Galleries-to-Calories (G2C): An International Collaboration Evaluating Thermal Energy Storage in Abandoned Mines for District Heating

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ABSTRACT

With the increasing focus on sustainable energy solutions and national net-zero emissions goals, repurposing of abandoned underground mines for thermal energy storage has the potential to make significant impacts. The international Geothermica consortium, Galleries to Calories (G2C), is investigating the potential for storing waste heat from a supercomputing facility in abandoned, flooded coal mines southeast of Edinburgh, Scotland. The system termed the Geobattery or GeoTES involves injecting heat into mine workings, conveying it using regional groundwater flow, and then using the stored thermal energy for district heating and cooling via heat pumps. The Edinburgh site is unique due to the connection of three individual collieries that are linked by underground roadways and hydraulically conductive coal seams, thus enabling heat to be readily stored and transported over several kilometers.

The internal structure of collieries poses challenges due to their partially unknown internal structure, involving fully excavated seams, partially mined pillars, open and collapsed tunnels, and unmined rock formations. To address these uncertainties, we propose to use a multi-level stochastic modeling approach using the open-source Multiphysics Object-Oriented Simulation Environment (MOOSE). Our team has developed a preliminary and geometrically simplified numerical model that focuses on the main coal seams. These seams are further subdivided into multiple subdomains so that they can be discretized individually. Initially, a stochastic analysis involving many thermo-hydraulic simulations is conducted to identify promising bulk parameter combinations that replicate field observations. Once these parameter combinations are determined, the model is extended in a second phase to incorporate the geomechanical effects associated with

various operational conditions of the Geobattery. This extension facilitates the necessary evaluation of heat plume migration and stress field changes, critical for assessing the mechanical stability of the collieries and heat losses that may occur during the operation of the Geobattery.

1. Introduction

The energy transition towards net-zero emissions will require viable long-term energy storage solutions that support communities formerly dependent on fossil fuels. An important application of subsurface energy storage is direct-use heating and cooling. Globally, heating and cooling represents almost half of energy consumption (IRENA, 2023). Repurposing of underground infrastructure including abandoned mines for thermal energy storage and district heating offers a promising avenue to address widespread energy storage challenges. Abandoned flooded coal mines commonly have relatively stable temperatures throughout the year, rendering them ideal candidates for thermal energy storage. The water in the extensive flooded workings is available as a working fluid for thermal energy transport. Moreover, their pre-existing interconnections, often across kilometers of lateral distance, minimize the need for costly drilling, which is a major expense in traditional geothermal energy endeavors involving heat pumps. This system, called the Geobattery or GeoTES, involves injecting heated water into mine workings, conveying it using regional groundwater flow, and then using the stored thermal energy for district heating and cooling via heat pumps as shown in Figure 1.

Internationally, abandoned coal mines have been effectively repurposed into district heating and cooling systems, exemplified by initiatives in Heerlen, the Netherlands (Roijen et al., 2007; Bazargan Sabet et al., 2008; Verhoeven et al., 2014; Adams et al., 2019), Springhill, Canada (Jessop et al., 1995), Asturias, Spain (Jardón et al., 2013; HUNOSA, 2019), and Bochum, Germany (Hahn et al., 2023). In the United Kingdom, ongoing research at the Glasgow Geothermal Energy Research Center (Adams et al., 2019; Monaghan et al., 2022) explores the feasibility of utilizing abandoned Scottish mines for thermal energy storage and district heating applications. Additionally, the utilization of subsurface reservoirs for data center cooling is a current interest of the United States Department of Energy with analyses having been completed in Colorado, Texas, and Virginia (Zhang et al., 2023, Zhang et al., in review).

