NATIONAL ACADEMIES Sciences Engineering Medicine

2017: Safer Offshore Energy Systems 3 Final Report

GULF RESEARCH PROGRAM

Project Title: Mitigating Risks to Hydrocarbon Release throughIntegr ative Advanced Materials for Wellbore Plugging and Remediation
Award Amount: $2,614,143
Awardee: Oklahoma State University (previously Louisiana State University)
Award Start Date: December 1, 2017
Award End Date: November 30, 2021
NAS Grant ID: 2000009939

Project Director: Mileva Radonjic
Affiliation: Oklahoma State University

Project Key Personnel:

- Raissa Ferron, UT Austin
- Andrew Bunger, University of Pittsburgh
- Ipsita Gupta, Louisiana State University
- Malin Toarsater, SINTEF, Norway

I. PROJECT SUMMARY (from proposal)

Construction of wellbores is always disrupting geological subsurface equilibrium, especially in challenging offshore environments. According to the Society of Petroleum Engineers (SPE) webinar release in 2013, every third existing wellbore is leaking. The leakage pathways are often impossible to locate and even more difficult to remediate.

The mission of this project is to contribute towards effective and permanent plugging and abandonment (P&A) of leaky wellbores in the Gulf of Mexico (GoM). The main objectives are a) design and testing of novel barrier materials, b) improved placement of those barriers through application of 3D printing and c) optimization for long term durability under evolving subsurface conditions.

The main challenges of the current offshore P&A technology are:

1. P&A of subsea wells requires rigs, resulting in slow and expensive casing strings removal, prior to barrier plugs placement.
2. Wellbore cements that cannot be placed effectively, resulting in weak interfaces and compromised zonal isolation.
3. New regulatory requirements for “eternal” permanent barriers, accounting for potential P recharge, geomechanical and geochemical changes over 10,000s years.
4. Inability to perform logging through multiple casing strings, not knowing the state of the wellbore materials prior P&A, which is essential for optimal/safe operations.

At the SINTEF P&A Research Conference in March 2017, the reports on ongoing R&D in industry showed the following topics: a) Investigating use amplified in situ corrosion for casing removal, b) Biodegradation of cement/casing through downhole-placed termites, c) Shale cap-rock as P&A barrier (creep over time).

This project will test new materials and/or improve existing barriers, investigate the possibility of novel placement methods, and obtain quantitative scientific data on long term sealing capability of the respective barriers. This would be achieved through research activities that embrace collaborative interdisciplinary expertise of each team member (Materials Science/Manufacturing, Hydrogeology/Geochemistry, Wellbore Engineering/ Reservoir Simulation and Rock Mechanics). In addition, all team members (collectively and individually) will seek feedback from the stakeholders (industry and regulators).

The data from all tasks will be integrated to fit the main objectives of the project: Advanced performance economical barrier materials (Task 1), Improved placement of P&A barriers (Tasks 2,3), and Robustness & Long-term performance of HC-barriers (Tasks 4, 5,6,7). Finally, outcomes from Tasks 9 & 10 will provide critical data towards technological advancement, societal impact in terms of public awareness, and educational effort on offshore P&A in the GoM and elsewhere.

The Oil and Gas industry is endowed with cutting edge technology which is being employed by drilling and completion activities in the GoM; the goal is to have GoM P&A be equally

II. PROJECT SUMMARY (from final report)

The NASEM GRP-funded research "Mitigating Risks to Hydrocarbon Release through Integrative Advanced Materials for Wellbore Plugging and Remediation" (Grant Number:10002358) aimed to address the fundamental problem of leaky wellbores in the offshore Gulf of Mexico (GoM). Our project team proposed to design/make novel materials for the long-term integrity of the wellbore plugs that are compatible with geological formations over hundreds of years and our modeling efforts focused on predicting the durability of these novel barrier materials over thousands of years.

The purpose of permanent plugging and abandonment of wellbores is to reinstate geological seals in the subsurface that existed before the drilling process. Nature's seals were formed over a geologic time scale, while the engineered barrier materials need to be ready to seal much faster in order to stop the migration of sub-surface fluids to the surface and prevent potential contamination of air, water, and soil. In order to achieve these objectives, wellbore materials need to be placed across the entire cross-section of a wellbore and maintain zero permeability and mechanical integrity ideally indefinitely. This project focused primarily on improving the durability and functionality of the wellbore barrier materials, by first investigating the weaknesses of the currently used Portland cement plugs. The conclusion was that we needed to redesign slurries to be geochemically compatible with subsurface formation fluids and rocks, reduce brittleness, enable self-healing upon fracturing, mitigate low pH fluids such as CO_2-rich brines, by implementing various fillers and additives that would provide such outcomes. Furthermore, all of our designed materials needed to fit the purpose, by having adequate rheologic properties that would enable the placement, and favorable testing results at subsurface temperatures, pressures, and fluid-flow rates reported from the Gulf of Mexico field operations.

III. PROJECT RESULTS

<u>Accomplishments</u>

i) Develop, test, or apply new approaches, technologies, or methodologies.
ii) Facilitate syntheses and cross-disciplinary integration of data and information.
iii) Generate novel insights and accelerate the translation of new understanding into action.

iv) Generate knowledge that is transferable between the Gulf of Mexico and other offshore energy producing regions.
v) Foster science that serves the needs of the Gulf region's numerous and diverse communities.
vi) Develop new professional relationships.
vii) Form collaborations with experts in other disciplines.

Implications

The research performed by SINTEF as our only industry partner with an extensive and impressive record on technology and R&I projects in the field of energy and offshore engineering opens for further testing of the promising new sealant formulations proposed by the US project partners; these materials are tailor-made for the GoM conditions. Testing in concentric reduced-scale geometry under CT imaging could show-case performance improvement compared to neat Portland and flexible cement, particularly in terms of fracture sealing ability. Thus further funding would be welcome to continue collaborative research with the same project partners. In addition, exploration of combined engineered sealants and innovative placement in the subsurface would be a natural improvement to the composite cement plug concept.

At the UTA, with multiple expertise in cement and concrete research there was a potential to transfer some of that know-how to design novel wellbore barrier materials. Recent research on ternary blended limestone calcined clay cements (LC3) have yielded good performance when compared to ordinary Portland cements for surface level construction. To our knowledge no significant work has been done with oil well cements incorporating the blended LC3. Hence experiments were conducted on hardened specimens to determine how limestone and clay impact oil well cement performance at elevated temperature. The purpose of this research was to develop wellbore barrier materials with improved zonal isolation utilizing both limestone and calcined clay. Tests were conducted on hardened specimens to understand how limestone and clay influence oil well cement performance at subsurface temperature.

