Science Plan for the SECUREarth Initiative

- *Urgent Solutions to Subsurface Energy and Environmental Problems*

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Abstract

This document presents a science plan to address principle scientific questions and drivers of the SECUREarth initiative (Scientific Energy/Environmental Crosscutting Underground Research for Urgent Solutions to Secure the Earth's Future). The SECUREarth science plan is developed as part of a grass roots effort to identify fundamental crosscutting geoscience questions that will allow the research community to solve the key roadblocks preventing us from securing the nation's energy and environmental future. Geosciences must play a central role in addressing these issues, which if not solved, will result in catastrophic societal consequences within the next 50 years. SECUREarth asks "What are the common obstacles and lack of crosscutting fundamental science that is preventing us from accelerating progress in such areas as optimizing the retrieval of energy and mineral resources from the earth, sequestering greenhouse gases in the subsurface, isolating and containing contaminants in geological media, and ensuring adequate and affordable water supplies". SECUREarth is also based on the premise that our approach in performing this research must change to meet these challenges. Two main themes have emerged for SECUREarth - *"Diverse problems have similar solutions"* while addressing the common thread in our quest to study subsurface flow - *"isolate or produce"*. While SECUREarth will promote research by individual principal investigator-driven research teams, we see a critical need to expand the current mode of most research programs to encourage the formation of multidisciplinary research teams. The SECUREarth initiative is not to replace, but to build on, current research approaches, incorporating lessons learned from directed and mission-oriented programs and geoscience-related initiatives.

The SECUREarth Workshop in 2005, together with the National Research Council board meeting and other meetings in 2004, have initiated the identification of crosscutting themes in subsurface processes related to energy and the environment. We advocate that we start the SECUREarth with four basic multidisciplinary teams with foci on flow delineation, physical modification, geochemical alteration, and microbial control. Specific themes can be identified to address, for examples, the assessment for mass balance in field testing, the establishment of fundamental constitutive relationships of fractured network, the optimal use of carbon dioxide in enhanced oil recovery. More teams can be formed as additional themes or other urgent needs are identified. Each team will set specific goals to measure success. All teams have finite duration set to reach the specified goals. New topics for SECUREarth will be aggressively pursued to update and replace the goals and themes. The teams have the grand vision to achieve revolutionary breakthroughs while maintain the flexibility to improve and refine the approaches.

Abstract

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Acronyms

BER	Biological and Environmental Research
BES	Basic Energy Sciences
BESAC	Basic Energy Science Advisory Committee
DOE	Department of Energy
DUSEL	Deep Underground Science and Engineering Laboratory
EERE	DOE's Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
GPS	Global Position System
GT	Billion Metric Tone
IAC	The InterAcademy Council
INL	Idaho National Laboratory
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
MRFEC	NSF's Major Research Equipment and Facilities Construction account
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory

NRC	National Research Council
NSF	National Science Foundation
OCRWM	Office of Civilian Radioactive Waste Management
OS	Office of Science
PACE	Protecting America's Competitive Edge Acts
SAIC	Science Applications International Corporation
SECUREarth	Scientific Energy/Environmental Crosscutting Underground Research for Urgent Solutions to Secure the Earth's Future
UC	University of California
UCB	University of California, Berkeley
USGS	United States Geological Survey

1. Introduction and Drivers of the SECUREarth Initiative

SECUREarth (Scientific Energy/Environmental Crosscutting Underground Research for Urgent Solutions to Secure the Earth's Future) is a geoscience initiative that is developed to conceptualize and execute fundamental, crosscutting research to address common obstacles in solving and accelerating solutions to critical energy and environmental problems related to the subsurface. It is envisioned to be a multi-agency, multi-laboratory, university, and industry-supported initiative. The following is based on discussions from workshops and meetings, with researchers in academia, industry, national laboratories, National Research Council (NRC) boards, federal agencies, and reviews of national initiatives in global climate, solid earth, physics, and other scientific and technical fields[1,2].

The U.S. economic stability, energy outlook and supply, together with environmental security, will require the development of new approaches and scientific thrusts that can accelerate our current progress. Currently over 85 % of the U.S. energy consumption is fossil fuel based (US DOE EIA 2004 statistics: nuclear is 8.3% and renewables are 5.8%)[3]. Furthermore it appears that we will have to rely on this mix of energy sources for decades to come. In 2003, the Basic Energy Science Advisory Committee recommended that "*a new national energy program is essential and must be initiated with the intensity and commitment of the Manhattan Project, and sustained until this problem is solved*"[1], i.e.,

"*Considering the urgency of the energy problem, the magnitude of the needed scientific breakthroughs, and the historic rate of scientific discovery, current efforts will likely be too little, too late.*"

"BESAC recommends that BES review its research activities and user facilities to make sure they are optimized for the energy challenge, and develop a strategy for a much more aggressive program in the future."

More recently, the report "Rising Above the Gathering Storm"[2], whose 20 proposed

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[1] http://www.sc.doe.gov/bes/reports/files/SEF_rpt.pdf DOE BESAC 2003. Basic Research Needs to Assure a Secure Energy Future (420 pages). For geoscience research, BESAC recommended two primary directions: "subsurface imaging and in-situ alteration of fluid/rock interactions …increasing the mobility of oil and gas phases, thereby increasing the amount of extract resources." The BESAC also recommended the development of "the knowledge base to enable widespread creation of geothermal reservoirs."

[2] http://fermat.nap.edu/catalog/11463.html February 2006. Rising Above The Gathering Storm: Energizing and Employing America for a Brighter Economic Future (543 pages). Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. http://www.lbl.gov/today/2006/Jan/27-Fri/PACEsectionbysection0.pdf January 2006 for the section-by-section summaries of the PACE bill's provisions (5 pages). Among the bill's provisions are: doubling

actions were combined in three bills collectively known as the PACE (Protecting America's Competitive Edge) Acts, identified two key challenges facing the country: creating high quality jobs for Americans and responding to the nation's need for clean, affordable, and reliable energy. In 2006 President Bush launched two key energy initiatives: the American Competitiveness Initiative and the Advanced Energy Initiative for science, technology, and engineering to answer many critical challenges.

Crosscutting science integration is identified in 2006 DOE Strategy Plan for energy security, nuclear security, and environmental responsibility themes. Significant science opportunities for energy security include nanoscale understanding, advanced computation and predictive modeling, control of chemical transformation, and biology for energy applications. Breakthroughs are required for nuclear security in advanced sensors and monitoring, new materials for and understanding of materials properties at extreme conditions, and modeling and simulation. Several areas are identified in which fundamental breakthroughs across a range of scales in basic science could greatly advance the DOE clean-up mission. Molecular/atomic-scale science addressing the chemical nature of environmental processes furthers the basic understanding of chemical, physical, and biological processes occurring at larger scales in the subsurface. Investigations of biological processes will lead to better understanding of myriad capabilities of microorganisms to affect contaminant transport in the subsurface. The integration of molecular biology and genomics techniques into subsurface science is essential to a mechanistic understanding of biology processes controlling contaminant transport and bioremediation processes in the subsurface. This research coupled with a more complete understanding of groundwater movement and the chemical nature of reactive transport will help to advance new conceptual models of mobility and fate of contaminants in the environment. Research into novel monitoring and measurement tools is needed to verify the performance of groundwater remediation techniques and long-term stewardship strategies. Resolving subsurface contamination issues requires an integrative science approach with teams of researchers working in the laboratory and in the field across scales to decipher and predict the mechanisms controlling contaminant mobility in the environment. These lists represent an initial and ambitious set that offer high potential payoff, thus challenging the science and technology communities to work together in the years ahead.

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To continue use of our current sources of energy[3] (especially fossil-based energy

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funding for science agencies, including the DOE, and creating an Advanced Research Projects Authority-Energy, a new agency for transformational energy research.
See Section 6.1 for discussion and links to President Bush's 2006 initiatives and 2007 budget requests.
The DOE Strategic Plan is based on Draft K (6/19/2006, 34 pages) for the report to be issued in August 2006.

[3] The transition to a nonpetroleum-based economy will require the development of alternative energy sources: nuclear, geothermal, and solar energy, plus far-less-developed energy sources (hydrogen, biofuels, fusion energy, etc.). All alternatives are decades away from supplying enough energy to replace current sources of energy. We recognize that oil and gas remain the predominant energy sources for at least the next few decades, and the associated carbon emission continues to grow.
http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2006).pdf DOE EIA February 2006. Annual Energy Outlook with Projection to 2030 DOE/EIA-0383 (236 pages). Table 1 presents the total energy supply and disposition 2003-2030, with 2004 consumption in quadrillion Btu: nuclear - 8.23 (8.3%), renewable

resources of oil, natural gas, and coal), we must rely heavily on advanced and innovative technology applied in and to the geosciences to avoid economically, environmentally, and politically catastrophic consequences. It is indisputable that almost every current form of energy source or proposed form of energy source relies on either extracting something from the earth or disposing of something back into the earth. The use of fossil fuels will continue to stress our environment, with global warming reducing the supply of clean water from snow melts and population growth increasing the demand on water resources. We must become more efficient in obtaining and using our current sources of energy or suffer the consequences.

To address these issues in a timely efficient manner we must overcome the crosscutting roadblocks common to many of the problems rather than in a piece meal fashion. This is a shift in the current mode of geoscience research. Although the individual principal investigator (PI) or small-project research produces excellent science, and should continue, we believe that an acceleration is needed in the synthesis and development of the science addressing complex and cross disciplinary science that will be needed to solve the problems before us.