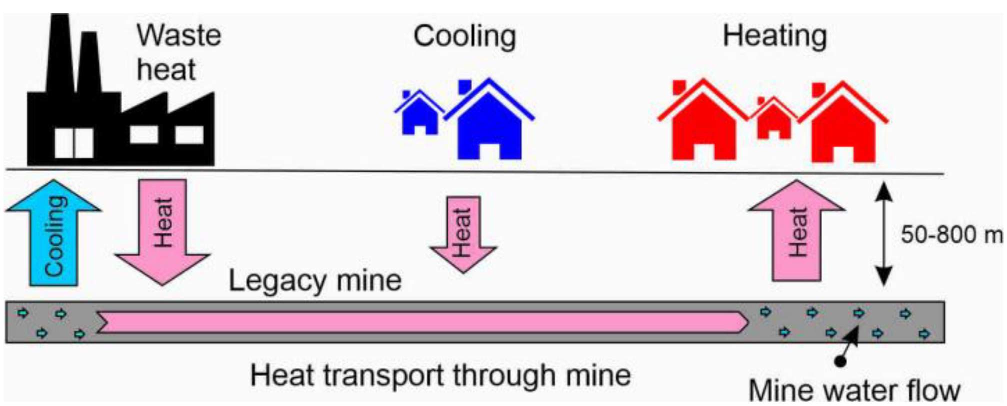

Figure 1: Schematic diagram showing the G2C Geobattery concept with waste heat injected in the mine that is recovered downgradient for heating.

Galleries to Calories (G2C) is an internationally supported Geothermica project led by industry and researchers from the University of Edinburgh and Townrock Energy as well as University of

Strathclyde-Glasgow, University College Dublin, Sandown Ltd, Scene, Idaho National Laboratory, and Lawrence Berkeley National Laboratory. The team aims to demonstrate heat storage and transport in legacy mine workings for recycled heat utilization via heat pump extraction near Edinburgh, Scotland. The specific application is to store waste industrial heat from a university data center in flooded abandoned coal mine workings and use that heat downgradient for community heating during winter months. Repurposing these mines presents technical and commercial challenges due to their intricate and unpredictable nature. We plan to employ advanced modeling methodologies to forecast the system's long-term performance, inform decision making, and conduct risk assessments. Presently, our efforts entail simplified modeling approaches pending the acquisition of more comprehensive field data. This paper provides an overview of the G2C field site, synthesizes pertinent literature, elucidates our initial modeling strategies, and outlines our forthcoming research agenda.

2. Site Description

2.1 Overview

The project site is located approximately 9 km south of Edinburgh, Scotland near the towns of Roslin, Bilston, Straiton, and Loanhead. The abandoned mine workings and their mine water in the Midlothian Coalfield (Figure 2) will serve as both the thermal storage and transport medium. The depth of these mine workings ranges from 50-800 m below the surface, but this project is focused on the upper 150 m to minimize drilling and future operational costs. The heat source for the project is the University of Edinburgh’s Advanced Computing Facility (ACF) near the Easter Bush Campus. This facility will provide between 3-9 MW of waste heat to the subsurface. Adjacent communities located approximately 5 km downgradient of groundwater flow will be the main beneficiaries of the heat stored in the mines.

2.2 Geology and Hydrology

Southwest of Edinburgh lies the Pentland Hills rising to an elevation of approximately 578 m above sea level (masl). These hills consist of Devonian and Silurian sedimentary formations of the Old Red Sandstone and North Esk Group as well as extrusive volcanics of the Pentland Hills Volcanic Formation with basaltic and andesitic compositions (Tulloch and Walton, 1958). The Pentland Hills Fault forms the southeast edge of the hills with substantial downthrow to the southeast. Parallel to the Pentland Hills and approximately 13 km to the east of the Pentland Hills lies an unnamed set of hills extending from the coast at Prestonpans stretching towards D’Arcy Farm. Between these two prominent topographic features lies the Midland Valley and the Midlothian Coalfield (Figure 2, British Geological Survey, 2003).

The geology of the Midlothian Coalfield consists of basin-fill sandstones, siltstones, mudstones, ironstones, marine limestones, and coal-bearing units (Figure 3). The main units of interest for this study include the Upper Limestone, Limestone Coal, and Lower Limestone Formations, which contain various coal seams (Figure 4) including the Peacock and Kittlepurse Coals. These coals seams are semi-parallel and highly inclined with thicknesses of approximately 1 m (Figure 5).