The results provided us with an insight on the impact of limestone and clay when mixed with oil well cements at high temperature. The ternary LC3 binder systems showed promising performances in terms of strength, resistivity, and carbonation resistance, which are crucial for durability aspects of wellbore applications. The LC3 addition series performed better than the LC3 replacement series from a zonal isolation perspective, however considering that the LC3 replacement series also had good zonal performance, from an economical, engineering, and environmental perspective the LC3 replacement approach is recommended due to it minimizing carbon footprint and reduced material cost. Compared to traditional barrier cement systems, the LC3 systems is expected to have an extra edge at the subsurface depths owing to the synergistic hydration dynamics of the inherent system. Calcined clay has been observed to possess pozzolanic properties, such that it reacts with the hydroxide to form more calcium -silicate hydrate and calcium-alumina-silicate hydrates which contributes to increased strength and durability. The presence of silica and alumina in the clay is denoted to its reactivity with calcium hydroxide. The alumina present in the clay is also expected to react to with the limestone to form more C-C-A. Hence instead a higher dosage of limestone can be used in cohort with clay for our target binder system. The extra alumina provided by the metakaolin will react with additional limestone, allowing good properties such as strength and permeability, to be maintained at higher levels of substitution.

The effectiveness of our team and the freedom to pursue each groups strengths allowed us to further expand our search for the best materials by looking at nature. The Pitt team focused on investigating what is geological response to CO_2 mitigation, also known as carbonation of olivine. The discovery and proof of concept demonstration of GAC and OBC provides two new pathways for development of resilient, self-sealing wellbore sealing and plugging systems. These have different time frames for development.

The OBC can be utilized as an operationally minor modification of current practice, and therefore can be deployed for impact in the immediate future. On the other hand, the GAC will require different operations for conveyance of the materials to the plugging zone, as well has further study to ensure short term competence of the material. It therefore will have impact on a 5-10 year horizon. However, the benefit of pursuing GAC could be significant because it will open the door to using waste products such as ultramafic mine tailings with little additional processing. Such a pursuit could lead to plugging systems that are not only self-sealing, but also substantially less expensive than the state of the art. Because plugging and abandoning wells is an industry and society liability, economically efficient solutions are critical. Additionally, generation of Portland cement is energy intensive and therefore a significant source of carbon emissions, whereas carbonation of ultramafic miners comprises a carbon sink, and therefore a cement-free system will contribute to the pursuit of carbon neutral and/or carbon negative technologies for the future.

At geomimicry and barrier materials lab at OSU, once we identified what were the main shortcomings of the currently used plugging materials, we decided to evaluate the strongest engineered material known today, graphene, and the natural zeolite that is often found in hydrothermally altered rocks. The graphene nanoplatelets (GNP) have advantage that can be used in less than 1% by weight of cement replacement, while having impactful effect on reducing cement brittleness and potentially enabling monitoring via self-sensing. In addition, GNP reinforces weakest parts of cement- pores, and with its hydrophobicity would potentially slow ingress of aqueous geofluids that often chemically degrade cements. On the other hand, zeolites provide delayed pozzolanic reactions, somewhat like a "slow-release medications", and if these reactions occur later in life of cement, they would potentially prolong the life or perhaps add to the self-healing, as it was observed in geothermal cements, previously tested for geothermal wellbore applications at BNL. The major implication of this approach is that we do not have to settle for just inorganic additives, we have shown that organic materials like graphene, can add ductility to cement the way kerogen does it in the best-known barriers in subsurface- shale rocks. This approach indicates that boutique barrier materials designed for purpose are the future, where we can add components based on functionality: olivine can be added to mitigate CO_2, zeolite can be used to provide delayed strength and self-healing, while graphene would provide elasticity, self-sensing and potentially what we all want to know, ability for long-term monitoring because of its superior electrical and thermal conductivity. The list of ingredients does not end here, adding materials tested at UTA and Pitt, and creating a nano-composite where Portland cement would go from currently being the main binder, to being just one of the additives, would be transformational, in various aspects: improved performance, durability, CO_2 reduction, and geo-compatibility and sustainability. The best part is that such materials could cross over into other applications, on Earth, or elsewhere.

And finally, all these new materials needed to be evaluated in the context of long-term performance in subsurface conditions. There is no better way to do this currently than to use approach from the reservoir engineering and porous media behavior in these reservoirs and to think of engineered barrier materials as "very tight rocks". This is exactly what the LSU team did, and successfully combined geochemistry and geomechanics modeling in order to predict long term performance of some of these barrier materials we proposed and compare them with currently used cements. The results derived here

are important for understanding the impact of fluids and rocks present in the subsurface on the long-term integrity of sealing materials. By providing this, new materials can be developed in the laboratory which would assist in mitigating hydrocarbon release in the subsurface. The results are important to science and society because new materials developed would provide better sealing materials which ultimately would prevent hydrocarbon release to the ocean/groundwater which could harm marine life in offshore environments or affect the quality of drinking water available to mankind in onshore settings. The results from our component of the project would be interesting to wellbore integrity and to the reactive transport community. It would be interesting to wellbore integrity modelers because work in this area is limited especially those involving long term simulations. Therefore, modelers will be interested in the application of the outcome. In the same vein, reactive transport modelers will also be interested because it provides new applications of reactive transport which hitherto had not been explored. The plug and abandonment research community will also be interested. A cross-section of energy and environmental scientists will also be interested in this research. Prior to the start of the project, we expected that current barrier materials would be able to sustain integrity over a considerable length of time (1000s of years).
However, our results (Ajayi and Gupta, 2021) indicate that while this may be plausible, the simulation case studies conducted generated geochemical integrity losses in 100s of years. Combined with geomechanical effects, this can only be less thus indicating the need for developing newer barrier materials that can last longer, particularly after plugging and abandonment.

Education and Training

Number of students, postdoctoral scholars, or educational components involved in the project:

- K-12 students: 0
- Undergraduate students: 9
- Graduate students: 9
- Postdoctoral scholars: 4
- Citizen Scientists: 0
- Other Trainees: 0

IV. DATA AND INFORMATION PRODUCTS

This project produced data and information products of the following types:

- Data
- Information Products

DATA

Data Management Report:

Each partner will keep data available within their institution as we agreed in our DM plan. In addition, we also have some data stored at the DOE NETL, which can be accessed by the public.

