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Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Supplemental Information

Oil and Gas Technologies

Subsurface Science, Technology, and Engineering

U.S. DEPARTMENT OF ENERGY

Subsurface Science, Technology, and Engineering

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Introduction

The mechanics and chemistry of the subsurface (flow and exchange of fluids within and between rocks) play enormous roles in our energy system. Over 80% of our energy needs are met with fuels extracted from the ground (coal, oil and natural gas).[1] Additionally, emerging and future components of our energy system will rely on new technologies and practices to engineer the subsurface. These include environmentally sound development of:

- Enhanced geothermal systems
- Carbon storage
- Shale and tight hydrocarbons
- Fluid waste disposal
- Radioactive waste disposal
- Energy storage

These opportunities are directly linked to broad societal needs. Clean energy deployment and CO_2 storage are necessary to meet greenhouse gas (GHG) emissions reductions requirements if the most severe impacts of climate change are to be avoided.[2] Increasing domestic hydrocarbon resource recovery in a sustainable and environmentally sound manner enhances national security and supports economic growth. Thus, discovering and effectively harnessing subsurface resources while mitigating impacts of their development and use are critical for the national energy strategy moving forward.[3]

In response to these challenges, there are four main topic areas or "pillars" addressing research, development, demonstrations, and deployment (RDD&D):

- Wellbore Integrity
- Subsurface stress and induced seismicity
- Permeability manipulation
- New subsurface signals

Technology Areas

Wellbore Integrity & Drilling Technology

Well integrity and drilling technology is critical for the success of technologies focused on subsurface extraction of resources, energy storage, disposition of civilian and defense waste streams, and the remediation of sites contaminated from past endeavors. Manipulation and control of the subsurface requires access to that environment and well integrity and drilling technology are of paramount importance to this end.[4] Issues related to well integrity and drilling technology occur throughout the lifecycle of the well, from well control during the time of construction to post abandonment security of the well system, and time-scales from seconds to eons. This need extends across a wide range of geologic environments from deep, high-temperature applications in hard and fractured rock to unlithified sediments in the vadose zone.[5] Despite industry interest and investment in well integrity and drilling technology, better solutions are needed. Key research needs are described in the sections below.

Key Technology Areas

The technical areas identified where research needs exist include:

- Improved Well Construction Materials and Techniques
- Autonomous Completions for Wellbore Integrity Monitoring
- New Diagnostics for Wellbore Integrity
- Remediation Tools and Technologies
- Fit-For-Purpose Drilling and Completion Tools
- High Temperature/High Pressure (HT/HP) Well Construction/Completion Technologies

Improved Well Construction Materials and Techniques: Development of novel and enhanced engineered materials is crucial to creating more robust and reliable wellbore systems. Critical materials research problems include enhanced casing, cement, centralizers, lost circulation mitigation materials, and drilling fluids. In current practice, cemented steel casing is a passive component of the well system.[6] There is potential to make the casing system an active probe of the subsurface environment where the casing system integrates sensors to monitor a suite of parameters (e.g., hydraulic containment, casing stress, corrosion, …).[7] Additionally, there is a need to develop casing/cementing systems that are tailored to the target application and subsurface system using materials and processes appropriate for the application.[8] While expandable casing has seen increasing use in the Oil and Gas (O&G) sector, there exists the need to continue advancement of "cementless" casing systems to increase wellbore performance and to reduce costs. New casing systems that provide superior performance at costs appropriate for the application are needed, including next-generation casing/cement systems that self-heal in response to mechanical or chemical damage and are more durable in aggressive chemical environments and at high temperatures.[9] Casing centralization methods that do not impede installation but enhance cementing processes would reduce casing failures and are an important R&D opportunity.[10] Bonding of cement to casing and rock can be enhanced through improved drilling technologies (e.g., drilling "gun barrel" holes) or new methods of annulus cleaning or chemical pre-treatment of the system.[11] New techniques for the installation/application of advanced materials that would enhance wellbore integrity throughout the productive life of the well and beyond after the well has been decommissioned are an important research area. Also, improvements to current techniques using existing systems can and should be made.[12]

Autonomous Completions for Wellbore Integrity Monitoring: While systems for real-time logging and directional control exist for drilling operations (at moderate temperatures), there is a paucity of autonomous "health-of-system" downhole monitoring options available today following the construction phase of a well.[13] These sensing systems are needed across a wide-spectrum of applications and across time-frames not considered today. For example, the ability to monitor and transmit parameters such as hydraulic containment, casing stress, corrosion, rock/cement/casing bond, and other system performance parameters are not available but are of great interest in all borehole applications.[14] Given that the wellbore is the conduit to the subsurface, developing completions that can assist in probing the subsurface beyond the wellbore can provide valuable information that is largely missed today.[15]

New Diagnostics for Wellbore Integrity: Robust logging systems and diagnostic capabilities, fit for the purpose of the well, are needed to diagnose the precise location and character of possible wellbore integrity problems.[16] These tools could utilize specific physical signals or could involve the development of analytical techniques based on more general tools that allow reliable diagnostics of the integrity of the wellbore. These diagnostics would facilitate accurate targeting of remediation efforts and the selection of the appropriate remediation methodology.[17]

Remediation Tools and Technologies: Today's remediation tools rely on placing patches over the unintended breaches in the casing system or purposefully breaching the casing/cement sheath and injecting materials into the offending region. Remediation tools that selectively perforate and inject materials tailored for the particular geologic region or tools that are nonintrusive and perhaps activate a built-in healing capacity of the well system would significantly improve the ability to address casing breaches and are an important R&D opportunity.[18]

Fit-For-Purpose Drilling and Completion Tools: Drilling and completion technologies are well advanced in O&G and other sectors but not wholly applicable to the various wellbore requirements considered in the full range of subsurface applications that need to be addressed—e.g., geothermal, carbon storage, nuclear waste disposal, and others listed above.[19, 20] There are significant opportunities to improve performance and costs of drilling and completion technologies. Wellbores require a wide range of well types and adapting, modifying, or developing targeted drilling technologies and processes for specific applications is needed for the range of well types envisioned (e.g., wells for seismic monitoring of deep borehole disposal of nuclear waste).[21] Well completions that incorporate "smart" technologies (e.g., zonal isolation, valves, sensors) for applications ranging from geothermal development to environmental restoration are required. Next generation logging-while-drilling and measurement-while-drilling systems are needed: examples include providing enhanced seismic and electromagnetic imaging and geosteering relevant to the application (e.g., salinity, temperature, and others).[22, 23] Concepts regarding the development of multilateral systems to provide greater subsurface access with minimal surface infrastructure should be examined. More efficient hole advancement methods, fit for purpose drilling fluids, and advancements in downhole telemetry systems will benefit all well construction applications.[24]

