# YEAR-END TECHNICAL REPORT

September 29, 2022 to September 28, 2023

# Long-Term Stewardship of Environmental Remedies: Contaminated Soils and Water and STEM Workforce Development

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FIU | Applied Research Center
FLORIDA INTERNATIONAL UNIVERSITY

Addendum:

This document represents one (1) of five (5) reports that comprise the Year End Reports for the period of September 29, 2022 to September 28, 2023 prepared by the Applied Research Center at Florida International University for the U.S. Department of Energy Office of Environmental Management (DOE-EM) under Cooperative Agreement No. DE-EM0005213.

The complete set of FIU's Year End Reports for this reporting period includes the following documents:

Project 1: Chemical Process Alternatives for Radioactive Waste
    Document number: FIU-ARC-2022-800012997-04b-007

Project 2: Environmental Remediation Science and Technology
    Document number: FIU-ARC-2022-800013918-04b-006

Project 3: Waste and D&D Engineering and Technology Development
    Document number: FIU-ARC-2022-800013919-04b-007

Project 4: DOE-FIU Science & Technology Workforce Development Initiative
    Document number: FIU-ARC-2022-800013920-04b-011

Project 5: Long-Term Stewardship of Environmental Remedies: Contaminated Soils and Water and STEM Workforce Development
    Document number: FIU-ARC-2022-800013922-04b-005

Each document will be submitted to OSTI separately under the respective project title and document number as shown above. In addition, the documents are available at the DOE Research website for the Cooperative Agreement between the U.S. Department of Energy Office of Environmental Management and the Applied Research Center at Florida International University: https://doeresearch.fiu.edu

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# PROJECT 5 EXECUTIVE SUMMARY

The Department of Energy (DOE) established Legacy Management (LM) in December of 2003, to manage its responsibilities associated with the legacy of the Cold War. DOE has taken major steps in satisfying environmental cleanup and LM ensures post-closure responsibilities are met for the protection of human health and the environment. LM coordinates closely with other Government organizations, including those within DOE, to ensure post-closure obligations are maintained when mission-related sites are closed and transferred to LM for long-term management. LM conducts post-closure site operations at approximately 98 sites in the United States and the territory of Puerto Rico and anticipates increasing to 128 sites by 2030. LM sites are generally described by the regulatory program and the types of environmental residual contamination remaining at the sites after remediation. Recognizing that LM sites are driven by their unique requirements such as operation and maintenance of remedial action systems, routine inspection and maintenance, and records related activities, Florida International University's Applied Research Center envisions developing a unique program to address LM's goals and preparing and securing the next generation workforce that will be required to accomplish these goals.

Florida International University (FIU), the largest Hispanic serving research-extensive institution in the continental United States, is one of the nation's leading producers of scientists and engineers from underrepresented groups. In 1995, DOE created a unique partnership with FIU to support environmental cleanup technology development, testing and deployment at DOE sites. This partnership spawned a research center at FIU dedicated to environmental research and development (R&D). The center, now known as the Applied Research Center, has tackled and helped solve problems at many DOE sites.

Since 1995, the Applied Research Center (ARC) at Florida International University (FIU) has provided critical support to the Department of Energy's Office of Environmental Management (DOE-EM) mission of accelerated risk reduction and cleanup of the environmental legacy of the nation's nuclear weapons program. ARC's applied research is performed under the DOE-FIU Cooperative Agreement. ARC's applied research, technology development; test & evaluation; and STEM workforce development covers four major areas of environmental cleanup operations: radioactive waste processing, facility decontamination and decommissioning, soil & groundwater remediation and modeling, and information technology (IT) development for environmental management. As discussed, and agreed among DOE EM and LM, FIU infrastructure and expertise developed under the Cooperative Agreement will be leveraged to initiate the pilot program for LM. To this end, the research & student training will be structured closely following the DOE Fellows program model.

To date, the DOE LM Fellows Program has inducted a total of four (4) minority FIU STEM students and engaged them in research topics investigating the use of apatite for uranium sequestration at the Old Rifle site, and the application of remote sensing technologies at LM sites.

The following lists the DOE LM Fellows that provided support in FIU Year 3 to the two research tasks executed under this project:

Task 1: Olivia Bustillo (graduate, M.S., environmental engineering - graduated Summer 2023)

Task 2: Shawn Cameron (graduate, M.S., mechanical engineering)

The following ARC researchers are supporting this project and mentoring the DOE-LM Fellows: Ravi Gudavalli (Ph.D., Env. Engineering, Mentor/Project Manager), Anthony Abrahao (M.S., Mechanical Engineering, Mentor), Pieter Hazenberg (Ph.D., Hydrology and Quantitative Water Management, Sr. Research Scientist), Leonel Lagos (Ph.D., PMP®, Mechanical Eng./Civil/Env. Engineering, PI, DOE Fellows Program Director), and Angelique Lawrence (M.S., Environmental Science, Technical support).

# MAJOR ACCOMPLISHMENTS

Major accomplishments of this program to date include:

*For Task 1:*

- FIU has completed SEM-EDS analysis of dry precipitate from the “incorporation and co-precipitation of uranium onto hydroxyapatite” experiment and calculated atomic ratios to validate the formation of hydroxyapatite.
- FIU conducted the sorption of uranium onto hydroxyapatite experiment to find the optimum solid-to-liquid ratio for future studies and analyzed samples via ICP-MS. Sorption of uranium reached equilibrium in two (2) weeks.
- FIU performed XRD analysis on the precipitate being used to ensure that it was pure hydroxyapatite. This precipitate was used in the subsequent experiments.
- FIU drafted a poster based on the research performed under Task 1 on uranium sequestration using hydroxyapatite.
- FIU conducted experiments to study the sorption of uranium onto hydroxyapatite at varying environmental conditions such as pH, temperature, and oxidation-reduction potential (ORP), to assess their influence on the uranium-hydroxyapatite interaction.
- Milestone 2022-P5-M4 was completed which involved an investigation of environmental factors that influence uranium and hydroxyapatite interactions.
- FIU has completed Deliverable 2022-P5-D2 in support of the Long -Term Stewardship of Environmental Remedies: Contaminated Soils and Water and STEM Workforce Development Project (Project 5, Task 1) under the DOE-FIU Cooperative Agreement, which involved preparation of a report on the investigation of environmental factors that influence uranium and hydroxyapatite interactions.
- FIU initiated isotherm experiments to study the sorption capacity of uranium at pH 7, room temperature and oxic conditions.
- A paper based on the research conducted under Task 1 that was submitted to the Waste Management Symposia 2023 titled *“Interaction of Hydroxyapatite and Uranium in Groundwater at the Old Rifle Site to Facilitate Site Remediation”* was designated a “Superior Paper”.

*For Task 2:*

- FIU conducted an assessment of the mobile robotic platform’s autonomous behavior by improving the turn radius and the overshooting between each desired point. FIU also tested the all-terrain wheeled robot system that is designed to traverse Legacy Management’s Rifle Site disposal cell. In addition, the ground penetrating radar and the software development kit for mapping the subsurface of LM’s Rifle, CO disposal cell was received, and each component modeled in CAD software.
- The DOE Fellow manufactured the components needed to assemble the mobile robotic platform to deploy a ground-penetrating radar (GPR) at the Legacy Management's disposal cells during his summer internship.

- The FIU team designed and built three testbeds to evaluate the GPR's capabilities in mapping subsurface erosion at LM's disposal cells. DOE Fellow, Shawn Cameron, also continued the GPR's deployment platform development. Shawn focused on building a functional prototype of FIU's autonomous ground-penetrating radar (GPR) ground platform and prepared the system for deployment at LM's disposal cell during the summer. In addition, he drafted a summer learning experience plan and discussed it with LM and FIU. Shawn participated in an 8-week summer internship at Grand Junction, CO from July 10 – Aug 25, 2023 where he conducted site deployments and participated in sampling activities with LM site managers.
- FIU completed milestone 2022-P5-M6, Deployment of GPR at LM Sites. The DOE Fellow, Shawn Cameron, and the FIU team successfully deployed FIU's ground penetrating radar (GPR) autonomous rover at LM's Mexican Hat, and Rifle disposal cells during the Fellow's summer internship. Additionally, the GPR robot was deployed at Basin 6 of the Nash Draw region near the WIPP in support of Project 2's hydrology modeling and research activities in Carlsbad, New Mexico.
- DOE Fellow Shawn Cameron presented his research accomplishments during the Annual DOE-FIU Cooperative Agreement Research Review held on August 24, 2023.
- A draft summary document for the GPR Summer Deployment at LM Sites (Deliverable 2022-P5-D4) was completed.

*For Task 3:*

- Since the inception of the program with DOE LM, four (4) FIU students have been competitively selected to become part of this program and officially inducted during the annual DOE Fellows Induction Ceremony hosted at FIU in November 2019, in November 2020 (virtually) and in November 2021.
- Two DOE-LM Fellows participated in the annual DOE Fellows poster exhibition and competition and Olivia Bustillo won third place in the competition and received an award during the 16th Annual DOE Fellows Induction Ceremony held on Nov. 8, 2022.
- DOE Fellows Olivia Bustillo and Shawn Cameron attended and participated at the Waste Management Symposia 2023 held in Phoenix, AZ from February 26 - March 2, 2023.
- DOE Fellow Olivia Bustillo participated in various sessions at the Waste Management Symposia conference:
    - A poster presentation, as a Roy G. Post foundation scholarships recipient, on Sunday, Feb. 26, 2023 during session *039 Posters: Roy G. Post Scholarship 2023 Winners*.
    - A poster presentation on Tuesday, Feb. 28, 2023 during session *095 Posters: Environmental Remediation (7.1)*. The poster Olivia presented won the best in Track 7- Environmental Remediation.
    - Panelist in panel *130B: US DOE National Labs and Academia Successful Partnerships in the Development and Training of STEM Workforce*. In this panel, she gave a student's perspective on the benefits of universities partnering with national labs and her personal perspective on current workforce development programs.

- DOE Fellow Shawn Cameron participated in a 10-week summer internship (2023) at Grand Junction, CO under the mentorship of Ms. Jalena Dayvault.
- DOE Fellow and Shawn Cameron presented his 2022 summer research accomplishments to LM Senior management and staff.
- Shawn Cameron also participated in the Annual FIU Research Review held on 9/28/22 with DOE-HQ and site POCs and presented his research accomplishments including GPR deployments during his summer internship.
- Two (2) DOE Fellows prepared and presented posters at the 16th Annual DOE Fellows Poster Exhibition and Competition held on Nov 7, 2022.
- DOE Fellow Olivia Bustillo was awarded third place in the poster exhibition and competition and was presented with the award during the DOE Fellows Induction Ceremony held on Nov 8, 2022.
- DOE Fellow Olivia Bustillo received the Presidential Management Fellow (PMF) Class of 2023 award.
- DOE Fellow Olivia Bustillo participated in a summer 2023 internship at DOE's Oak Ridge Reservation directly sponsored by United Cleanup Oak Ridge (UCOR)
- FIU has completed Deliverable 2022-P5-D3 in support of the Long--Term Stewardship of Environmental Remedies: Contaminated Soils and Water and STEM Workforce Development Project under the DOE-FIU Cooperative Agreement due on September 22, 2023, which involved the development of a draft summary document for GPR summer deployment at LM sites.

# TASK 1: USE OF APATITE FOR URANIUM SEQUESTRATION AT OLD RIFLE SITE

## Task 1: Introduction

The Office of Legacy Management (LM) is charged with managing former Department of Energy (DOE) defense sites that have undergone cleanup but still have continuing post-closure management requirements. Although the goal of LM is to transition facilities/lands of these sites to beneficial use, site-specific factors often limit release for unrestricted use. These factors include groundwater that is still being treated or which could not be effectively treated to regulatory standards, contaminants in the unsaturated zone that are inaccessible, and the presence of on-site disposal cells and landfills.

