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This special issue is the second of two on the topic of Deep Underground Laboratories (DUL). The first, on European experience, was published as ARMA Letters No. 30 (Winter, 2021).

Introduction to the Special Issue: Deep Underground Laboratories II (USA):

Mathew D. Ingraham, Geomechanics Department, Sandia National Laboratories (Tijeras, New Mexico); Special Issue Editor

As the state of geoscience continues to evolve, meso-scale experiments (larger than laboratory scale, but not at the scale of energy production, oil or otherwise) which take place under realistic conditions become more and more important. To reach realistic stress states required for these meso-scale tests, a significant depth into the earth is required. The simplest and most efficient way to achieve these required conditions is to utilize a deep mine facility which already exists and piggyback on the infrastructure. In the United States, the Department of Energy and the State of South Dakota reopened the former Homestake Gold Mine as the Sanford Underground Research Facility (SURF), for the express purpose of cutting-edge science.

One such project at SURF is the EGS Collab project where multiple National Laboratories, universities and industry partners have come together to work on improving the techniques, modeling, and understanding of the complex thermal-hydrological-mechanical-chemical environment required for Enhanced Geothermal Systems (EGS). EGS are potential geothermal power locations where there is insufficient permeability and fluid to perform traditional geothermal operations. Many potential EGS locations are near traditional plate boundaries, where hydraulic fracturing and stimulation are required in order to enhance the natural permeability. The EGS Collab project seeks to investigate some of these technologies through performing experiments on hydraulic fracturing between two wells to create sufficient permeability for geothermal operations (Experiment 1), as well as shear stimulation of pre-existing features to generate the required permeability for geothermal operations (Experiment 2).

The following articles include a description of the SURF facility, an overview of the EGS Collab project, design of the Experiment 1 EGS Collab test bed, and a description of the hydrofracturing and flow systems used to perform the tests in the Experiment 1 EGS Collab test bed.

Opportunities at the Sanford Underground Research Facility

Submitted by Jaret Heise, Sanford Underground Research Facility (Lead, South Dakota)

Introduction

Building on rich legacies in both mining and transformational physics research, the Sanford Underground Research Facility (SURF) is a deep underground facility that has been developed in the former Homestake gold mine in Lead, South Dakota. Its purpose is to advance compelling research in a variety of disciplines, including physics, biology, geology and engineering [1,2]. With strong support from the scientific community and relying on federal, state and private (T. Denny Sanford) funding, SURF has been operating as a dedicated research facility for over 12 years. Since Fall 2011, SURF operation has been funded by the U.S. Department of Energy's Office of Science, initially through sub-contracts with various national laboratories, and since Fall, 2019, through a renewable 5-year Cooperative Agreement.

With strong support SURF has a robust organization with resources to ensure safe and successful science, including personnel who directly support science as well as others who provide important services such as full-time emergency response and support in areas such as safety, engineering and operations.

Specific SURF attributes attractive to researchers in various disciplines include the following:

- **Physics:** As a deep site with high-density rock overburden, SURF provides significant shielding for current and future experiments (see Figure 1). Geotechnical measurements made in a number of areas on the 4850-foot Level (4850L) indicate ideal properties for constructing large caverns.

- **Biology:** The underground environment provides isolation from surface microorganisms and offers a variety of different environmental conditions (temperature and humidity), niches (different rock formations) and access to water courses/seeps from various sources, including legacy and recent drill holes.

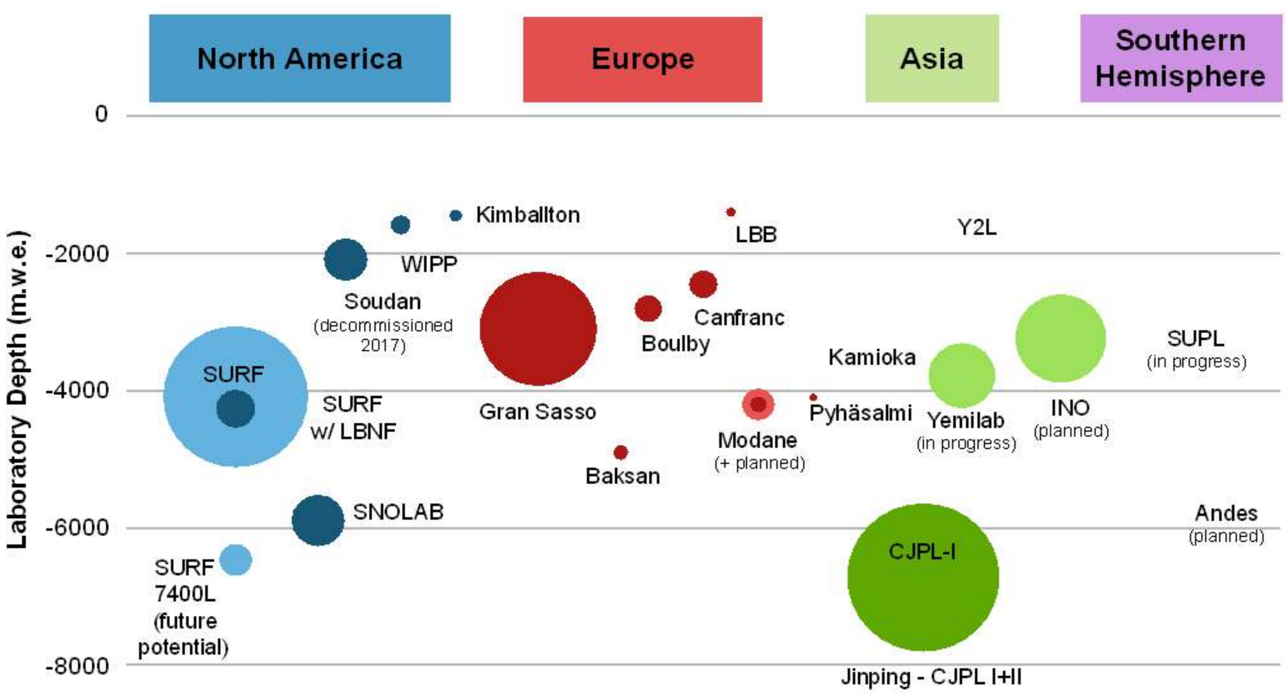

Figure 1. Comparison of the world's main existing and proposed underground (physics) research facilities organized by geographical region. The vertical scale is the depth of the facilities in meters water equivalent (mwe), and the size of the circle scales with the total volume of the research facility.