HT/HP Well Construction/Completion Technologies: The availability of downhole tools that can withstand temperature in excess of 150 – 175 C are quite limited. Obviously, the geothermal sector suffers as a result, but as other endeavors extend deeper into the Earth's crust, issues of temperature and pressure tolerant downhole devices will become increasingly important across a broad range of subsurface applications.[25]

Underpinning all of the aforementioned technological needs is the development of fundamental understanding of the interactions between the subsurface and engineered systems. Previous work has often focused on the properties of the individual materials comprising the wellbore seal: casing, cement, and rock. However, wellbore integrity involves the performance of the coupled casing+cement+rock system. Failure occurs when the coupled system is unable to accommodate the thermal, chemical, and geomechanical stresses imposed by drilling operations and the geological environment. For example, little is known of corrosion rates and impacts when aggressive (e.g., CO_2- or H_2S-bearing) fluids attack the composite steel-cement system.[26] Similarly, we do not yet understand whether geomechanical stresses are aggravated or mitigated by the contrasting mechanical properties of steel, cement, and rock; or how to properly modify designs to mitigate geomechanical stresses.[27] Research is needed to study coupled processes experimentally, computationally, and in the field to quantify the behavior of seal materials, the mechanisms of seal failure, and the consequences of failure in terms of fluid flow, loss of well stability, and damage to the environment.[28] In addition, enabling technologies for many of the challenges noted above need to be developed. As an example, the development of high-temperature tolerant electronic components and sensors is needed; and materials research to improve long-term thermal, mechanical, and chemical compatibility of engineered systems emplaced in the subsurface is required to achieve this.[29]

Basis for Technology Interest

Over the last few years, on the order of 40,000 wells have been drilled annually in the United States for the extraction of resources needed to power our economy. Improvements in the reliability of the wellbore, from the well construction process through and beyond plugging and abandonment, is required to reduce or eliminate compromises to the biosphere or to other subsurface resources (e.g., ground water and mineral reserves).[30] Injection or disposal of energy waste streams face similar challenges and need improvements to minimize environmental and financial costs.[31] The general concept of improved wellbore reliability applies to all of the technology areas noted above--from the use of appropriate drilling technologies to the development of "smarter" materials--all lead to improve well integrity.[32, 33]

Performance Advances to Date

Through regulations and governmental and industrial investments, wellbore integrity and drilling technology have progressed dramatically over the last century. Materials, diagnostics, remediation tools, and drilling systems have improved as the well construction industry has matured. However, advances in well development methods have been accompanied by increases in well complexity in increasingly challenging environments. Associated with the more recent advancements in well construction and completion methods have been some notable problems (e.g., Deepwater Horizon and multistage stimulations in extended reach horizontal wells), causing the public to become increasingly concerned about such wells, leading to concerns about construction methods and wellbore integrity.[34, 35, 36] While advances have been made, they have not kept pace with the technological and societal demands of the increasingly challenging subsurface environment that is being accessed today.

RDD&D Needs and Implications

The research needs associated with this technology area encompass the entire suite of wellbore construction and abandonment technologies. Research needs include: (1) new materials and smarter materials, and techniques for wellbore construction; (2) innovations in and applications of autonomous monitoring technologies, improved wellbore diagnostics, and tools for targeted remediation of wellbores; (3) adaptation and development of drilling methods and tools that suit the application purpose; and (4) the development of materials, sensors, and systems that can survive increasing harsh high-temperature/high pressure environments.[37, 38]

Improvements in wellbore integrity and drilling technology alone will not result in adoption of such in the vast majority of wellbores created in the U.S. if the new technologies are not economically viable. Cost savings or cost equality is needed for commercial adaptation. RDD&D in these technology areas must continually address the economics associated with the proposed improvements.

Subsurface Stress and Induced Seismicity

This pillar focuses on the interrelated topics of subsurface stress and induced seismicity (IS). In addition to addressing the characterization and manipulation of stress and IS, the pillar includes elements focused on their use to assess and modify permeability and on risk analysis for subsurface processes (including induced seismicity).

The subsurface stress state is very important to energy activities, but current abilities to characterize or manipulate stress are inadequate. To guide and optimize sustainable energy strategies while simultaneously reducing the environmental risk of activities such as subsurface injection, new approaches are needed to quantify the subsurface stress regime, both local and regional. Such quantification will require characterizing the local and regional geology (lithology, tectonics), the nature and presence of faults and natural seismic activity, the pressure and properties of existing fluids, and the mechanical properties of rocks.[39]

Induced seismicity is a potential component of any manipulation of the subsurface, such as fluid injection or withdrawal. Induced seismicity is both a tool used to understand subsurface processes, especially fracturing, and a hazard when seismic events are too large. Both aspects of IS need greatly improved characterization to reduce the hazard while improving our ability to manipulate seismicity to improve its use as a tool.[40]

To address the energy system needs listed at the beginning of this paper—geothermal systems, carbon storage, improved resource extraction from shales and tight sands, waste disposal, and others, requires substantial advancements in our understanding of the subsurface. To do this will require the integrated characterization and manipulation of stress and IS for the specific needs of engineering permeability. This integration requires a specific focus on permeability impacts from manipulation of stress and the relationship between stress, seismicity and permeability.