The Old Rifle Site, CO is a former operating mill which once processed uranium (U) ore from 1942 to 1958. The site was then obtained by the State of Colorado in 1988, until the ownership was transferred to the City of Rifle in 2000. During this period, surface remediation of the site began in early 1992 and was completed in October 1996. Although the facility has since been demolished and the uranium mill tailings have been moved to a disposal cell, the alluvial aquifer below is contaminated with uranium, vanadium, and selenium. This contamination occurred via seepage from the previous mill tailing piles and the raffinate pond at the site. The uranium remaining in the subsurface under the capped waste piles was predicted to be flushed by natural groundwater flow. However, today uranium has persisted at elevated concentrations in groundwater much longer than predicted. This has been determined by analyzing groundwater samples twice a year, from 1998 to 2015. Uranium, as a contaminant, poses severe potential health hazards to humans and the environment. When unmonitored in the environment, uranium has the potential to affect the quality of surface water, groundwater, and food supplies. This is a toxic chemical that can lead to acute health effects such as kidney damage and various forms of cancer.

Previous studies have shown that the injection of hydroxyapatite (HA) as a permeable reactive barrier (PRB) in groundwater leads to uranium sequestration. One investigation included a pilot study LM conducted using the PRB technology to remediate uranium at the Old Rifle Site in Colorado. While this process has proved to be effective, a better understanding of the uranium removal mechanisms behind the interaction is required. The site is currently being reused by housing an operations and maintenance facility as well as conducting biogeochemical research on constituents of concern.

FIU in collaboration with DOE-LM is investigating the use of apatite injection for sequestering uranium in groundwater. Specifically, FIU is studying the mechanism of U removal from groundwater using apatite as well as the environmental factors that influence the stability of U removal. The experiment described herein was designed to imitate the real-life conditions when applying this technology as a permeable reactive barrier. It studies the interaction of hydroxyapatite and uranium when aqueous HA is first injected and is in the process of precipitating, which takes approximately 3.5 - 5.3 weeks. The purpose of this experiment is to study the incorporation and co-precipitation of uranium onto HA. The data obtained in this study will help fill the knowledge gaps on the mechanisms involved in the removal of U and the stability of U removal and assist DOE-LM in remediating uranium at other sites where uranium is present in groundwater.

## Task 1: Objectives

The purpose of this study is to identify the mechanisms of uranium removal by apatite and the stability of uranium removal under various environmental conditions (such as temperature, ORP, etc.). The specific objectives of this research include the following:

- Determine the mechanism of uranium removal from groundwater by apatite.
- Study the environmental factors that influence the stability of U removal over time.

A three-phase approach has been designed to identify the mechanisms of uranium removal. The first phase focuses on studying the synthesis, formation kinetics, and characterization of apatite by mixing calcium (Ca), citrate ($C_6H_8O_7$) and phosphate ($PO_4^-$) solutions. Phases two and three studies the interaction of uranium with apatite during and after formation of apatite. The mechanisms behind the interaction of uranium and apatite could include adsorption/sequestration of uranium onto apatite, precipitation of U-phosphate surface phases, phosphate precipitates coating uranium surface phases, or surface complexation. This year, the research completed phase one characterization and then focused on the second and third phase of the experiment, including the incorporation and co-precipitation of uranium onto hydroxyapatite as well as the sorption and desorption of uranium from hydroxyapatite. Hydroxyapatite takes approximately 3.5 - 5.3 weeks to fully form so the samples were allotted 6 weeks to reach equilibrium in all experiments. (Szecsody et al. 2017).

Phase two, the incorporation and co-precipitation experiment, will imitate the real-life conditions when applying this technology as a permeable reactive barrier. It studies the interaction of hydroxyapatite and uranium when aqueous HA is first injected and is in the process of precipitating. The purpose of this experiment is to study the incorporation and co-precipitation of uranium during the formation of HA.

Phase three focuses on studying the sorption and desorption of hydroxyapatite onto uranium. This step intends to imitate the application of this technology once the hydroxyapatite has fully precipitated in the treatment zone and is interacting with the contaminated groundwater.

## Task 1: Methodology

### *Hydroxyapatite Synthesis*

Hydroxyapatite was synthesized by combining calcium-citrate and phosphate solutions in triplicates at varying stoichiometric ratios, with a constant citrate concentration of 100 mM (Figure 1). Sample pH was monitored regularly for 6 weeks, supernatant was removed, and solid samples were washed three times with deionized water to remove impurities. Washing was achieved by mixing the precipitate with deionized water, followed by centrifuging, removing supernatant, and replacing it with fresh deionized water. Once washing was complete, precipitate was placed in an oven at 30°C until dry. Synthesized hydroxyapatite was brought into contact with a 250 ppb uranium solution while varying environmental factors such as pH, ORP and temperature. Uranium concentration is based on background concentrations at the Old Rifle, CO site (Rigali, 2018).

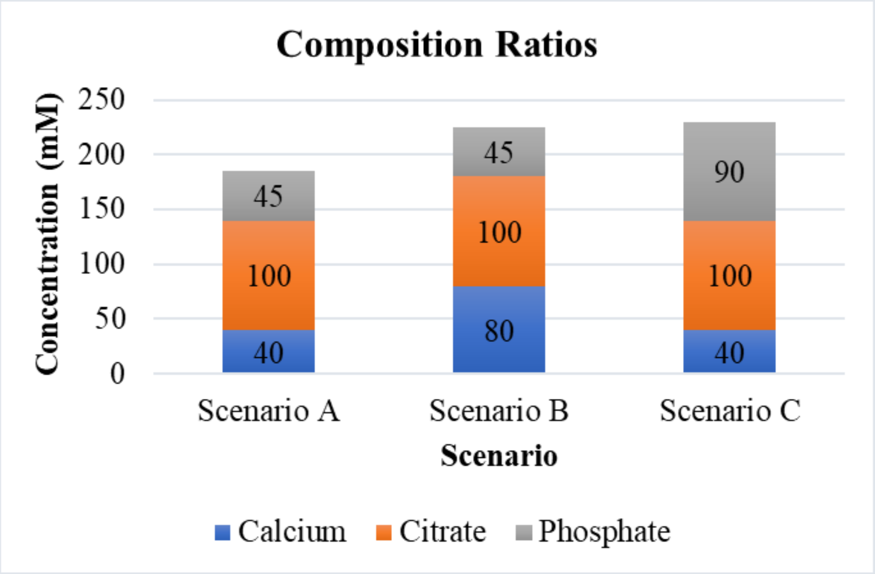

**Figure 1. Composition of calcium, citrate, and phosphate ratios.**

*Sorption Studies*

Preliminary solid to liquid ratio experiments were conducted at 0.5, 1.0, and 2.0 g/L to determine the influence of an initial amount of hydroxyapatite on uranium sequestration. An appropriate amount of hydroxyapatite was brought in contact with 40 ml of 250 ppb uranium solution. The pH of the samples was monitored and 200 µL aliquots were collected at regular intervals for the duration of the experiment. Aliquots were analyzed via inductively coupled plasma - mass spectroscopy (ICP-MS) to measure aqueous concentrations of total Ca, P, and aqueous U. From this, a 0.5 g/L ratio was chosen, and 0.02 mg of HA was brought into contact with 40 mL of 250 ppb uranium.

To determine when the samples would reach equilibrium, kinetic experiments were conducted. These experiments followed the method described previously, except 500 µL aliquots were collected at regular time intervals. All aliquots collected were analyzed on an ICP-MS to obtain the aqueous uranium concentration and it was determined that equilibrium was reached within two weeks.

Sorption studies were conducted under various conditions, as shown in

Table **1**. These factors were studied since geochemical factors, such as pH, and their effects on U(VI) aqueous speciation have a significant impact on U(VI) adsorption in aquifers (Bond et al., 2007; Curtis et al., 2006; Fox et al., 2006; Hyun et al., 2009; Qafoku & Icenhower, 2008). Similarly, the fundamental processes of uranium mobility in the subsurface can be affected by numerous variables, such as redox potential, temperature, and pH (Gavrilescu et al., 2009; Smedley & Kinniburgh, 2022; Xu et al., 2019).

The pH and ORP of these samples were monitored or adjusted as needed, and samples were analyzed after two weeks. Uranium exhibits complex aqueous speciation when exposed to oxygen, with the hexavalent uranyl ion ($UO_2^{2+}$) predominating at low pH and its numerous hydrolysis and carbonate complexes predominating at neutral to alkaline pH levels (Hyun et al., 2009; Waite et al., 1994). Since uranium is redox-sensitive, it is necessary to gain information on the hydroxyapatite-uranium interaction in both oxic and anoxic conditions.

**Table 1. Environmental Conditions Studied**

| Temperature | pH | | | ORP |
|---|---|---|---|---|
| | 4 | 7 | 9 | |
| Low Temperature (7°C) | Condition 1 | Condition 2 | Condition 3 | Oxic |
| Room Temperature (22°) | Condition 4 | Condition 5 | Condition 6 | Oxic |
| Room Temperature (22°) | Condition 7 | Condition 8 | Condition 9 | Anoxic |

Additionally, sorption isotherm investigations were coordinated to gain more information about the sorption capacity of HA. Uranium concentrations of 500, 750, and 1000 ppb were examined. This analysis was completed by bringing HA into contact with the respective uranium concentrations at the same solid to liquid ratio for the same duration used previously. Samples were analyzed via ICP-MS at the end of the experiments to collect aqueous uranium concentrations.

*XRD Analysis*

A Bruker D2 PHASER XRD instrument (Figure 2) was used for characterization of the hydroxyapatite solids that formed throughout these experiments. Samples were individually packed flat onto a sample holder (Figure 3) and analyzed via XRD from a 2θ value of 5-90˚ with a 0.05° step size. Observed X-ray diffraction patterns were matched to the International Centre for Diffraction Data's power diffraction file database (PDF) with the pattern matching software DIFFRAC.EVA.V5.1 for analysis.

**Figure 2. Bruker D2 PHASER XRD instrument.**

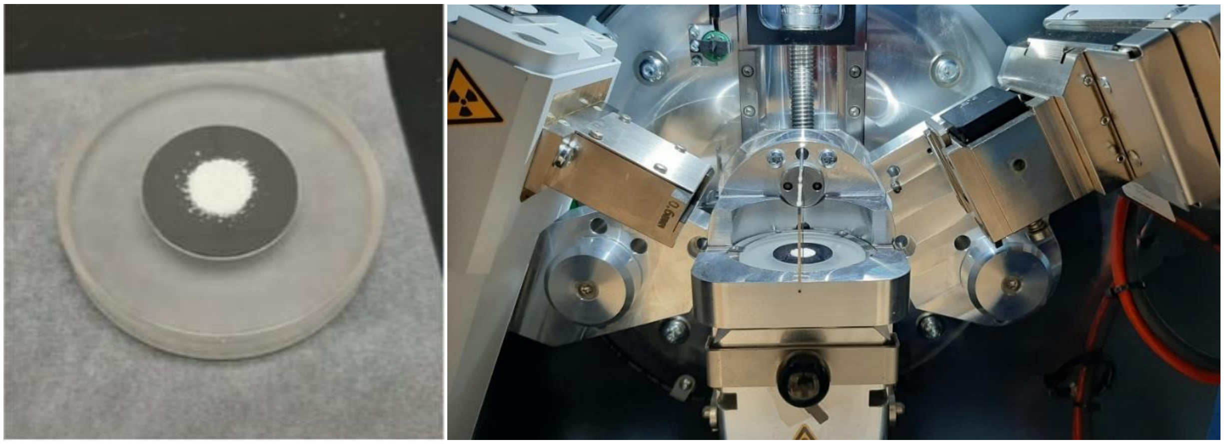

**Figure 3. Hydroxyapatite powder on sample holder prepared for XRD analysis.**

### *SEM-EDS Analysis*

SEM analysis was conducted at FIU's Florida Center for Analytical Electron Microscopy (FCAEM) facility to obtain clear images that could show the structure of the HA precipitate. Prior to being loaded into the instrument, the respective samples were mounted on metal studs layered with carbon tape and loaded into a six-stub holder to ensure that the samples were secured properly (Figure 4). The surface characterization was accomplished using a JEOL IT500HR Field Emission Microscope equipped with the Bruker XFlash 6160 energy dispersive x-ray spectroscope (EDS) with a 60 mm window SDD detector. EDS analysis was conducted at a 15 kV accelerating voltage with a 10 mm working distance to properly observe the surface characteristics. When conducting EDS analysis, at least three points from each sample were selected to detect the presence of elements. Due to the use of the carbon tape, carbon was deconvoluted when interpreting the data obtained from the EDS analysis. Samples for SEM analysis were sputter coated with gold using an SPI Module Sputter Coater and Vacuum Base with Pump 110v to obtain sharp, clear images (Figure 5).