- **Geology:** The underground rock mass includes the following geologic formations: Deadwood, Flagrock, Northwestern, Ellison, Homestake, Poorman, Yates Amphibolite, Rhyolite and Phonolite. SURF is the steward of the Homestake core repository and a database of all underground workings.

- **Engineering:** The facility provides a variety of environments for testing real-world applications (especially related to mining) at great depth.

Facilities

SURF property comprises approximately 1 km2 (223 acres) on the surface, and more than 31 km2 (7700 acres) underground. In total, the facility consists of more than 600 km of tunnels extending to over 2450 meters (8000 feet) below ground; two main shafts provide redundancy in terms of safe access and some services such as power and network. Of the 29 underground elevations that are currently accessible, the following have been identified as key levels for science activities: 300L, 800L, 1700L, 2000L, 4100L, 4550L, 4850L.

SURF facilities support research activities both on the surface as well as underground, and at a minimum the seven underground levels identified above have power and network services in limited areas. Enhanced services are available on the 4100L, and especially the 4850L, to support significant research needs and laboratory facilities. Near the Yates shaft on the 4850L, a state-of-the-art laboratory complex called the Davis Campus has been operating since 2012. It includes the cavern originally developed for Ray Davis in the mid-1960s and has a total footprint consisting of 3020 m2, including clean laboratory spaces.

The 4850L Ross Campus encompasses a set of four existing excavations that were used to support previous mining activities. Since 2015, two spaces (670 m^2) have accommodated science activities. Another space is used as a SURF maintenance shop (formerly used as a copper electroforming laboratory) and the fourth space is used as a dedicated Refuge Chamber that can accommodate 144 people, which is the current maximum capacity. (Plans are advancing to increase the maximum occupancy to 250 people.)

Other space has been developed on the 4850L, most notably in the West Drift, where additional power and network services have been installed and where successive geothermal projects have drilled a series of holes. Plans are being developed for a similar testbed on the 4100L near the Yates shaft.

Plans to accommodate future experiments at SURF are well advanced and include the Fermilab-led international Deep Underground Neutrino Experiment (DUNE) at the Long Baseline Neutrino Facility (LBNF) – the largest international science project ever attempted on U.S. soil. Initial construction for LBNF started in January 2019. The main 4850L excavation for two large halls (each 150 m L x 20 m W x 28 m H) and a utility cavern (190 m L x 20 m W x 11 m H) is scheduled to begin in early 2021; excavation related to a new ventilation borehole for the project is expected to begin in 2020. See Figure 2 for the layout and relationship to the main Yates and Ross shafts as well as the 4100L.

While no mandate currently exists beyond LBNF to develop additional significant laboratory space at SURF, preliminary design plans have been developed for expansion of laboratory space on the 4850L and 7400L. More generally, SURF is exploring opportunities to accommodate new experiments that can exploit SURF's unique potential, and there is significant opportunity for expansion to meet the needs of a wide range of research disciplines into the future.

Science Program

Integral to SURF's institutional mission, SURF has a strong science program. The discoveries sought by SURF's current and future experiments will transform our understanding of the underpinning of physics, Earth and life sciences, as well as important engineering topics. SURF has a formal framework for implementing experiments in an effective and efficient manner [3]. In particular, specific documentation helps identify interfaces with the facility, address hazards and establish and define the relationship between an experiment and SURF. Under the DOE Cooperative Agreement, experiments at SURF are offered basic support services.The SURF science program currently includes 29 experiments (~60% non-