The immediate risks associated with IS, including public nuisance, surface damage, unintended subsurface slip and/or opening of fractures, need to be addressed in a consistent framework applicable to all the subsurface engineering activities.[41]

With these elements in mind, the overarching goals of the Stress/IS pillar are: (1) advance technologies to quantify in-situ subsurface stresses; (2) manipulate such stresses to improve reservoir performance and reduce risk; (3) image and characterize faults and probe their critical stress state; (4) measure and manipulate induced seismicity to reduce risk and to monitor subsurface processes contributing to the adaptive control of fluids; and (5) develop risk driven adaptive controls.[42]

Key Technologies

To advance our control of subsurface stress and induced seismicity we need technology to first characterize and then manipulate stress. The characterization of stress is needed over large spatial extents (borehole to interwell to reservoir/field scale) and with sufficient temporal and spatial resolution for various subsurface activities.[43] Acquiring this knowledge at each site requires technology in many topics including: sensing stress state along and beyond the borehole, characterizing the spatially varying stress field away from the borehole up to regional scale, and development of a risk assessment framework. Adaptive control of subsurface fractures and flow requires pairing capabilities gained through this theme with new abilities to manipulate and predict subsurface permeability.[44]

Examples of current stress measurement techniques include: <u>(1) core-based studies</u> (e.g., inelastic strain recovery, core disking, and petal fractures) can provide estimates of the stress tensor; (2) Seismic based measurements infer stress from matrix or fracture properties via anisotropy/heterogeneity (e.g. stress-dependent velocity, shear-wave splitting); and (3) wellbore observations (e.g., wireline logs such as dipole velocity which gives seismic anisotropy and imaging logs which give information on wellbore breakout and drilling induced fractures. All of these are used to provide stress orientations and/or magnitudes with rock properties. Small hydraulic fractures (mini fracs) are used to measure minimum stress directly (with assumptions) and are combined with density and imaging logs to estimate the stress tensor along the hole.[45, 46]

Strain relief methods (e.g., overcoring) are suitable in shallow holes, with full stress tensor characterization, if possible, under certain assumptions and with separate measures of rock properties. Advances in stress characterization would come from advances in any or all of these methods.[47]

To advance our characterization of induced seismicity, large improvements are needed in monitoring network design and instrumentation, velocity structure characterization, and geologic characterization—especially faults and fracture zones as well as rock properties and the in-situ stress field.[48]

Basis for Interest in Technology

Knowledge of the subsurface stress state is important for many subsurface activities related to energy production and storage (or disposal) of waste, including prediction and control of hydraulically induced fractures and the activation and/or re-opening of faults. The induced seismicity associated with subsurface operations is a related topic, but one of singular concern given the current increase in mid-continent seismicity.[49] Current capabilities to directly measure or infer the in-situ stress are woefully inadequate, especially away from boreholes. This limitation leads to significant uncertainties and lost opportunities to take advantage of the subsurface for energy production and waste storage, as well as public distrust in the subsurface energy sector. A recent report to DOE by the JASON committee recommended "that DOE take a leadership role in the science and technology for improved measurement, characterization, and understanding of the state of stress of engineered subsurface systems in order to address major energy and security challenges of the nation". The report says "the science appears ripe for breakthroughs (e.g., in applying laboratory-proven measurement techniques in the field), disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can effect these advances".[50]

Existing methods for determining reservoir stress state are largely indirect or interpretive. These methods also depend on assumptions of rock properties that are typically overly simplified, such as homogeneity or isotropy, and/or they are difficult to validate. Significant breakthroughs are needed to quantify both the local and regional stress states and their evolutions in response to perturbations.[51] Additionally, breakthroughs are needed to relate stress changes and IS to permeability and fluid content of fractures. To meet these challenges, new approaches are needed for measuring stress and seismicity and their indirect effects on flow, temperature, and reactions, as well as integration approaches.

Performance advances to date

Current approaches to interrogating subsurface stress states either provide information about only a very small fraction of the relevant subsurface region (e.g., wellbore pressure transducers) or provide an unacceptably fuzzy interpretation of in-situ conditions (e.g., inversion of induced micro-earthquake data).

The field of well-logging, for example, has developed an assortment of tools to measure subsurface properties, but these tools are typically used with a limited goal – production of oil and gas.[52] For example, measurements of density, needed to estimate vertical stress, often do not extend to the surface, requiring use of empirical relationships to estimate the vertical stress above reservoirs. Beyond the borehole, at interwell or reservoir scales, geophysical inversion modelling using seismic or geodetic data estimates changes in stress by proxy, but absolute stress at any scale beyond the borehole is very poorly constrained. At the largest scale, a worldwide stress map has been developed (often using small scale borehole measurements).[53]

The metrics for individual measurements needed to understand stress and induced seismicity (e.g. density, elastic moduli, seismic velocity, fracture density, and orientation) are too numerous to describe.[54] The overarching metric should be stress tensor values with spatial and temporal variation, all with specified uncertainty.

Technology needs and potential

Research associated with this topic should aim for a new class of capabilities that would enable accurate quantification of the pre-injection and temporal evolution of *in situ* stress magnitudes and directions (full stress tensor) throughout the affected rock volume, including the reservoir and cap-rock, and from borehole to field and regional scales. Establishing the relation between the evolution of effective and poro-elastic stresses and the deformation, in particular the potential of shear slip along faults, will be essential for this endeavor.[55, 56]

Research aims to develop new approaches to quantify both local reservoir and surrounding (regional) stress state, both of which are important to eventually manipulate stress for adaptive control of subsurface fractures and flow. Well controlled and calibrated subsurface perturbations may provide useful information about the local stress state. Examples include well-designed injection, energetics, or push-pull tests that temporarily modify the local stress field in the vicinity of wellbores. Small hydraulic fracture experiments (e.g., mini fracs) can be systematically employed on a large scale to measure minimum stress directly.[57] Improved measurements will aid the understanding of instantaneous shut-in pressure. Such stress tests could be combined with seismic, temperature, geochemical, or other tracers that indirectly respond to pressure perturbations. Meso- to macro-scale stress state, natural fracture networks, and permeability are strongly influenced by the tectonic stress field, which is particularly difficult to quantify. Entirely new approaches are needed to meet this challenge.[58]

An ensemble of boreholes, distributed around the volume of interest, could be used to perform purposefully designed, large-scale pressure and flow perturbations. The design of the perturbation should be partially based on core studies of reservoir rock under relevant conditions. The induced subsurface field response, including micro-earthquakes and fluid flow, could be monitored using a variety of new instrumentation, and deployment of existing instruments in significantly larger quantities and greater spatial sampling.[59] Improving subsurface access for monitoring instrumentation is essential. Research developments associated with this topic are expected to be critical for guiding the optimal management of new reservoirs as well as systems that have been subjected to multiple injection experiments.