Relationships Between Data Sets:

Each partner will have the data (lab or modeling) stored in their institutional storage and the links for those will be provided in the EXCEL worksheet or submitted directly to NASEM GRP.
Some of the data collected for OSU and Pitt is stored at the NETL:

1. Pre-Test Characterization, 2020.8, URL: https://edx.netl.doe.gov/workspace/wellbore-cement-nasemgrp/
folder/ee3b3208-2f38-47f6-a84d-a22dda3c9bd7 (These are the CT scan of all samples (graphene and neat) before any triaxial test and creep test)
2. Post Fractured CT Scans, 2020.10, URL: https://edx.netl.doe.gov/workspace/wellbore-cement-nasemgrp/folder/e3a47403-3d88-4c87-9540-01118c804f8f (These are the CT scan of first batch samples (graphene and neat) after the triaxial test)
3. CT Scans, 2021.1, URL: https://edx.netl.doe.gov/workspace/wellbore-cement-nasemgrp/
folder/aaa5dc87-d582-4193-a067-9f1eb7f2f90d (These are the pre and post CT scan of second batch samples, including zeolite, graphene, olivine, and neat)
4. Saw cut. 2021.10, URL: https://edx.netl.doe.gov/workspace/wellbore-cement-nasemgrp/
folder/3779cc8b-eacd-4228-a0fb-a566b8679d93 (These are the pre-CT scan of the semi-circular OBC samples for evidencing the ultramafic carbonation, will be disclosed with future publications)
5. All the data stored at OSU: https://doi.org/10.22488/okstate.22.000001
6. All the data stored at LSU: URL: https://digitalcommons.lsu.edu/petroleum_engineering_data/1/
Doi: 10.31390/petroleum_engineering_data.01

Additional Documentation Produced to Describe Data:

OSU data:
Mitigating Risks to Hydrocarbon Release Through Integrative Advanced Materials for Wellbore Plugging and Remediation
National Academies of Sciences, Engineering, and Medicine: Gulf Research Program
Graphene Cement
Data
Microscopy
CT Scanning
Indentation
Unconfined Compression
Triaxial Loading
Porosity
Permeability
Project Deliverables
MS Thesis
Publications & Presentations
Ferrierite Cement
Data
Microscopy
CT Scanning
Indentation
Unconfined Compression
Triaxial Loading
Porosity
Permeability
Project Deliverables

MS Thesis
Publications & Presentations
Olivine Cement
Data
Microscopy
CT Scanning
Indentation
Unconfined Compression
Triaxial Loading
Porosity
Permeability
Project Deliverables
Publications & Presentations
Lab Facilities and Training
Thermofischer Scios2 FIB/SEM
Witec alpha300R
Yxlon FF20 CT Scanner
Nanovea PB1000 Micro/Nano Indenter
Corelab AFS-300

Other Activities to Make Data Discoverable:
This will be done through our published work, in journal papers and conference papers, presentations and posters, as well as workshop recordings from the SPE P&A forum and the GRC SPE Cementing workshop. For example, here we will upload a list of our publications in this report and several manuscripts and conference papers/session chairing and workshop organizing are planned for 2022 and will be reported when completed.

Sensitive, Confidential, or Proprietary Data:
N/A

INFORMATION PRODUCTS

Information Products Report:
Scholarly publications, reports or monographs, workshop summaries, or conference proceedings

Citations for Project Publications, Reports and Monographs, and Workshop and Conference Proceedings:
Peer Reviewed Journal Papers published:
1. Taghipour, A., Ghaderi, A., Cerasi, P., & Gheibi, S. (2022). Novel Laboratory Setup for Realistic Wellbore Cement and Formation Integrity Studies. Journal of Petroleum Science and Engineering, 208, 109664. https://doi.org/10.1016/j.petrol.2021.109664.
2. Achang, M. & Radonjic, M. (2021). Adding Olivine Micro Particles to Portland Cement-based Wellbore Cement Slurry as a Sacrificial Material: A Quest for the Solution in Mitigating Corrosion of Wellbore Cement. Cement and Concrete Composites, 121, 104078.

3. Ajayi, T. & Gupta, I. (2021). Long term assessment of the geochemical integrity of offshore wellbore cement- results from numerical modeling. Journal of Petroleum Science and Engineering, 201, 108443.
4. Achang, M., Yanyao, L., & Radonjic, M. (2020). A review of past, present, and future technologies for permanent plugging and abandonment of wellbores and restoration of subsurface geologic barriers, Environmental Engineering Science, 37 (6), 395-408.
5. Katende, A., Lu, Y., Bunger, AP., & Radonjic, M. (2020). Experimental Quantification of the Effect of Oil Based Drilling Fluid Contamination on Properties of Wellbore Cement. Journal of Natural Gas and Science and Engineering, 79, 103328.
6. Ajayi, T., & Gupta, I. (2019). A Review of Reactive Transport Modeling in Wellbore Integrity Problems. Journal of Petroleum Science and Engineering, 175, 785-803, 2019.

Peer Reviewed Journal Papers under review and in preparation:
1. Lu, Y., Spencer-Williams, I., Chang-Frizzell, N., Radonjic, M., & Bunger, A.P. Experimental Study of Genesis of Geologically Activated and Self-Sealing Cementing Materials for Deep Wellbore Plugging and Abandonment. In preparation, will submit to Cement and Concrete Research.
2. Lu, Y. & Bunger, A.P. Thermoporoleastic Analysis of Stresses in a Cement Plug Behavior in a Deep-Water Wellbore. In preparation, will submit to International Journal of Numerical and Analytical Methods in Geomechanics.
3. Lu, Y., Veveakis, M., & Bunger, A.P. Periodic Fractures Induced by Rapid Decompression of Low Permeability Cement. In preparation, will submit to Geophysical Research Letters.
4. Lu, Y. & Bunger, A.P. Evolving Permeability of Olivine Based Wellbore Cement under High Temperature Reservoir Conditions after Incurring Damage. In preparation, will submit to Cement and Concrete Research.
5. Massion, C., Lu, Y., Bunger, A.P., Crandall, D., & Radonjic, M. Graphene Nanoplatelets Reinforced Cement as a Solution to Leaky Wellbores. In preparation, will submit to Cement and Concrete Research.

