pave the ground for future development of more promising technologies such as electrochemical separation for cases where zeolite filters may work inadequately.

Did the project implementation develop as foreseen and according to milestones agreed upon? The project implementation did not entirely develop as foreseen. A significant deviation was the unexpected poor performance of natural zeolites (clinoptilolite) in real geothermal brines. This led to a substantial research effort to identify and develop synthetic zeolite materials, requiring an adaptation of the original work plan and a shift in focus for material selection. Despite this, milestones and deliverables were fulfilled as originally planned. The overall result, however, was not as simple as originally suggested and described above.

Since the Danish sub-project was mainly contributing to the initial findings and understanding of differences between natural and synthetic zeolites, the Danish sub-project can as an isolated effort be considered to have fulfilled its purpose.

The milestones and deliverables of the Danish sub-project are listed below:

Milestone	Description	Month delivered
M1	*Specification for filters operationalized*	*M13*
M2	*Basic understanding of mechanisms for sorption on zeolite filters and numerical models established*	*M31*
M3	*Filters demonstrated*	*M39*

Deliverable	Description	Month delivered
D1.1/1.2	*WP 1. Defining filter requirements and criteria* *Deliverable number 1.1 and 1.2* *Report on literature review, experience of drinking water filtration* *and criteria for filter requirement*	*M13*
D2.1	*Report on binding structures/processes of Pb and Cu on zeolite/chitosan* *WP2: Characterization and Demonstration of the Adsorption/Desorption Performance of Filter Materials under Conditions of Geothermal Application*	*M31*
D2.4	*Report on Numerical Models for Understanding and Optimization of the Filter* *WP2: Characterization and Demonstration of the Sorption/Desorption Performance of Filter Materials under Conditions of Geothermal Application*	*M39*
Scientific papers, etc.	*Scientific paper submitted to: "Environmental Science: Water Research & Technology" – title: "Molecular-scale investigation of Cu(II) interactions with synthetic and natural zeolites during removal and recovery"* *Paper in proceedings at European Geothermal Congress 2025 – October 2025*	*M42* *M38*
Other	*Update of PERFORM website: https://www.geothermperform.eu/*	

Did the project experience problems not expected? Yes, two major unexpected problems were encountered:

1. **Ineffectiveness of Natural Zeolites:** Natural zeolites, initially considered promising in the precursor PERFORM project, proved largely ineffective for chemically complex geothermal brines due to their inherent properties. This necessitated a significant and time-consuming pivot to synthetic zeolites, which required substantial redirection of research efforts.
2. **Radioactive Waste Generation:** A critical and unexpected problem was the finding that radioactive Pb-210 (and other Ra isotopes) can be present in the filter material even after inadequate regeneration. This means the technology, while effectively removing NORM components from the brine, also concentrates radioactive material, leading to the generation of radioactive waste that requires specific management and disposal strategies. This issue poses a new regulatory and environmental challenge that was not fully anticipated in the initial project scope and demands further dedicated research for safe handling and disposal.

Thus overall, the project did not bring the filter technology as far in development as originally assumed. However, important results were obtained in relation to understanding the limitations of the technology and the need to look for alternative solutions in many cases.

5. Project results

The PERFORM II project partly obtained its original objective of developing and demonstrating an innovative filter technology for geothermal systems. As already mentioned, the technology is after project termination at a stage where promising ways forward for implementation can possibly be seen for certain specific geothermal plants while for other types of plants, the technology as it is currently does not seem to have a viable future. However, the boundary conditions at which the technology works and does not work cannot be fully understood from the project results, and further research and development is needed if this is a desire.

Obstacles and Changes: The primary obstacle encountered was the poor performance of natural zeolites in real geothermal brines. This indeed deviated significantly from initial expectations. To mitigate this, a substantial research effort was redirected towards identifying and developing synthetic zeolite materials capable of withstanding the high-salinity, chemical complexity, and high-temperature conditions of geothermal fluids. This required a critical adjustment to the project plan and resource allocation, including detailed studies on material properties and performance. Although this effort was substantial, no universal solution was found and the synthetic zeolites eventually chosen in the project – although much more efficient and useful than the natural zeolites - performed well only under certain circumstances.

Obtained Technological Results:

- **TRL Advancement:** The project advanced the Technology Readiness Level (TRL) of zeolite filter technology from TRL4 to TRL6 for certain specific conditions as for example those prevailing at the Amerlaan site, signifying a possible step towards commercial deployment and practical application.
- **Material Identification:** Specific synthetic zeolite types, particularly 4AK and 4ABFK, were identified and validated as highly efficient for the selective uptake of lead, copper, and other cations in high-salinity and high-temperature brines under certain circumstances. These materials demonstrated superior performance and stability compared to natural zeolites. However, their performance and associated boundary conditions are not fully understood yet.
- **Mini-Plant Demonstration:** A fully functional zeolite-filter miniplant was designed, constructed, and successfully demonstrated at a real geothermal operating site (Ammerlaan Geothermie B.V.). This critical step validated the technology's performance under actual field conditions, including realistic brine temperatures and salinities for this specific site. At another site in Insheim, the filter performance was not promising with regard to possible future implementation.
- **Modelling and Design Tools:** Kinetic and geochemical models were developed to predict filter performance, optimize filter design parameters, and understand ion-exchange mechanisms. Comprehensive design guidelines for industrial application were also produced, covering aspects like material selection, flow conditions, and regeneration protocols. If better understanding of the boundary conditions for synthetic zeolite performance is obtained in the future, these will be applicable to facilitate filter design.
- **Unexpected NORM Concentration:** An unexpected, yet significant, finding was the detection of radioactive Pb-210 (and other Ra isotopes like Ra-224, Ra-226, Ra-228) in the filter material, after inadequate regeneration. This indicates that the technology, while capable of removing NORM components from the brine, concentrates these radioactive materials, thereby creating a radioactive waste stream that requires specific handling and disposal strategies. This was an unforeseen challenge with significant implications for future implementation and regulatory compliance.

Obtained Commercial Results: The project did not directly produce commercial sales but laid a foundation for future commercialization if better understanding of filter efficiencies at specific physico-chemical conditions is obtained. The validation of the filter technology in the real geothermal environment at Amerlaan, coupled with comprehensive design guidelines and predictive models, to some extend de-risks the technology which is needed if a future market entry is still envisaged. However, in the Danish sub-project we assess that some

fundamental understanding of “when and where” the technology works satisfactorily is still lacking for a commercial market to take up the technology.

Target Group and Added Value: The primary target group for this technology includes:

- **Geothermal Operators:** Value proposition: Possible reduced operational costs due to less downtime, improved plant reliability, and enhanced environmental compliance through effective prevention of scaling and corrosion, and proactive NORM management. However, this cannot be offered completely from the project results that rather suggests that specific investigations to support this value proposition should be carried out at each specific geothermal site before it can be concluded whether it is worthwhile implementing the technology. This is a major obstacle for possible commercialization of the technology and uptake in the market.
- **Energy Companies:** Value proposition: Enables more secure, sustainable, and economically competitive geothermal energy production, supporting broader energy transition goals and reducing reliance on fossil fuels. Same challenges as for the geothermal operators.
- **Filter Technology Providers:** Value proposition: Access to validated technology, optimized materials, and comprehensive design guidelines for new product development, expanding their market offerings into the specialized geothermal sector.

Dissemination Activities: The tran-European project results have been widely disseminated to a diverse audience, including scientific communities, industry stakeholders, and the public, through various channels:

- **Conferences:** Active participation and presentations at major national and international geothermal and energy technology conferences, such as Deutscher Geothermiekongress 2024, European Geothermal Congress 2025, Goldschmidt Prague 2025, FVEE-Jahrestagung 2025, European Geothermal conference Zurich, and the 7th European Congress of the International Radiation Protection Association.
- **Journal Publications:** Publishing of one peer-reviewed article detailing specific research findings and methodologies: "Effect of acetate and chloride on Pb sorption onto clinoptilolite at geothermal conditions" in Applied Geochemistry 192 (2025) 106533 as well as one article submitted to Environmental Science: *Water Research & Technology* (see above).
- **Workshops and Knowledge Sharing Events:** Active participation and presentations at knowledge sharing workshops and specialized sessions organized by Geothermica and CET Partners (e.g., Knowledge Sharing Workshop Bern 2024, TNO knowledge sessions on Heat Transfer and Fluid Dynamics, 14th International Symposium on Supercritical Fluids).
- **Project Website:** The dedicated project website (www.geothermperform.eu/) serves as a central repository for project information, results, publications, and news, ensuring broad public accessibility and transparency.
- **Reports:** Regular and comprehensive reporting to national funding agencies (e.g., EUDP, PTJ) and the Joint Call Secretariat, ensuring accountability and communication of progress and findings to funding bodies.

6. Utilization of project results

The obtained technological results demonstrate that zeolite filter technology holds promise for geothermal systems but also highlight significant complexities and limitations that must be addressed before widespread commercial utilization is possible.

Utilization of Technological Results in the Future: The project results provide a valuable knowledge base for further research and development rather than immediate, broad commercial deployment.

- **Industrial Partners & Geothermal Operators:** Will likely use these findings to identify specific niches or sites where the technology *could* be viable, but this will require further site-specific investigation and adaptation. The generic models developed will aid in initial assessments, but direct application without further tailored R&D is currently challenging.
- **Research Institutions:** The project's most immediate and certain utilization will be within academic and research environments, guiding future studies to precisely define the boundary conditions under which specific zeolite types function effectively. This includes developing more robust models that account for the observed site-specificity and material limitations.

Commercial Utilization: The project did not directly yield commercial sales, and current results suggest that broad commercialization is not yet feasible without further development.