Examples of sensor advances which can address challenges in this pillar include broadband fiber-optic 3D component seismometers that are placed inside of multiple wellbores and shallow wells below the ground surface to monitor background and induced seismicity; distributed acoustic fiber optic sensor strings (allowing variable spatial sampling) placed outside of casing together with tilt, INSAR, lidar and other deformation sensing; seismoelectric and piezoelectric signatures; and nanoscale temperature, flow, and pressure sensing devices that can be distributed throughout the volume of interest.[60, 61, 62] Continuous monitoring during engineered activities, over a broad range of properties, will be needed to address multi-physics impacts of coupled processes. Development of new wireline logging tools for direct measurement of stress in high-temperature environments (e.g., integrated mini-frac logging tools / density / imaging) is envisioned.[63] A new class of non-elastic approaches would be needed to inform geophysical inversion models that use these diverse (direct and indirect) measurements, together with other information that is often available (such as from geological knowledge, wellbore breakout observations and geophysical monitoring).

Potential to meet drivers/objectives

The objectives of this pillar can be met with a combination of cross-cutting application of existing technology (e.g. applying earthquake seismology algorithms to the industrial scale measurement of induced seismicity) and development of new measurements or geometry of measurement (e.g. dedicated boreholes for sampling and probing fault/fracture properties). Opportunities for advancement exist by improving coordination among scientific communities: e.g. academia–industry–government and field–laboratory–theoretical. By using expertise in DOE laboratories to focus multi-instrument measurements at multiple dedicated field sites and user facilities, significant breakthroughs in understanding subsurface engineered systems are possible.[64]

The metrics for success include: (1) increasing the spatial and/or temporal resolution of stress tensor values in one or more of the dedicated field observatories; and (2) increasing the predictive ability of induced seismicity in magnitude and location.

Potential Impacts

A real and permanent control of the subsurface state of stress should become the new paradigm in order to optimize fracturing processes and ensure efficient and environmentally safe fluid pathways. Comprehensive designs of fluid injection systems (for example increasing and varying the number, length and direction of horizontal wells) and various injection rate scenarios should be adapted to the existing local stress field.[65] In order to locally release stress and balance the increase in pressure due to fluid injection, optimized water/brine pumping techniques could be deployed.[66] Innovative techniques can be envisioned and tested such as changing rock properties and/or temperature at depth to modify stress and exploring the effect of induced dynamic transients by energetic means on stress.[67]

The number of seismic events induced by human activities and felt by the population in the United States has increased over the last decade.[68] It is thus of primary importance to establish a framework and protocol for assessing key risk drivers associated with subsurface engineering activities. A systematic framework is needed to identify the risk factors associated with all engineered subsurface activity, and activities such as DOE's National Risk Assessment Partnership (NRAP), tasked with identifying and quantifying risk uncertainty associated with carbon storage, can and will play a key role in ensuring safe subsurface operations.[69] Examples of risk contributors could potentially include the natural geological fabric and stress state, existing fracture and fault networks, and wellbore and natural subsurface fastpaths that serve as conduits to environmental systems. The objective will be to develop an understanding of the different factors contributing to the overall probability of environmental and population impacts under a variety of subsurface conditions and perturbations. As with the DOE NRAP project, it will be imperative to develop and test a risk assessment framework hand-in-hand with development of process understanding and simulation capabilities.[70]

Permeability Manipulation and Fluid Control

The main objective of this pillar is to develop a knowledge base and technologies to manipulate subsurface flow through an integration of physical alterations, physicochemical fluid/rock interaction processes, and novel stimulation methods implemented at the field scale. Achieving this objective will significantly advance long-term safety of waste and CO_2 storage, enable step change increases in hydrocarbon recovery, and enable creation of large volume heat exchangers in geothermal reservoirs. The permeability manipulation and fluid control technologies provide a basis for "adaptive control" of subsurface fractures and fluid flow.

Description of Key Technologies

1. Rock fracturing technologies: These technologies are focused on creating fractures to increase effective permeability and/or contact area between fluid and rock. The technologies include fluid based technologies where fluids (water-based, non-water based) are injected in rocks at high-pressure as well as high-rates. Water-based technologies are currently used widely in petroleum as well as geothermal operations. Waterless fluid technologies use fluids such as CO_2, propane/butane, or diesel. Some of these technologies have been tried in the field but are currently not as widely used as water-based technologies. Other rock fracturing technologies include non-fluid based technologies such as use of energetic processes. In addition to creating fractures, it is also necessary to keep the stimulated fractures open using proppants. Various engineered and natural materials including sands are currently being used in fields.[71]

2. Fluid flow control technologies: These technologies are primarily aimed at controlling fluid flow, including completely plugging flow paths. Viscous materials such as muds and cements as well as polymers and gels that respond to various stimulants in sub-surface have been used for flow conformance in various subsurface applications.[72] Novel materials such as smart particles are being developed but are not yet widely applied in the field.
3. Fracture/flow characterization technologies: Technologies to characterize fracture networks and their properties as well as fluid flow are necessary to determine the effectiveness of permeability and flow manipulation technologies. Technologies such as tracers, smart particles, and acoustics are currently being used.[73]
4. Enhancing extraction of immiscible fluids: The injection of chemicals to desorb desirable gases from organics and the injection of surfactants during secondary recovery of oil in conventional reservoirs are two examples of enhancing the extraction of desirable products from the subsurface.[74] Currently, unconventional oil recovery is being performed by hydraulically fracturing in tight shale formations with little understanding of the long-term effect of the non-recovered injected water on resource recovery.

Motivation

Manipulating subsurface fracture characteristics and associated fluid flow is critical for multiple subsurface energy applications. In order to improve recovery efficiency of unconventional hydrocarbons and geothermal energy, it is necessary to manipulate subsurface fracture characteristics and associated fluid flow. In nuclear waste disposal, minimization of fracturing and fluid flow in the near-field damage zone surrounding emplacement tunnels is needed for ensuring safe long-term storage. For CO_2 storage, energy storage (natural gas or compressed air), or large-scale disposal of liquid wastes, fluid flow may need to be enhanced to improve well injectivity, while also sealing potential fracture leakage pathways in the overlying confining layers.[75]

The current lack of precise control over fracturing and fluid flow despite decades of industrial practice is testimony to the huge challenges involved, primarily related to the difficulty of characterizing the heterogeneous deep subsurface and incomplete understanding of the coupled processes related to fluid flow, geomechanics, and geochemistry over scales from nanometers to kilometers. To address these challenges this will require a substantial and sustained research effort focused on the overall theme of fracture and fluid flow control.[76, 77]

Performance advances to date and metrics

The technologies needed for manipulating subsurface fractures and fluid flow have been developed and advanced through both industrial RD&D efforts (primarily oil & gas) as well as DOE RD&D investments (geothermal). Most of the advances have been through field trial and error with mixed results on effectiveness. Also, successful deployment of hydraulic fracturing at a site in a field has not translated into similar results in other fields in the same region or even at other sites in the same field.