Conference Sessions:
1. Liu, G. & Radonjic, M. Session 6: Achieving Effective Cement Placement in Horizontal Wells. SPE Workshop: Cementing in an Unconventional World. Postponed from 6-8 October 2021 to 2022 due to Pandemic. Galveston, TX, USA.
2. Badalamenti, A. & Bunger, A.P. Session Title: Use of Non-Portland Cement to Repair a Failed Cement Barrier. SPE Workshop: Cementing in an Unconventional World. Postponed from 6-8 October 2021 to 2022 due to Pandemic. Galveston, TX, USA.
3. Radonjic, M. & Brennen, M. GRC/SPE Workshop: High Temperature Cementing and Integrity Session 5 chair: Other Uses of Cement/Research and Development. 30 March – 1 April 2020 postponed to 7-9 October 2021.
4. Radonjic, M. & Bour, D. GRC/SPE Workshop: High Temperature Cementing and Integrity Session 7 Chair: What is Needed for Future Cement Blends and Cement Placement Technologies. 30 March – 1 April 2020 postponed to 7-9 October 2021.
5. Radonjic, M. & Pyatina, T. Session on Wellbore Materials at the GRC Annual Meeting & Expo, San Diego, 7-9 October 2021.
6. Radonjic, M. & Pyatina, T. Session on Wellbore Materials at the GRC Annual Meeting & Expo, Palm Springs, September 2020.
7. Radonjic, M., served on the organizing committee for the SPE Forum at The Hague, The Netherlands

from March 18, 2019, to March 22, 2019. A poster (Offshore Plugging and Abandonment (P&A) Material Issues and Future Advances) was presented on behalf of our Project team. session co-chair on Novel Plugging Materials, The Hague. Netherlands, March 2019. The main learning outcome was that the plugging and abandonment should be completely different from the conventional wellbore cementing. Radonjic co-chaired a session on novel technologies for P&A and contributed to the final session. This was by the invitation-only event.
8. ALL Members: Organized and chaired: Symposium on “Taming Leaky Wellbores-Plugging and Abandonment in Gulf of Mexico Wellbores” at the Interpore 10th Annual Meeting and Jubilee, New Orleans, Louisiana May 14 – 17, 2018.

Dissertations:
1. Lu, Y. Self-Sealing Materials for Plugging High Temperature Oil and Gas Wells. PhD Dissertation, University of Pittsburgh, Expected Graduation April 2022.
2. Ajayi, T. Lifecycle Reactive Transport Modeling for Assessing Integrity in Offshore Energy Systems. PhD Dissertation, Louisiana State University, Expected Graduation May 2022.
3. Rahman, F. Wellbore Barrier Material Design for Oil and Gas Wells (tentative title). PhD Dissertation, the University of Texas at Austin, Expected Graduation Spring 2023.

Theses:
1. Rahman, F. Laboratory framework for understanding mix formulation for 3D printed cementitious materials. Master’s Thesis, the University of Texas at Austin, Fall 2018.
2. Vissa, S.V.K. Microstructural and Mechanical Characterization of Zeolite Enhanced Wellbore Cement for Plugging and Abandonment. Master’s Thesis, Oklahoma State University, Fall 2021.
3. Massion, C. Characterization of Graphene Nano Platelets Reinforced Wellbore Cement, Master’s Thesis, Oklahoma State University, Fall 2021.

Peer-Reviewed Full Conference Papers:
1. Massion, C., Vissa, S.V.K., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2022). Geomimicry inspired MicroNano Concrete as Subsurface Hydraulic Barrier Materials: Learning from Shale Rocks as Best Geological Seals. REWAS 2022: Energy Technologies and CO2 Management.
2. Cerasi P. (2021). The Advantage of Using Dual Cement Property Plugs for Rock-to-Rock Plugging. Geothermal Resources Council Transactions, Vol 45, 152-168.
3. Lu, Y., Radonjic, M., Crandall, D., & Bunger, A. (2021). Evidence for Self-restoration of Olivine Based Cement under Geothermal conditions: Olivine Micro-aggregate As Mitigation to Portland Cement Acidic Attack. Geothermal Resources Council Transactions, Vol 45, 191-202.
4. Massion, C., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2021). Improvement of Wellbore Cement by Addition of Graphene Nanoplatelets. Geothermal Resources Council Transactions, Vol 45, 222-236.
5. Vissa, SVK., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2021) Natural Zeolite Cement Blend for Geothermal Wellbore Applications: The Zeolite Mechanism in Making Resilient Cement Formulations. Geothermal Resources Council Transactions, Vol 45, 312-328.
6. Massion, C., Radonjic, M., Lu, Y. and Bunger, A., & Crandall, D. (2021) Impact of Graphene and the Testing Conditions on the Wellbore Cement Mechanical and Microstructural Properties. 55th US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association.
7. Coquard, R. & Cerasi, P. (2021). Finite Element Modeling of a Dual-Cement Well Plug. Proceedings of

the 15th Greenhouse Gas Control Technologies Conference. Available at SSRN: https://ssrn.com/abstract=3811378.
8. Taghipour, A., Ghaderi, A., & Cerasi, P. (2021). Novel Experimental Technique for Simulating Near Wellbore Integrity Challenges at Field Conditions. Proceedings of the 15th Greenhouse Gas Control Technologies Conference. Available at SSRN: https://ssrn.com/abstract=3822662 or http://dx.doi.org/10.2139/ssrn.3822662.
9. Achang, M. & Radonjic, M. (2020). Olivine – Portland Cement as a Solution to Wellbore Integrity Issues in CO2-rich Geothermal Reservoirs. Geothermal Resources Council Transactions, Vol 44, 2-14.
10. Cerasi, P., Ghaderi, A., Taghipour, A., Todorovic, J., Gawel, K., Coquard, R., Edvardsen, L., Agofack, N., & Bhuiyan, H. (2020). Testing methods to assess improved well cementing and remediation. Geothermal Resources Council Transactions, Vol 44, 29-37.
11. Lu, Y., Spencer-Williams, I., Chang-Frizzell, N., & Bunger, A.P. (2020). Evidence for Self-Healing of Carbonated Olivine for Wellbore Cementing and Plugging under High Temperature High Pressure (HTHP) Reservoir Conditions. Geothermal Resources Council Transactions, Vol 44, 58-66.
12. Massion, C., Achang, M., Bour, D., & Radonjic, M. (2020). Graphene-enhanced wellbore cement: improving cement performance in the construction of geothermal wellbores. Geothermal Resources Council Transactions, Vol 44, 67-81.
13. Vissa, S.V.K. & Radonjic, M. (2020). Designing Wellbore Plugging and Abandonment Materials Based on Nature's Hydraulic Barrier Materials: A Solution to Prevent Hydrocarbon Leakage Over Time. In SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability.
14. Asala, H. I., & Gupta, I. (2019). Numerical Modeling Aspects of Fluid-driven Interface Debonding after Well Plugging and Abandonment. 53rd US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association.
15. Radonjic, M. was interviewed by Dr. T. Plaxina: Article Title Making a Difference: Women in Academia, JPT, 30 https://pubs.spe.org/en/jpt/jpt-article-detail/?art=5784; (July, 2019).
16. Event Covers State of the Art in Plugging and Abandonment, JPT, Volume: 71, Issue: 8 01, https://www.spe.org/en/jpt/jpt-article-detail/?art=5730, (August 2019).