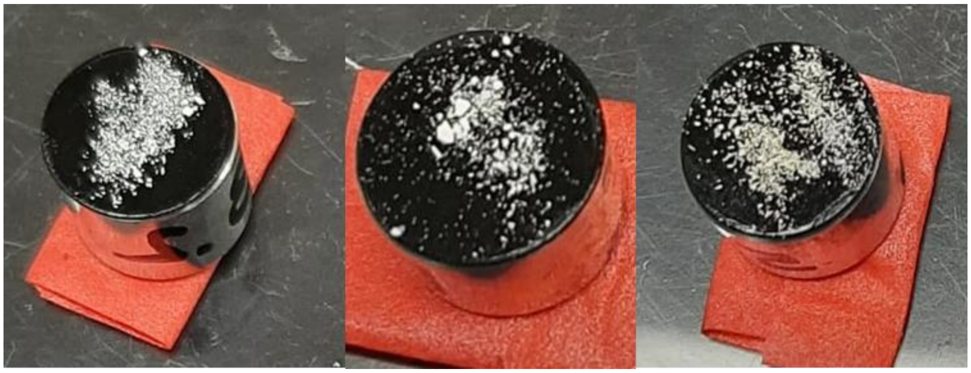

**Figure 4. Dried HA Precipitate Prepared for SEM Analysis.**

**Figure 5. Instrument used to gold coat samples.**

*ICP-OES/MS Analysis*

Aqueous samples were analyzed via iCAP RQ Quadrupole (Thermo Fisher) inductively coupled plasma - mass spectrometry (ICP-MS) and Optima 7300 DV (Perkin Elmer) inductively coupled plasma - optical emission spectrometry (ICP-OES) to measure aqueous concentrations of Ca, P, and U over time. Prior to analysis, aliquots were further diluted to ensure the concentrations of Ca, P, and U would be within the range of the calibration curve. The ranges included 0.5 - 20 ppm for P, 0.5 - 20 ppm for Ca, and 0.1 - 100 ppb for U.

## Task 1: Results and Discussions

*Solid to Liquid Ratio*

Analysis of aqueous samples via ICP-MS provided remaining aqueous uranium concentrations over time. Percentage of uranium removal was calculated from ICP-MS data and as shown in Figure 6 - Figure 8, equilibrium was reached within approximately seven days. Scenario A and C with 0.5 and 1.0 g/L ratios followed a similar trend for each respective scenario. Scenario A had a gradual increase in U removal, followed by rapid removal and reached equilibrium in 7 days. Scenario C displayed drastic U removal within the first three days and stabilized. For the 2.0 g/L ratio, swift removal of U was observed for both scenarios within the first three days and equilibrium was achieved in 7 days. Scenario A’s slower reaction time for the smaller ratios could be due to less available surface area, hence more time required to equilibrate. Since both scenarios accomplished high removal at all ratios, 0.5 g/L was chosen for subsequent experiments for efficiency purposes. From these results, the following experiments were allotted two weeks to ensure equilibrium was reached.

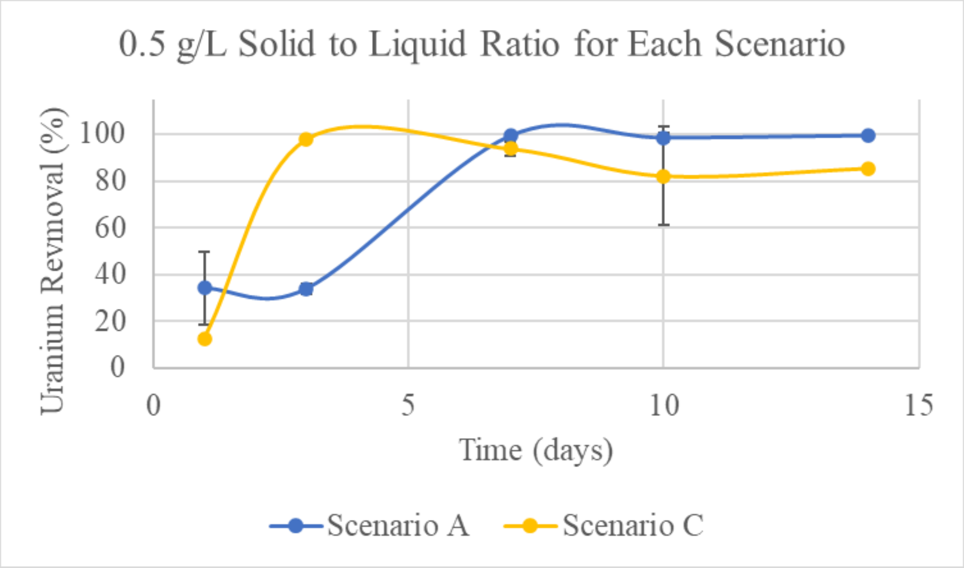

**Figure 6. Uranium removal over time for 0.5 g/L solid to liquid ratio.**

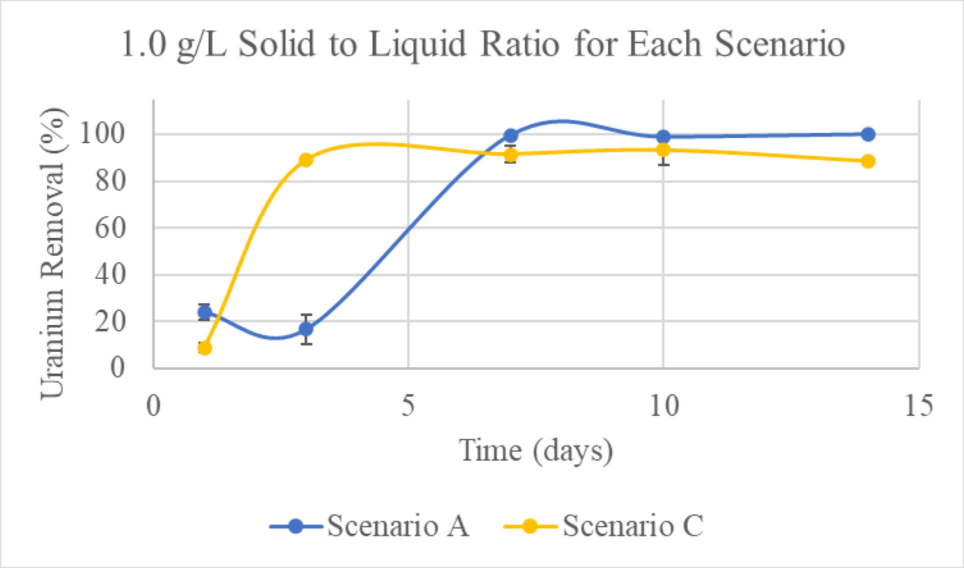

**Figure 7. Uranium removal over time for 1.0 g/L solid to liquid ratio.**

*Sorption Experiments*

ICP-MS analysis provided aqueous uranium concentrations for each environmental condition studied, which can be seen in Figure 9 - Figure 15. Figure 9 reveals that at low temperatures, pH 4 had the least amount of uranium removal for both Scenarios A and C, at 27% and 13% respectively. Samples at neutral and alkaline pH had removal between 87 – 97%. At room temperature, pH had a significant effect on Scenario C (Figure 10) with relatively low removal at pH 4 and 9 compared to pH 7. In these conditions, Scenario C obtained only 44 and 46% removal, respectively, while pH 7 achieved 92% removal, similar to Scenario A at all pH values. The effect of pH was also apparent in anoxic, room temperature conditions for both scenarios (Figure 11). Uranium removal as low as 6 and 3% was recorded at pH 4 for Scenarios A and C, respectively. Scenario A obtained 71 - 81% removal at pH 7 and 9, while Scenario C reached 54 - 68% removal.

Lower uranium removal at pH 4 could be due to uranium mobility being favored in these conditions, and therefore less removal is occurring. Overall, this analysis revealed that anoxic and acidic conditions had a negative effect on uranium removal via HA.