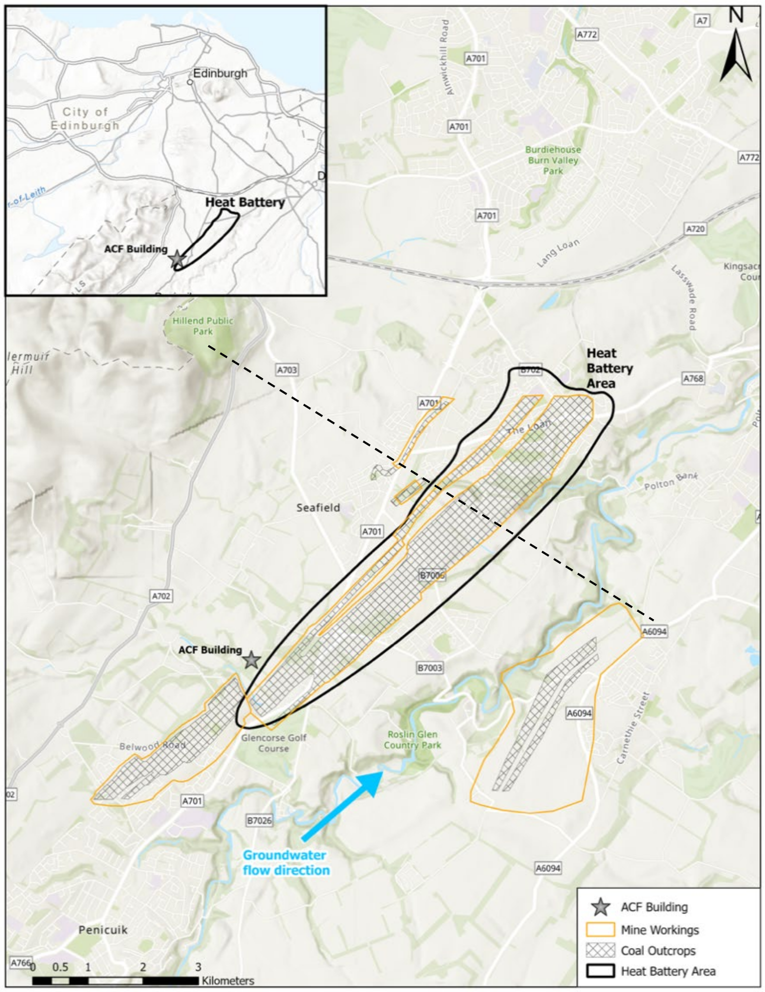

Figure 2: A regional map of the project location south of Edinburgh. Advanced Computing Facility (ACF) is the cooling-waste-heat source indicated by the green star. Hatched pattern represents portions of the legacy mine workings that will be utilized for the Geobattery. Dashed line represents the approximate location of the cross section in Figure 3.

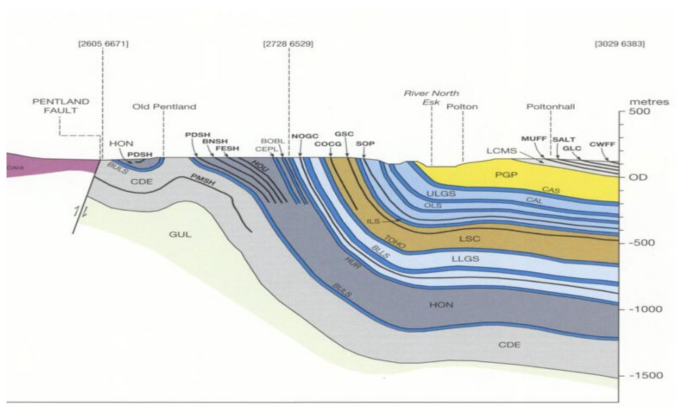

Figure 3: Cross section of the Midlothian Coalfield highlighting the edge and flat coals. Note the Pentland Hills Fault forming the western boundary of the field. Relevant geologic units include Lower Coal Measures (LCMS) Passage Formation (PGP), Upper Limestone Formation (ULGS), Limestone Coal Formation (LSC), and the Lower Limestone Formation (LLGS). (modified after British Geological Survey, 2003)