Presentations, Posters, Abstracts:

1. Massion, C., Vissa, S. V. K., Lu, Y., Crandall, D., Bunger, A., & Radonjic, M. (2022). Designing Novel MicroNano Concrete as Subsurface Hydraulic Barrier Materials Using Shale Rocks as Templates. The Minerals, Metals & Materials Society 2022 Annual Meeting & Exhibition, 27 February - 3 March 2022. Oral presentation.
2. Ajayi, T., & Gupta, I. (2021). Reactive Transport Simulations of Cement-Rock Integrity. GRC/SPE Workshop: High-Temperature Well Cementing Part II: 7-9 October 2021, San Diego, CA, USA. Oral presentation.
3. Lu, Y., Bunger, A.P., & Radonjic, M. (2021). Evidence for Self-restoration of Olivine Based Cement (OBC) under Acidic Geofluids, High Temperature and High Pressure (AG-HT-HP) Conditions. GRC/SPE Workshop: High-Temperature Well Cementing Part II: 7-9 October 2021, San Diego, CA, USA. Oral presentation.
4. Massion, C., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2021). Improvement of Wellbore Cement by Addition of Graphene Nanoplatelets. 2021 Geothermal Rising Conference, San Diego, CA, 3-6 October 2021. Oral presentation.
5. Rahman, F. & Ferron, R. (2021). Limestone Calcined Clay Cements for Wellbore Leakage. 2021

Geothermal Rising Conference, San Diego, CA, 3-6 October 2021. Poster session.
6. Vissa, S.V.K., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2021). Natural Zeolite Cement Blend for Geothermal Wellbore Applications: The Zeolite Mechanism in Making Resilient Cement Formulations. 2021 Geothermal Rising Conference, 3-6 October 2021. Oral presentation.
7. Massion, C., Vissa, S.V.K., & Radonjic, M. (2021). Wellbore Cement Mechanical Enhancement by Addition of Zeolite and Graphene. American Association of Petroleum Geologists Midcontinent Section Meeting 2021, 3-5 October 2021. Oral presentation.
8. Rahman, F. & Ferron, R. (2021). Performance of Limestone Calcined Clay at elevated temperature. 11th Advances in Cement-Based Materials (Cements 2021), Virtual Conference, 23-25 June 2021. Poster session.
9. Massion, C., Lu, Y., Bunger, A., Crandall, D., & Radonjic, M. (2021). Impact of Graphene and the Testing Conditions on the Wellbore Cement Mechanical and Microstructural Properties. 55th US Rock Mechanics/Geomechanics Symposium, American Rock Mechanics Association, 20-23 June 2021. Oral presentation.
10. Massion, C. (2021). Microstructural and Mechanical Properties of Wellbore Cement Enhanced by Graphene Nanoplatelets. 2021 SPE Mid-Continent Student Paper Competition. 22 May 2021. Oral presentation.
11. Cerasi, P. (2021). Finite Element Modeling of a Dual-Cement Well Plug. Greenhouse Gas Control Technologies (GHGT-15), 15-18 March 2021. Poster session.
12. Taghipour, A. (2021). Novel Experimental Technique for Simulating Near Wellbore Integrity Challenges at Field Conditions. Greenhouse Gas Control Technologies (GHGT-15), 15-18 March 2021. Oral presentation.
13. Rahman, F. & Ferron, R. (2021). Performance of Limestone Calcined Clay (LC3) Binders for Oil Well Cementing Applications. CAEE Grad Student Symposium, University of Texas at Austin, Virtual Conference. Poster session.
14. Ajayi, T., & Gupta, I. (2020). Thermo Hydro Chemical Numerical Analysis of the Efficacy of Subsurface Sealing Materials. AGU Fall Meeting Abstracts, December 2020.
15. Achang, M. & Radonjic, M. (2020). Olivine - Portland Cement as a Solution to Wellbore Integrity Issues in CO_2-rich Geothermal Reservoirs. Geothermal Resources Council (GRC) Virtual Annual Meeting & Expo, 18-23 October 2020. Oral presentation.
16. Cerasi, P. (2020). Testing methods to assess improved well cementing and remediation. Geothermal Resources Council (GRC) Virtual Annual Meeting & Expo, 18-23 October 2020. Oral presentation.
17. Massion, C., Achang, M., Bour, D., & Radonjic, M. (2020). Graphene-Enhanced Wellbore Cement: Improving Cement Performance in the Construction of Geothermal Wellbores. Geothermal Resources Council (GRC) Virtual Annual Meeting & Expo, 18-23 October 2020. Oral presentation.
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19. Vissa, S.V.K., & Radonjic, M. (2020). Designing Wellbore Plugging and Abandonment Materials Based on Nature's Hydraulic Barrier Materials: A Solution to Prevent Hydrocarbon Leakage Over Time. SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability, 28-30 July 2020. Poster presentation.
20. Achang M., Massion, C., Ray, C., Beasant, P., Bour D., & Radonjic M. (2020) Graphene Enhanced Wellbore Cement. GRC/SPE Workshop: High Temperature Cementing and Integrity, 30 March - 1 April

2020 postponed to 7-9 October 2021, San Diego, CA, USA. Oral presentation.
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22. Lu, Y. & Bunger, A.P. (2020). Experimental Study of Genesis of Geologically Activated Cementing Materials for Deep Wellbore Plugging and Its Self-healing Behaviour for the Resilient P&A System. GRC/SPE Workshop: High-Temperature Well Cementing and integrity - Exploring Geothermal and Oil and Gas Synergies, 30 March-1April 2020 postponed to 7-9 October 2021, San Diego, CA, USA. Oral presentation.
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25. Vissa, S.V.K., & Radonjic, M. (2019). Sealing wellbores at the end of their life cycle to restore sub surface seal integrity and prevent offshore wellbore leakage. AGU Centennial at Fall Meeting 2019, 8-13 December 2019. Poster presentation.
26. Coquard, R. (2019). Numerical simulation by finite elements of plugs needed for abandonment of oil production or CO2 injection wells. Master project defense, Ecole Polytechnique, Paris, France, September
2019.
27. Ajayi, T., & Gupta, I. (2019). A Pitzer Ion Interaction Model for Gulf of Mexico Wellbore Integrity Assessments. 23rd Annual Gulf of Mexico Deepwater Technical Symposium, New Orleans, Louisiana, 26-28 August 2019.
28. Radonjic, M., Bunger, A., Cerasi, P., Ferron, R., & Gupta, I. (2019). GoM P&A - Where We Are, Where We Need To Be. 23rd Annual Gulf of Mexico Deepwater Technical Symposium, New Orleans, Louisiana, 26-28 August 2019.
29. Rahman, F. & Ferron, R. (2019). Laboratory framework for understanding mix formulation for 3D printed cementitious materials via extrusion. Graduate and Industry Networking, GAIN 2019, Graduate School, University of Texas at Austin.
30. Rahman, F. & Ferron, R. (2019) Laboratory framework for understanding mix formulation for 3D printed cementitious materials via extrusion. ACERS 2019 Annual Meeting, Urbana, IL, Poster session.
31. Ferron, R. (2019). Overview of Research Activities. Presentation at Howard University, Washington DC, 15 January 2019.
32. Cerasi P. (2019, 2020, 2021). EU project SECURe presentations to Advisory Board Annual meetings. The AB has members from the Alberta Energy Regulator, Shell, Texas Bureau of Economic Geology at UT Austin, Carbon Management Canada Inc, Golder Associates, Environment Agency UK.
33. Asala, H., & Gupta, I. (2018). 3D Finite Element Sub-modeling of Fluid-driven Interface De-bonding after Well Plugging and Abandonment. AGU Fall Meeting Abstracts, December 2018.
34. Ajayi, T., & Gupta, I. (2018). Geochemical considerations for Gulf of Mexico wellbore integrity predictions. AGU Fall Meeting Abstracts, December 2018.
35. Ferron, R. (2018). Natural Pozzolans as Sustainable Supplementary Cementitious Materials. ACI Fall Convention, Session on The Role of Materials in Sustainable Concrete Construction (Part 2), Las Vegas, NV, 15 October 2018.