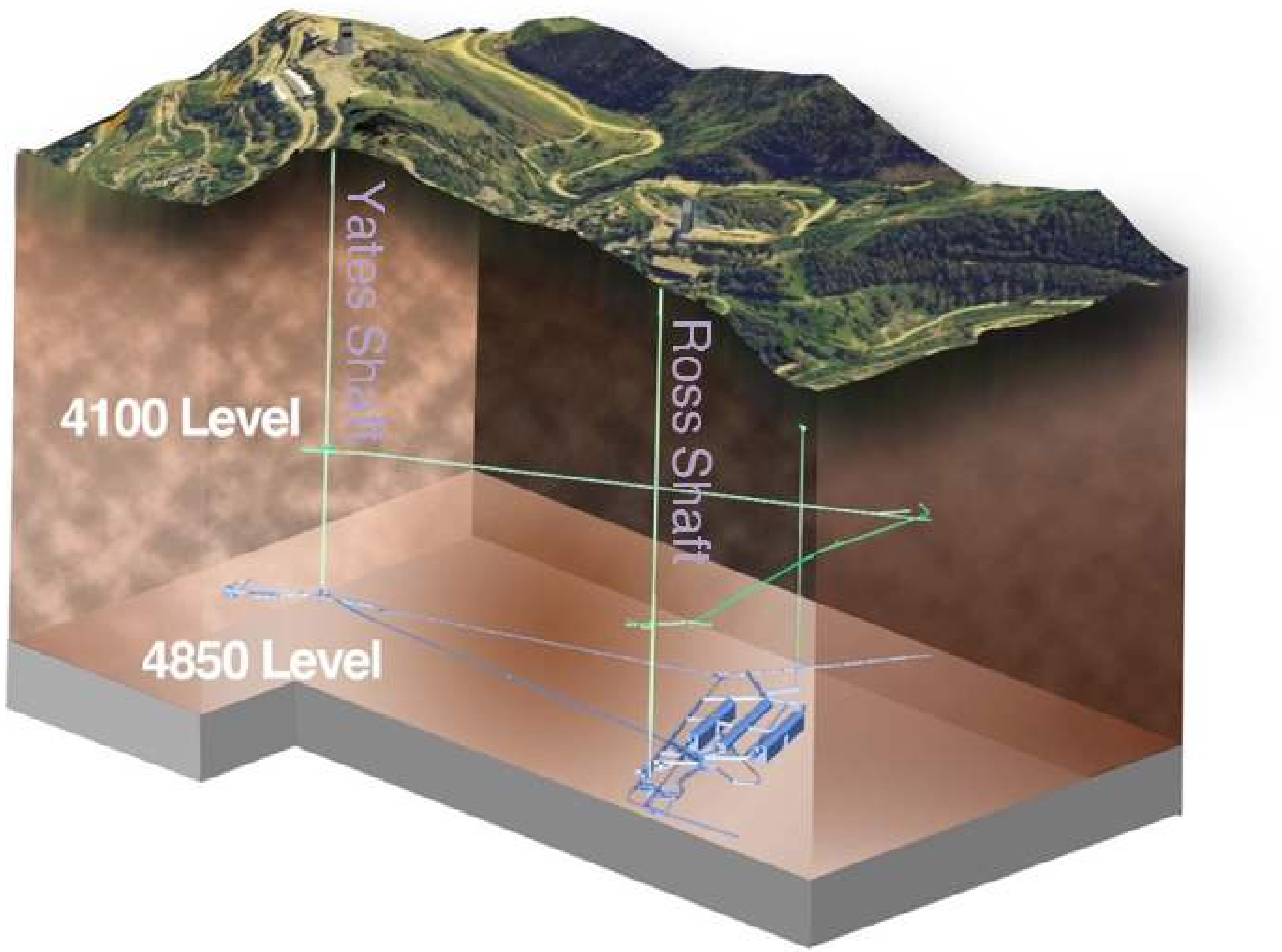

Figure 2. 3D perspective of SURF's surface topography, the main underground access shafts and two of the most developed underground levels. The prominent structures in blue (lower right) represent the Long Baseline Neutrino Facility (LBNF) spaces.

physics) with approximately 400 users from 82 institutions in 9 countries.

Summary

SURF is a deep underground research facility dedicated to scientific uses. Significant expansion at SURF is on the near-term horizon, with plans for additional space in development to advance research in multiple disciplines. Applications from new experiments are welcome!

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[2] J. Heise, J. Phys.: *Conf. Ser. 606, 12015 (2015), arXiv:1503.01112 [physics.ins-det].*

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EGS Collab Project

Submitted by Timothy Kneafsey, Lawrence Berkeley National Laboratory and the EGS COLLAB Team[1]

Enhanced/Engineered Geothermal Systems

Geothermal resources exploited today tend to be along plate boundaries where naturally occurring, highly permeable, convective hydrothermal systems are accessed and where high temperature fluids can be extracted to generate electrical power or used as a direct source of heat. Globally, on the order of 13 GWe is generated from geothermal systems (Lund et al., 2015). While opportunities exist to expand the resource base of these naturally occurring systems, the heat resource in the crust is vast. To support traditional geothermal production, enhanced or engineered geothermal systems (EGS) offer an opportunity to extract heat from hot rock resources by providing needed permeability and fluid to rock that does not have the natural permeability. The US Geological Survey (USGS) has estimated that EGS resources in the western U.S. alone could exceed 500 GWe (Williams et al., 2008), about half of the current US electricty generation capacity. This is an impressive resource estimate, but there are technological challenges associated with extracting and utilizing this resource that will need to be addressed including: (1) lack of a thorough understanding of techniques to effectively stimulate fractures in different rock types and under different stress conditions, (2) inability of techniques to image/monitor permeability enhancement and evolution at the reservoir scale to the resolution of individual fractures, (3) limited technologies for effective zonal isolation for multistage stimulations under elevated temperatures, (4) lack of technologies to isolate zones for controlling fast-flow paths and early thermal breakthrough, and (5) lack of scientifically-based long-term EGS reservoir sustainability and management techniques. The EGS Collab Project is focusing on understanding stimulation, seismicity, flow, and validation of predictive capabilities in fractured crystalline rock.

EGS Collab

The EGS Collab project was initiated by the DOE Geothermal Technologies Office (GTO) to facilitate the success of the Frontier Observatory for Research in Geothermal Energy (FORGE), a field laboratory for EGS research (https://www.energy.gov/eere/forge/forge-home). The EGS Collab project is using readily accessible underground facilities to refine our understanding of rock mass response to stimulation at the approximately 10 m scale for the validation of thermal - hydrological - mechanical - chemical (THMC) modeling approaches as well as to compare novel and conventional monitoring tools. The project is located at the Sanford Underground Research Facility (SURF) in Lead, South Dakota (Figure 1). SURF is located in the former Homestake gold mine and is operated by the South Dakota Science and Technology Authority. It is the host to a number of world-class physics experiments related to neutrinos and dark matter, as well as geoscience research projects (Heise, 2015). SURF offers a number of advantages that allow the EGS Collab project work to move forward quickly, including cost-effective proximal monitoring of a crystalline rock mass before, during, and after stimulation through multiple boreholes drilled from an underground tunnel at an appropriate depth. The EGS Collab project is a collaborative multi-lab and university research endeavor bringing together a team of skilled and experienced researchers and engineers in the areas of subsurface process

[1]J. Ajo-Franklin, T. Baumgartner, K. Beckers, D. Blankenship, A. Bonneville, L. Boyd, S. Brown, J.A. Burghardt, C. Chai, Y. Chen, B. Chi, K. Condon, P.J. Cook, D. Crandall, P.F. Dobson, T. Doe, C.A. Doughty, D. Elsworth, J. Feldman, Z. Feng, A. Foris, L.P. Frash, Z. Frone, P. Fu, K. Gao, A. Ghassemi, Y. Guglielmi, B. Haimson, A. Hawkins, J. Heise, C. Hopp, M. Horn, R.N. Horne, J. Horner, M. Hu, H. Huang, L. Huang, K.J. Im, M. Ingraham, E. Jafarov, R.S. Jayne, S.E. Johnson, T.C. Johnson, B. Johnston, K. Kim, D.K. King, T. Kneafsey, H. Knox, J. Knox, D. Kumar, M. Lee, K. Li, Z. Li, M. Maceira, P. Mackey, N. Makedonska, E. Mattson, M.W. McClure, J. McLennan, C. Medler, R.J. Mellors, E. Metcalfe, J. Moore, C.E. Morency, J.P. Morris, T. Myers, S. Nakagawa, G. Neupane, G. Newman, A. Nieto, C.M. Oldenburg, T. Paronish, R. Pawar, P. Petrov, B. Pietzyk, R. Podgorney, Y. Polsky, J. Pope, S. Porse, J.C. Primo, C. Reimers, B.Q. Roberts, M. Robertson, W. Roggenthen, J. Rutqvist, D. Rynders, M. Schoenball, P. Schwering, V. Sesetty, C.S. Sherman, A. Singh, M.M. Smith, H. Sone, E.L. Sonnenthal, F.A. Soom, P. Sprinkle, C.E. Strickland, J. Su, D. Templeton, J.N. Thomle, V.R. Tribaldos, C. Ulrich, N. Uzunlar, A. Vachaparampil, C.A. Valladao, W. Vandermeer, G. Vandine, D. Vardiman, V.R. Vermeul, J.L. Wagoner, H.F. Wang, J. Weers, N. Welch, J. White, M.D. White, P. Winterfeld, T. Wood, S. Workman, H. Wu, Y.S. Wu, E.C. Yildirim, Y. Zhang, Y.Q. Zhang, Q. Zhou, M.D. Zoback