This science plan lays out the crosscutting approaches, forms the multidisciplinary teams to carry out those approaches, and leads to revolutionary advances. The goal of this document is twofold: (1) to describe the development of this national initiative identifying the crosscutting problems that geosciences will encounter in achieving a secure and environmentally safe future, and (2) to lay out the critical science approaches that are necessary to successfully overcome these crosscutting challenges in a timely fashion. Input was gathered from a workshop held on September 11–13, 2005, in Golden, Colorado[4], and from discussions and presentations at national meetings, conferences, and

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energy - 5.74 (5.8%), total – 99.68. (see also http://www.eia.doe.gov/emeu/aer/pdf/aer.pdf DOE EIA July 2006. Annual Energy Review DOE/EIA-0384 (435 pages). Figure 4 and Table 1.3 present the US energy consumption by source 1949-2005, with the 2004 (revised) values in quadrillion Btu: nuclear - 8.222 (8.2%), renewables - 6.220 (6.2%), total - 100.414.)
http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2006).pdf (http://www.eia.doe.gov/oiaf/ieo/highlights.html) DOE EIA June 2006. International Energy Outlook DOE/EIA-0484 (2006, 202 pages). Figures 3 and 4 present the world marketed energy use 1980-2030. Both nuclear and renewables fractions are below 9% in projections to 2030. The U.S. consumes about a quarter of the world's total energy. From these and other information, it is becoming increasingly obvious that there is an urgent need to develop a plan to transition from a fossil-based economy to a new, alternative-energy-based economy—urgent, because that transition will take years, if not decades.
http://www.exxonmobil.com/Corporate/Citizenship/Imports/EnergyOutlook05/2005_energy_outlook.pdf (http://www.exxonmobil.com/Corporate/Citizenship/Corp_citizenship_energy_outlook.asp) ExxonMobile 2005. The Outlook for Energy – A View to 2030 (23 pages). The annual updates include projections of global energy supply/demand and CO_2 growth.

[4] http://www.agu.org/pubs/crossref/2006/2006EO020004.shtml "Initiative Addresses Subsurface Energy and Environmental Problems". G.S. Bodvarsson et al., EOS, Transactions American Geophysical Union, 87(2), p. 18, January 10, 2006 for a summary of the workshop.
See http://esd.lbl.gov/SECUREarth/index.html for presentations, white paper, workshops, and other SECUREarth information. SECUREarth, initiated in 2004 by Idaho National Laboratory (INL) and Lawrence Berkeley National Laboratory (LBNL)—and subsequently joined by Pacific Northwest, Oak Ridge, Sandia, Los Alamos, and Lawrence Livermore National Laboratories—resulted from discussions within the geosciences and environmental sciences community.

at federal agencies in 2004 and 2005[5].

1.1. Initiative Development

SECUREarth is based on the premise that the geosciences must not only occupy a central role in meeting our energy and environmental challenges, but that our approach to performing this research must change to meet these challenges. Two main themes have emerged for SECUREarth. *"Diverse problems have similar solutions"* while addressing the common thread in our quest to study subsurface flow-*"isolate or produce"*.

A number of attempts have been made over the last decade to identify major research issues in the solid-earth sciences. The most comprehensive national report was "Solid-Earth Sciences and Society"[6], which considered earth science and applications in ten federal agencies. The report stated that the solid-earth sciences are essential to provide sufficient resources, cope with hazards, avoid perturbing geological environments, and learn how to anticipate and adjust to environmental and global changes. Other reports have dealt with research opportunities for individual agencies, including the NSF[7], USGS[8], DOE[9], and NASA[10]. These recommendations take into account the agency's mission, budget, and history.

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[5] The SECUREarth concept was first presented in Spring 2004 to the Department of Energy (DOE) Office of Science (OS): Ray Orbach, the Director, Ari Patrinos, Biological and Environmental Research (BER), and Pat Dehmer, Basic Energy Sciences (BES). To aid in the initial stages, an Advisory Panel was formed and met in 2004, with members from universities (Pat Maurice, Notre Dame; Frank Schwartz, Ohio State), companies (Leon Thomsen, BP America; Susan Landon, Thomasson Partner Associates), and national laboratories (Mark Peters, Argonne National Laboratory; Henry Shaw, Lawrence Livermore National Laboratory; Jim Fredrickson, Pacific Northwest National Laboratory). In a July 2004 NRC board meeting, SECUREarth was presented to representatives of ten federal agencies and several industries. In the discussion sessions, all agreed that the devil was in the details, and recommended that a focused science and implementation plan be developed that meets the goals of SECUREarth, sets out the science drivers and builds upon current ongoing research in the geosciences, as well as take advantage of various current scientific programs and facilities. In addition to meetings with the geoscience communities and agencies, the SECUREarth concept was presented to the University of California (UC) Science and Technology Panel and two town hall meetings: Geological Society of America in November 2004, and Fall meeting of American Geophysical Union in December 2004.

[6] http://www.nap.edu/books/0309047390/html NRC 1993. Solid-Earth Sciences and Society (346 pages). Committee on Status and Research Objectives in the Solid-Earth Sciences: A Critical Assessment. Board on Earth Sciences and Resources, Commission on Geosciences, Environment, and Resources.

[7] http://darwin.nap.edu/books/030907133X/html NRC 2001. Basic Research Opportunities in Earth Sciences (NSF, 154 pages). Board on Earth Sciences and Resources, Commission on Geosciences, Environment, and Resources.

[8] http://darwin.nap.edu/books/0309072646/html NRC 2001. Future Roles and Opportunities for the U.S. Geological Survey (179 pages). Commission on Geosciences, Environment, and Resources.

[9] http://darwin.nap.edu/books/0309066468/html NRC 2000. Research Needs in Subsurface Science: U.S. Department of Energy's Environmental Management Science Program (166 pages). Board on Radioactive Waste Management.
http://www.nap.edu/books/0309075602/html NRC 2001. A Strategic Vision for Department of Energy Environmental Quality Research and Development (170 pages). Board on Radioactive Waste Management.

[10] http://www.nap.edu/books/0309092523/html NRC 2004. Review of NASA's Solid-Earth Science Strategy (44 pages). Board on Earth Sciences and Resources.

The broad question SECUREarth aims to answer is "what role must geosciecnces play in sustaining our energy supply and protecting our environment?" The SECUREarth initiative thus is more focused, but aimed to crosscut the physical, chemical, biological, and geological sciences to achieve the breakthroughs necessary to solve our coming energy and environmental needs.

1.2 Primary Elements of SECUREarth

The September 11–13, 2005 SECUREarth workshop (at Colorado School of Mines, Golden, Colorado) focused on problems of energy and environmental research program areas and on crosscutting issues. Workshop presentations and summaries are in the companion Proceeding to this document.

Over 70 researchers in carbon storage, enhanced fossil energy recovery, environmental remediation, nuclear waste disposal, geothermal energy, and groundwater evaluation first discussed (in breakout sessions) the major challenges in each topical area, and then regrouped to define issues common to all areas. The workshop started with the consensus that oil and gas will remain the world's predominant energy sources for at least the next few decades—with the associated carbon emissions continuing to grow. Increasing demand from developing countries will increase fossil-fuel consumption, thus further increasing the need to transition to a nonpetroleum-based economy employing current alternative energy sources such as nuclear and geothermal energy. Global warming is expected to alter supplies of clean water, with population growth increasing its demand. All of these issues will require geoscientific solutions. Thus, the role of fluid movement or isolation in the subsurface, and the associated need to predict and control fluids, was identified as a common theme.

We focused on the concept and motivation to understand fluid flow in the subsurface, control of fluid flow, and the relationship between fluid flow and subsurface physical, chemical, and biological processes. The following key questions were posted as critical problems that are preventing significant progress in solving energy needs and environmental impacts[11].