36. Ajayi, T., & Gupta, I. (2018). Reactive Chemistry in Offshore Well Integrity Problems - What We Know, What We Should Know. 22nd Annual Gulf of Mexico Deepwater Technical Symposium, New Orleans, LA, 27-29 August 2018.
37. Cerasi, P. (2018). Cement bond testing methods. Presentation at Interpore 10th Annual Meeting, New Orleans, LA, 14-17 May 2018.

Additional Documentation Produced to Describe Information Products:
N/A

Other Activities to Make Information Products Accessible and Discoverable:
We will continue to present and publish the work that has not been published/presented, and we still have students to graduate. We also have upcoming activities in organizing sessions at conferences and workshops and are on organizing committees etc

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V. PUBLIC INTEREST AND COMMUNICATIONS

Most Exciting or Surprising Thing Learned During the Project

The most exciting thing about the project was the variety of factors that could influence the integrity of sealing materials in the subsurface, both from the geological environment as well as the engineering practices involved. This project was able to show that from a geochemical perspective alone, factors such as fluid compositions, rock compositions, pH of fluids, temperature, presence, or absence of an interface all could play a role in the maintenance of geochemical integrity. The surprising result was that cement and cement-rock interface integrity lasted much less than anticipated for the simulations performed.
From the rock-mechanics perspective, we have shown that testing materials at the subsurface conditions, primarily T and P, is critical in predicting will these materials function adequately over time. Finally, we have shown that combing engineered materials such as graphene, with rock materials like olivine, limestone, and zeolites, can significantly enhance the chemical and mechanical integrity of wellbore materials.

Outcomes Achieved During the Project

Portland Cement based materials have been used for a long time for plugging and abandonment applications. However, all the current cements face these common issues of shrinkage, fractures, and micro annuli formations to name a few. To overcome these setbacks, additives need to be added to the cement to accelerate or retard the rate of cement setting depending on the requirement, as well as increasing the strength and performance of those cements under unstable sub-surface conditions. Experiment studies on zeolite and graphene have been conducted at the Geomimicry and Barrier Materials Laboratory at OSU, with the intention of determine the impact of these additives on the cement performance and integrity when in the wellbore environment. Cement samples were cured and tested at conditions as close to the well environment as possible by simulating pressure and temperature when

possible.
The material of interest that could provide improvements to cement is graphene, as one of the currently strongest materials available. Carbon atoms form thin sheets that create graphene nanoplatelets that have high strength and flexibility. These mechanical characteristics can be transferred when added in low quantity (of less than 0.1%) to improve cement performance, maintain integrity, and reduce the failure of plugs. Graphene nanoplatelets were then added to cement at 0, 0.008%, 0.016%, 0.05%, and 0.1% by weight of cement during the slurry mixing. Cement samples were cured in calcium hydroxide solution in an environmental chamber at 90°C and 95% relative humidity for 21-28 days. Some samples were cut and polished to view the microstructure under scanning electron microscope when graphene was added.
It was observed that graphene nanoplatelets tended to accumulate within the empty pore space within the cement matrix. The pores are the weakest points in the cement and reinforcement with the strongest material, graphene, could be a mechanism of one way in which the addition of this additive improves the overall cement mechanical performance. The petrophysical properties and strength properties play an important role in deciding the efficiency of a plugging material. Given the low percentages of addition which make this a cost-efficient alternative that does not compromise the porosity or permeability of the cement. Mechanical properties were obtained for the micro and macrostructure using Vickers micro indentation and simulated triaxial loading, respectively. Indentation was done on the cut and polished samples, and average elastic modulus and hardness are obtained from the data as shown below. A higher rebounding elastic modulus in 0.008%graphene added cement as observed, could provide more fracture resistance. The indentation marks were studied under SEM which showed little to no propagating fractures which shows that the resultant cement is not brittle but more elastic in nature. This observation was also backed up by the lower amount of void space observed in the computed tomography images of the fractured cores after triaxial testing. Triaxial loading at simulated reservoir conditions of 13.7Mpa confining pressure and temperature of 90°C to view the cement mechanical behavior with the addition of graphene. At these simulated conditions, graphene cement increased the sample failure axial stress while also providing a higher axial failure strain. In addition, the graphene nanoplatelets had provided an additional resistance to brittle failure unlike the abrupt decrease axial stress in neat cement. Computed tomography of samples after failure had provided further insight to the failure mechanism and behavior of each cement. It is evident that the fracture network and void area are significantly reduced with the addition of graphene. This could help to prevent migration of subsurface fluids even after the failure and fracturing of the cement plug.
At OSU we also investigating the use of natural nanomaterials as additives to achieve geomimicry in cement making it stable just like the naturally occurring shale in the subsurface. Few of the naturally occurring or nature derived nano additives are Fe_2O_3, SiO_2 , TiO_2 and Zeolites (Aluminosilicates). While addition of Fe_2O_3, SiO_2 and TiO_2 show favorable changes in the properties, Zeolites are currently gathering a lot of interest given their abundance in Earth's crust and the variety in their composition. Zeolites are Aluminosilicates of alkaline earth metals like Potassium, Calcium and Sodium. Various characterization techniques had been used to get an initial understanding of both the additive (zeolite) and the resultant cement slurries. The publications contain more detailed information on our findings, and in this report, we will report the main trends. This report concentrates on the characterization of the

zeolite enhanced cement slurries after full hydration. Complete materials characterization of zeolite enhanced cements were conducted, from scanning electron microscopy to Raman spectroscopy had been done to resolve the cement phases and check the phase stability of the zeolite (Ferrierite) in the cement matrix trying to understand the mechanism of its working in cement. In this case, it indicates that the zeolites are found to be stable not only in sub-surface conditions, but also in cement hydration conditions hence paving way to the hypothesis that the zeolite acts as a substrate for the hydration to take place.