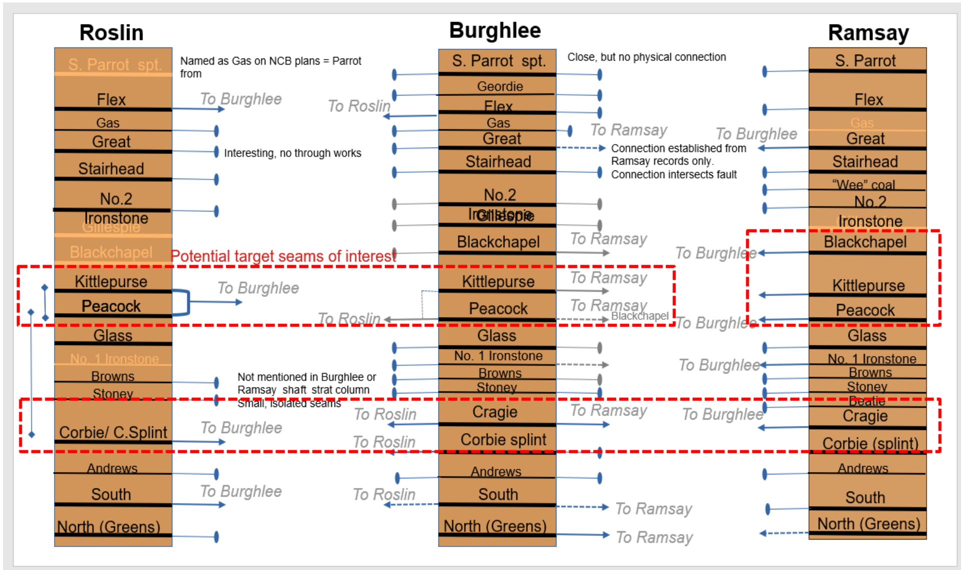

Figure 4. Named coal seams in each of the three collieries. The red dashed lines indicate seams that are hydraulically connected between collieries. Courtesy of Dr. Samuel Graham, University of Edinburgh.

The coalfield area is drained by the North and South Esk Rivers and their tributaries. After coal mining ceased in Scotland in the late 20th century, natural groundwater began filling voids left behind flowing from the southwest to the northeast. Groundwater is recharged by precipitation runoff from the surrounding Pentland Hills. Ambient groundwater temperatures can vary in the mines across Scotland ranging from 12-21° C with a mean of 17° C (Gillespie and Crane, 2013) but measurements from the Bilston Glen Colliery show 15° C. These temperatures can vary due to a variety of factors including the sampling location, the recharging source, the depth of the formation, and the local geothermal gradient, which can range from 17-34 °C/km in similar coal fields in Britain (Farr et al., 2020). Groundwater flow rates can vary widely due to the complex hydrogeological systems created from legacy mine workings and the result of decades of groundwater flow re-entering a system that had been modified for mining for so many years.

2.3 Legacy Mine Workings

For 200+ years coal mining in the UK was performed at differing intensity due to various supply and demand scenarios (Todd, 2023). Older mines utilized manual labor, employing the 'pillar and room' technique. Here, support props sustained the structure while explosives were employed to extract coal manually. Variations of this method were referred to as 'stoop and room' in Scotland (Younger and Adams, 1999). Typically, certain portions of coal, termed stoops or pillars, were intentionally left intact to ensure the stability of the workings (Figure 5). A series of these rooms and pillars would exist and be interconnected with tunnels containing mining rails and other equipment associated with coal extraction. These workings and all associated infrastructure are referred to as a colliery.