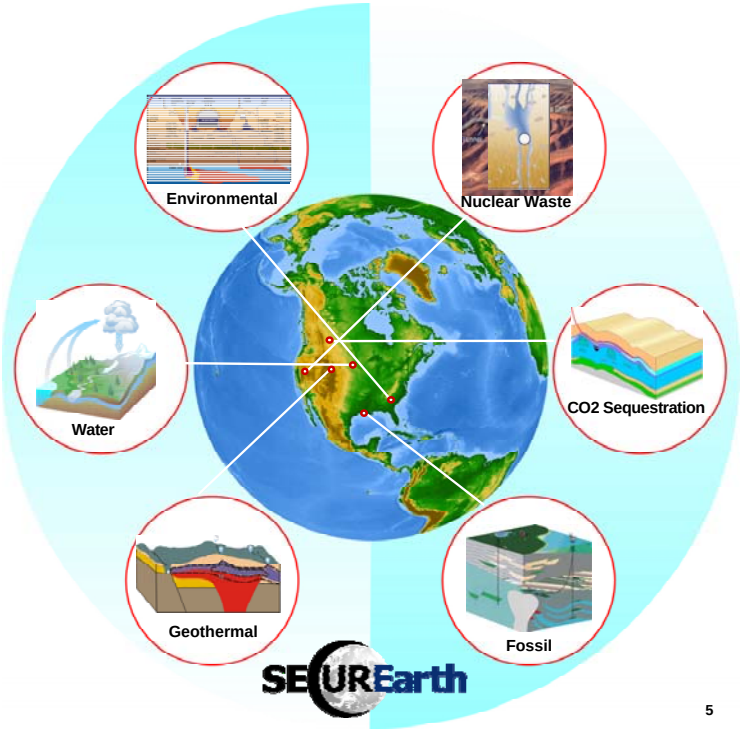
[11] Bo Bodvarsson, LBNL, began the workshop with a review of SECUREarth. Following the introduction, Rick Colwell, INL, and Ernie Majer, LBNL, assigned tasks for attendees, with seven breakout sessions for problem areas to be discussed: (1) *CO_2 storage*, led by Sally Benson, LBNL; (2) *Energy*, led by Phil Bording, Memorial University of Newfoundland; (3) *Environment*, led by Tullis Onstott, Princeton University; (4) *Nuclear Waste*, led by Mark Peters, Argonne National Laboratory; (5) *Geothermal*, led by Sabodh Garg, SAIC; (6) *Groundwater*, led by Bruce Robinson, Los Alamos National Laboratory; and (7) *DUSEL*, led by Joe Wang, LBNL, and Charles Fairhurst, University of Minnesota. After the breakout sessions, the participants reassembled in a plenary session to discuss the findings from the seven groups and to identify crosscutting issues from each group's prospective. The crosscutting issues were further discussed in the following breakout sessions: (1) *Flow Delineation*, summarized by Mike Feher, LANL; (2) *Modeling*, summarized by Karten Pruess, LBNL; (3) *Flow Manipulation*, summarized by George Redden, INL; (4) *Faults/Fractures*, summarized by Joanne Fredrich, Sandia National Laboratories; (5) *New Orleans*, summarized by Susan Hubbard, LBNL; (6) *System Biology*, summarized by Joe Suflita, University of Oklahoma; (7) *Management*, summarized by Bob Smith, University of Idaho; and (8) *Instrumentation*, summarized by Ernie Majer, LBNL.

(1) In CO_2 storage, can the injected carbon dioxide remain in the reservoir for long term?
(2) For oil and gas, why are we limited to only 30-40% of maximum recovery?
(3) In environmental remediation, is a natural attenuation approach safe and in the long term cost effective?
(4) For nuclear waste disposal, can the natural system meet the million-year dose standard?
(5) For geothermal systems, can we increase thermal outputs ten fold?
(6) In water supply and quality, can we meet all our future needs?

SECUREarth:

Scientific Environmental/Energy Cross-cutting Underground Research

- Environmental Remediation - Cost effective and safe?
- Nuclear waste disposal – meet 1,000,000 year standard?
- CO_2 Sequestration - can it be safely stored long term?
- Oil and gas – why only 30 - 40 % maximum recovery?
- New and enhanced geothermal systems - ten fold?
- Water supply and quality – Meet all future needs?



All of these questions can be then grouped into two broad areas, Energy and Environmental:

2. Energy and Environmental Needs

As stated above in terms of fluids in the subsurface the main issue is how to most efficiently locate and extract the subsurface resources that drive the nation's economy. These include methane hydrates, oil and gas, geothermal energy such as hot water and steam, and water for agriculture, power plants, and drinking needs. The second is how best to clean up and isolate subsurface waste, whether it be existing waste, such as at the Hanford Site in Washington state, or potential waste, such as at the proposed Yucca Mountain nuclear waste repository in Nevada. To meet tomorrow's demands, we need a quantum leap in our understanding of subsurface processes[12].

2.1. Resource Production

For energy production, we need accurate location and identification of fluids, i.e., fluid imaging for pockets of oil, gas, steam, etc. To double the extraction of fossil reserves, or to increase geothermal heat extraction by ten fold, drilling efficiency and borehole stimulation must be drastically improved, hazards controlled, and borehole lifetime extended. The World Energy Assessment[13] of the United Nations Development Programme reports on global primary energy use, including commercial and non-commercial sources of energy. The percentage contribution of "new renewable energy sources" has changed little in recent years. In the long term by 2050, the projection is that we will need ~20 TW of carbon-free energy if the CO_2 concentration in the atmosphere stabilizes at 550 ppm level and energy demand follows "business as usual" scenario. The 2050 need of "carbon-free" energy alone is nearly twice as much as the "total" power produced around 2000 from all sources globally[14].

There is an ever-widening gulf between U.S. energy needs and the ability of this country to meet the demand. Projections for the immediate future indicate that this situation will be exacerbated, as domestic energy production remains stable, while consumption continues to grow despite improvements in energy efficiency, conservation measures, and

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[12] http://www.lbl.gov/Publications/annual-report/2005-2006/files/01-energy-tech-2.html LBNL 2006. A View to the Future (33 pages). The world is at a crossroads. Each year, energy consumption increases and more greenhouse gases are emitted into the atmosphere. By 2020, one-third of the world's population may lack access to clean water, air, or affordable energy. That same year, it is estimated that U.S. energy demands will have risen 40% from today's levels, an increase that far outpaces the nation's energy production capabilities. If steps are not taken soon, tomorrow's generation will inherit a world with world's natural energy resources greatly, perhaps even cripplingly, depleted compared to the situation that exists today.

[13] The 2004 update http://www.undp.org/energy/docs/WEAOU_full.pdf United Nation 2004. World Energy Assessment: Overview 2004 Update (88 pages). Figure 5 shows that the total world primary energy use is 10.2 giga ton of oil equivalent (Gtoe, or the equivalent of 13.6 terawatt (TW) burn rate). In 2001, fossil fuels represented nearly 80% of the total (with oil 35.1%, coal 22.6%, and natural gas 21.7%). Nuclear power contributes approximately 7%. Large hydropower and "new" renewables (including modern uses of biomass and small hydropower, geothermal, wind, solar, and marine energy) each contributes slightly over 2%. (The balance is from traditional biomass, another source of CO_2.)

[14] http://www7.nationalacademies.org/bpa/SSSC_Presentations_Oct05_Lewis.pdf (http://www.its.caltech.edu/~mmrc/nsl/energy.html) Nathan S. Lewis 2005. Global Energy Perspective (66 pages). The presentation (also at the Charles V. Shank Symposium, May 24, 2005) and synopsis included the carbon-free energy need projections, the assessments of alternative energy sources, and the potential of solar energy to satisfy the carbon-free supply constraint in 2050.

renewable energy usage. Vice President Cheney's energy task force anticipated in its May 2001 report[15] that U.S. energy consumption will increase 25%, by 2010. Beyond initial exploration, enhanced oil production will play a critical role in extending our natural resources. The DOE Fossil Energy has the program to enable enhanced recovery of nation's "stranded" oil reserves[16]. Only about 10 percent of a reservoir's original oil in place is typically produced during primary recovery. Secondary recovery techniques to prolong the field's productive life are based on injecting water or gas into depleted oil wells to re-pressurize wells and "push" additional oil toward production well, resulting in the recovery of 20 to 40% of the original oil in place. However, with much of the easy-to-produce oil already recovered from U.S. oil fields, producers have attempted several tertiary, or enhanced oil recovery (EOR), techniques that offer prospects for ultimately recovering 30 to 60%, or more, of the reservoir's original oil in place.

Reasonably, the U.S. will attempt to ensure adequate energy supplies via a myriad of mechanisms, but this diversification means greater dependence on foreign suppliers. The U.S. has become dangerously dependent on OPEC oil supplies - again. The cartel's share of crude oil production dropped from 56% in 1973 to 29% in 1985, but is now back over 40% and is projected to increase to 68% by 2015. Any serious attempt to reverse this trend will need to consider improved mechanisms for the exploitation of domestic energy reserves. **It is well known that an estimated two-thirds of all U.S. oil still remains in the ground. Further, many natural gas reserves remain unexploited**.

2.1.1. Fossil Fuel Recovery

Considerable oil and gas resources remain in the ground. Innovative and cost-effective means to find, enhance, and produce these resources are needed. Research could be accelerated by dedicating field sites for collaborative investigations. Specifically, the limitations of existing poroelastic theory for fluid interactions with waves in solids, the extensions of full-wave-form methods to 3-D, and the endorsement of joint inversion and new sensor development are critical area of research[17].

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[15] http://www.whitehouse.gov/energy/National-Energy-Policy.pdf White House, May 2001. National Energy Policy, Report of the National Energy Development Group (170 pages).

[16] http://www.fossil.energy.gov/programs/oilgas/eor/index.html DOE FE 2006. Enhanced Oil Recovery /CO_2 Injection. The program describes how crude oil development and production in U.S. oil reservoirs can include up to three distinct phases: primary, secondary, and tertiary (or enhanced) recovery. During primary recovery, the natural pressure of the reservoir or gravity drive oil into the wellbore, combined with pumping to bring the oil to the surface. Secondary recovery techniques to prolong the field's productive life include injection of water or gas to displace oil and drive it to a production well.

[17] Phil Bording summarized recommendations by the group on Energy. While energy supplies can be obtained from many sources, SECUREarth will mainly examine those found within the earth. The exploitation of wind, solar, and surf resources for energy are beyond SECUREarth scope on subsurface research and science actions. Obviously, many above ground engineering and science research in these areas can have a large impact on the earth and on the energy mix.

Thermal recovery involves the introduction of heat such as the injection of steam to lower the viscosity or thin the heavy, viscous oil, and improve its ability to flow through the reservoir. Currently, thermal techniques account for over 50% of U.S. EOR production, primarily in California. Gas injection accounts for nearly 50% of EOR production in the United States. Chemical techniques account for less than one percent of U.S. EOR production. Each of these techniques has been hampered by its relatively high cost and, in some cases, by the unpredictability of its effectiveness.