These phase analyses support the improved mechanical properties of zeolite enhanced cements. We investigated natural zeolites as they have shown promising results in a study conducted on geothermal cements, at elevated temperatures, where self-healing was reported. However, we did not have enough time to test self-healing aspects of these materials at GoM conditions, and hope to do that in the near future.

The goal of our research at UTA was to develop wellbore barrier materials with robust zonal isolation, based on their performance at high temperature degradation. The performance of candidate binder systems of limestone calcined clay cements (LC3) were tested at elevated temperature for plugging and abandonment (P&A) of geothermal wells. Under such extreme geothermal conditions, cement sheaths and permanent plugging materials needs to be robust in terms of zonal isolation, mechanical integrity and durability. The research team identified suitable dosages to be used and tailored the rheological properties of the system to ensure suitable flowability. The effect of using the LC3 system in an addition approach (i.e., the limestone and calcined clay is added to a cement system) versus using the LC3 system in a replacement approach (i.e., portions of cement is replaced with limestone and calcined clay) was investigated. It was determined that both approaches would be suitable to be used in well bore applications and overall, the LC3 systems show tremendous potential for zonal isolation. The reduced permeability in the LC3 systems was due to pore structure refinement that occurs at the nano and micro levels. This increased refinement and tortuosity of the pore structure network results in a reduction in gas and liquid penetration which makes these ternary binders particularly attractive for wellbore applications.

The Pitt team firstly accomplished a baseline via an experimental evaluation of the current plugging materials under the harsh conditions. This was accomplished by performing experimental characterizations of class H cement in a triaxial compression and permeability cell with acidic geofluid, high temperature and high pressure (AG-HT-HP) conditions typical of the GoM. Expanding on this baseline evaluation of status quo materials, the effect of drilling fluid contaminations on the performance of the plugging materials was also studied, showing that cement performance deteriorates even further under conditions of contamination by residual drilling fluid. Perhaps most notably, the baseline experiments show that existing class H cement plugging material is not resilient to damage it will likely sustain at some point during its service life. Instead, the hydraulic conductivity of damaged material continues to increase, meaning that a breach will worsen as time goes on. To overcome this shortcoming, novel self-sealing, therefore resilient plugging, materials have been developed based on the accelerated carbonation reaction of the ultramafic rock. These leverage the challenging conditions of the AG-HT-HP in GoM as an advantage because these conditions happen to be optimal for accelerating carbonation rate of olivine. The two main materials of focus are geologically activated cement (GAC) and olivine-based cement (OBC), both of which exhibit self-sealing within a few hours thus providing for a resilient system that restores itself after damage. GAC is based on direct hydration and carbonation of olivine to turn the granular ultramafic raw materials into competent rock without use of Portland cement binder. On the other hand, in OBC the olivine can serve as a micro-filler in cement that does not interfere with classical cement hydration reactions but remains available to react with CO2 that is typically present in low pH carbonated brines to form carbonates that plug and seal flow pathways.

The research question LSU was trying to address was 'how long will the geochemical integrity of barrier materials last under Gulf of Mexico (GoM) like subsurface conditions?'. Reactive transport models, using GoM brine compositions and subsurface pressure, temperature and pH conditions were built to simulate the expected long-term integrity of current sealing materials and some new tested materials in the laboratory. Continuum scale simulations are performed using TOUGHREACT (Xu et al., 2011) on chemical reactions which could occur in offshore settings like the Gulf of Mexico (GOM) especially as they relate to wellbore integrity. Cement and mineralogical data used for the simulation are from experimental work performed by Labus and Wertz (2017). The brine compositions used in the simulations are from Land and Macpherson (1989, 1992) and Land et al. (1988). These are Gulf of Mexico (GoM) formations, namely, Eugene Island (EI) 313, Tiger Shoal, and Picaroon, all offshore fields, and Armstrong Don Thomas, an onshore GoM Texas field. The subsurface temperatures, pressures used in the model correspond to these reservoirs. The data is thus real and the models representative of Gulf of Mexico formations. Initial batch simulations were run in the cement to equilibrate the brines with the initial cement composition and generate initial conditions for transient simulations of rock-fluid-cement interactions. Porosity changes are used as indicators of the geochemical integrity (Ajayi and Gupta, 2021). "Our study provides first information on the possible evolution of geochemical integrity of cement and cement-rock interface subjected to different fluid compositions over long time frames in offshore settings like the Gulf of Mexico" (Ajayi and Gupta, 2021). Our results indicate that the geochemical longevity of cement in these conditions can last up to one hundred years or more but the fluid-fluid and cement-rock-fluid compositions and interactions are controlling factors. Higher temperatures result in greater porosity loss with the main drivers being the dissolution of ettringite, calcite, and portlandite. Substantial differences in pH at higher and lower depths also accounted for the loss of geochemical integrity. Cement-rock interfaces are zones of increased chemical reactions due to the contrasting fluid and host rock/cement compositions. For the case studies performed, the cement-rock interface zone increased porosity by up to 71% in shale-cement and ~ 64% at sandstone-cement interfaces (Ajayi and Gupta, 2021). While these are purely geochemical results, the incorporation of geomechanical effects will only tend to lower the longevity of barrier materials.