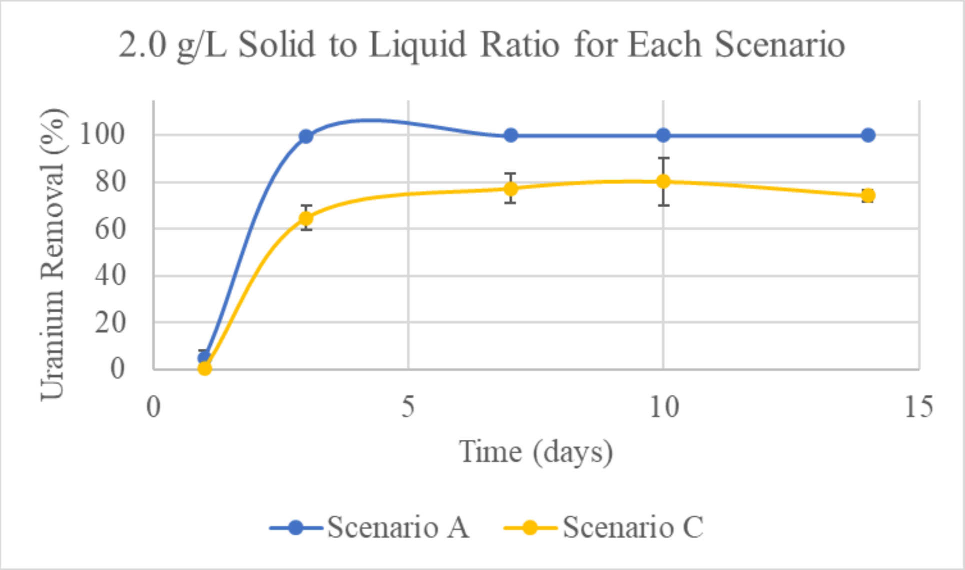

**Figure 8. Uranium removal over time for 2.0 g/L solid to liquid ratio.**

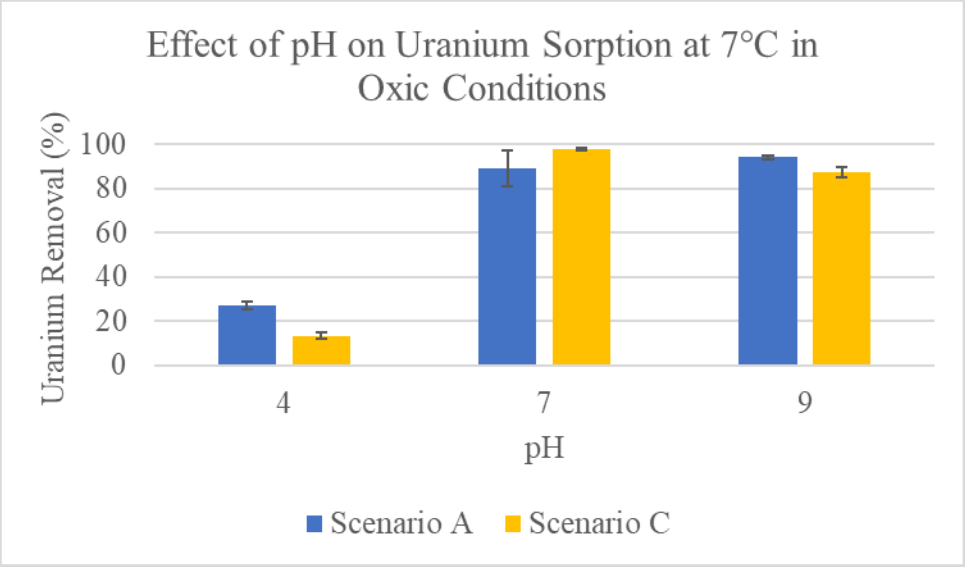

**Figure 9. Effect of pH on uranium sorption at 7°C in oxic conditions.**

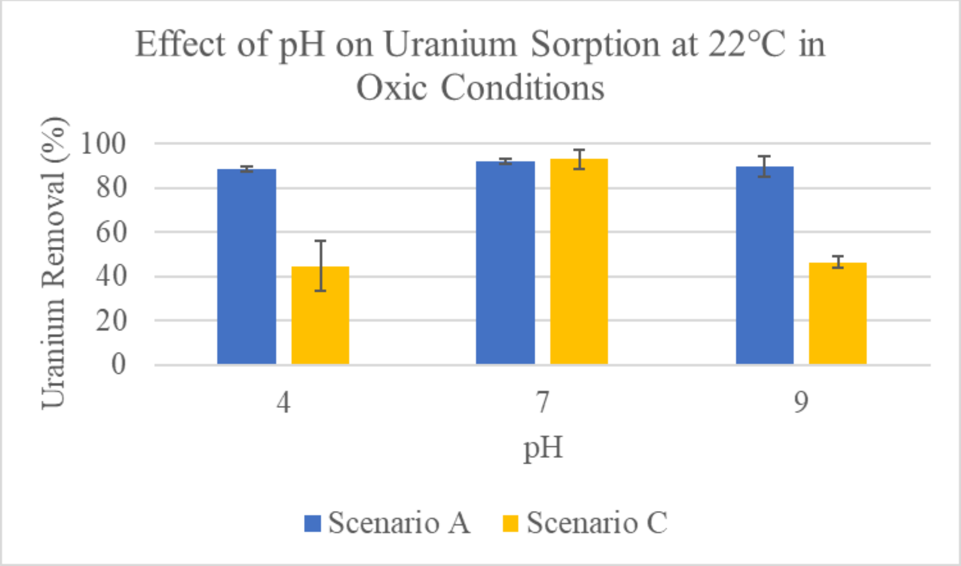

**Figure 10. Effect of pH on uranium sorption at 22°C in oxic conditions.**

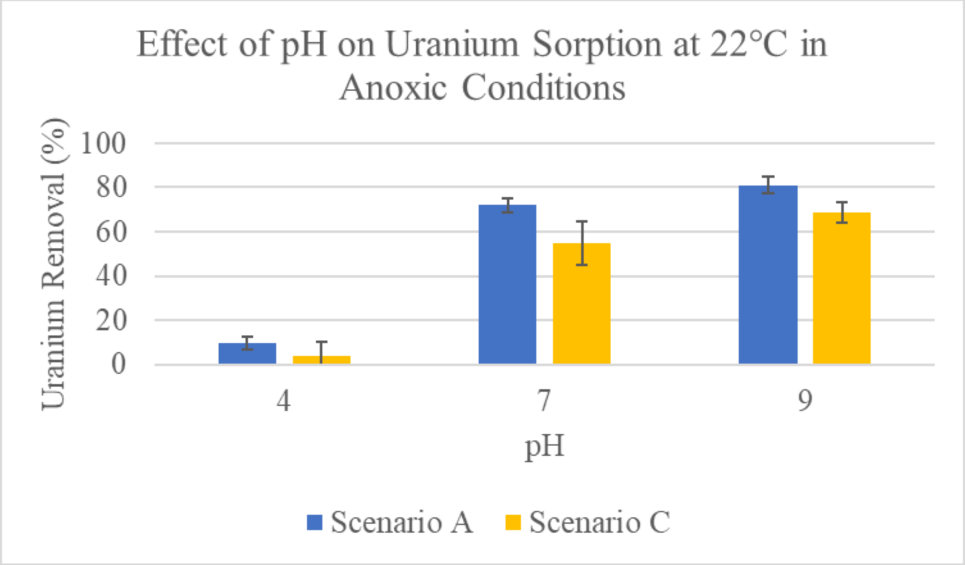

**Figure 11. Effect of pH on uranium sorption at 22°C in anoxic conditions.**

Figure 12 and Figure 13 can be examined to evaluate the effect of temperature on the sorption of uranium via HA. The effect of temperature is most apparent in acidic conditions, while some variance was observed in alkaline conditions for Scenario C. In Scenario A, temperature appeared to have a prominent negative effect on uranium removal at pH 4. Removal decreased from 88% at 22°C to 27% at 7°C. At pH 7 and 9 in Scenario A, the removal was comparable ranging between 88 – 93%. Scenario C removal was significantly lower at pH 4 for low temperatures. Acidic conditions accomplished merely 13% and 44% removal at low and room temperatures, respectively. In contrast, alkaline pH observed higher removal in cooler temperatures (87%), while higher temperatures achieved only 46%. Neutral pH consistently achieved high levels of removal at all temperatures.

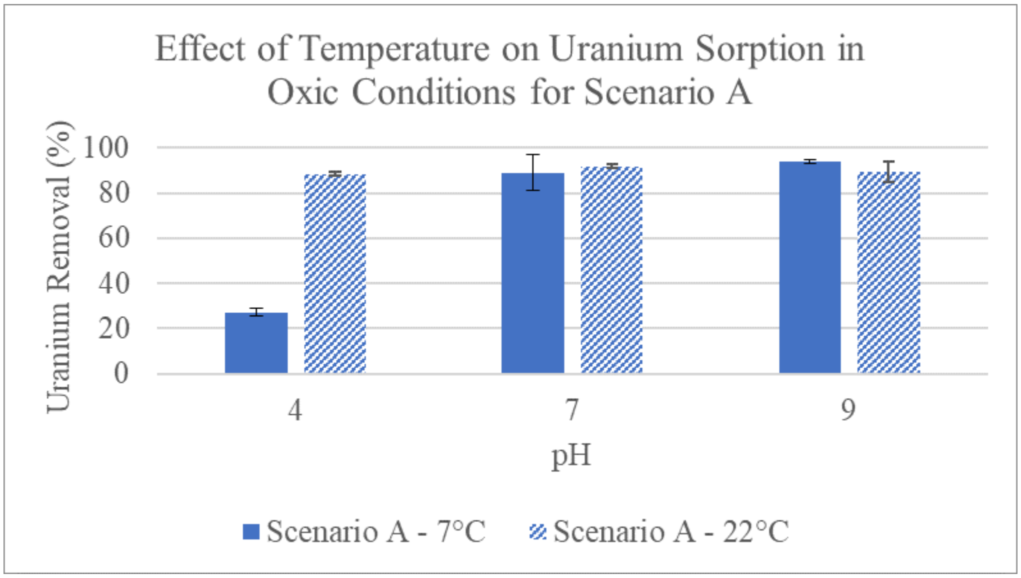

Figure 12. Effect of temperature on uranium sorption in oxic conditions for Scenario A.

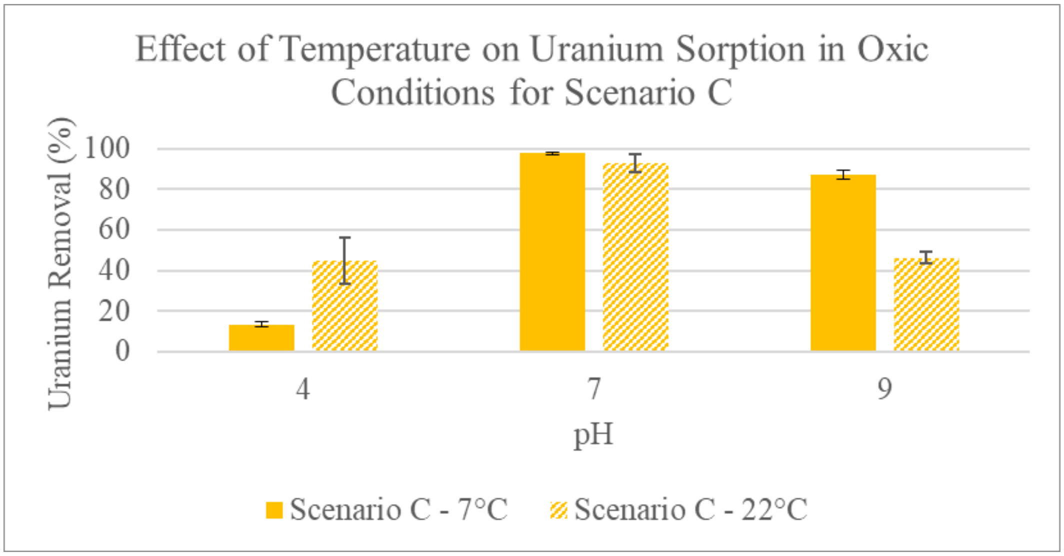

Figure 13. Effect of temperature on uranium sorption in oxic conditions for Scenario C.

The effect of ORP on uranium removal can be seen in Figure 14 and Figure 15. In almost all cases, less uranium was sorbed in anoxic conditions, apart from Scenario C at pH 9. The most significant difference in removal is seen at pH 4. Scenario A in oxic conditions appeared to have 88% removal while anoxic conditions only removed 9%. Removal at other pH values for Scenario A did not have such a stark contrast, however there was still noticeable variability. For example, anoxic conditions had removals of 71% and 81% at pH 7 and 9, respectively, while oxic conditions revealed 91% and 89% removal. Distinct changes were also witnessed for Scenario C at pH 4, with 3% removal in anoxic conditions and 44% in oxic. There was distinct variation at pH 7, with 54% in anoxic and 92% in oxic. Higher removal was only observed under alkaline pH in anoxic conditions, with 68% removal versus 46% in oxic. Minimal removal in anoxic conditions could be due to uranite being more prevalent, which is less soluble and would not be apparent in aqueous solution.

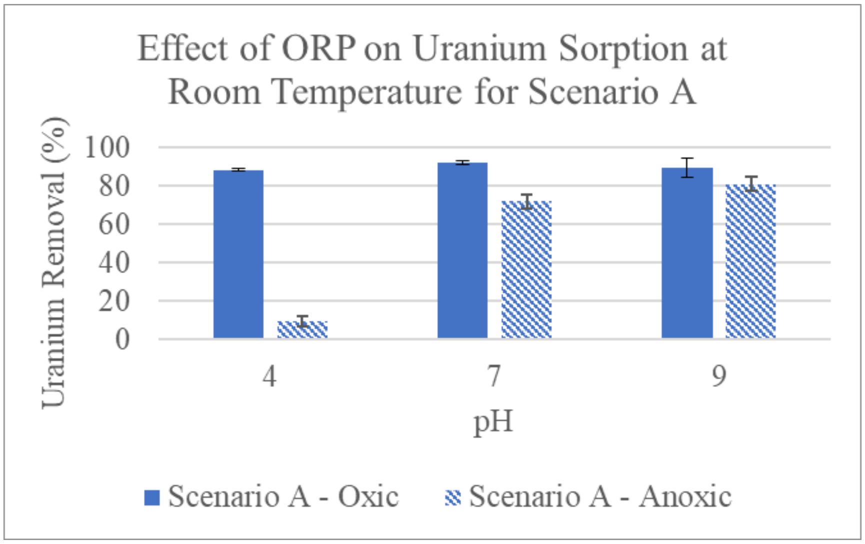

Figure 14. Effect of ORP on uranium sorption at room temperature for Scenario A.