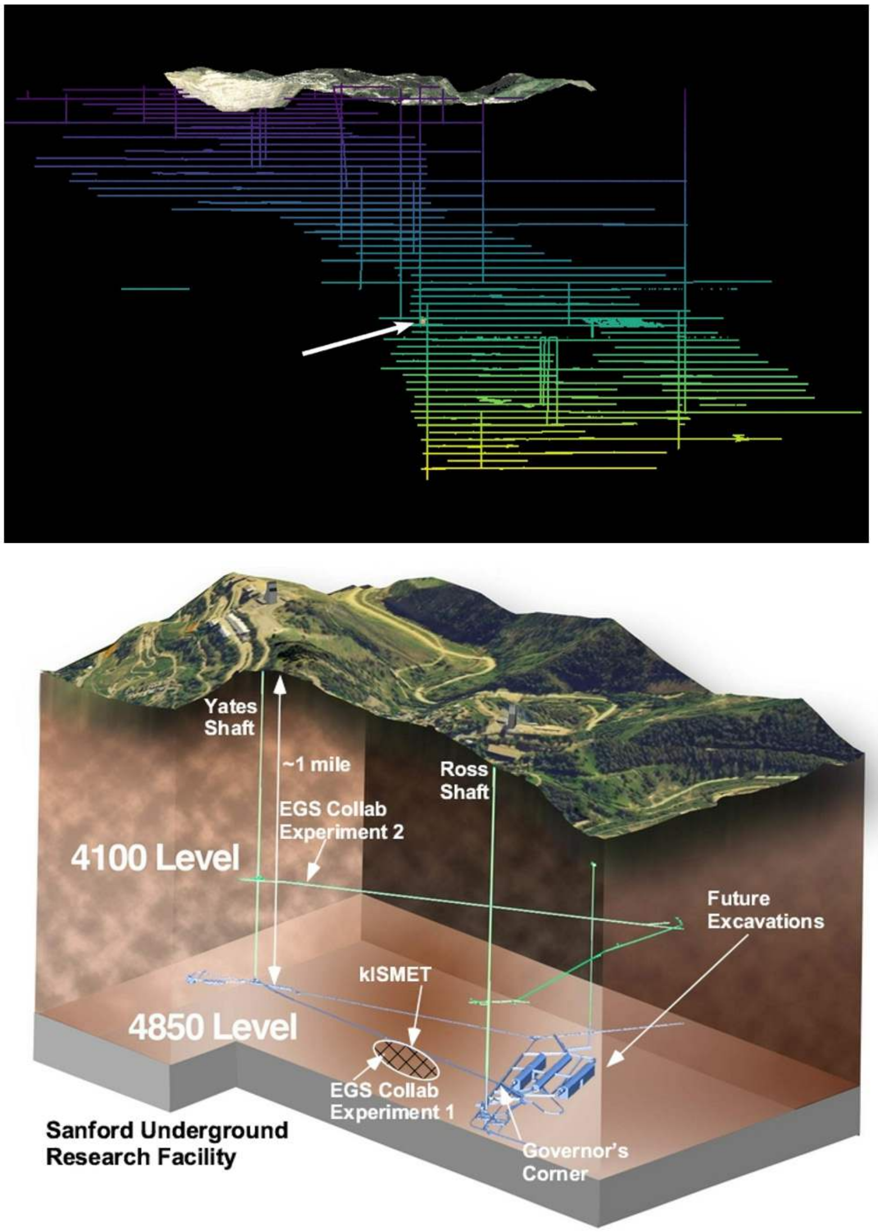


Figure 1. Top - Schematic view of the Sanford Underground Research Facility (SURF) showing active and inactive underground areas, with the arrow indicating the Experiment 1 location on the 4850 level. Bottom – schematic of the 4850 level.

modeling, monitoring, and experimentation to focus on intermediate-scale EGS reservoir creation processes and related model validation in crystalline rock (Kneafsey et al., 2019).

The project consists of three experiments, each consisting of multiple tests, and each test requiring simulation for guiding and interpreting the test. The primary goal of Experiment 1 is to investigate hydraulic fracturing to enhance permeability. The primary goal of Experiment 2 is to investigate hydraulic shearing to enhance permeability, and the primary goal of Experiment 3 is to refine and extend promising observations.