Within the proposed Geobattery area, there are three distinct collieries: Roslin, Burghlee, and Ramsay. Groundwater flow and mine water flow from the southwest to the northeast from Roslin to Ramsay, approximately 5 km away (see Figure 5). Vertical shafts at each colliery intersect various coal seams, as depicted in Figure 4. At Roslin, the coal seams are separated by distances ranging from 17 m to 55 m, with an average separation of around 35 m, and the pit bottom reaches a depth of 280 m. Many of these coal seams are present in all three collieries, and some exhibit hydraulic connectivity, as indicated by the red dashed lines in Figure 4. These connected seams serve as the main pathways for fluid flow within the Geobattery.

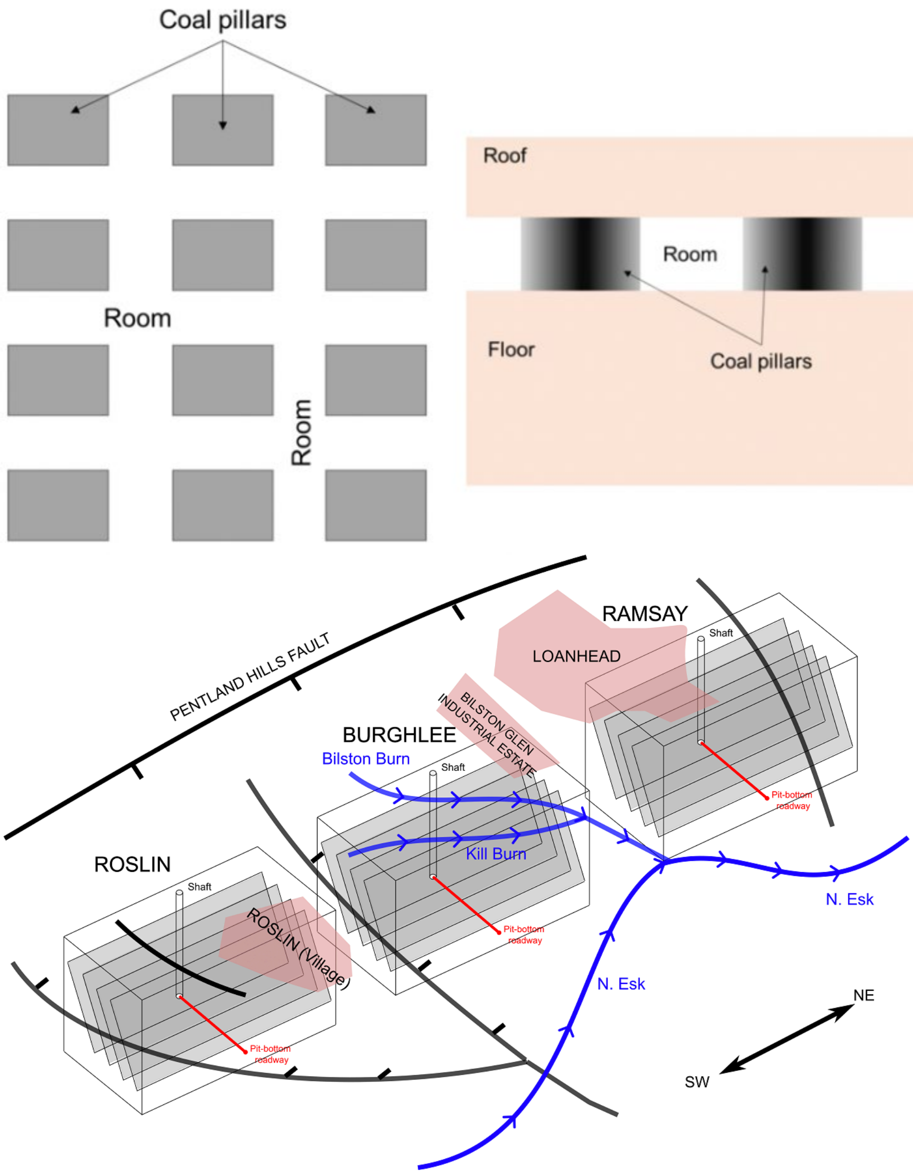

Figure 5: Top-Plan view and cross section view (left) of a simplified layout of a pilar and room working adapted from Younger and Adams (1999). Bottom-Schematic diagram of the tilted planar mined-out coal seams separated by low-permeability rock in the three collieries making up the Geobattery. The pit-bottom roadway connecting the coal seams at the bottom of the mine workings (~300 m deep) is also shown in red (Todd, 2023). Black curves are fault surface traces and blue lines are surface water courses.

3. Preliminary Modeling