Coal is likely to remain one of the nation's lowest-cost electric power suppliers for the foreseeable future. The current efforts include the advances in clean coal technology with the Clean Coal Power Initiative on energy processes at power plants that sharply reduce greenhouse gas emissions and other pollutants (sulfur for acid rain on forests and watersheds, mercury, nitrate for relief on respiratory problems, etc.), compared to older coal-burning systems[18]. CO_2 emission is also an issue for coal-to-oil technology (Fischer-Tropsch reactor[19]). Ninety percent of coal reserves are currently estimated to be unminable. There are also interests in underground coal gasification[20] by injecting oxidants and pumping gas through boreholes. Coal beds in the subsurface typically contain large volumes of methane-rich natural gas[21], which can be recovered by depressurizing the reservoir with water pumped out of the coal. The alternative approach for methane recovery is to inject CO_2 into the coal bed (see Section 2.2.1 for references and further discussion).

There are also many challenging evaluations needed to realize the natural gas potential available as methane hydrate in continental shelves and below permafrost[22]. Methane hydrate is with methane (CH_4) surrounded by a lattice of water without chemical bonding, and is formed naturally under conditions of low temperature and high pressure wherever sufficient gas exists in porewater. It has been found in Arctic regions and in marine sediment on the slopes flanking every continent. The U.S. in-place hydrated

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[18] http://www.fossil.energy.gov/programs/powersystems/cleancoal/ DOE FE 2006. Clean Coal Technology & the President's Clean Coal Power Initiative.

[19] http://www1.eere.energy.gov/biomass/catalytic_conversion.html DOE ERRE 2006. Catalytic Conversion.
"Black Gold: South Africa Has a Way to Get More Oil: Make It From Oil", Patrick Barta, The Wall Street Journal, August 16, 2006: The U.S. has 27% of the world's coal reserves and just over 2% of oil reserves. Source: Quantifying Energy, BP Statistical Review of World Energy, June 2006 (48 pages, http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/publications/energy_reviews_2006/STAGING/local_assets/downloads/pdf/statistical_review_of_world_energy_full_report_2006.pdf)

[20] "Underground Coal Gasification and Unconventional Gas Research, Development, and Demonstration Act", United States Congress. Senate. Committee on Energy and Natural Resources. Subcommittee on Energy Research and Development - U.S. G.P.O., 1981 (471 pages). Examples of more recent industry and academy interests can be found in http://www.coal-ucg.com/ of UCG Engineering Ltd. in U.K, http://www.undeerc.org/programareas/energyresources/underground.asp at University of North Dakota.

[21] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/CoalBedNG/CoalBed_NG.html DOE NETL 2006. Future Supply and Emerging Resources – Coal Bed Natural Gas.

[22] http://lab.nap.edu/books/0309092922/html/15.html NRC 2004. Charting the Future of Methane Hydrate Research in the United States (213 pages). Ocean Studies Board, Board on Earth Sciences and Resources. See also Kvenvolden, K.A., and T.D. Lorenson. 2001. The global occurrence of natural gas hydrate. Pp. 3-18 in *Natural Gas Hydrates: Occurrence, Distribution and Detection*, C.K. Paull, and W.P. Dillon, eds. Geophysical Monograph 124, American Geophysical Union, Washington, D.C.

methane gas resource may exceed the recoverable natural gas resources of the nation. If methane can be produced from hydrate deposits, the nation's natural gas energy supply could be extended for many years to come.

However, many uncertainties must be addressed before anyone will know whether gas hydrate can be produced safely and profitably, including pipeline and borehole instability, the effect of gas hydrates on the environment (gas hydrates may play a role in global climate change, because methane is a powerful greenhouse gas and has been postulated to have caused past episodes of global warming), and the importance of methane hydrate in the global carbon cycle, seafloor stability, and biological communities near sub-marine outcrops. In 2000, Congress passed the Methane Hydrate Research and Development Act authorizing the DOE, in consultation with the USGS, the Minerals Management Service, the National Oceanic and Atmospheric Administration, NSF, and the Naval Research Laboratory, to conduct methane hydrate research and development for the resolution of methane hydrate uncertainties.

2.1.2. Geothermal Heat Extraction

For commercial exploitation (i.e., an increase to 40,000 MWe), hydrothermal systems need to be identified with adequate permeability and presence of working fluids. Enabling technology is needed to find or create, maintain, and control permeable fracture systems to sustain high flow rates[23].

The natural heat of the Earth is virtually inexhaustible. The USGS has estimated that electrical energy producible from geothermal reservoirs to a depth of 3 km exceeds 300,000 MWe for thirty years. In addition, beneficial heat recovered from geothermal systems may be used for a variety of applications (e.g., heat pumps to heat and cool buildings, agricultural greenhouses, recovery of oil from tar sands, etc.). The current installed geothermal electric power production is less than 3,000 MWe. From a societal perspective, the grand challenge is to greatly increase the contribution of geothermal energy to the U.S. energy supply mix over the next 10 to 50 years.

A geothermal system is a fluid-rock volume within which, at some depth, temperatures are elevated with respect to the adjacent terrain. At present, almost all of the commercially exploited geothermal systems are of the hydrothermal variety. In hydrothermal systems, thermal energy in the crust of the Earth is usually extracted by bringing hot water and steam that occur naturally in the open spaces (pores, fractures, faults) in subsurface rocks to the surface, using a system of deep wells. Two characteristics of hydrothermal systems, which are important for commercial exploitation, are (1) good permeability, and (2) presence of water and steam. It need hardly be stressed here that hydrothermal systems constitute only a small fraction of geothermal resources; most geothermal resources are deficient in either one (i.e., water or permeability) or both desired characteristics (i.e., good permeability and water).

[23] Saboth Garg presented the science plan developed on geothermal energy by the Geothermal group.

For geothermal energy to become a significant contributor to the U.S. energy supply over the long term (i.e., over the next 10–50 years), it will be essential to develop the technology needed to exploit permeability and/or fluid-poor geothermal systems. To-date, a few experiments have been carried out using "hydrofracturing technology" borrowed from the oil and gas industry; the results of these experiments have been at best mixed. There are important differences between "petroleum" and geothermal applications. Most petroleum reservoirs are associated with sedimentary formations, whereas geothermal systems are in the main hosted by igneous or metamorphic rocks. The geothermal flow rates are substantially higher than "oil and gas" flow rates. Also, high temperatures for geothermal systems mean that oilfield fracture proppants (i.e., silica) cannot be used in geothermal applications.

In addition to an increase in electrical production from hydrothermal systems, SECUREarth has the potential to impact the use of geothermal energy for direct use applications, such as geothermal heat pumps. At present, most geothermal heat pumps are installed without a systematic investigation of surface properties such as thermal conductivity. It is expected that SECUREarth will result in important advances in characterizing the shallow subsurface. This research will directly and beneficially impact the direct uses of geothermal energy.

2.1.3. Groundwater Resource Management

Understanding the response of subsurface water supplies and flow to perturbations that are engineered, or induced by other (surface or atmospheric) events, is a critical need for sustaining groundwater resources. This understanding must be incorporated in models, and those models must be linked with decision tools that allow the science to be used in practice[24].

It is well established that groundwater supplies are becoming scarce and are heavily impacted by competing demands for resources and space in the earth's subsurface. There is a wide recognition that to address emerging societal issues related to groundwater and to provide the scientific basis for sound policy decisions, the science of complex interactions between groundwater processes must be advanced, and must be advanced at a rate comparable to the rate at which problems must be addressed. Useable water supplies have become one of the most important domestic and worldwide environmental and development issues, particularly in arid environments and where climate change and multiple exploitations of the Earth's subsurface are involved.

The National Academy of Sciences addresses "The Role of Science in Solving the Earth's Emerging Water Problems"[25]. Optimum management of global water resources presents

[24] Bruce Robinson presented the discussions in the Groundwater group.

[25] www.nasonline.org/water NAS October 2004. Arthur M. Sackler Colloquia. http://www.pnas.org/cgi/content/extract/102/44/15715?ck=nck W. A. Jury and H. Vaux, 2005. The Role of Science in Solving the World's Emerging Water Problems, PNAS, 102(44): 15715-15720 (6 pages).

one of the most crucial challenges of the 21st century. Global population will increase by three billion or more over the next 50–75 years, and the number of people living in urban areas will more than double. Most of the world's population growth will occur in developing countries where water is already critically short and many of the residents are impoverished. Even today, more than 1 billion people do not have access to safe and affordable drinking water, and perhaps twice that many lack adequate sanitation services. In fact, inadequate drinking water quality is a leading cause of infant mortality worldwide.

Food production may soon be limited by water availability. Agricultural water use is not sustainable in many locales around the world for reasons that include soil salinization, groundwater overdraft, and the over-allocation of available surface water supplies. This situation raises questions about whether sufficient water resources exist to support the existing population on a long-term basis, to say nothing of the significantly larger population that will have to be fed in the remaining decades of this century.

Intensifying competition for water resources by agricultural, industrial, and domestic users has led to a sharp increase in stress on aquatic and wetland ecosystems. Moreover, the inadequacy of environmental water supplies in much of the world has been significantly exacerbated by declining trends in water quality. The findings and recommendations by the NAS about the role of science in addressing the world's water problems include advances in technology (membrane, desalination, bioreactors, rainwater harvesting, micro-irrigation, etc.), in managing water for agricultural and environmental purposes, in modeling climate and climate changes, and in developing management institutions and policies.