Success metrics can include:

- Improved recovery efficiencies in unconventional oil/gas fields as well as geothermal fields
- Demonstrated long-term effectiveness of flow control technologies at a CO_2 storage site
- Improved sensitivities and accuracies of subsurface fracture/flow characterization technologies

Technology needs and potential

High-pressure fluid injection stimulation activates a wide variety of coupled processes involving thermal-hydrological-mechanical-chemical (THMC) effects that play out over a wide range of length and time scales. A better understanding of the stimulation of tight rocks (e.g., carbonaceous shales) is needed to design effective and sustainable fluid flow pathways.[78] There is a need to characterize rock properties, including textures, mineralogy, composition, and mechanical properties, at all relevant scales and their effect on induced fracture characteristics.[79] In addition to rock properties, the effects of fluid properties on induced and natural fractures need to be characterized in order to design and control the stimulation.[80] An underlying need for realizing such control is a set of validated, rate-dependent poro-mechanical models for tight unconventional reservoirs and caprocks.

In addition, there are large uncertainties in predicting and modeling the geochemical interactions between the injectate, pore fluids (e.g. in nanopores), and minerals as well as organics in tight hydrocarbon-bearing rocks and the effect of geochemical interactions on rock's geomechanical response.[81, 82, 83] To remedy this shortcoming, research is needed to improve understanding of fracture-matrix fluid flow, fluid-organic-mineral, and fracture-tip interactions as a function of stress, temperature, and solution composition. Knowledge about fluids, geomechanics, and geochemistry is essential to achieving mastery of control of fracturing (orientation, aperture, and size) from near-well-scale to reservoir-scale for efficient and sustained fluid extraction while minimizing formation damage and environmental impacts.

A sustained research program involving characterization, high resolution imaging, geomechanics, geochemistry, and coupled process experimentation and modeling is needed to address existing gaps in knowledge. Reservoir geologic material from sites such as unconventional hydrocarbon reservoirs, potential nuclear waste repository formations, and caprock from prospective geologic carbon storage sites should be used[84, 85, 86] Studies should be carried out on a range of scales from core, to block, to field scales, and laboratory observations should be compared against targeted field observations.

The primary means by which fluid flow can be manipulated is to control the fluid flow path. Some energy applications demand enhancements to fluid flow (e.g., hydrocarbon production), while others demand reducing or eliminating fluid flow (e.g., nuclear waste disposal). While hydraulic fracturing is widely used, and grouting of fast-flow paths is successful in some applications, there is a clear need for improved capabilities in this area as evidenced by rapid declines in production of gas from shale.[87]

In the area of stimulation by hydraulic fracturing, what is needed is the ability to adaptively control fracturing in real time. This demands a coupled injection-monitoring-modeling approach with a short response time. Improved understanding of fracture-matrix fluid flow in tight rocks is needed to enhance production. For reducing or eliminating flow paths, fluids or materials that change properties (e.g., solidify or become more viscous) as a function of natural or applied conditions are needed. This is useful for multi-step stimulations to create pervasive fracture networks in the face of single, large fractures dominating flow.[88] The plugging of leakage pathways through caprock and thermal breakthrough pathways are obvious applications for such technology. Another application is the delivery of fluids/materials to target zones for treatment or flow control.

While the current stimulation methods have been successfully deployed to produce unconventional fossil and geothermal resources, there is a need to develop environmentally sustainable novel stimulation methods. In some cases, novel stimulation approaches including combinations of approaches could make the difference between an economical and sustainable production well and one that would otherwise be abandoned.[89] Depending on the relevant fracture initiation mechanisms, energetic approaches may provide advantages. Chemical approaches (e.g., acidization) coupled with mechanical stimulation could also have advantages.

Laboratory and field experiments on new materials, propellants, and energetics are needed to develop the capability to deliver precise stimulation at precise locations with the desired rate of energy release. There is also the possibility of developing alternate fracturing fluids (less or zero water) all of which need research and development.[90] Finally, full-scale simulation codes for fracture propagation with realistic heterogeneity and fluid properties with iterative coupling of models and experiments across scales are needed to optimize effectiveness of stimulation approaches, including extent of stimulation, fracture spacing, fracture surface area, and fracture dynamics.[91]

Potential to meet drivers/objectives

To meet the objectives of this pillar sustained, focused RD&D efforts are needed. With careful planning there is potential to successfully meet the overall objectives through demonstrations in pilot or small-scale field tests. As with any field demonstrations and experimental R&D program, there are risks associated with logistical issues related to field availability as well as technical uncertainties in the success of field work, experiments, and numerical modeling studies. It is in the nature of these studies that it may not be possible to control all variables.

Potential Impacts

At a time when the subsurface is being called upon to provide primary energy resources, storage, and disposal solutions for energy and energy wastes, the benefits of manipulating subsurface fracture and fluid flow are potentially enormous, including:

- Dramatically improved efficiency of energy resource recovery leading to stronger national energy and economic security with less environmental impact
- Robust design of energy/carbon/waste storage solutions
- Reduced environmental risks and water use associated with subsurface energy strategies
- Stronger scientific basis and increased public confidence in subsurface energy operations

New subsurface signals

The ‘New Subsurface Signals’ pillar seeks to transform our ability to characterize subsurface systems by focusing on four areas of research: new sensors, integration of multiple datasets, identification of critical system transitions, and automated data collection and processing. A focus is on co-characterization of physical, geochemical, and mechanical properties using multiple datasets and on leveraging advances in material science, nano-manufacturing, fiber optics, and high-performance computing. Success in addressing this challenge is needed to master the subsurface, enabling efficient and environmentally sound subsurface energy production and energy waste storage. Figure 1 illustrates some of the issues in monitoring and controlling subsurface processes.