Based on the geology described in Section 2, the project team has built a geological model with details on faults, fractures, and formation layers (Figure 6a). It is challenging to create a robust mesh considering all these features for multiphysics coupled simulation. The uncertainties related to formation parameters (e.g., hydraulic conductivity) as well as the legacy mine working (i.e., pillar versus room) may lead to misinformed predictions of the system. Consequently, we focus on a simplified subset of the original large-scale structural mode while preserving essential geometric information concerning the extent of three collieries, the identified primary conduits for heat storage and transfer (i.e., the Kittlepurse and Peacock coal seams), the primary fault zone between the Roslin and Burghlee collieries, and the associated dip and thickness for each feature as shown in Figure 6b. Note that the team is using two distinct modeling approaches to represent the mine system: one involves a deterministic model implemented in the TOUGH code (Doughty et al., 2024), and the second employs a stochastic approach, using the MOOSE simulator. The initial results of the MOOSE simulations are described below.

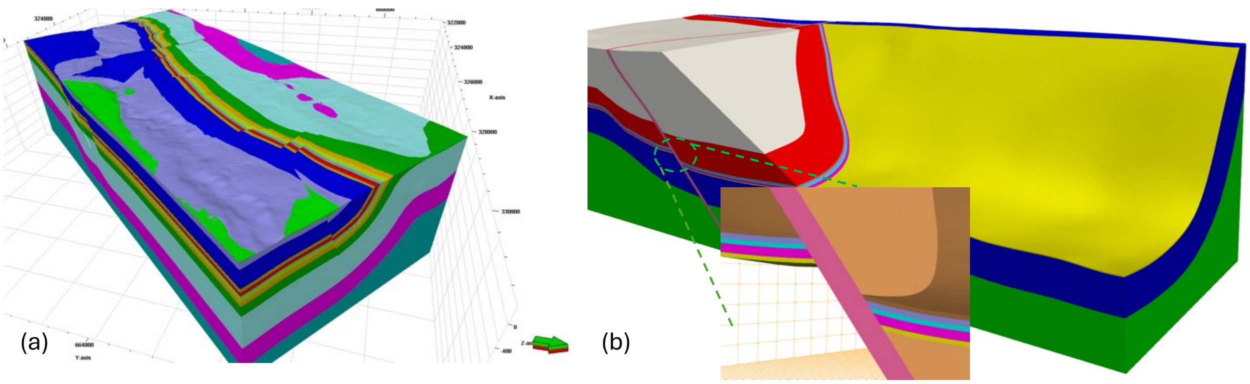

Figure 6. (a) A geological model with detailed structural features. (b) A simplified geological model with key features (i.e., heat transfer conduit – the Kittlepurse and Peacock coal seams and the fault between the Roslin and Burghlee collieries).