2.2 Underground Sequestration

Energy and resource utilizations place tremendous strains on the environment. It is critical to solve the environmental problems associated with every type of energy production. The scope of carbon dioxide emission from burning of woods and fossil fuels, the accumulation of radioactive wastes from nuclear power plants, and the contamination from defense and industrial activities are summarized in this section.

2.2.1. Carbon Dioxide Storage

Effective carbon storage in underground formations with sufficient capacity (depleted oil and gas fields and brine-filled formations) is impeded by leakage. Knowledge gaps center on the need to monitor CO_2 fate and transport, understand chemical reactions at large time scales, and evaluate the durability of manmade materials[26].

For carbon sequestration, the challenges include the location of reservoirs, identification of leakage paths and rates, understanding of transport mechanisms and phase partition among carbon dioxide, oil, gas, brine, etc. The efficient and cost-effective containment

[26] Sally Benson presented a comprehensive summary of CO_2 Storage group discussions.

requires assessments of injection volume and rates, borehole and reservoir lifetime, and monitoring requirements.

The growing realization that anthropogenic climate change is a reality has focused the attention of the scientific community, policymakers, and the general public on the rising concentration of greenhouse gases, especially carbon dioxide in the atmosphere, and on the carbon cycle in general. The societal actions needed to address climate change require a scientific understanding of the carbon cycle, its interactions with climate, and the ways humans can influence its future trajectories. The Global Carbon Project was established in 2001 to address the enormous scientific challenge and fundamental criticality of the issue for Earth sustainability[27]. Conferences are organized in many regions over the world.

Today, 22 billion tones of CO_2 are emitted into the atmosphere from manmade sources. Burning oil, coal, and natural gas is the source of these emissions, and these fossil fuels provide for nearly 80% of the world's energy needs. Over the next hundred years, demand for energy is expected to more than double. Growth will be particularly critical in developing nations, where industrialization and improved quality of life will increase demand. By 2100 estimated annual emissions of CO_2 from fossil fuels will range from 16 to 110 billion tones per year, with an average value of 58 billions tones per year—more than double today's emissions. It is not yet possible to predict precisely the consequences of this unprecedented rise in CO_2 concentrations. However, likely consequences include ocean acidification, sea level rise, climate perturbations and ecosystem disruption. Today, CO_2 concentrations continue to rise at about 2 ppm per year. Unchecked, within the next several decades CO_2 concentrations will exceed levels believed to cause dangerous interference with the climate system. Energy technologies with low or no CO_2 emissions will be needed to slow the growth of emissions and eventually stabilize atmospheric concentrations of CO_2.

One proposed remedy to stabilize atmospheric concentration of CO_2 is to separate and capture CO_2 from fossil-fuel power plants and other stationary industrial sources and inject the CO_2 into deep subsurface formations for long-term storage and sequestration. The Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage[28] states that "Site characterization, selection and performance prediction are crucial for successful geological storage. Before selecting a site, the geological setting must be characterized to determine if the overlying cap rock will provide an effective seal, if there is a sufficient voluminous and permeable storage formation, and whether any abandoned or active wells will compromise the integrity of the seal. Moreover, the availability of good site characterization data is critical for the

[27] http://www.globalcarbonproject.org/ Global Carbon Project.
[28] http://www.ipcc.ch/activity/srccs/index.htm IPCC 2005. Carbon Dioxide Capture and Storage (443 pages).

reliability of models." An International Symposium on Site Characterization for CO_2 Geological Storage was recently held on March 20–22, 2006[29].

Carbon dioxide can be stored in deep underground formations such as depleted oil and gas reservoirs, brine-filled formations, or deep unmineable coal beds. This option is in practice today at three industrial-scale projects and many smaller pilot tests. In addition, over 30 Mt of CO_2 is injected underground yearly for enhancing oil recovery from depleted fields. In EOR application, with a combination of CO_2 and water pumping into depleted oil wells to re-pressurize wells and "push" additional oil toward production well, CO_2 is generally considered an added production expense and, thus, the amount left in the reservoir is minimized. There are common interests for alternative strategies to optimally combining EOR with CO_2 sequestration[30].

At appropriately selected storage sites, retention rates are expected to be very high—with CO_2 remaining securely stored for geologic time periods of millions of years. The IPCC Special Report on CO_2 Capture and Storage concluded that for appropriately selected and managed storage sites, retention rates are likely to exceed 99% over 1,000 years, with the largest risk of leakage associated with abandoned wells.

Worldwide estimates indicate that the storage capacity in oil and gas fields ranges from 900 to 1,200 billion tones of CO_2, and the estimated capacity in brine-filled formations is expected to be at least 1,000 Gt CO_2 and is likely to be significantly more. These capacity estimates indicate that storage capacity is likely to be sufficient to accommodate CO_2 emissions from power plants for a century or more. To realize this potential, technical challenges, including leakage, must be addressed.

In addition to deep sequestration potential, there is uncertainty as to whether vegetation and soils on the Earth's surface will act as a sink or source of atmospheric CO_2 in coming years[31]. Soils represent the largest baseline pool of carbon in the continental U.S. Protection of terrestrial ecosystems in regions with woody litter and surface soils is

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[29] http://www-esd.lbl.gov/CO2SC LBNL March 2006. International Symposium on Site Characterization for CO2 Geological Storage. The symposium includes site selections for the west coast states, in the Illinois Basin, in unminable coal beds of Canada's Alberta Basin, in Australia's Gippsland Basin, in deep aquifers of France's Paris Basin, and in Spain's Central Coal Basin; Case studies and characterization methods at Weyburn Field, Frio Pilot, Salah, West Pearl Queen Pilot, Teapot Dome, Cincinnati Arch Site, Powder River Basin, Casablanca Offshore Field, Netherlands Offshore Gas Field, and Australia's Otway Basin.

[30].For example, CO_2 injection and EOR programs are summarized in http://198.87.0.58/Geologic.aspx. Experiments indicate that coal beds are able to absorb approximately twice as many CO_2 molecules compared to the number of methane molecules currently contained in a reservoir. Thus, the potential exists to displace and recover about one ton of coal-bed methane for every five tons of CO_2 stored. CO_2 recovery of coal-bed methane has been demonstrated in limited field tests; however, additional research is needed to understand and optimize the process. Examples of CO_2 flooding for EOR include: Chevron-DOE study in Buena Vista Hills and Lost Hills, San Joaquin Valley, CA http://aapgbull.geoscienceworld.org/cgi/content/abstract/85/4/561.

[31] "Estimating Carbon Budgets for U.S. Ecosystems", EOS, Transactions American Geophysical Union, 87(8), February 21, 2006.

important to prevent lost of carbon to the atmosphere. Land disturbances and elevated temperature can increase the respiration rates of CO_2 and make this large sink vulnerable to losses by wild fire, land use conversions, and climate changes.

2.2.2. Nuclear Waste Disposal

One of the grand challenges for nuclear waste disposal is the need to understand and predict with confidence flow and transport processes over geological time scales (at least to a million years), with long-term climate changes and the impact of extreme events taken into account. It is important to enhance the interaction of engineered "barriers" with natural systems, to maintain retrievability and monitoring, and to prioritize/address the performance in a regulatory framework. The longevity of engineered "barrier" components depends on the quantity and chemistry of fluids from the surrounding natural system. There is a need to establish a sound foundation for model abstraction and stochastic approaches used for performance assessment. One of the challenges for nuclear waste disposal is on the alteration of biological communities in the long term, with better understanding of biological and biogeochemical processes. The other challenge is waste minimization as part of a sustainable future for nuclear energy[32].

The potential site for a nuclear waste repository in the U.S. is at Yucca Mountain, Nevada, considered to have the following favorable hydrogeological characteristics: (1) a desert setting with arid climate, and (2) a deep water table below a thick unsaturated zone (UZ). In a desert environment, the total amount of available water is small. Even less water is expected to seep into underground drifts in the UZ. The evaluation of the Yucca Mountain site has evolved from intensive surface-based investigations in the early 1980s to testing in underground drifts starting in the mid 1990s. Data collection activities have evolved from mapping of faults and fractures, to estimation of percolation through tuff layers, and to quantification of seepage into drifts. Lessons learned from underground tests are used to focus on processes needed for additional quantification. Migration through the drift shadow zone below the drifts and liquid flow through faults are two important issues that have evolved from current knowledge about the UZ at Yucca Mountain.

In addition to support the licensing application, performance assessment, and repository design, current major research programs (thrusts) include source term, material performance, and natural barriers. The Natural Barriers Thrust stresses the realistic representation of the natural system with respect to processes and parameters, by means of laboratory, field, and modeling studies. This natural system is composed of the unsaturated and saturated zones at the Yucca Mountain site, and the hydrothermal-chemical environment within waste emplacement drifts.

The proposed 2005 Environmental Protection Agency (EPA) two-tier standard beyond the original period of 10,000 years emphasizes the significance of the natural system's

[32] Mark Peters presented the summary for the Nuclear Waste group.

contribution to repository performance over geological time scales. Human civilization with recorded history has existed for approximately 10,000 years. On the other hand, geologic records over tens of thousands to millions of years are well established for natural attributes. The challenge for realistic representation of natural system is the need to identify the accurate location of fluid transport pathways and to quantify the fast transport through fractures and faults and slow transport and retardation in the matrix. The system characterization needed for reliable million-year predictions include the effects of ice ages, metal failure mechanisms, and thermally driven coupled processes.