While the technology holds long-term potential to reduce operational costs and environmental impact, these benefits are currently highly conditional. Significant investments are still required to overcome the identified limitations before widespread commercial turnover can be expected.

The market entry strategy must acknowledge the technology's site-specific nature. It cannot be presented as a universal solution, but rather as a highly specialized tool that demands careful prior assessment for each geothermal site.

Competitive Situation: The zeolite filter technology offers a unique approach to managing scaling, corrosion, and NORM compared to traditional chemical inhibitors. Its potential to reduce environmental footprint is a strong differentiator.

However, its site-specificity and the unresolved NORM waste issue significantly complicate its competitive position. Traditional solutions, despite their drawbacks, offer a more predictable and broadly applicable approach in the short to medium term.

Entry or Sales Barriers: The most substantial barrier is the high dependence on site-specific conditions. This necessitates extensive, costly preliminary studies for each potential application, hindering rapid adoption.

The detection of radioactive Pb-210 in used filter material potentially creates an unexpected and complex regulatory and environmental barrier. Without a clear, safe, and cost-effective management strategy for this radioactive waste, commercialization remains severely constrained.

The project's findings indicate that a universally applicable filter technology for all geothermal conditions has not yet been achieved, limiting its broad market appeal.

Overcoming these barriers will require sustained, targeted R&D to:

- Precisely define the operational windows and boundary conditions for effective zeolite performance.
- Develop robust solutions for the safe handling and disposal of NORM-containing filter waste.
- Conduct further long-term field trials under diverse conditions to build a more comprehensive and reliable dataset on performance across varying geothermal settings.

7. Project conclusion and perspective

The trans-European PERFORM II project has advanced zeolite filter technology from TRL4 to TRL6 in specific cases. **Specific conclusions are**:

- Synthetic zeolites (e.g., 4AK, 4ABFK) demonstrated the ability to effectively remove problematic ions (e.g., lead, ~50% removal) from high-salinity, high-temperature formation water during the demonstration at Ammerlaan.
- Crucially, however, the technology's effectiveness is highly dependent on the specific conditions of a given geothermal plant. Not all zeolite types performed well under prevailing geothermal conditions.
- Despite achieving TRL6 status in certain contexts, a main conclusion is that the technology's application remains highly site-specific.
- The Danish sub-project contributed to a fundamental understanding of copper/lead sorption mechanisms on zeolites, which depend on zeolite type, thus providing a basis for generic numerical design models.
- An unexpected and critical finding was the detection of radioactive Pb-210 (and other Ra isotopes) in the filter material after inadequate regeneration. This constitutes a significant and unresolved challenge regarding radioactive waste.

Overall, the project has provided valuable knowledge about the *limitations* and *specific conditions* for the successful application of the filter technology, rather than delivering a broadly applicable and fully commercializable solution.

Next steps for the developed technology: If in the future, the technology should be developed towards broader commercial implementation, the following steps are crucial:

- **Precise Definition of Boundary Conditions:** There is an urgent need for further research and development to establish precise technical and geochemical boundary conditions for when and where the technology operates optimally. This will involve extensive mapping of geothermal brine chemistry and physical conditions.
- **Resolution of the NORM Waste Challenge:** A dedicated and safe solution for the handling, treatment, and disposal of the radioactive waste generated in the filter material must be developed. Without a clear and approved strategy for this, commercial implementation will be severely constrained by regulatory and environmental reasons.
- **Optimization and Validation of Zeolite Materials:** Continued research to optimize the selectivity, regeneration efficiency, and robustness of zeolite materials under various geothermal conditions, to expand the application range and reduce site dependency. This would include understanding fundamental differences between various synthetic zeolites.
- **Long-term Field Validation:** Execution of longer-duration and more varied field trials to obtain comprehensive data on the technology's performance and durability under diverse, representative geothermal conditions.

Perspective on future development: The PERFORM II project has yielded valuable insights that will shape future geothermal development, but it has also revealed the significant complexity that still needs to be addressed.

- **Highlighting Key Research Avenues:** The project has underscored the need for a strong, forward-looking research focus to understand and overcome the specific technical and environmental barriers identified.

- **Limited Immediate Impact:** The project's results contribute more to an increased understanding than to an immediate, broad acceleration of the green transition via this filter technology. The potential exists, but it depends on the successful resolution of the outstanding challenges and whether alternative technologies such as electrochemically based technologies are better suited for selectively taking problematic cations out of geothermal brines.
- **Strengthening Specific Applications:** The technology may find future application in specific locations where optimal conditions are present, but it will most likely not be a "one-size-fits-all" solution for the geothermal industry in the near future.

In summary, the PERFORM II project has provided a realistic evaluation of the zeolite filter technology's potential and limitations for geothermal applications. It has paved the way for future, more targeted research and development, but it also underscores that significant work remains before the technology can be widely commercialized and fully contribute to the green transition. This also opens for looking for other more optimal solutions for the “trace metal challenge” in some geothermal brines.

8. Appendices

Project deliverables are shared on the project website:

www.geothermperform.eu