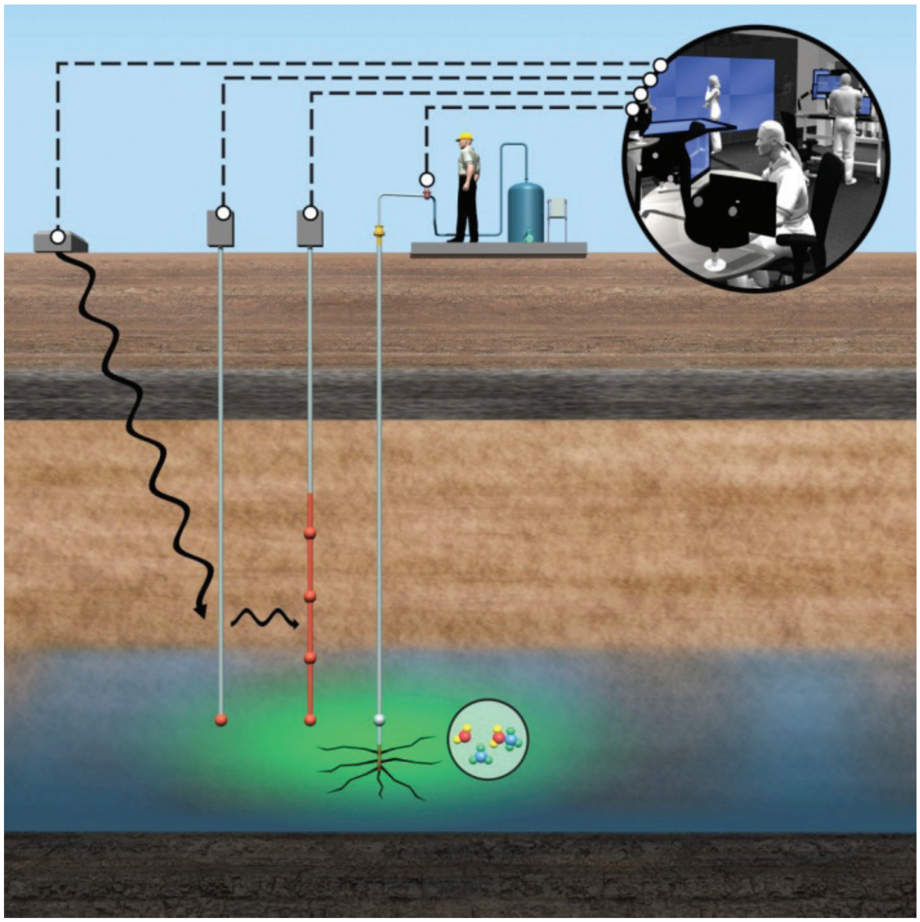
Description of key technologies

- New sensors and approaches for monitoring fracture evolution, reactions, and flow
- Autonomous data acquisition, processing, and assimilation
- Next generation integration approaches for data fusion
- Diagnostic signatures of critical transitions

Motivation

Figure 1 Artistic view of the concept of monitoring and control of subsurface processes.[92]

Credit: Lawrence Berkeley National Laboratory



A major obstacle to adaptive control of subsurface fractures, reactions, and flow is our inability to clearly characterize and monitor critical subsurface features. Although the energy industry has developed sophisticated tools to characterize the subsurface using both surface and wellbore methods, these tools are optimized for specific problems and settings and an entirely new class of capabilities is needed to characterize fractures and associated processes at sufficiently high spatial and temporal resolution and over large enough volumes to guide subsurface operations.[93, 94] The challenge is complicated by the wide range of relevant scales and the coupled nature of relevant thermal-hydrological-mechanical-chemical (THMC) processes.

Metrics

Metrics include improving performance of a sensor or analysis system. This might be measured as an increase in resolution either spatial or temporal, performance under extreme conditions (for example, capable of operation up to 225°C rather than 150°C), or simply the ability to identify a feature (such as a critical transition). Alternate measures for a new technology might include lower cost or adoption by stakeholders.

Technology needs and potential

New approaches are needed to remotely characterize fracture distribution and behavior in-situ as well as associated fluids flow and reactions with host rocks or other fluids. Development of both new sensors and time-lapse monitoring approaches are critical for meeting this objective. Advances in material science and manufacturing, especially nano-manufacturing, offer an exciting opportunity for development of next generation sensors that are cheap, small, and high-performance. Such sensors could facilitate widespread deployment within a reservoir and lead to the data redundancy needed for vastly improved characterization of subsurface geochemical, hydrological, and mechanical properties. The illumination of fractures and reactions could be greatly improved through the development of geophysically-detectable injectates, which could be deployed as tracers, proppants, or stimulation fluids, and remotely monitored using time-lapse geophysical methods.[95, 96] Manipulation of borehole pressures and associated monitoring of induced resonant modes could aid in the quantification of fracture distributions.[97] Advances in field-deployable lasers and fiber optics enable the development of new *in situ* sensing, including spectroscopic techniques to map wellbore chemistry with sufficient resolution to resolve mineralogic composition within fractures. At present, simple tracers and geochemical analyses provide limited information about the subsurface.[98] New geochemical monitoring approaches could include pH and redox potential (Eh) sensitive tracer chemicals, inert gas-cocktail injected tracers, isotopic approaches, dye molecule-coated nanoparticles, and reactive tracers that help interrogate fracture surface area or subsurface properties. The development of these new tracers and analyses will enhance fracture property assessment, the interpretation of subsurface conditions/reactions, and improve assessment for signals of subsurface conditions (e.g. tracers with specific geochemical interactions that target properties or processes of interest).[99, 100, 101]

In combination with new sensors, early research is indicating the potential of using repeated (time-lapse) surveys to highlight subsurface fracture evolution and flow. New avenues include the use of multiple time-lapse geophysical datasets and the development of time-lapse geochemical and geomechanical sensing approaches. Examples include: (1) joint use of time-lapse acoustic emission, seismic, gravity, and/or electromagnetic datasets to image fracture evolution; (2) strain using borehole tiltmeters or surface measurements; (3) fiber optic technologies for quantifying fracture dynamics; (4) use of trace chemical constituents and isotopes in produced fluids to infer changes in fracture density or spacing; and (5) the development of borehole muon detectors to map density change due to fluids motions and time-lapse geophysical methods to remotely quantify subsurface geochemical changes. Significant research is needed to fully explore the potential of these methods and to develop field-deployable techniques. Time-lapse measurements are especially powerful when used to validate modeling codes.[102, 103, 104]