Far-reaching questions for nuclear waste disposal include the following: Should the natural geothermal gradient, which influences post-emplacement convection (controlling water contacting waste packages and waste, and therefore impacting peak dose), be integrated into the design of the repository layout? Should emplacement drifts be designed to be smaller and to have alternative configurations, in order to suppress seepage and water contacting waste? Can sealants or bacteria be introduced to the drift walls to enhance isolation? Can microsensors be developed to detect radiation leaks and corrosion onsets? Can geophysical tools be advanced to delineate pH changes and flow paths?

Based on the requirement in the Nuclear Waste Policy Act, Office of Civilian Radioactive Waste Management (OCRWM) will support the Congressional decision to consider whether the United States needs a second repository for high-level radioactive waste between 2007 and 2010. The second repository could accommodate additional nuclear wastes if the first repository at Yucca Mountain reaches its designed capacity of 70,000 MT. Geological factors, environmental considerations, nuclear power expansion options, societal impacts, and economical optimizations are among the factors need to be evaluated and articulated. OCRWM needs to demonstrate to the Congress and the President that nuclear waste can be well managed with various storage options that will support the nation's ability to supply energy using nuclear power. OCRWM will provide the information to support the Congressional decision to either construct a second repository at a geologically stable (and simple), environmentally isolated, and socially acceptable location, or to implement various measures that expand the storage capacity within or in the vicinity of the first repository at Yucca Mountain.

2.2.3. Environmental Cleanup

Concern was expressed over the current practice of leaving waste in place. Because extraction of energy resources has major environmental impact, we must develop strategies to minimize that impact. The development of methods for *in situ* microbial liberation of CH_4 from oil or coal may resolve some of these issues[33].

[33] Tullis Onstott summarized many insightful suggestions discussed in the Environment group.

The Office of Inspector General criticized the Department of the Interior for its weaknesses in controls over environmental liabilities resulting from hazardous sites[34]; unable to characterize, monitor, inventory, or remediate contaminants under its prevue. DOE and EPA funding for science has gone away, applied research has gone away. Environmental remediation industry is fixed at $6B per year and is not expected to change over the next 10 years. This includes DOE funding. Twenty DOE sites will be closed in FY06 while the remaining sites will not close for several decades. The problem is that not even a conceptual model for contaminant transport exists for these sites (e.g., Ohio sites like Mound[35]).

Current solutions rely upon leaving it in place or moving it from point A to point B, but rarely rely upon remediation. The waste in the Hanford tanks will be mixed with grout as a means of stabilization[36]. It has been stated that "there are no scientific issues" regarding the procedure, a policy which is driven by the current administration and public complicity.

The current "better left alone" policy will come back to haunt us eventually. But the concern over environmental waste has been superseded by more pressing issues. Only with another "big disaster" like Love Canal will groundwater contamination come to light again. Of greater current concern is the energy profile of the U.S., the associated issues related to extracting energy, and the environmental consequences of consuming that energy. (e.g., how is carbon sequestration integrated into fossil-fuel consumption?)

Both existing contaminant problems (including MTBE, ^{99}Tc, contaminants associated with hard-rock metal mining at abandoned mine lands, Department of Defense storage depots, and military bases) and energy-related environmental problems (e.g., continuing increase in greenhouse gases) require careful analysis of what is/is not being done and how will the system evolve over the long term? These questions can only be answered by developing long-term predictive capability. We do not currently integrate the extraction of energy resources from the earth and the safe disposal of wastes in the subsurface. All

[34] http://www.epa.gov/oig/reports/2005/20050822-2005-P-00020.pdf. EPA August 15, 2005. Evaluation Report 2005-P-00020: EPA Practices for Identifying and Inventorying Hazardous Sites Could Assist Similar Department of Interior Efforts (42 pages). The report includes audit findings and promising practices in site discovery, in site assessment and prioritization, and in cost estimating.

[35] http://www.netl.doe.gov/publications/proceedings/01/indpartner/em4-2.pdf M.D. Jensen et al. Environmental Management Cooperative Agreements: The Partnership Between NETL and the Energy & Environmental Research Center (16 pages). This represents an effort and an example of the environmental technology acceptance program for long-term stewardship activity, in response to specific needs at the Mound site in Miamisburg, Ohio and other similar sites within the weapons complex. http://www.ig.doe.gov/pdf/ig-0501.pdf DOE/IG-0501 (14 pages) and http://www.ig.doe.DOE/IG-gov/pdf/IG-0721.pdf DOE/IG-0721 (15 pages) are audit reports on the Remediation and Closure Miamisburg Environment Management Project (Mound Plant) and on the Miamisburg Closure Project to illustrate the lessons learned for environment remediation.

[36] http://fermat.nap.edu/books/0309101700/html/1.html NRC 2006. Tank Waste Retrieval, Processing, and On-site Disposal at Three Department of Energy Sites: Final Report. (Savannah River site, Hanford, Idaho National Laboratory, 311 pages). Nuclear and Radiation Studies Board. Tank grouting and closure are discussed in Chapter V.

energy resources have impact as a result of production of energy and we need to address and minimize that impact.

For environmental remediation, we certainly need accurate location and identification of fluids and contaminants in partitioning of dense nonaqueous phase liquids, water, gas, radionuclides. The efficient extraction and/or remediation require manipulation of physical, chemical, and biological conditions, and an understanding of coupled processes. The long-term performance is assessed by the efficiency in containment without leakage.

3. SECUREarth Crosscutting Challenges

It is clear from the examples of critical problems and major challenges described in Section 2 that there are common, crosscutting challenges among our energy and environmental problems (fossil, geothermal, nuclear waste, carbon sequestration, environmental, and water resource evaluations). The current central theme of SECUREarth is characterizing, monitoring, and manipulating fluids in the subsurface.

Fluids are defined in the broadest sense as liquid, vapor and gases in all states. Characterization is also defined in a broad sense: we must characterize not only static properties (physical, chemical and biological), but also the interaction of these properties, how these change over time with external influences (initial and boundary conditions) and how we can influence the properties.

Because we are dealing with the Earth and can never examine the interior in every detail (impractical to mine it all out), there will be a certain level of uncertainty associated with defining the properties of interest (imperfect sampling). Also increasing the uncertainty is the issues of scale. We can extract samples and perform experiments in the lab, or take measurements in boreholes or tunnels but we are almost always extrapolating from one scale to another. If we can understand the fundamental physical, chemical and microbial processes that govern fluids, then we can devise ways to reduce uncertainties. If we can safely manipulate these fluids, it is a measure of success - control and reduced uncertainties.

The system we are dealing with is a complex, heterogeneous, multi-scale combination of fluids and solids interacting with external forces. With the initial overall goal to manipulate and modify the fluid flow paths to either enhance production or isolate the fluids, we can lay out four related areas of research: (1) flow characterization, (2) physical modification, (3) geochemical alternation, and (4) microbial control.

3.1. Flow Delineation and Characterization

The overall question is what are the critical parameters and information/knowledge needed to understand where, how much, what type, and how fast are the fluids moving. Therefore, accurately determining flow characterization (imaging or delineation) requires defining underground structures (or matrix) in which the fluid resides (faults, layers, lithology, etc), microbiology, chemical signatures, and the forces on the fluid phases (gravity, stress, pressure, capillary, etc.), and the properties of the fluid itself. The fluids of interest are often multiphase and have complex physical (density, viscosity, compressibility, conductivity, etc.) chemical (pH, eH, etc.) and microbial (attachment, anerobic or not, etc.) properties. These properties all or partially interact to influence the ability for flow. For the efficient subsurface structure characterization, we require enhancements in imaging approaches and focus on major flow paths through faults and fractures.

3.1.1. Geophysical Imaging

Flow delineation requires imaging underground structures (faults, layers) for fluid phases and chemical signatures. Sensitivity can be enhanced with the integration of geophysics and reactive transport, and the use of surface- and satellite-based monitoring systems to detect changes. The challenges include low resolution for fracture detection, poor integration of different geophysical methods, inaccuracy of models for low permeability formation and resolution of vertical heterogeneity. Integrated use of both seismic and electromagnetic methods can improve the application of geophysical methods for the vadose zone. There is also a need to develop more economical approaches to imaging large basins[37]. The seismic method is fairly well established for shallow subsurface characterization and deep monitoring[38]. Geophysical imaging methods are less intrusive and more effective than drilling of boreholes to different depths for flow delineation.

A major roadblock to the accelerated exploitation of hydrothermal sources is the high cost (about 1 to 2 million dollars) of drilling a successful “discovery” well. Typically, only about 20% of the exploration wells succeed in locating a commercially exploitable

[37] Mike Feher presented the discussions in the Flow Delineation group breakout session.

[38] http://www.nap.edu/catalog/11327.html NRC 2006. Improved Seismic Monitoring - Improved Decision-Making: Assessing the Value of Reduced Uncertainty (196 pages).
http://www.nap.edu/catalog/5786.html NRC 2000. Seeing into the Earth: Noninvasive Characterization of the Shallow Subsurface for Environmental and Engineering Applications (155 pages).

hydrothermal reservoir. To enhance the success ratio of exploration wells, it is important to devise imaging methods capable of locating permeable fractures or fracture zones[23].