Experiment 1

EGS Collab Experiment 1 is underway on the 4850 Level (~ 1.5 km depth) and was expected to conclude in early spring 2020. The site geology (rock type, fabric, stress orientations) has been well-characterized (e.g., (Caddey et al., 1991; Hart et al., 2014; Lisenbee and Terry, 2009)). The site required little preparation, already having good ground support, availability of power, water, and internet, which allows the experiment to be conducted with little delay and at lower cost. Additionally, the drift size and orientation were conducive for drilling the needed stimulation,

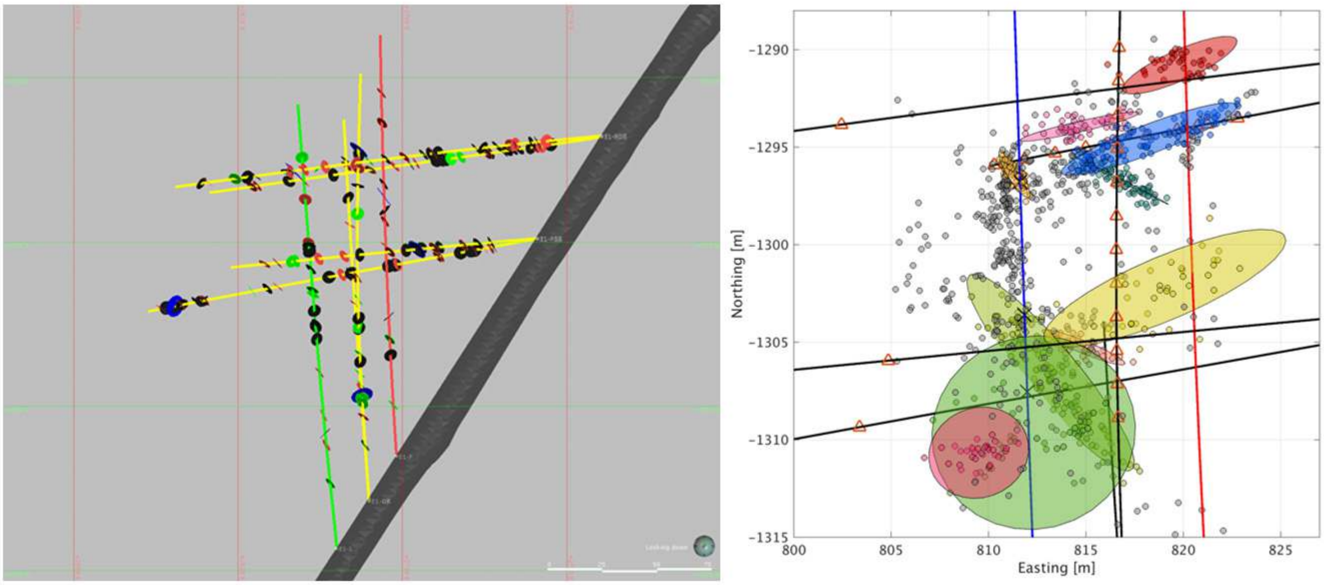


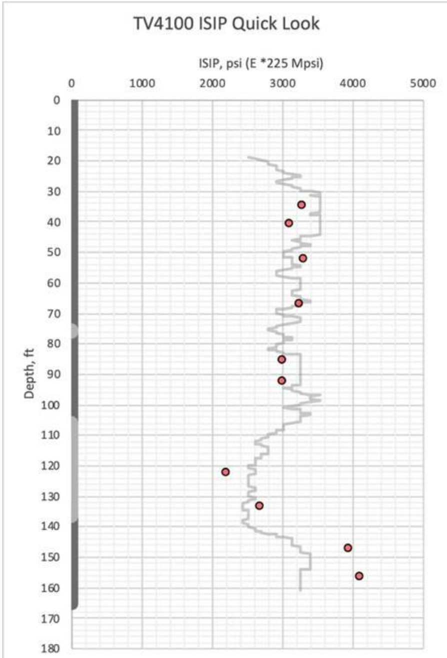
Figure 2. Left – Schematic of Experiment 1. Thick dark line is the drift (tunnel), yellow lines represent monitoring wells, the green line is the injection well, and the red line is the production well. Ellipses represent observed fractures. Right – microseismic events (dots) identifying stimulated fractures. The blue line is the injection well, red line is the production well, and the monitoring wells are black.

production, and monitoring boreholes and carrying out subsequent experimental activities. The Experiment 1 site is located within the Ross Member of the upper Poorman Formation. This formation consists of metasedimentary phyllite with abundant graphite, mica, and carbonate (Caddey et al., 1991; Steadman and Large, 2016). The adjacent Permeability (k) and Induced Seismicity Management for Energy Technologies (kISMET) project previously performed in the West Drift portion of the 4850 level (Oldenburg et al., 2017; Wang et al., 2017) conducted borehole stress measurements, indicating that the minimum horizontal stress averages 21.7MPa (3146 psi) and trends approximately N-S (azimuth of 2 degrees), with a slight plunge of 9.3 degrees to the NNW (corrected from (Ulrich et al., 2018; Wang et al., 2017)).

Numerous modeling studies have been conducted to support the design of Experiment 1, to estimate the volume of fluid for stimulation, and to estimate possible fracture apertures and extents (e.g. (Fu et al., 2018; White et al., 2018a; White et al., 2018b; White et al., 2019)). Initial modeling efforts focused on a number of initial questions to guide experiment design. Using guidance from initial measurements and modeling, the site was drilled (Figure 2) and heavily instrumented. Many stimulations were performed, connecting the injection and production wells. Flow tests injecting ambient temperature and chilled water have been performed for almost a year along with many tracer tests. Geophysical techniques including electrical resistance tomography, continuous active source seismic monitoring, acoustic emissions, passive seismic, and distributed thermal, acoustic, and strain sensing have been used to track the development of the fractures and flow through the system. Summaries are contained in numerous conference and journal papers (e.g. Google Scholar author = EGS Collab). Project data are available on the national geothermal database system (http://geothermaldata.org/). Additional data are migrated to that site as they are vetted.

Experiment 2

A testbed for a second set of experiments is being designed for implementation on the 4100 level at SURF (about 1.25 km deep) in the Yates amphibolite formation. In this experiment, the goal is shear stimulation. Characterization of the potential testbed has begun. We have drilled and cored one 50m vertical borehole, and one 10m subhorizontal hole. The vertical borehole identified and penetrated a ~11m thick rhyolite layer,