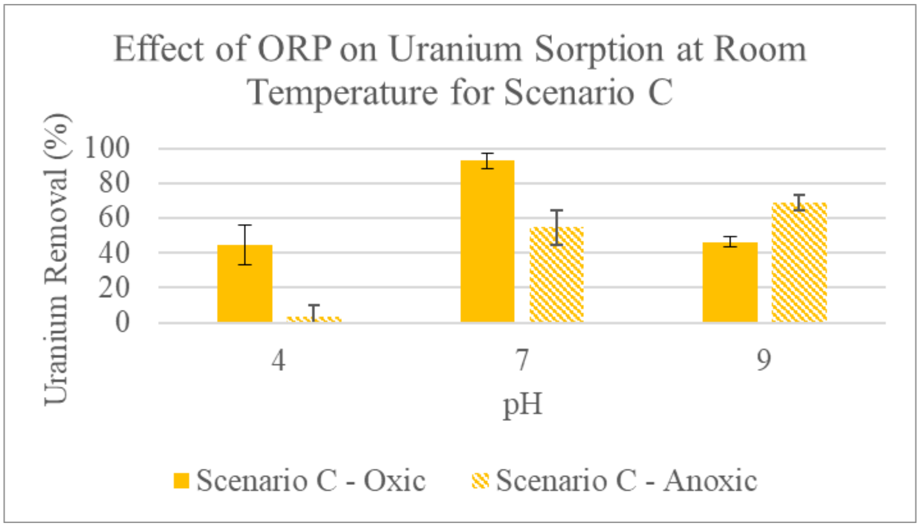

Figure 15. Effect of ORP on uranium sorption at room temperature for Scenario C.

*Sorption Isotherms*

Given the high removal of uranium observed in most environmental conditions investigated, an examination of hydroxyapatite's sorption capacity under Old Rifle site conditions was conducted. With higher uranium concentrations ranging from 500-1000 ppb, uranium removal was consistently found to be 91% or higher (Figure 16). From Figure 17, it is apparent that sorption has not reached equilibrium, indicating the sorption capacity has not been reached. This evidence suggests that hydroxyapatite can be used to sequester uranium at other sites that have higher uranium concentrations.

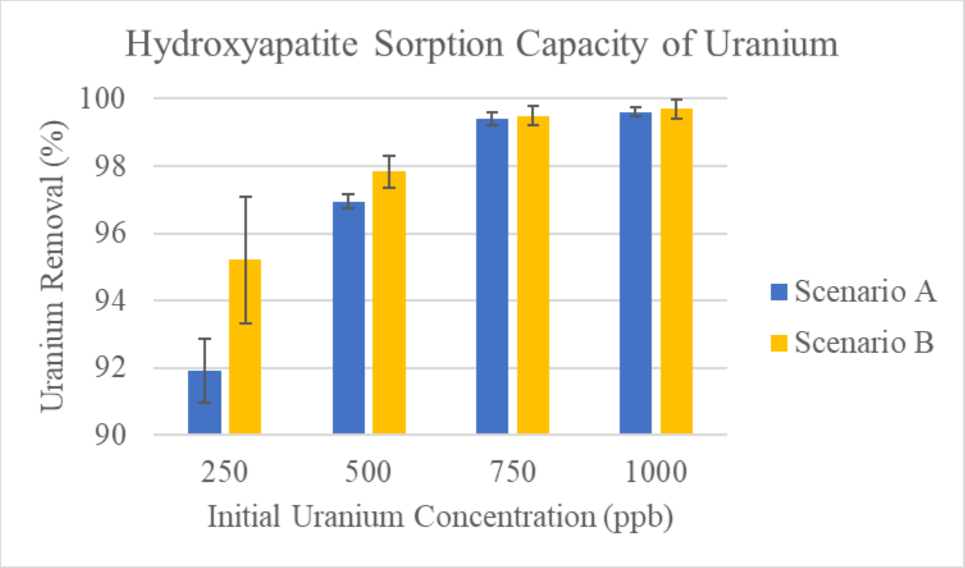

**Figure 16. Hydroxyapatite sorption capacity of uranium.**

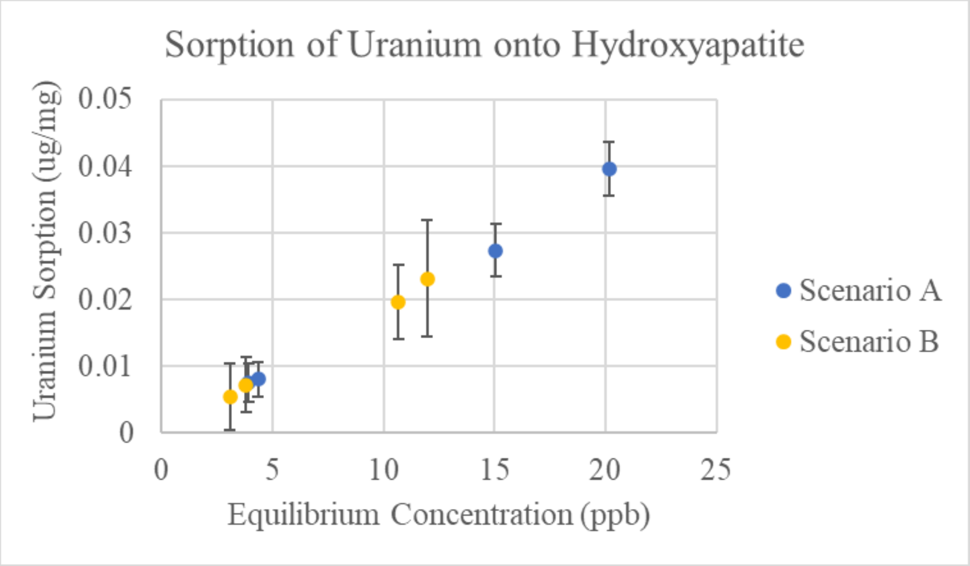

**Figure 17. Sorption of uranium onto hydroxyapatite.**

## Task 1: Conclusions

The most significant impact on uranium removal was at pH 4 throughout all conditions studied, with far less removal seen in most cases. In oxic conditions, pH 7 maintained the highest level of removal. Temperature had a greater effect on uranium sorption in Scenario C, while Scenario A only observed distinct differences at pH 4. It is evident that anoxic conditions had a significantly negative effect on uranium removal in comparison to oxygen-rich environments.

When uranium concentrations were raised up to 1,000 ppb at Old Rifle site conditions (pH 7, T=22°C), hydroxyapatite had the capacity to remove 91-99% of uranium. This indicates that hydroxyapatite technology would effectively remediate uranium at sites with similar conditions. Further studies would be useful to determine the full extent of hydroxyapatite's sorption capacity.

Overall, these studies support the use of hydroxyapatite for uranium remediation in groundwater. Results found here could help guide users on which site conditions would result in more effective uranium removal. Further investigation should be done to determine the possibility of desorption when utilizing HA technology.

The data obtained will help fill the knowledge gaps on the mechanisms involved in the removal of U and the stability of the removal and assist DOE-LM in remediating uranium at the sites where uranium is present.

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# TASK 2: CLIMATE RESILIENCY STUDIES FOR LONG-TERM SURVEILLANCE OF DOE-LM SITES

## Task 2: Introduction

FIU has been investigating the effects of climate change and premature erosion concerns in disposal cells in collaboration with the U.S. Department of Energy's Office of Legacy Management (LM). The study contributes to Goal 4 of LM's 2020-2025 Strategic Plan: *"Sustainably manage and optimize the use of land and assets, addressing severe weather events."*

Even though the LM's disposal cells were designed to be effective for at least 200 years, concerns started when subsurface erosion spots, shown in Figure 18, were discovered in 2017 at the Mexican Hat cell in Utah. The erosion only manifested in the surface as slight depressions where the rock cover had subsided into the voids. Construction issues, including dispersive clays in the interbed layers between the radon barrier and the overlying rock cover, are potential causes. However, LM does suspect climate change is a contributing cause.

**Figure 18. Utah Mexican Hat Disposal Cell (left) and subsurface erosion discovered in 2017 (right).**

Despite the southwest USA being in a terrible drought, climate change projections indicate that precipitation events will be more intense and are showing up in the meteorological record for the site. During short, severe rainfall events, the rock cover essentially plays little role in slowing runoff. Rounded cobbles, instead of angular rock, may also be a factor since water runs off them and into interstices faster than angular rock. Considering that other LM sites may have similar features, during Year 3, FIU evaluated the feasibility of utilizing traditional remote sensing and geophysical technologies for cost-effective site characterization, potentially detecting premature subsurface erosions.

## Task 2: Objectives

The main goal of this task is to evaluate the viability of using a Ground-Penetrating Radar (GPR) sensor for cost-effective site characterization and monitoring of existing subsurface conditions of LM's disposal cells. The investigation pursued the following objectives:

- Integration of a commercially available GPR sensor into an autonomous ground platform, and
- Deployment of a prototype at the Rifle Disposal Cell in Colorado and potentially other disposal sites during the summer.

Autonomous GPR surveys, producing detailed underground imagery, can effectively inform site managers in decision-making regarding existing subsurface conditions and hydrological trends. This non-invasive method images sites without surface disturbance or potential radiological exposure if the radon barrier erodes. Furthermore, using GPR surveys to inspect disposal cells over time will benefit LM in detecting many landfill changes, such as water flow, sinkholes, underground erosion, ground creep, and sediment flow. The GPR robot in development at FIU can monitor long-term effects, correlating underground erosion with climate resilience and extreme weather events.

## Task 2: Methodology

### GPR Sensor Procurement and Evaluation

A GPR sensor with a 250 MHz antenna was procured. The selection was guided by Table 2, considering a radar suitable to image subsurface erosion similar to the spots discovered at the Mexican Hat in 2017. The imager's performance was tested under different soil conditions around FIU's campus.

**Table 2. GPR antenna recommended by the Manufacturer.**

| Noggin Antenna (MHz) | Ideal Depth (feet) |
|---|---|
| 1000 | 4 |
| 500 | 15 |
| **250** | **20** |
| 100 | 30 - 45 |
| Ultra 100 | 60 - 70 |

Illustrated by Figure 19, some preliminary tests were designed to give the LM Fellow a better understating of the sensor characteristics, guiding him in the subsequent sensor integration into a mobile ground platform.

**Figure 19. GPR preliminary tests.**

Figure 20 shows preliminary subsurface images captured during tests evaluating the reflection properties in different soils.

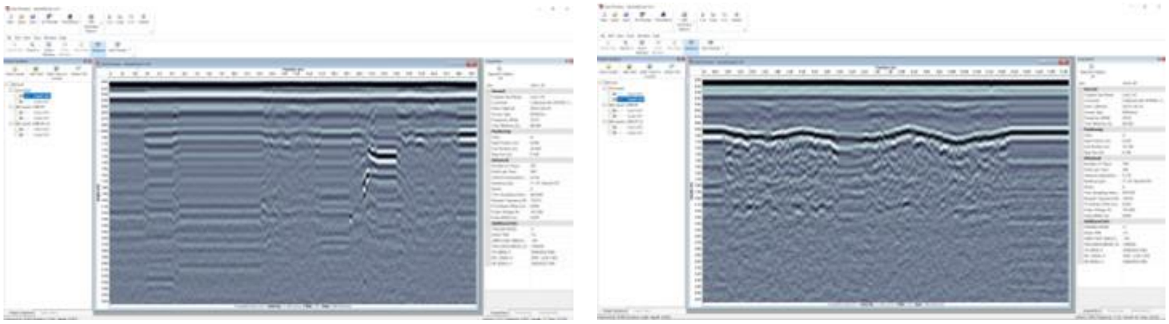

**Figure 20. Bare soil (left) and concrete cover (right) GPR data image.**

Figure 21 shows three mockups built at FIU to evaluate the procured GPR sensor further considering soil characteristics relevant to LM disposal cells.

**Figure 21. In-house Disposal Cell Mockups.**

Table 3 presents the mockups' respective soil layer compositions.