The site-specific initial distribution of temperature, effective stress, as well as pore pressure are all unknown at this stage. A 2D regional groundwater flow model at steady-state is used to approximate the pore pressure distribution. We used the open-source Multiphysics Object-Oriented Simulation Environment (MOOSE, Giudicelli et al. 2024) and performed hydraulic simulations using the parameters in Table 1. For boundary conditions, we applied no-flux boundaries for the two sides perpendicular to the ground water flow directions, while a hydraulic static pore pressure is applied at the downgradient surface. A ground water flow flux of 10^{-4} m/s is applied to the upgradient surface based on work done by Doughty et al. (2024). 15 L/s of water is injected into each of the targeted three coal seams (i.e., 45 L/s total water injection). Within this simulation, we used tracers to show the convective thermal plume distribution, excluding heat conduction. Figure 7 shows the tracer plume that reaches the fault and then continuously travels through the conductive coal seams to the downstream Burghlee and Ramsay collieries. The modeled tracer plumes show that the ground water flow difference across different coal seams within the Roslin colliery affects the tracer distribution. However, this impact is negligible once the plume passes through the fault.

Table 1: Parameters of coal seams and limestone bedrock used in initial modeling simulations.

Model component	Permeability (m^2)	Porosity
Coal Seam	10^{-12}	0.20
Fault	10^{-13}	0.05
Limestone bedrock	10^{-18}	0.01

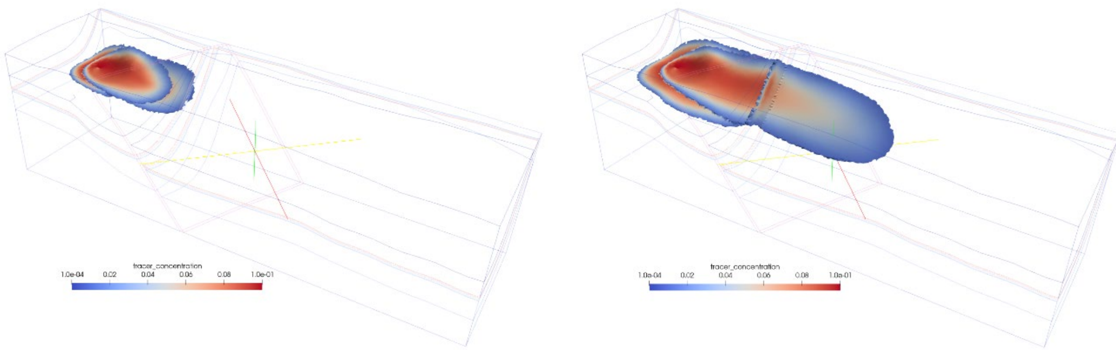

Figure 7. Tracer plume evolution after ½ year (left) and two years (right) of continuous water injection into the targeted Kittlepurse and Peacock coal seams.

The above hydraulic simulation will be expanded into thermo-hydraulic (TH) and thermo-hydro-mechanical (THM) coupled simulations with more *in-situ* data of effective stress and thermal gradient to constrain the model. In addition, we will subdivide the three coal seams into a suite of blocks and statistically assign material properties (e.g., Young's modulus, porosity, permeability) for those blocks so the pillars and rooms shown in Figure 5 can be represented. These statistical simulations will be used to reduce uncertainty by comparing and matching against future *in-situ* testing and monitoring data. Eventually, the THM models with reduced uncertainty will be used to predict performance, design operation, and quantify impacts of the Geobattery.

5. Conclusions and Future Work

The overall concept of storing waste heat in abandoned mine workings for seasonal district heating and cooling is of interest on the domestic and international scale. The mines beneath Edinburgh offer great a opportunity to explore the feasibility of mine thermal energy storage because of established flow paths, favorable groundwater flow magnitude, direction, and temperature, and interconnected mine workings. Initial modeling efforts show that flow is impacted by the fault separating the Roslin and Burghlee collieries. The plume of heated water then travels through the fault downstream, passing through the Kittlepurse and Peacock coal seams.

Over the next year, drilling will commence leading to data collection of key information to better constrain TH and THM simulation efforts. Once data are obtained on the various formations, the team will conduct more sophisticated modeling to ensure safe and efficient operations can be planned and executed for the project. The work being undertaken by the G2C consortium will be instrumental in evaluating this technology and in offering a solution for waste heat storage in mine workings and downstream utilization in community heating and cooling systems.

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