Geophysical surveys can be used to sense certain properties of the subsurface reservoir. Seismic velocities are sensitive to the presence (or absence) of a gas phase in the fractures. Electric and electromagnetic surveys (direct current resistivity, magneto-telluric, controlled source audio-frequency magneto-telluric) respond to variations in electricity resistivity and the magnetic fields of subsurface formations. Self-potential surveys may be used to locate upwelling and down-flowing zones. A concerted research effort for a combination of geophysical and geochemical techniques is needed to devise better imaging methods for locating permeable fractures and fracture zones. The basic research on imaging methods can be carried out in a facility such as that envisioned under SECUREarth. The imaging methods developed for ambient temperatures will also need to be verified under geothermal conditions[23].

Imaging technologies need to be improved for porosity, permeability, and mineralogical heterogeneity, boundaries between supercritical CO_2 and water/oil/gas interfaces, and biologically active zones. Induced polarization, self-potential, and nuclear magnetic resonance are additional research areas for detecting zones of higher biogeochemical activity. We also need new geophysical approaches to monitoring changes in viscosity[26].

The reliability of field site selection and monitoring could also be enhanced by developing better methods for high-resolution, three-dimensional characterization of the subsurface geological structure and fluids. Fluid, permeability, and process imaging in the subsurface requires integration of data sets and disciplines, installation of real-time, permanent arrays to guide operation, integration of forward modeling and inversion, and determination of constitutive relationships for geophysical properties.

3.1.2. Faults and Fractures

While there are many faults and fractures mapped in geological studies, only a small fraction of these features is associated with fluid flow for mass and energy transport. The determination of whether faults and fractures act as conduits or barriers to fluid flow is subject to considerations of geomechanics under changing stress and geochemical conditions. At the field scale, better understanding of the role of faults and fractures on fluid flow would aid in site selection and long-term performance prediction[39].

The characterization of faults and fractures involves flow channelization within fractures related to aperture distribution and roughness, breakthroughs related to topology and connectivity of fracture networks, ranking of fluid transport processes in accordance to geologic settings and depths, and surface/aerial mapping/monitoring and multispectral imaging for long-term fluid flow patterns, such as changes in vegetation distribution. For aboveground studies, it is possible to measure to accuracy of 1 mm for ground motions from satellite generated Interferometric Synthetic Aperture Radar (InSAR), to

[39] Joanne Fredrich presented for the breakout session on Faults and Fractures.

complement point measurements by the Global Position System (GPS)[40].

Fault information from surface mapping is frequently used in flow modeling without knowledge of subsurface fault distributions. It is not possible to significantly advance understanding of faults and fractures without development of test facilities at the field scale. Facility development starts with the identification of criteria useful in selecting candidate sites for different applications, and what multiple goals can be accomplished at a single site. Systematic fluid flow studies at one or more field test sites include surface geophysics, drilling of wells, downhole logging, crosswell imaging, injections, downhole instrumentation, and long-term monitoring.

3.2. Physical Modification

The challenge of physical engineering is to modify natural geological features or to create new subsurface features to meet our needs—specifically, fault and fracture manipulation for creation and/or destruction of permeability. Hydraulic fracturing, thermal cracking, use of explosive slurry, and laser drilling are examples of physical engineering.

For geothermal energy extraction, there is clearly a need to improve understanding of fracture propagation in naturally fractured crystalline rock (shear/tensile fracture propagation), and to develop new stimulation concepts (e.g., thermal cracking, shear slip on preexisting discontinuities) and technologies (e.g., explosive slurries) for exploiting low-permeability geothermal systems[23,39]. For CO_2 sequestration, it is important to control migration of fluids in the subsurface—sealing leaks, diverting fluids, achieving optimal sweep, permeability creation[26].

3.2.1. Hydraulic Fracturing

A hydraulic fracture is created by injecting fluid at pressure over the minimum *in situ* stress, and at a rate in excess of the reservoir flow capacity. The vast majority of all oil and gas wells drilled in North America are fracture-stimulated immediately after drilling, by creating a conductive fracture that greatly expands the contact area between the wellbore and the reservoir rock. A propping agent is added to the fracturing fluid to leave behind a conductive path for hydrocarbon to flow back to the wellbore. Most operations use water, but liquid CO_2 and other fluids are being evaluated as stimulation fluids[41]. The challenges

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[40] http://www.iris.iris.edu/HQ/EarthScope.org/site_folder/insar.com.html Components INSAR - Satellite-Generated Interferometric Synthetic Aperture Radar Images of Tectonically Active Regions of the Continent, Ideally Through a Dedicated Scientific Mission.

[41] http://www.netl.doe.gov/technologies/oil-gas/EP_Technologies/ImprovedRecovery/AdvancedStimulation/Adv_Stimulation.html NETL, 2006. Exploration & Production Technologies, Improved Recovery – Advanced Stimulation.
For field studies:
http://fossil.energy.gov/programs/oilgas/publications/environ_benefits/13fsdril.pdf DOE FE. CO_2-Sand Fracturing (22 pages).
http://www.netl.doe.gov/publications/press/2000/tl_rtzfracture.html. NETL 2000. New Mexico Test Shows Downhole Mixing Technology Can Boost Gas Production.

for hydraulic fracturing include the control of fracture orientation to connect to another borehole or to pockets of fluids, and the creation of multiple fractures with increased surface areas for improved fluid exchanges with the formations.

3.2.2 Thermal Cracking

Differential thermal expansion in rock under confining stress can create microcracks and weaken the rock. For injections of cold fluids into hot formations, this mechanism could be further exploited for permeability changes and reservoir impedance decline in enhanced geothermal systems[42].

3.2.3 Explosive Slurry

Slurry explosive uses a mixture of ammonium nitrate, aluminum powder, and water for blasting[43]. The inert-until-mixed agent and other water-based explosives could be used for fracture creation[23,39]. Dynamites and solid rocket fuel-like propellants can be ignited in the wellbore to create a controlled pressure pulse that creates fractures in a more predictable pattern[44].

3.2.4 Laser Drilling

Low laser power can achieve spalling and chipping of rock, as well as releasing of gas, inducing thermal stresses, and at high laser powers, rock will melt, fuse, or even vaporize[45]. Laser drilling is based on technology from the "Star Wars" missile defense research. The establishment of a minimum energy requirement and a demonstration of well-perforation capability are two current goals within the ongoing evaluation of this potentially significant advance in drilling technology. Directional or deviated drilling with lasers can be further developed.

3.3. Geochemical Alternation

Physical and chemical (including microbial) methods can be used to enhance, facilitate, direct or block flow. Fluid flow and chemical transport are coupled to mineral

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Reorientations were discussed, e.g., in http://tle.geoscienceworld.org/cgi/content/extract/20/10/1185 C.A. C.A. Wright and L. Weijers. 2001, Hydraulic Fracture Reorientation, Does It Occure? Does It Matter? The Leading Edge, 20(10), 1185-1189.
http://www.pttc.org/solutions/sol_2004/533.htm , J. Miskimins, 2004. Hydraulic Fracturing Measurement, Characterization and Analysis (5 pages). Petroleum Technology Transfer Council Rocky Mountain Regional Workshop.

[42] http://www.eere.energy.gov/geothermal/docs/egs_meet_summary.doc EERE 2002. Open Meeting on Enhanced Geothermal Systems (32 pages).

[43] http://www.dynonobel.com/dynonobelcom/en/northamerica/aboutus/ourhistory Dyno Nobel.

[44] http://www.netl.doe.gov/technologies/oil-gas/publications/eordrawings/BW/bwhf.PDF NETL.

[45] http://www.aapg.org/explorer/2002/02feb/laser drilling.sfm Laser Drilling Becoming a Reality (4 pages) http://www.fossil.energy.gov/fred/factsheet.jsp?doc=2104&projtitle=Laser%20Drilling DOE FE 2006. Laser Drilling Project DE-FC26-00NT40917 for a description on laser drilling.

precipitation and dissolution along flow paths, through rock-water interactions and alterations in fracture-matrix interflows, diffusions, filtrations, and other coupled hydro-chemical processes. Thermal treatments, multiphase fluid displacements, and stress-strain changes are fundamental processes (with engineering applications) that can either enhance resource production or delay contaminant migration.

Modification of flow and transport paths requires evaluation of coupled processes, as well as quantification of reaction equilibrium and kinetics. For waste sequestration, long-term solutions include flow control and modification and enhancement of reactive and physical barriers[32]. Because biogeochemical rates are slow, we have a poor understanding of the long-term effects of the processes we are observing. We are unable to measure energy exchange readily in subsurface environments, to determine if the energy is really limiting or if it is unavailable[33].

It is therefore a challenge to systematically evaluate the hydro-chemical coupling/interaction and reactive transport of introduced or natural species of chemicals in solutions with minerals in the subsurface environments. The use of foam in fracturing, acid in dissolution of carbonate rocks, crystallization of calcite along flow paths are some examples of geochemical engineering to be further generalized and developed for permeability enhancement or sealing.

3.3.1. Foam Fracturing and Acid Treatment

Foam fracturing and acid treatments are ways of enhancing permeability and storage volume by geochemical methods. Foam fracturing uses foam bubbles to transport and place proppant into fractures, using mostly nitrogen or carbon dioxide as their base gas. Incorporating inert gases with foaming agents and water reduces the amount of fracturing liquid required and achieves highly effective fracturing[46]. Surfactants and other additives can be included in the fracturing fluid mixtures. Use of foam under high pressure has the advantage over high-pressure water injection, with foam causing less damage to the formation and wellbore. Acid treatment is another geochemical method by which to increase reservoir permeability, dissolve limestone rocks, or open up a cavity in carbonate rocks. Typically a solution such as hydrochloric acid is pumped into a wellbore interval to dissolve and open up new or existing fractures.