**Table 3. In-house Disposal Cell Mockups**

| **Testbed 3** | **Testbed 2** | **Testbed 1** |
|---|---|---|
| 1' Riprap (Layer of rocks) | 0.656'Riprap (Layer of rocks) | 1'Riprap (Layer of rocks) |
| ½'Bedding (Layer of rock/soil mixture) | ½'Bedding (Layer of rock/soil mixture) | ½'Bedding (Layer of rock/soil mixture) |
| ½' Frost protection (Layer of compacted soil) | ½'Bentonite Clay (Radon barrier) | 1'Frost protection (Layer of compacted soil) |
| ½' Bentonite clay (Radon barrier) | N/A | N/A |

In testbeds 2 and 3, the first layer starts with ½' of bentonite clay. LM uses compacted bentonite clay as a radon barrier placed directly above the contaminated materials.

The mockup composition was based on the DOE Fellow's study of several LM disposal cells across the country, establishing a comparison matrix of the repositories' subsoil layers presented in Table 4.

**Table 4. Disposal Cell Comparison Matrix**

| Disposal Cell | Erosion Protection | Bedding | Frost Protection | Bio Intrusion Riprap Type A | Bedding | Radon Barrier |
|---|---|---|---|---|---|---|
| **Durango** | 1'0" | 6" | 1'6" | 1'6" | 6" | 2'0" |
| **Rifle** | 1'0" | 6" | 7'6" - 18' | None | 6" | 1'6" |
| **Mexican Hat** | 8” & 12” | 6" | None | None | None | 2'0" |
| **Lakeview** | 1'0" | 18" | None | None | None | 18" |
| **Sherwood** | 6" | 12.6' - 20' | None | None | None | None |

Figure 22 illustrates construction details, including PVC pipes with 2, 3, and 4 diameters embedded into the bedding layers to evaluate the GPR resolution and sensitivity. The bedding layer is located above the frost protection layer, which is composed of coarse sand and gravel for testbeds 1 and 3.

**Figure 22. Testbeds 1, 2, and 3 bedding layers, respectively.**

Figure 23 shows the completed testbeds 1, 2, and 3. Riprap rocks compose the top layer. LM uses variable-sized river rocks to isolate contaminated materials and protect them from weather conditions.

**Figure 23. Depiction of the riprap layer.**

Figure 24 illustrates subsurface images captured during FIU’s in-house tests.

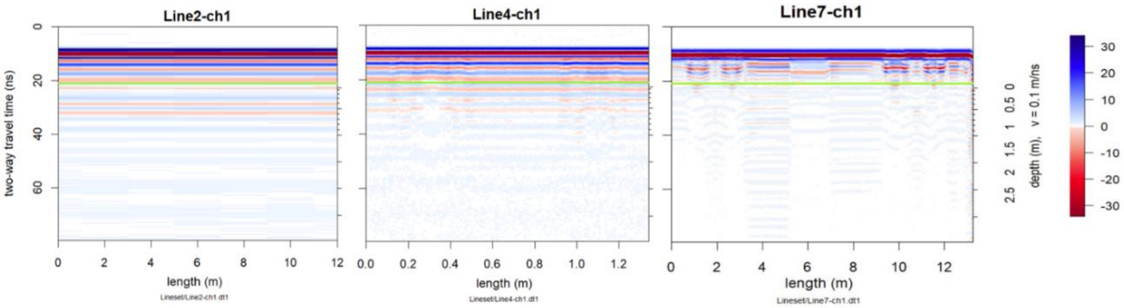

**Figure 24. Captured GPR subsurface images during in-house tests.**

## Autonomous Ground Platform Development and GPR Sensor Integration

Based on the GPR's characteristics and preliminary performance test, an autonomous ground platform was designed and built at FIU's Applied Robotics Laboratory. The design considered the peculiar terrain conditions gathered at the Rifle and Mexican Hat cells during summer inspections performed by the LM Fellow. Not disturbing the cells' rock coverage and producing tires or track scars during inspections is also a critical design aspect.

To guide the robot conceptual design, initial tests, shown in Figure 25, were performed with a conventional all-terrain wheeled ground platform traversing scenarios on rocky terrains typical of many LM disposal cells' coverage.

**Figure 25. Preliminary rocky terrain traversal tests using an all-terrain wheeled robot.**

Preliminary tests also included autonomous waypoint GPS navigation on an open field behind FIU’s Engineering Center. Figure 26 depict a ground control station tracking the robot's position in real-time, executing a preprogram waypoint trajectory simulating a GPR survey. The plan includes continuing to develop an organic semi-autonomous operator interface in the following performance period. The vision is to use a tablet custom graphical user interface where site personnel can select target areas of interest over the disposal cell's satellite images, and the system would perform the inspections autonomously, alleviating personal operational burdens.

**Figure 26. Autonomous waypoint GPS navigation tests.**

Figure 27 shows the GPR robot’s conceptual design. The ground platform's chassis has a U-shaped frame design, high floor clearance, and four-wheel drive suitable for traversing LM disposal cells’ rocky coverage.

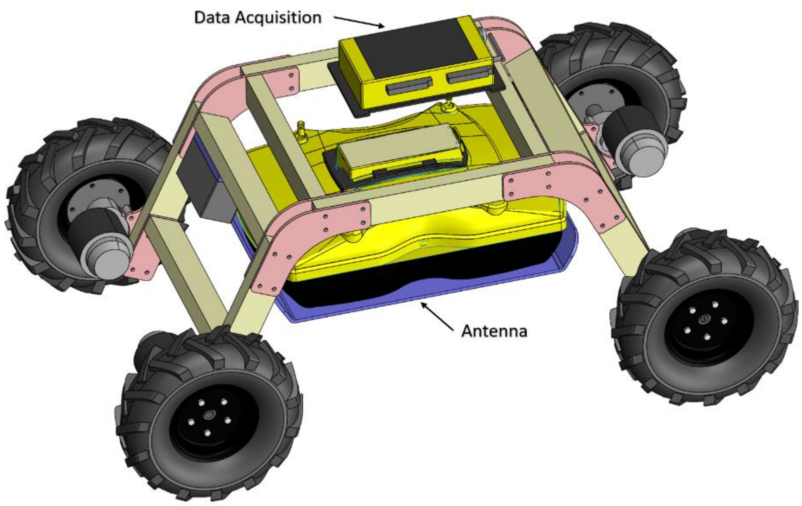

**Figure 27. GPR robot conceptual design.**

Figure 28 depicts crucial dimensions of the platform and sensor clearance. The dimensions consider transport and field deployment using a mid-size sports utility vehicle (SUV).

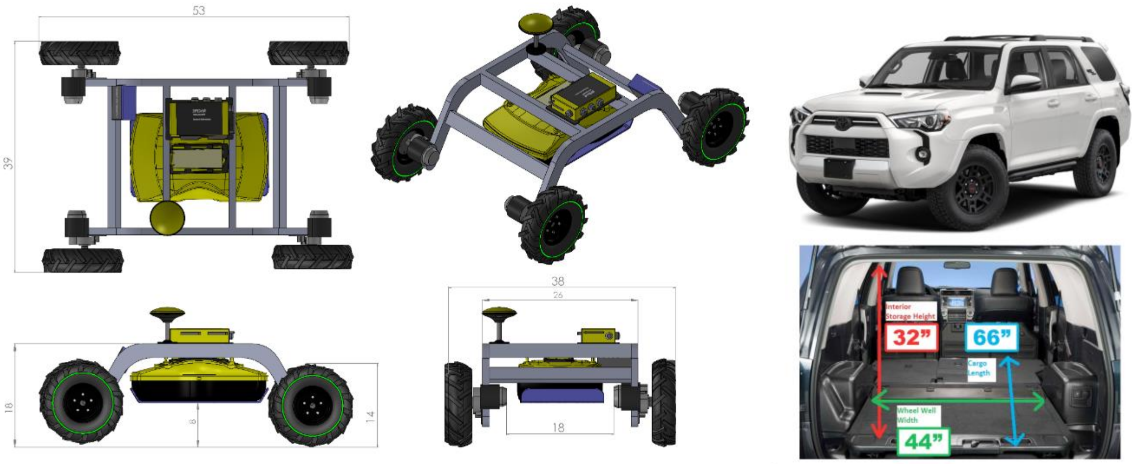

**Figure 28. Robotic platform conceptual design (in inches).**

Figure 29 shows the GPR rover functional prototype. The ground platform uses four independent high-torque motors directly connected to the wheels. The platform's direct drive capabilities increase torque, accuracy, and responsiveness when traversing challenging terrains.

**Figure 29. GPR robot prototype.**

Figure 30 shows the GPR rover’s mechatronics integration.

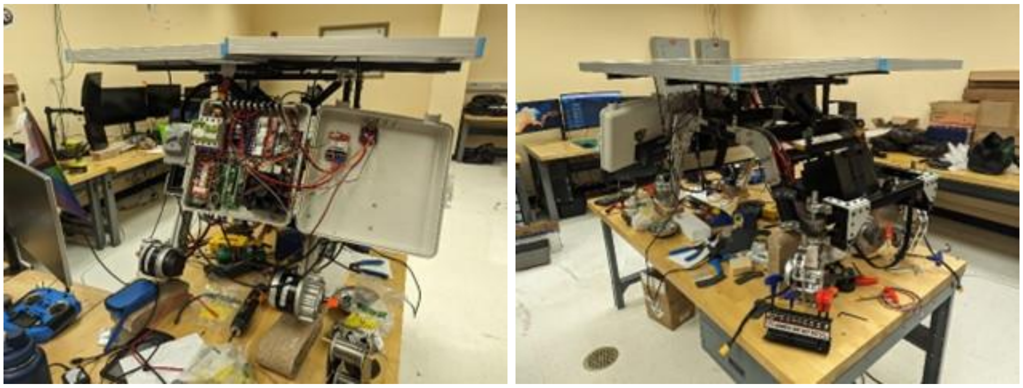

**Figure 30. FIU's GPR platform final electrical and mechanical adjustments.**

Figure 31 shows final tests controlling the GPR platform's solar panel actuators, retracting for transport and deployment. The solar panels fully power the platform 100% during inspections. They are also used as heat shields for main electrical components.

**Figure 31. GPR mobile robotic platform.**

Figure 32 illustrated the GPR antenna actuators designed to raise and lower the sensor along the rough terrain during surveys at LM's disposal cells.

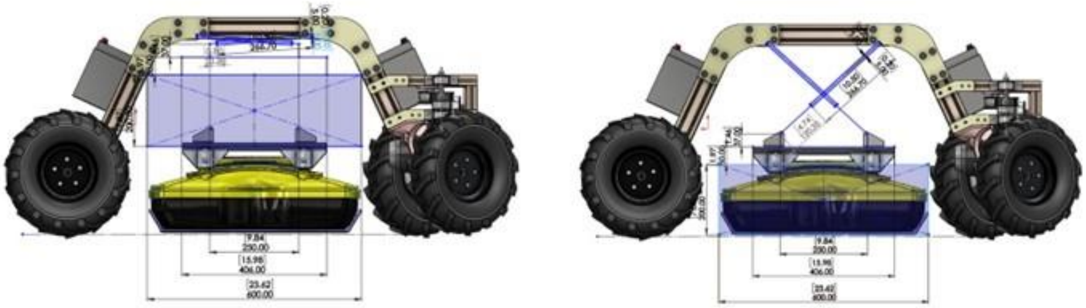

**Figure 32. Robot's GPR antenna actuator.**

Figure 33 shows robot loading and unloading from a USV truck, testing transport, and field deployment.

**Figure 33. GPR Robot transport tests.**

Figure 34 shows FIU's GPR Robot final prototype ready for the summer deployments at LM sites.