In addition to new sensors and approaches, a next step is to combine multiple different measurements and models in a rigorous manner to simultaneously estimate subsurface properties of interest and associated parameter uncertainty. While methods for joint geophysical and hydrological inverse modeling (converting geophysical and hydrological measurements into 3D images of the subsurface that can be integrated with other surface and subsurface observations) have been developed to characterize subsurface systems, several significant research gaps exist. These include incorporation of rich geomechanical and geochemical information and the development of hierarchical and dynamic inversion modelling approaches that consider the multi-scale, coupled and temporal nature of subsurface processes and datasets as well as information about antecedent conditions.[105]

Stochastic approaches offer an avenue for tackling these problems. These techniques are flexible and robust; can incorporate multiple types of data, petrophysical relationships, and process models; and can provide realistic error estimates. A benefit of advanced uncertainty techniques comes from determining the covariance of measured parameters, which can lead to a better physical understanding of coupled processes as well as indicate which parameters are most valuable under specific conditions. For problems that require concurrent modeling of complex phenomena (such as of fluid flow, reactions, and wave propagation) co-development of new inversion approaches with hardware/software could greatly improve computational feasibility, as could development of reduced order solutions.[106, 107] Finally, new techniques are needed to quantify the value of derived information, which can in turn be used to guide the development of optimized and cost-effective sensing suites, such as next generation fiber optic sensors or nano-sensors.

The development of autonomous acquisition, processes, and assimilation approaches is critical for adaptive control of subsurface systems and inextricably linked to simulation capabilities. Research associated with advancing autonomous analytics blends systems engineering, computational, and subsurface expertise. New acquisition software will be needed to autonomously trigger and co-acquire data from multiple sensors and to stream those datasets to computational centers. Data management, processing, and visualization workflows and tools are needed that are capable of handling large and heterogeneous datasets and of performing real-time quality control steps. Inversion approaches, such as those described above, could be automated to allow estimation of key parameters or states using the acquired field datasets. Performance increases can be obtained by constructing reduced order models based on the high-fidelity numerical models and by using subsampled datasets. Approaches to assimilate direct measurements and inversion results into Thermal-Hydrological-Mechanical-Chemical (THMC) models will be needed to guide 'adaptive control' of subsurface fractures, flow and reactions.[108, 109]

Finally, the last step is the identification of signatures that are diagnostic of critical thresholds, where system behavior is dramatically different from previous conditions. Examples of critical transitions relevant for sustainable energy production and waste storage include the breaching of caprock, the connection of hydraulically-induced fractures with an existing fault, wellbore integrity failures, or the influence of abrupt precipitation and dissolution processes on fluid flow.[110] Most characterization approaches typically focus on quantification of a single subsurface property or state (such as permeability or gas saturation); multiple approaches are commonly used together to characterize different aspects of a single system as described above. In contrast, research in this topic should seek to identify an integrated signature, where integrated implies the combined use of a variety of subsurface signals to diagnose abrupt changes in any subset of THMC processes associated with step changes in system behavior. Using laboratory and field data collected during abrupt transitions in subsurface system behavior, physics-based as well as complexity-based (e.g., graph theory, pattern, and fuzzy) approaches could be advanced to identify diagnostic signatures of critical system transitions using multiple datasets. Knowledge of integrated diagnostic signatures could pave the way for research focused on identifying precursors leading to critical transformations and the development of new sensor suites particularly optimized for early detection of such thresholds.[111, 112, 113, 114]

Potential to meet drivers/objectives

The development of low cost monitoring techniques, most of them without the need of using active sources or a large amount of expensive chemicals, is an important goal of this pillar. Another is the optimization of the deployment of sensors and borehole geometry in the field allowed by a thorough understanding of the studied system behavior: definition of the most efficient methods for a given site, minimum number and optimized emplacement of sensors, etc. The highly improved processing and interpretation of the combined geophysical and geochemical signals will lead to quasi real time decisions and thus increase the efficiency of operations and likely reduce overall cost.

Potential Impacts

The potential impacts are significant. By improving understanding of the subsurface processes and our ability to control them in quasi real time, this should lead to more efficient and therefore lower cost operations. The likelihood of unexpected events should decrease and therefore inadvertent environmental impact should be reduced while the public confidence in the employed technologies should be increased. Ideally, application of these improved techniques may lead to a better knowledge of subsurface energy resources and aid energy security.

Public and Private Roles

There are a number of large companies that work on extracting resources from the subsurface—oil, gas, coal, mining, etc.—but for many other aspects of the subsurface, markets do not drive significant private R&D investment. In some cases, the barrier to private-sector R&D is simply limited funding available to advance the state of the art (e.g., geothermal). In other cases, the large capitalization required and the high risk involved limit investment. Even for large energy companies, the roller-coaster of energy prices impacts R&D investment. Further, for some aspects, there is a public need to develop technologies where no market driver currently exists (e.g., carbon capture and storage), or to meet Federal obligations (e.g., nuclear and other high-level waste storage/disposal). And in others, health and safety regulations may limit some corporate activities and encourage improved practices, but companies may have little motivation to conduct R&D to explore the technology frontier of what environmental safeguards are potentially viable in order to push the frontier of where regulations should be set. These and other factors motivate a public role in subsurface R&D.

DOE has long funded competitive, cost-shared R&D with industry, universities, national labs, and others that has led to a number of transformative technologies. Examples include DOE's pathbreaking investments in oil and gas rock stimulation, coupled with R&D into innovative drilling-related technologies, such as polycrystalline diamond compact drill heads, led to the shale oil and gas production revolution.[115, 116] As it is not a market competitor, DOE also has the unique ability to pull together a consortium involving data sharing between multiple Labs, industry, and academic partners to tackle identified subsurface challenges across a variety of geologies. Technology advancements with the potential to revolutionize the global energy landscape usually require sustained long-term R&D investments that are not addressed by the short-term private sector R&D that is typically focused on current company profit-center concerns rather than long-term exploratory research. However, such longer-term basic science and applied technology RDD&D investments drive U.S. energy leadership, competitiveness, and independence; environmental responsibility, sustainability, and safety; and economic prosperity through cost reduction and job creation. These factors motivate DOE's subsurface engineering investments' focus on solving high-impact challenges that are not sufficiently addressed by the private sector.