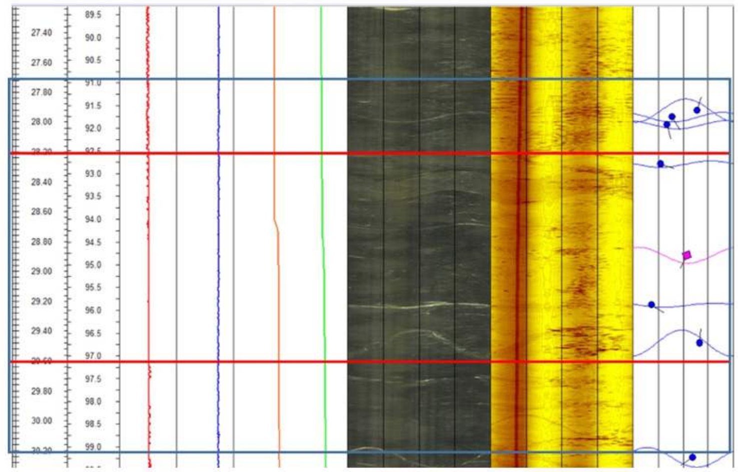


Figure 3. Left - Instantaneous shut-in pressures for tests at 10 locations in the 50 m vertical borehole on the 4100 level. The grey line is the Young's modulus, and the shaded bar on the left indicates the rock type encountered (dark = amphibolite, light = rhyolite). Note the high ISIP below the rhyolite, low ISIP in the rhyolite, and moderate relative consistent ISIP above the rhyolite. Right – one location selected for a SIMFIP test.

having a significantly different stress regime than either the upper and lower amphibolite (Figure 3). More than ten stress tests have been performed in the vertical borehole, including the use of the Step-rate Injection Method for Fracture In-situ Properties (SIMFIP) tool to identify displacement across the interval upon stimulation. In addition, cores have been distributed for initial laboratory tests. These data are feeding into concepts to be used in the design of the test bed. Drilling and coring for this test bed is expected in coming months.

Concluding Remarks

The potential EGS resource is large, but producing this resource will require careful science to improve knowledge, and quality engineering. The EGS Collab project and similar projects have the ability to investigate processes at smaller scales to provide some of this needed understanding. Interpreting these learnings in concert with larger-scale tests such as FORGE and previously performed EGS implementations will aid in understanding the conditions under which EGS can be implemented.

Acknowledgements

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EGS Collab Project: Experiment 1 Design

Submitted by Joseph Morris, Lawrence Livermore National Laboratory and the EGS COLLAB Team (see Team listing in ARMA Letters, Page 5, footnote)

Perhaps the greatest technical challenge to developing an experimental plan is anticipating the inherent uncertainty in the subsurface. Our goal was to design a robust stimulation and flow-through experiment to enable model validation. However, we cannot know everything about the rock mass and uncertainty in stress orientation and magnitude along with the unknown presence of preexisting discontinuities that can dominate system response. Consequently, our first objective was to select a specific location at SURF consistent with a borehole geometry that would best facilitate direct observation of stimulation via hydraulic fracturing and subsequent flow-through tests. However, such advantages must also be weighed against logistical necessities (access to transportation, power, water, internet, etc.) that vary with location throughout the mine.

Experiment 1 sought to stimulate the rock via hydraulic fracturing and so the basic layout of the test bed was dictated to first order by the orientation and size of the hydraulic fractures. Stress orientation is well known to dictate hydraulic fracture orientation in the absence of strong heterogeneity or preexisting fractures (Hubbert and Willis, 1957). In fact, hydraulic fracturing is often used to infer stress orientation and the magnitude of the minimum horizontal stress. Field measurements of the stress field by hydraulic fracturing showed that the minimum horizontal stress at the kISMET site (Oldenburg et al., 2017; Wang et al., 2017) averages 21.7 MPa (3146 psi) pointing approximately N-S (355 degrees azimuth) and plunging slightly NNW at 9 degrees from horizontal. Figure 1 shows a hypothetical testbed geometry utilizing a corner between two drifts to provide access to both suitably oriented stimulation, production, and observation boreholes. Such a drift geometry would facilitate deploying observation boreholes both parallel and perpendicular to the stimulated fractures. Even though such a location was sought during site selection at SURF, we were unable to identify such an arrangement within the portions of SURF currently serviced with utilities necessary for the experiment.

It was subsequently realized that siting the first experiment in a drift at an angle to the stress field provides the advantage that a single drift can be used effectively to place the boreholes such that they straddle the stimulation zone by locating the borehole collars sufficiently distant along the length of the drift. The location of the previous kISMET experiment is within in a drift of such orientation, has all the necessary supporting infrastructure, and was ultimately selected to be the site for Experiment 1 (see Figure 2 for borehole layouts).

The basic design of Experiment 1 shown in Figure 2 includes a number of largely horizontal wells, including a stimulation/injection well, a production (flow-back) well, and several monitoring wells, from the West Access Drift of SURF at 4850 ft (1478 m) below ground in phyllite of Precambrian

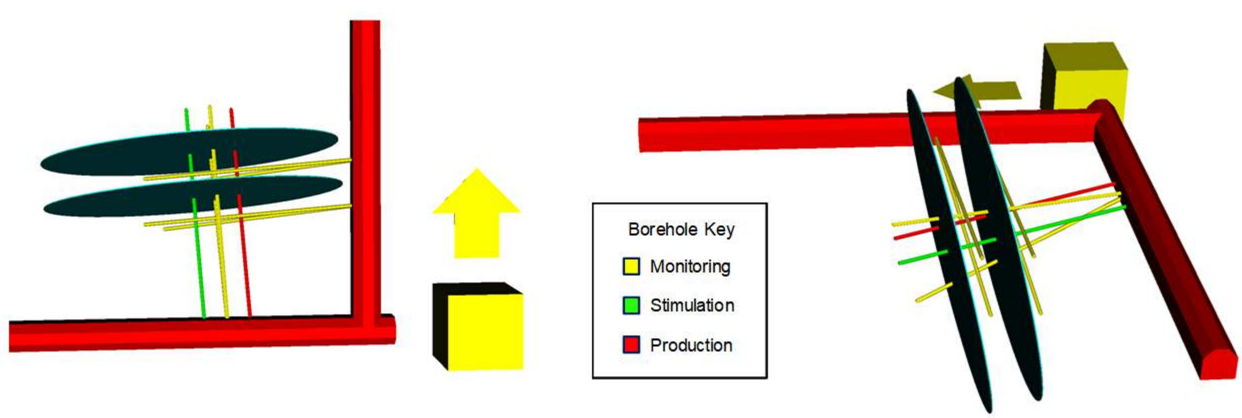

Figure 1. Hypothetical test bed geometry at an intersection of two drifts. The arrow indicates North and the 10 m yellow cube is included as a scale indicator. The disks correspond to idealized hydraulic fractures, opening against the minimum horizontal stress with a design radius of 20 m.