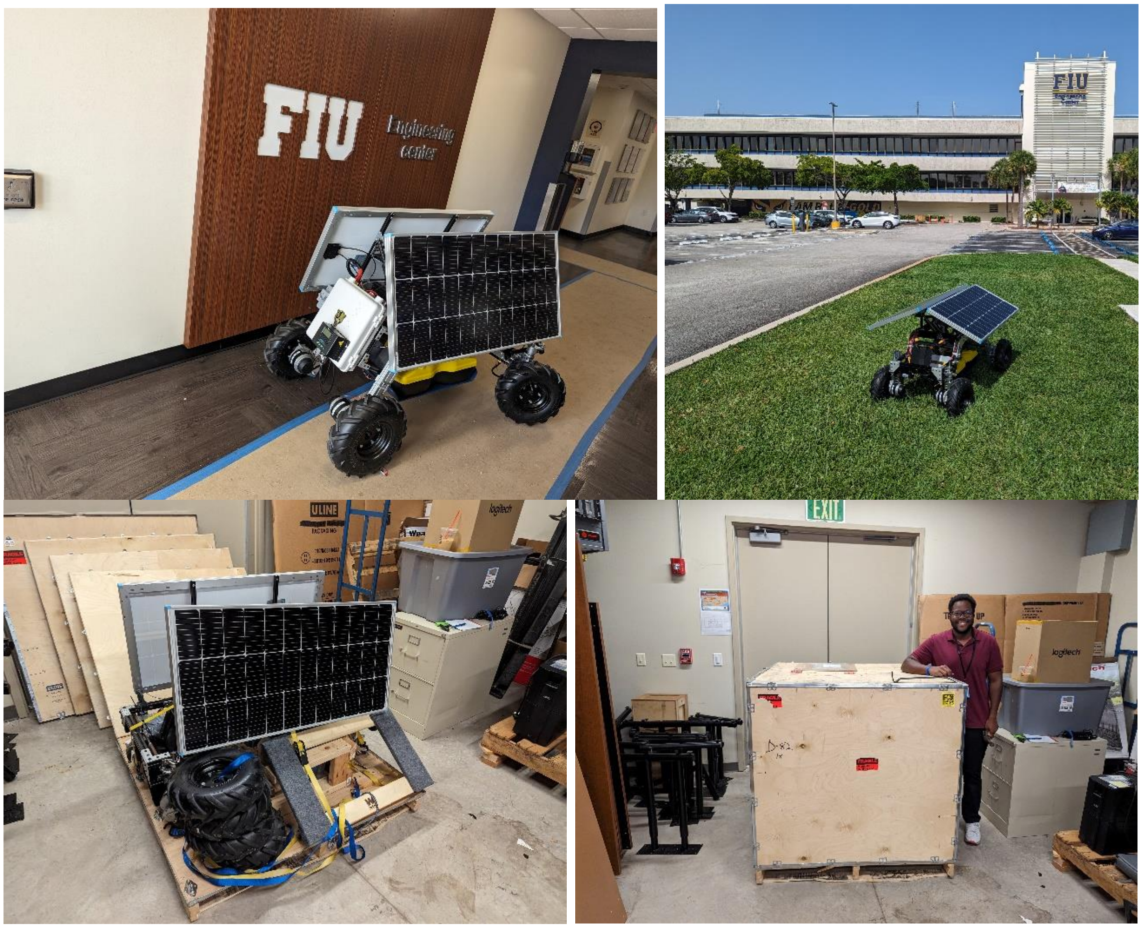

**Figure 34. FIU's GPR Robot.**

## Summer Deployments

The developed mobile GPR system designed and built at FIU was successfully deployed at the Mexican Hat cell in Utah, the Rifle cell in Colorado, and the Basin 6 at the Waste Isolation Pilot Plant (WIPP) in New Mexico during the summer. Figure 35, Figure 36, Figure 37 show pictures of the summer deployments respectively.

**Figure 35. Mexican Hat Disposal Cell deployment in Utah.**

**Figure 36. Rifle Disposal Cell deployment in Colorado.**

Figure 37. Basin 6 west of the WIPP in New Mexico.

## GPR Image Reconstruction

Returning to FIU, the captured topographical and GPR data has been post-processed, and subsurface maps of the disposal cells are still being generated. Figure 38 shows a typical transect line from the Rifle Cell survey. The disposal cell cross-section was created, combining elevation from GPS data and GPR subsurface images.

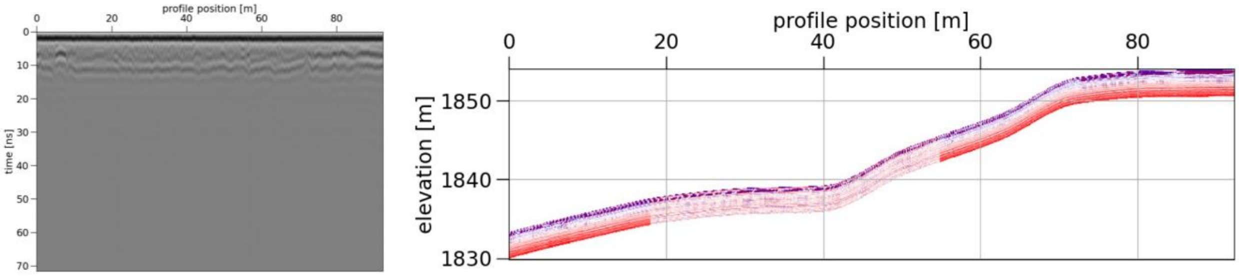

Figure 38. Transect line scanned at the Rifle Disposal Cell.

The data processing captured on the summer surveys, 3D subsurface reconstruction, and soil characterization will be the focus in FIU Year 4 (Sep. 2023 – Sep. 2024); however, Figure 39 shows a preliminary subsurface 3D model reconstruction. Noticeable depressions in the model show potential as a cost-effective tool for monitoring LM disposal cells' current subsurface conditions and premature erosion.

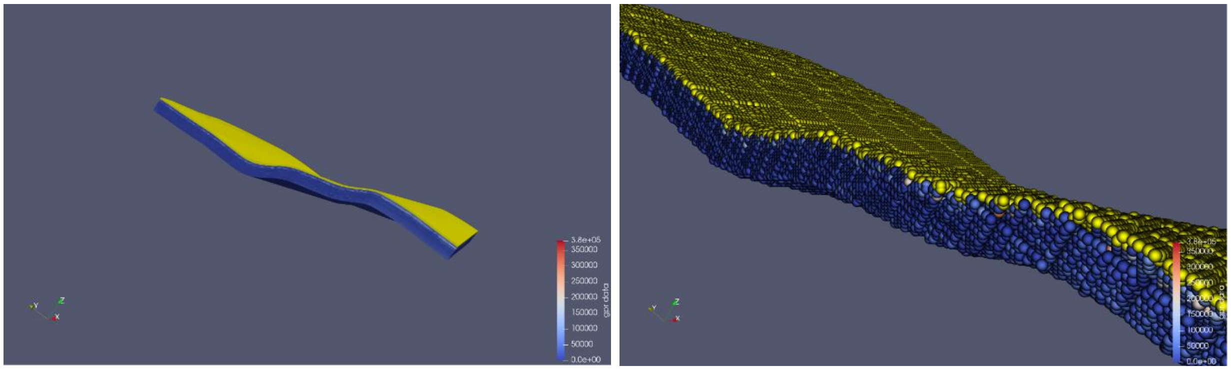

**Figure 39. Preliminary disposal cell subsurface construction.**

Plans for FIU Year 4 also include correlating the generated subsurface maps to our digital elevation model captured from an aerial lidar and photogrammetry survey performed by the previous DOE-LM Fellow during the summer of 2022.

## Task 2: Conclusions

Autonomous GPR surveys producing detailed underground imagery can effectively inform site managers in decision-making regarding existing subsurface conditions and hydrological trends. This non-invasive method images sites without surface disturbance or potential radiological exposure if the radon barrier erodes. Furthermore, using GPR surveys to inspect disposal cells over time will benefit LM in detecting many landfill changes, such as water flow, sinkholes, underground erosion, ground creep, and sediment flow. The GPR robot being developed at FIU can monitor long-term effects, correlating underground erosion with climate resilience and extreme weather events.

FIU will continue improving the robot hardware, software, and subsurface image reconstruction. A high-precision GPS will be integrated into the system's sensory network to improve data acquisition geolocation. A GPS-based mapping algorithm will also be implemented to scan the cells autonomously. Finally, the GPR robot will be redeployed at Mexican Hat, Rifle, and potentially other LM disposal cells during the summer of 2024.

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# TASK 3: STEM WORKFORCE DEVELOPMENT

## Task 3: Introduction

Florida International University (FIU), the largest Hispanic serving research-extensive institution in the continental United States, is one of the nation’s leading producers of scientists and engineers from underrepresented groups. In 1995, the U.S. Department of Energy created a unique partnership with FIU to support environmental cleanup technology development, testing and deployment at DOE sites. This partnership spawned a research center at FIU dedicated to environmental R&D. The center, now known as the Applied Research Center, has tackled and helped solve multiple problems at many DOE sites. The DOE-FIU Science and Technology Workforce Development Program is designed to build upon this relationship by creating a pipeline of minority engineers specifically trained and mentored to enter the DOE workforce in technical areas of need. This innovative program was designed to help address DOE’s future workforce needs by partnering with academic, government and DOE contractor organizations to mentor future minority scientists and engineers in the research, development, and deployment of new technologies addressing DOE’s environmental cleanup challenges.

## Task 3: Objectives

FIU ARC has expanded the DOE EM Cooperative Agreement (CA) to include this project (Project #5) within the already established DOE-FIU Cooperative Agreement to support LM’s main goals and mission. Two (2) FIU STEM minority students are competitively selected to support the research conducted under this project. To ensure that the students will be trained in pertinent technical areas that directly support LM’s goals, FIU works closely with LM management to define high target, high priority technical topics. Based on past performance, skill sets, and infrastructure at FIU, some of the technical areas of concentration may include long-term monitoring; technology identification, selection, testing/evaluation; big data/data analytics; IT tools for knowledge management and transfer; fate and transport modeling of contaminants of concern; and deactivation & decommissioning (D&D). The selected students will present their research in relevant conferences such as the Waste Management Symposia. The students will also participate in a summer traineeship program at selected LM sites. Students will use the research topics for their dissertation/thesis and publish their research results in appropriate peer-reviewed journals.

# Task 3: Results and Discussion

## DOE Fellows Poster Exhibition/Competition and Induction Ceremony

DOE-LM Fellows Oliva Bustillo and Shawn Cameron prepared and presented posters at the 16th Annual DOE Fellows Poster Exhibition and Competition held on Nov. 7, 2022, along with 16 other DOE-EM Fellows. Olivia Bustillo received third place in the competition and received an award during the 16th Annual DOE Fellows Induction Ceremony held on Nov. 8, 2022.