Enabling Science activities; and Cross-cutting Technologies and Issues

The DOE Office of Science supports a broad spectrum of fundamental research in subsurface science, focusing on topics including geology, geophysics, and biogeochemistry. In the context of the subsurface crosscut, basic science on subsurface chemistry, monitoring and characterization, and complex fluid flow are all critical.

Fundamental advancements in materials science also feed directly into the goals of the subsurface crosscut. In particular, the research directed at adaptive materials and the deployment of small scale sensors will leverage enabling science capabilities. The development of materials for harsh conditions (specifically addressed in Technology Assessment Ch.6.H Materials for Harsh Service Conditions) will have strong ties to the intelligent wellbores pillar.

To optimize the role of the subsurface in creating a safe and effective energy future, the DOE is advancing a new crosscutting RDD&D strategy focused on identifying and addressing technical challenges that are faced by multiple sectors. Through cross-cutting RDD&D the energy grand challenges associated with the subsurface can be more quickly and effectively addressed. The DOE Subsurface Technology and Engineering RD&D (SubTER) Crosscutting Team was formed to develop and execute this strategy. In collaboration with the National Laboratories, SubTER has identified *Adaptive Control of Subsurface Fractures and Fluid Flow* as a key crosscutting theme. The ability to have real-time control of the subsurface can have a transformative effect on numerous industries and sectors, impacting the strategies deployed for subsurface energy production and storage. Such control of the subsurface requires efforts to address the following key challenges to optimize energy production, energy/CO_2 storage, and waste storage/disposal:

- *Discovering, characterizing, and predicting:* Efficiently and accurately locating target subsurface geologic environments; quantitatively inferring their evolution under future engineered conditions; and characterizing the subsurface at a relevant scale;
- *Accessing:* Safe and cost-effective drilling or mining with properly managed reservoir integrity;
- *Engineering:* Creating the desired conditions in challenging high-pressure/high-temperature environments;
- *Sustaining:* Maintaining these conditions over long time frames throughout complex system evolution; and
- *Monitoring:* Improving observational methods and advancing understanding of the microscopic basis of macroscopic complexity throughout system lifetimes.

Program Partnerships

Partnerships with industry, universities, other federal agencies, non-profits, and other entities will be critical to the success of this crosscutting RDD&D strategy. The network of field observatories will rely heavily on "sites of opportunity", which, in many cases, can be provided by private entities. The Federal role in RDD&D includes releasing research results into the public domain. By partnering with the Federal government in research, both the public and private sectors can leverage technical and economic risk which is of mutual benefit. A component of the RDD&D strategy involves unlocking large data sets and making them broadly available. Doing so will require strong partnerships with the owners of the data and with organizations experienced in data governance and stewardship.

Program Considerations

The technology assessments presented here constitute the four pillars of an overarching RDD&D strategy to achieve the outcome of *Adaptive Control of Subsurface Fractures and Fluid Flow*. This coupled RDD&D program presents a phased schedule of RDD&D in conjunction with testing at a network of energy field observatories for validation of fundamentally new and timely capabilities. Fit-for-purpose modeling and simulation is a key component of advancing technologies in all of the pillars and will be used to better understand complex subsurface systems and explore scaling from laboratory results to the scales of natural systems.

Field activities are essential to advance the state-of-the-art in subsurface technology and engineering. In order to extrapolate insights gained in the laboratory through experiments, theory, and simulation to the scale of field observations, heavily instrumented sites generating streams of high-fidelity data that industry either does not routinely collect or make publicly available are critical. The subsurface crosscut is rooted in a coordinated approach to strategically leverage a wide variety of new and ongoing field operations to support the four proposed technical thrusts.

Advanced computing technologies applied to the subsurface underpin technological advancement in all of the pillars. Advanced modeling and simulation that is fit-for-purpose, or targeted at the most important aspects of the problems, is essential for tuning how the subsurface is engineered for both energy production, storage, and waste disposal.[117] Adaptive control of the subsurface requires rapidly assimilating, processing, and interpreting large data streams; and then representing the governing processes and responses at appropriate scales to provide decision support for real-time operational changes for enhanced production and risk reduction. Achieving mastery of the subsurface will require new scaling techniques that utilize the full suite of signatures from geophysical, geochemical, and hydrologic observations. Some of the capabilities required in this workflow exist, but currently lack integration, whereas others need to be developed or significantly improved.

Issues of International Cooperation and Competition

Federal investment in crosscutting subsurface research helps maintain U.S. leadership in subsurface technology and engineering and the large benefits that result. However, opportunities for international collaboration exist to accelerate the RDD&D of new and emerging technologies. The involvement of U.S. researchers in foreign demonstration projects presents opportunities to leverage foreign investment to inform domestic RDD&D strategies. Similarly, foreign involvement in U.S. research and demonstration projects can add value.

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Acronyms and Glossary

Elastic Moduli	Describes tensile elasticity, or the tendency of an object to deform along an axis when opposing forces are applied along that axis.
HT/HP	High Temperature/High Pressure
INSAR	INSAR stands for Interferometric Synthetic Aperture Radar. Satellites record images of the Earth's surface, and these images can be combined to show subtle movements of the ground surface, called deformation.
O&G	Oil and Gas
Poro-elastic	Poroelasticity is the term used to describe the interaction between fluid flow and solids deformation within a porous medium.
Redox Potential (Eh)	*Eh* is measured in millivolts (mV). A high positive *Eh* indicates an environment that favors oxidation reaction such as free oxygen. A low negative Eh indicates a strong reducing environment, such as free metals.

Seismic Velocity	Seismic wave fields are recorded by a seismometer, hydrophone (in water), or accelerometer. The propagation velocity of the waves depends on density and elasticity of the medium.
Unlithified	Soft sediments that have little strength and are readily deformed under the pressure of a fingernail or the broad blade of a spatula.
Vadose Zone	Region of aeration above the water table