The project team at SINTEF in Norway looked at experimental methods to investigate possible fractures in a well cement sheath occurring when pressure cycles arise in wellbores. These cycles can stem from unplanned events such as well shut-ins for maintenance operations, periodic temperature changes related to varying flow conditions in the well, or long-term changes in the environment around the well after abandonment, affecting stress and pressure distributions in the area. The main accomplishments were to finalize and run tests in a new X-ray transparent cell, where a steel tube could be cemented to a surrounding sandstone plug. The tests produced images that clearly showed different types of fractures arising in the cement sheath and surrounding sandstone as a function of the pressure variation in the wellbore and the applied outside pressure on the assembly. This tool has thus promising capabilities for screening of improved cement-like materials that could better handle the pressure solicitations and guarantee lower risk of fracturing and thus better containment of fluids from reaching sensitive zones in the sub-surface or ocean floor in the worst-case scenario. SINTEF engaged Ecole Polytechnique, Paris, France, to perform a numerical simulation study of the stability of a cement plug inside a steel casing. The commercially available DIANA FEA (finite element analysis) software was used to investigate the

effect of implementing a dual cement composition scheme to well plugging. The purpose of the numerical work was to investigate plug failure in realistic geometry and scale. The studied case looked at a cement plug placed in a steel casing, itself cemented to an outside rock formation (not explicitly modelled). The cement plug incorporated a softer and more flexible part at its front exposed to well pressure (higher than the well pressure on the other side of the plug). A comparison was made to a single component plug in terms of resistance to differential pressure and friction against the steel casing.
The simulation's boundary conditions applied to the casing were seen to influence the yield stress of the cement interface deformation. Several degrees of debonding of the cement sheath from the surrounding formation were simulated, also including perfect bonding. Varying the radial stress applied on the casing was simulated by the amount of radial deformation allowed. Three composite plug simulations were run, with one quarter, one half or three quarters of the plug being made of softer cement, with the soft part exposed to the highest well pressure. The shear yield strength increases the larger the proportion of soft to stiffer cement in the plug; however, the soft cement section leads to larger deformation of the entire plug.
Further optimization can perhaps be achieved by varying the placement and alternance of the soft and rigid cement sections. For instance, the soft cement may be placed in the middle of the plug, to shield it from potentially aggressive well chemicals. Additional numerical simulations were performed to upscale cement plug integrity with sacrificial end part. A shale domain was defined in the DIANA Finite Element software, in plane strain 2D mode. The dimensions of the domain were 500 m in lateral extent by 500 m vertically. Approximately in the middle of the domain, a small vertical well section was added, with 25 m total length. A 10 m long cement plug is placed in the well section, with either one cement type, or where 1 m length at the deeper end is replaced with a softer cement type. Note that for simplicity and computation speed, the rest of the well (to surface and deeper layers) is not modelled. The in-situ stress conditions adopted are a vertical stress sv = 15 MPa and horizontal stress sh = 10 MPa. The initial well pressure (equal pressure above and below the cement plug) is taken to be Pw = 12.5 MPa.
The stresses are applied by implementing normal loads on the upper and right domain boundaries, with fixed left and lower boundaries. The domain is meshed with quadratic, adaptive rectangular elements, seeded either by specifying number of elements per given boundary (several different values can be given at different edges in the domain) or by specifying element size, with linear interpolation for midside element node location. Around 12 000 elements are generated in the models considered here. The SCP phase is implemented as a second load sequence, where additional loading is applied on the cement plug's lower boundary, due to increased pressure in the lower part of the well, below the plug. This additional pressure is set at 1.5 MPa. To compare the dual cement plug to reference single material plug, we plot the estimated crack width occurrences for the single and the dual cases. One significant difference between single and dual plug is additional fracturing in the plug itself for the soft cement section, at the deeper plug face, which is as intended: the soft plug part functions as a sacrificial zone. The simulations in this study confirm, although weakly, the previous results obtained by Rémi Coquard for the case of a dual cement plug inside a steel casing. An important difference is that sliding of part or the whole plug was not simulated here, as a perfect bonding is assumed in the way the elements are set up in this study. When differential straining between two elements overcomes the strength limits, a fracture is seeded at the corresponding location, with essentially "post peak" mechanical properties. These properties are what one would measure as residual strength in a strain-controlled triaxial

experiment taken beyond peak strength of the investigated material. It is important to stress the fact that these 2D simulations may over-evaluate the importance of a created discontinuity in the cement plug or the surrounding rock. In 3D there may be other parts still intact, which could make a difference in assessing for example hydraulic connectivity or outright support loss.
Finally, experimental pushout tests were carried out to verify the dual cement plug concept in the laboratory. 26.8 mm diameter cement plugs were cured in a steel tube, which was then inserted in a bottom, larger diameter tube, while a smaller diameter tube was fitted on top, in contact with the hardened cement top face. A strain gauge was inserted in the lower tube, contacting the cement's lower face. The whole assembly was then inserted in an MTS load frame, with an additional strain gauge connected to the load frame's piston and thus reading the deformation state of the cement plug's top face. This allowed for logging the deformation of the top and bottom faces of the cement plug, and comparing to the numerical simulations, for single cement plugs and composite plugs. Neat Portland G cement was used for the "conventional" plugs, while half of the plug was replaced with flexible cement in the composite plugs. Neat and flexible plugs were tested separately and compared in terms of deformation of top and bottom surfaces to the composite plugs. The test results average values are used for all similar types of tests. In all cases, there is a slight delay between mobilization of the lower plug face after the onset of deformation in the top face, where the force from the load piston is applied. From the figure, we see that no systematic strength hierarchy arises before the long-term frictional regime at large deformation values. Looking at the initial part of the graphs, one can compare the static friction part of the curve; since mobilization of friction is undetermined, the peak strength will vary from trial to trial. The interesting comparison is on the obtained separation in terms of deformation between the two end surfaces. The best ratio is obtained for the flexible cement; however, the composite plug is nearer the flexible ratio than the neat cement ratio. In terms of bulk strength and hydraulic integrity, it is best to maintain a neat cement core in the plug, unless new materials are used, where good strength and permeability properties can be engineered.

Communications, Outreach, and Dissemination Activities of Project

Dr. Gupta, LSU: Organized two hands-on sessions to Girls Scouts B.I.G. elementary school children on "Responsible Energy Engineering; Learning outcomes - discover, learn about natural energy resources, how they are extracted, and how leaks can be prevented. Hands-on experiment on poorly cemented, and well cemented pipes (well bores) and their impact on leaks.

Dr. Ferron has led 3 workshops to faculty at UT Austin on inclusive teaching practices.

Dr. Ferron organized and facilitated a student town-hall in her department focused on diversity, equity and inclusion.

Dr. Ferron presented an outreach presentation at Partners in Parenting When I Grow Up Festival, 2018

Dr. Ferron served as a Science Fair Judge for Kathy Caraway Elementary School, 2018, 2019

Dr. Ferron served as a reviewer for Delta Sigma Theta-Austin Alumnae Chapter College Scholarship Program (Spring 2018)

Dr. Ferron served as a reviewer for the National Academies of Sciences, Engineering and Medicine Ford Foundation Fellowship Program, 2018, 2019, 2020

Mileva Radonjic, OSU: Organizing committee, panel discussion lead, and presenter at the SPE P&A Forum, March 2019, by invitation only, 90% industry participation. Session chairing at ARMA, GRC and SPE Cementing workshops, 2019, 2020, 2021 and 2022.