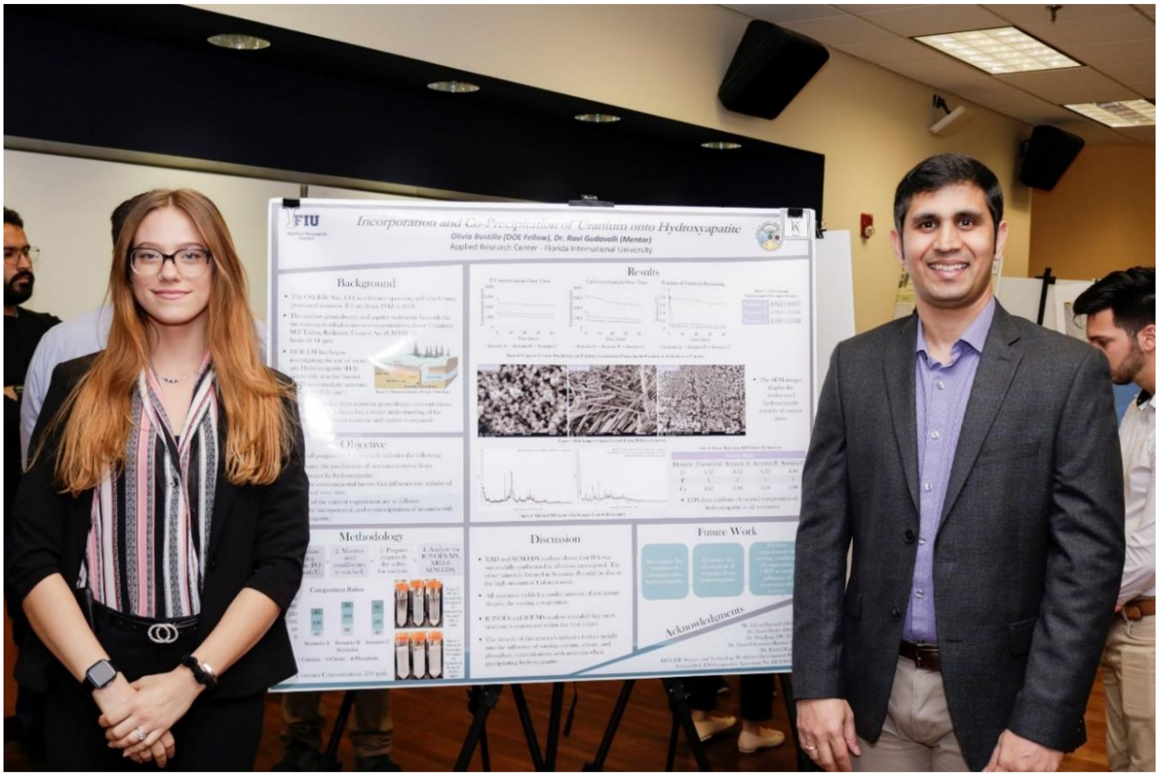

**Figure 40. DOE Fellow Olivia Bustillo with Dr. Ravi Gudavalli at the 16th Annual DOE Fellows Poster Exhibition.**

**Figure 41. DOE Fellow Shawn Cameron presenting his poster at the 16th Annual DOE Fellows Poster Exhibition.**

**Figure 42. DOE Fellow Olivia Bustillo receiving the 3rd place Poster Award Winner Certificate from Dr. Leonel Lagos (Program Director) and Dr. Ravi Gudavalli (Program Manager).**

The DOE Fellows participated in lab tours and showcased their research activities during the lab tour held on Nov. 8, 2022, prior to the induction ceremony.

**Figure 43. DOE Fellow Shawn Cameron showcasing his research work during lab tours.**

DOE Fellow Olivia Bustillo had the opportunity to give a presentation in the morning of the induction ceremony discussing her experiences as a DOE Fellow, which was very well received. She also delivered the "Message to the New Class" speech in the afternoon after the inductees had been initiated into the program. In this speech she discussed how to take advantage of the myriad of opportunities that will arise as being a part of the program, as well as how to have a successful experience as a DOE Fellow.

**Figure 44. Ms. Bustillo presenting her research in the morning of the induction ceremony.**

**Figure 45. Ms. Bustillo delivering the "Message to the New Class" during the induction ceremony.**

**Figure 46. Ms. Jalena Dayvault (Site Manager, DOE-LM), Ms. Olivia Bustillo (DOE Fellow Class of 2019), Dr. Ravi Gudavalli (Research Scientist and DOE Fellows Program Manager), and Ms. Darina Castillo (Site Manager, DOE-LM) after the induction ceremony.**

## DOE Fellows Conference Participation

Two DOE LM Fellows attended and participated at the Waste Management Symposia 2023 held in Phoenix, AZ from February 26 - March 2, 2023. DOE Fellow, Olivia Bustillo, participated in various sessions at the conference:

- A poster presentation, as a Roy G. Post foundation scholarships recipient, on Sunday, Feb. 26, 2023 during session *039 Posters: Roy G. Post Scholarship 2023 Winners*.
- A poster presentation on Tuesday, Feb. 28, 2023 during session *095 Posters: Environmental Remediation (7.1)*. The poster Olivia presented won the best in Track 7-Environmental Remediation.
- Panelist in panel *130B: US DOE National Labs and Academia Successful Partnerships in the Development and Training of STEM Workforce*. In this panel, she gave a student's perspective on the benefits of universities partnering with national labs and her personal perspective on current workforce development programs.
- Speed networking event: this event was a one-on-one conversation between students and professionals, where the students had an opportunity to talk with a professional for several minutes and then rotate tables to talk with professionals from other companies. This provided a great networking experience and exposure to the students as well as the companies.
- In addition, she participated in Waste Management's first annual job fair. At the job fair, she had the opportunity to meet and talk with representatives from many different companies and learn about careers within each organization. This was very beneficial for her as she was graduating in the summer and wanted to learn about potential opportunities as she enters the workforce.

**Figure 47. DOE Fellow, Olivia Bustillo, with Dr. Ravi Gudavalli (Mentor and Program manager) during the Roy G. Post Foundation winners' poster display session.**

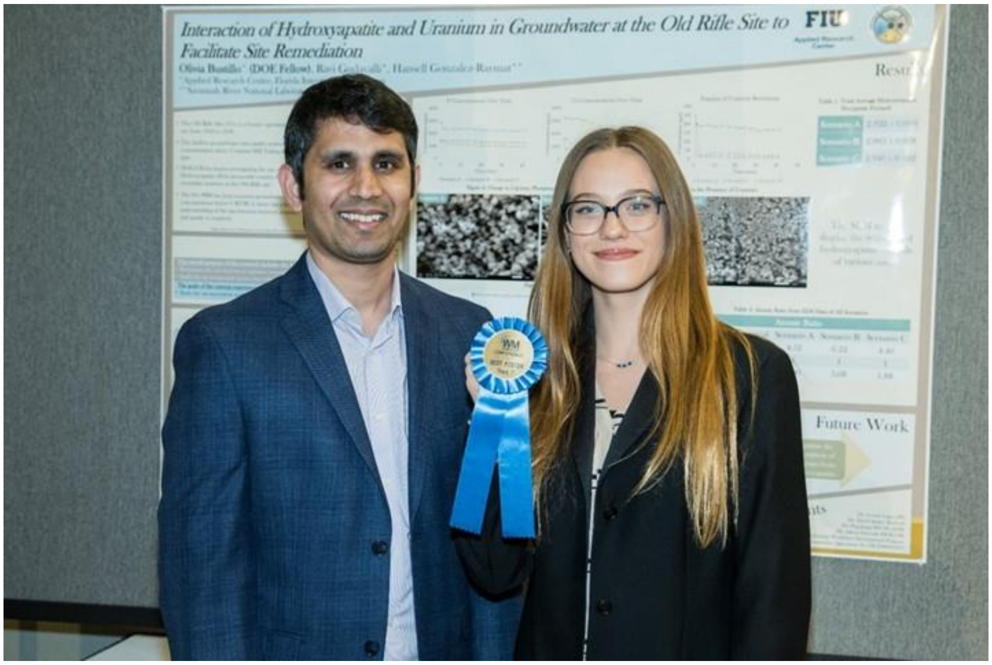

**Figure 48. DOE Fellow, Olivia Bustillo, with Dr. Ravi Gudavalli (Mentor and Program Manager) won the best poster for Track 7 - Environmental Remediation.**

**Figure 49. DOE Fellow Olivia Bustillo at Roy G. Post Foundation winners' display.**

DOE Fellow, Shawn Cameron, participated in session 040 Posters: Student Competition: Future Industry Leaders of Tomorrow (1.2a) on Monday, February 27, 2023 and presented a poster based on his DOE-LM research accomplishments.

**Figure 50. DOE Fellow, Shawn Cameron, presenting a poster at the Waste Management Symposia 2023.**

## DOE Fellows Summer Internship

During the summer of 2023, the DOE Fellow intern, Shawn Cameron, participated in a 10-week summer internship at Grand Junction, Colorado and Department of Energy-Legacy Management under the supervision and guidance of Jalena Dayvault. The intern's project was initiated on July 5, 2023, and continued through September 1, 2023 with the objective of deploying an integrated ground penetrating radar (GPR) robotic platform.

Shawn completed his summer internship stationed at the Grand Junction office with site deployments at Mexican Hat Site, Rifle Site and Basin 6 near the WIPP site.

**Figure 51. GPR mobile robot CAD design (top-left), GPR robotic platform Mexican Hat, UT deployment (top-right), GPR robotic platform deployment in Basin 6 west of the WIPP, New Mexico (bottom-left), and Rifle Colorado GPR robotic platform near the depression areas (bottom-right).**

## DOE Fellows Other Activities

DOE Fellow, Olivia Bustillo, submitted an application for the Presidential Management Fellow in September 2022 and in October, was notified of her selection as a Finalist for the Presidential Management Fellow (PMF) Class of 2023, which made her eligible to seek placement at a participating Federal agency as a PMF. The PMF program received over 10,000 applications and only 850 applicants were selected for the Class of 2023. This was thus a great achievement by our DOE Fellow Olivia Bustillo.

Ms. Bustillo was also notified that she was a recipient of the Zonta Club of Miami Lakes Amelia Earhart scholarship. The club awarded three scholarships to women who demonstrate a superior academic record in engineering disciplines.

Olivia graduated with a master’s degree in environmental engineering by successfully passing her master’s thesis defense, titled *“Investigating the interaction between hydroxyapatite and uranium in groundwater to facilitate remediation”*.

**Figure 52. Dr. Anna Bricker, Dr. Ravi Gudavalli (Mentor, Co-major Professor), DOE Fellow Olivia Bustillo, Dr. Leonel Lagos (Program Director, Major Professor), and Dr. Berrin Tansel (from left to right).**

FIU was also notified that the paper submitted to the Waste Management Symposia 2023 titled *"Interaction of Hydroxyapatite and Uranium in Groundwater at the Old Rifle Site to Facilitate Site Remediation"* was designated a "Superior Paper".

Lastly, Shawn Cameron participated in the Annual FIU Research Review held on 9/24/2023 with DOE-HQ and site POCs and presented his research accomplishments on Task 2 - "Climate Resiliency and Long-Term Surveillance of DOE-LM Disposal Cells".

## Task 3: Conclusion

This project is successfully meeting its objectives by providing research training and mentoring for students from underrepresented groups on environmental problems at DOE LM.

# ACKNOWLEDGEMENTS

Funding for this research was provided by U.S. DOE Cooperative Agreement #DE-EM0005213. Office of Legacy Management provided the funding for FIU Project 5 this year. During this period of performance, four (4) new DOE LM Fellows were hired and participated in the new pilot program between DOE LM and FIU. The FIU researchers and STEM students are grateful to DOE LM for initiating this new program at FIU.

# APPENDIX

The following documents are available at the DOE Research website for the Cooperative Agreement between the U.S. Department of Energy Office of Environmental Management and the Applied Research Center at Florida International University: https://doeresearch.fiu.edu/SitePages/Welcome.aspx

FIU Year 3 Annual Research Review Presentations:

1. FIU Research Review - Project 1
2. FIU Research Review - Project 2
3. FIU Research Review - Project 3 - D&D IT ML
4. FIU Research Review - Project 4 & 5
5. FIU Research Review - Project 4 - DOE Fellow Aris Duani Rojas
6. FIU Research Review - Project 4 - DOE Fellow Aubrey Litzinger
7. FIU Research Review - Project 4 - DOE Fellow Brendon Cintas
8. FIU Research Review - Project 4 - DOE Fellow Bryan Torres
9. FIU Research Review - Project 4 - DOE Fellow Carolina Trummer
10. FIU Research Review - Project 4 - DOE Fellow Joel Adams
11. FIU Research Review - Project 4 - DOE Fellow Josue Estrada
12. FIU Research Review - Project 5 - DOE Fellow Shawn Cameron*
13. FIU Research Review - Wrap Up - Project 1
14. FIU Research Review - Wrap Up - Project 2
15. FIU Research Review - Wrap Up - Project 3 – D&D IT ML
16. FIU Research Review - Wrap Up - Project 4
17. FIU Research Review - Wrap Up - Project 5

*highlighted entry above denotes presentation made by DOE LM Fellow Shawn Cameron