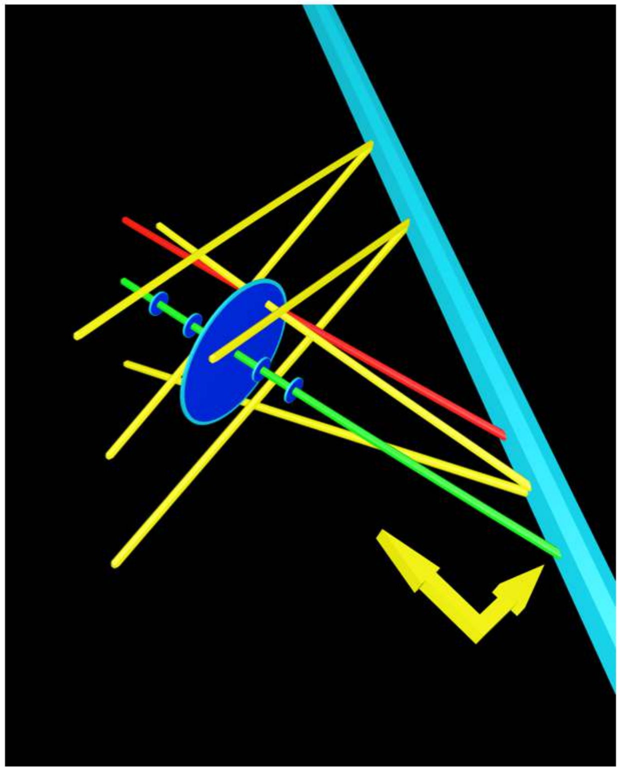

Figure 2. Layout of the EGS Collab borehole test bed developed on the 4850 Level (1478 m below ground surface) for fracture stimulation and flow experiments of Experiment 1 (Morris et al., 2018). Boreholes are ~ 60m in length. The green borehole is the stimulation/injection borehole, the red borehole is the production borehole, and the yellow boreholes contain an array of sensors to monitor the experiments. The larger yellow arrow indicates north, the other points to the east. The blue discs represent zones in the stimulation well that were notched to facilitate hydrofracturing in the design direction, which is perpendicular to Shmin; the larger blue disc is a conceptual fracture trajectory from a notched section of the borehole.

Poorman Formation. The stimulation well is along the interpreted minimum principal stress (Shmin) direction. Because the drift axis orients N33.5°E, the angle between the stimulation well axis and the drift axis is approximately 35° on a plan view.

One concern for developing a hydraulic fracture from a near-horizontal well is to avoid near wellbore complexity due to perturbed stresses near the borehole. Jeffrey et al. (2014) demonstrated that notching the borehole prior to stimulation can reduce near wellbore fracture complexity. We cut circumferential notches in the borehole at selected fracturing locations using a custom-designed mechanical system that progressively extends carbide/polycrystalline-diamond cutters into the borehole wall (see Figure 3). The notching system includes a device intended to be deployed on HQ-sized coring rod using the drill rig and rotated by the rig to cut the circumferential notch. The notch cutters extend diametrically using water pressure supplied by the drilling system.

We have discussed the fundamental process for the design and build out of the Experiment 1 geometry. Analyses of the subsequent stimulations, flow tests, and associated geophysics are discussed elsewhere.

Acknowledgements

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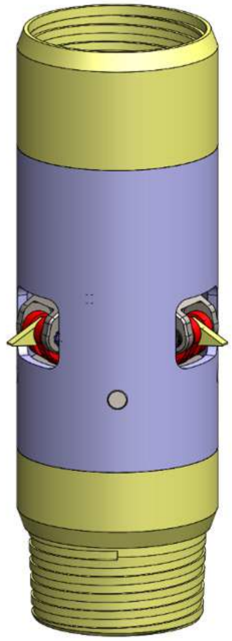

Figure 3. Left: The notching tool developed by Sandia National Laboratory. Right: An example of the notch engineered by the tool.

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Pressure systems for underground hydraulic fracturing at the Collab site at the Sanford Underground Research Facility 4850 level.

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(See Team listing in ARMA Letters, Page 5, footnote)

Introduction

The system required for this project had a long list of requirements, to include precise system flow from 10 mL/min to 6 L/min, the ability to chill the injected water, pressure and flow control modes, the ability to inject tracers into the system, downhole temperature measurements, measurement of water conductivity, back pressure control of the production interval, filtration of the water, and over pressure safety features.

System

The stimulation and flow system was designed to be as versatile as possible, and therefore included the potential for 3 pumping mechanisms: a continuous flow syringe pump system capable of generating 34 MPa and flow rates up to 400 mL/min; an air driven liquid piston pump capable of producing 3.2 L/min at 69 MPa; and, a variable frequency drive triplex pump capable of producing 13.6 L/min at 48 MPa. Each of these systems has its benefits and disadvantages. For example, high pressures and flowrates exclude the use of the syringe pump, at the cost of the high resolution flow measurements. Alternatively for leakoff tests below fracture opening pressure, the high flow resolution of the syringe pump is highly desirable.

Along with the flexibility of different pumping systems, the plumbing directing flow was also designed to be as flexible as possible. The flow system was comprised of 4 primary panels, shown in Figure 1, with inputs and outputs that could be changed and reconfigured via a

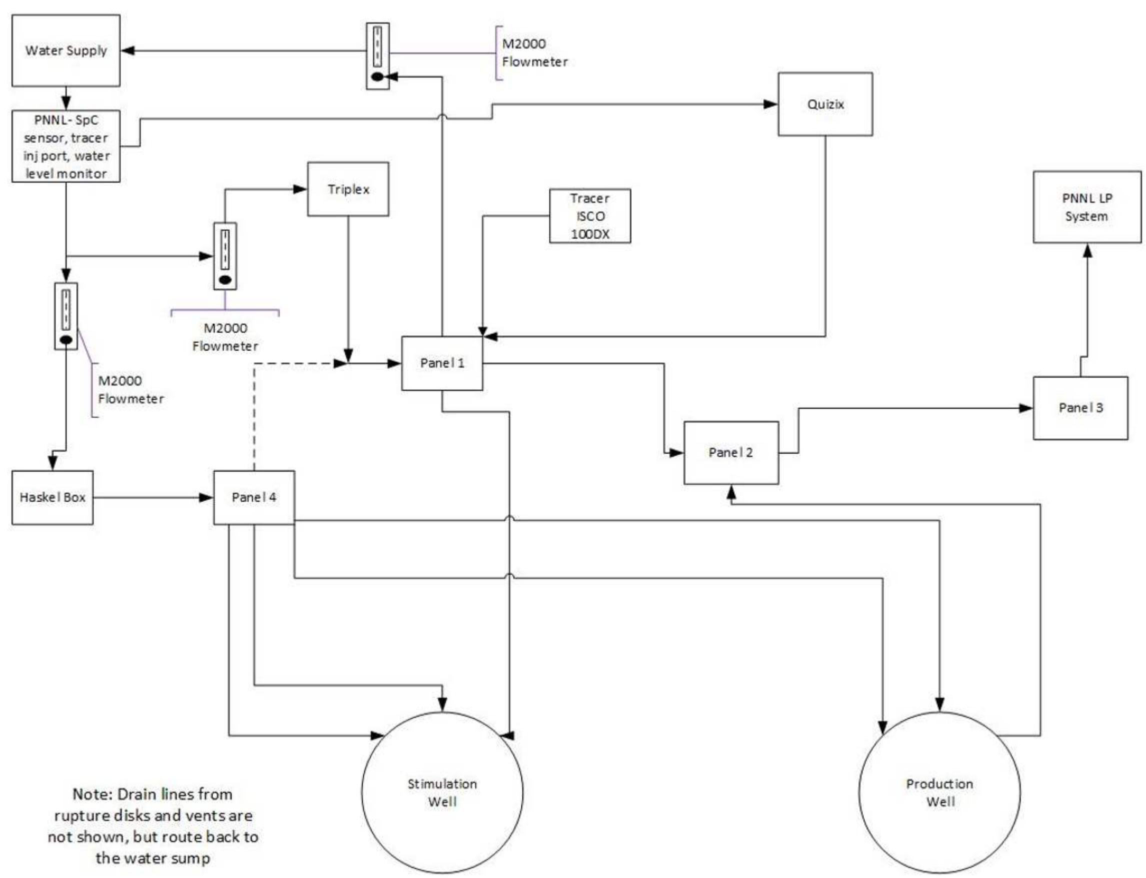

Figure 1: High level flow diagram for the pressure systems used at the 4850 level Collab Site.

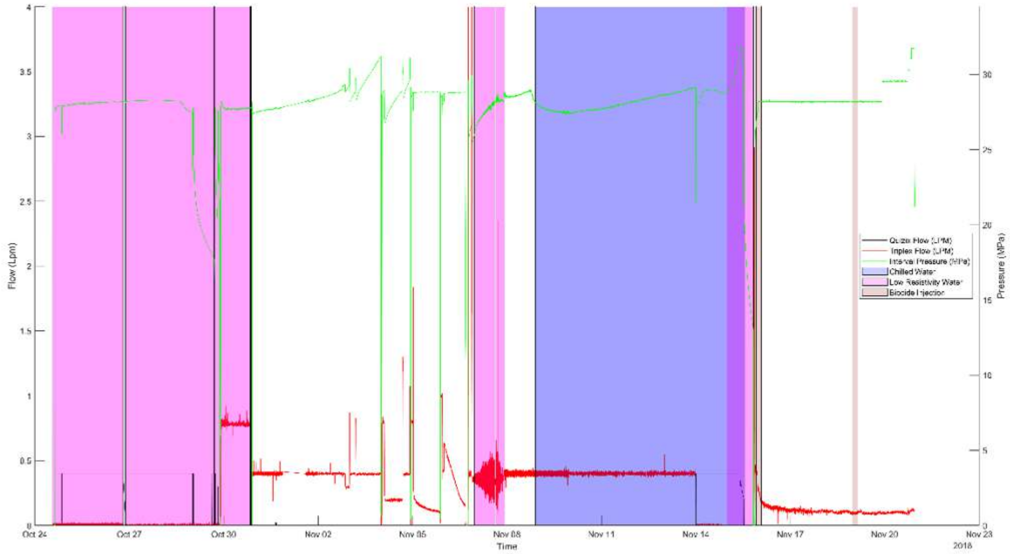

Figure 2: High level flow diagram for the pressure systems used at the 4850 level Collab Site.

series of high pressure flexible hoses to achieve different desired flow conditions (e.g., reversing the injection and production wells or utilizing two of the pumping systems to control pressure in both the straddle interval and the toe of a well to effectively pinch-off certain fracture sets). One primary feature of the system is the use of an air pressure pilot-operated back pressure control valve. This coupled with a PID loop allowed for precise control of either pressure or flow into the wells at intermediate flow levels. When the required flow exceeded the limits of the syringe pump, but was still below the idle speed of the triplex pump, the back pressure valve allowed for precise control of the injected fluid volume by dumping a portion of the flow to a drain line.

Results

As of the publication of this document there have been many tests undertaken with the system and it has performed admirably. There have been periodic failures due to minor leaks and unexpected pressure conditions which tripped system limits. However, the system has run almost continuously for over a year. Figure 2 shows an example of the pressure and flow time history during a month of operations (October to November 2018). Note the switches between the syringe pump and the triplex pump for flow operations, depending on the needs of the test. During this time a few different systems were being tested, including the injection of ambient vs chilled water, the effect of the conductivity of the water (normal mine water at ~500 μS/cm vs deinonized water at ~ 5μS/cm), and the effect of the addition of a biocide to the injected water.

Conclusions

Ultimately when designing a pumping system for this sort of situation, the most important considerations are robustness of the system for long term operations and the ability to complete the desired work with adequate resolution. Multiple pumping systems were found to be quite advantageous in this work; if there was a failure with one, another could be brought online to continue operations. Despite the tradeoffs associated with using one pump system versus the other, the agility and resilience offered by this multi-pump system has been crucial for meeting the core project needs of performing stimulations, maintaining circulation, and providing reliable data throughout the experimentation phases.

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