3.3.2. *In Situ* Crystallization and Precipitation

To reduce permeability and seal off flow paths, precipitations of natural minerals along flow paths are effective in the long term, as evidenced from the presence of fracture fillings in many field observations. The challenge is to have control over the onset of precipitation if supersaturated solutions are injected. The use of chemical inhibitors and the use of boiling are two examples for the controls needed.

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[46] http://www.epa.gov/safewater/uic/cbmstudy/pdfs/completestudy/ch4_6-8-04.pdf EPA 2004. Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs. EPA 816-R-04-003 Chapter 4: Hydraulic Fracturing Fluids (26 pages).

In the presence of precipitation inhibitors, solutions supersaturated in natural minerals (such as calcite) can be injected into the formation before spontaneous precipitation and crystallization, to seal off the flow paths or immobilize heavy metals within treated flow paths. The permeability reduction and the long-term stability of blocks treated with supersaturated solution can be further tested by additional leaching with water[47].

We can also use temperature and phase transition to trigger precipitation. Small amounts of amorphous silica precipitation at the boiling front can effectively block the flow through fracture, with bridging structures closing off the flow[48].

3.3.3. Geochemical Engineering and Contaminated Site Study

Use of gypsum expansion to seal off acid mine drainage, neutralization of acids with olivine without CO_2 emission, removal of fluoride from ground water—are all examples of geochemical engineering for solutions inspired by natural geochemical processes[49]. Many studies of contaminated sites worldwide are sources of information that could be useful for remediation technology development[50].

3.4. System Biology and Microbe Control

Understanding of the genomics and metabolomics of microbes under subsurface conditions are needed to control subsurface communities. Microbes can be used in remediation and in resource conversion (e.g., oil, coal, CO_2 to CH_4). Microbes may be used to alter the viscosity of complex organics (heavy oils) in the subsurface. Integrating a geochemical understanding of the environment from which the cells come will help to quantify metabolic behavior, cultivate environmental microbes, and use biological evolution in bioactive zones to our advantage[51].

Genomics reveals the blueprint for life, and is the starting point for understanding biological functions as well as a link between biological research and the development of biotechnology solutions. The system biology approach evaluates the interaction and relationships among various parts of a biological system and studies critical microbial

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[47] http://www.idswater.com/Common/Paper/Paper_29/Groundwater%20protection%20and%20remediation%20.htm G. Ziegenbalg, IDS Water – White paper. Groundwater Protection and Remediation by Induced "In-Situ" Immobilize Crystallization Processes.

[48] http://www-library.lbl.gov/docs/LBNL/488/72/PDF/LBNL-48872.pdf PF Dobson, TJ Kneafsey, E.L. Sonnenthal, N. Spycher, J.A. Apps, 2003. Experimental and Numerical Simulation of Dissolution and Precipitation: Implications for Fracture Sealing at Yucca Mountain (32 pages).

[49] http://www.eco-web.com/editorial/01361.html R.D. Schuiling and J.J.P. Zijlstra, 2001. Geochemical Engineering: Natural Solutions for Environmental Problems (16 pages).

[50] http://clu-in.org/download/partner/2002_annual_report.pdf (291 pages) http://cluin.org/download/partner/2001annualreport.pdf (285 pages) http://www.cluin.org/download/partner/2000annualreport.pdf (253 pages) are on NATO/CCMS Pilot Study on Evaluation of Demonstrated and Emerging Technologies for the Treatment and Clean Up of Contaminated Land and Groundwater (Phase III), sponsored by EPA, NATO Committee on the Challenges of Modern Society (CCMS).

[51] Joe Suflita summarized and presented for the breakout session on Microbes and System Biology.

properties and processes on three levels—molecular, cellular and community. The challenge is to understand how microbes carry out their diverse and useful functions—with studies beyond DNA sequences or proteins or cell by-products. Now that we have this molecular-level knowledge, we need to scale upwards, taking advantage of the investment and gains in molecular-scale science over the past few years to improve predictability and control at a higher level[33]. It is now possible to design and construct new biological parts, devices, and systems or to redesign existing, natural biological systems for useful purposes with synthetic biology development[52]. The SECUREarth approach may start by studies of biodiversity, microbial structures under extreme conditions, and interactions between microbes and subsurface carbon products.

3.4.1. Biodiversity

We lack a sufficient understanding of what microbes are present in the subsurface and their corresponding metabolic potential. This deficit can only be filled by metagenomic and community proteomic analysis of subsurface communities. Such analysis can be advanced by microarray technologies, but only if we are sure of the genes for which to probe. So there is a critical need for innovative and accelerated efforts to culture the normally unculturable subsurface microorganisms, using the microgel droplet method, to cultivate environmental microbes and evaluate their metabolic capabilities, and to advance the annotation of the genetic capabilities of cells in the subsurface and the associated bioinformatics. Methods for collecting large amounts of high-quality DNA and RNA for use in functional arrays are needed. We need to develop a holistic picture (*gestalt*) of the metabolic processes in the subsurface (and thus move beyond genomics). With an integrated geochemical understanding of the environment of cells, we can better understand the metabolic processes that occur in the subsurface[33].

3.4.2. Nanowires and Life under Extreme Conditions

We require new technologies that can be used to establish and measure electron flux in subsurface environments (AC impedance and self potential) to determine whether the subsurface is hardwired with nanowires. Nanowires were observed under electron-acceptor limitation conditions[53]. The study of life forms under extreme conditions in temperature, pH, nutrient supply, geogas at depths, etc., can elucidate the unique capabilities of microbial communities in response to environmental stresses and further shed light on the bio-inspired solutions for energy and environment.

3.4.3. Closing the Carbon Cycle (C^3) and Microbial Enhanced Energy Recovery

We must strive to close the carbon cycle with respect to energy extraction and sequestration. We need to develop methods for *in situ* microbial liberation of CH_4 from oil in place or coal without removing the resource. There is a specific need to convert

[52] http://www.syntheticbiology.org/ Synthetic Biology.
[53] http://doegenomestolife.org/research/progress_nanowires.shtml Genomics: GTL. Bacteria Use "Nanowires" to Facilitate Extracellular Electron Transfer (4 pages).

underutilized domestic energy reserves into methane by microbially enhanced energy recovery[51]. We should integrate our present understanding of metabolic processes and capabilities (e.g., nanowires) to access these resources for conversion. We need to identify signatures of important microbial activities, including terminal electron-acceptor cycles in the subsurface. We need to learn how to create conditions in the subsurface under which the appropriate communities can be made to flourish in the conversion of complex organics to methane[33].

There is abundant evidence of an active microflora in terrestrial subsurface environments, including areas where fossil energy resources exist. In addition to methane, it is also important to understand microbial production of surfactants, co-solvents, other gases, acids, etc., to mobilize oil in reservoirs. Microbial modification of heavy oils is important in converting these vast and underutilized reserves to forms that can be more easily recovered. We need to develop strategies for modifying the viscosity of complex organics in heavy oils using microbes or metabolic products.

4. SECUREarth Crosscutting Approaches

The SECUREarth initiative is aimed to crosscut physical, chemical, biological, and geological sciences within the geosciences. The SECUREarth research approach to face cross-cutting challenges will be based on the implementation of field research centers, laboratory studies, and computing. A concerted laboratory, computational, and field effort is required for developing the necessary technology. The establishment of dedicated research facilities can serve as the focal point for field staging, computation, and laboratory analysis. The facilities can be used to improve imaging, quantify heterogeneity, evaluate scaling, and study coupled processes. With multi-disciplinary collaboration teams formed from academia, industry, and national laboratories to use existing and initiate new facilities, the SECUREarth approach can not only generate evolutionary advances but also achieve revolutionary breakthroughs in crosscutting issues common to different program areas.

We believe that advances over the last 10 to 15 years in fundamental science, as well as the creation of major research facilities, must be utilized and integrated into geosciences research community. These advanced and new facilities are key to addressing the major roadblocks that prevent us from making significant advances in characterizing, predicting, and manipulating subsurface properties related to energy and environmental needs. The major DOE[54] and NSF[55] facilities include supercomputing centers, advanced imaging synchrotron sources, high-flux neutron sources, electron-beam sources, nano-scale science research centers, the Environmental Molecular Science Laboratory, the Joint Genome Institute, the Deep Underground Science and Engineering Laboratory (DUSEL), etc. Laboratory testing, modeling, and field testing with existing, planned, and dedicated facilities are discussed in this section. The following subsections include summaries of the current status and planned upgrades of some of these advanced facilities.

4.1. Laboratory Measurements and the Use of Advanced Facilities

Careful laboratory experiments are needed to characterize the effects of fluid circulation in fractured rocks. Also, many concepts for creating or enhancing fracture permeability (e.g., thermal cracking) can be initially evaluated in the laboratory[23]. Laboratory experiments at representative pressure and temperature conditions, and range of spatial scales, from submicrons up to meters, are needed to enhance fundamental understanding of multiphase flow and transport, geochemical and biogeochemical interactions, and to develop reliable constitutive relations for geophysical parameters. A dedicated user facility for making these measurements and computational support in data interpretation would allow significant and rapid progress in this area. Needed capabilities include elemental and mineralogical analysis on the micron scale, x-ray microtomography to characterize pore network geometry, 1-, 2-, and 3- D high pressure and temperature cells, x-ray CT real-time pore-fluid imaging and active interrogation with seismic and electromagnetic energy.

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[54] http://www.sc.doe.gov/Sub/Facilities_for_future/20-Year-Outlook-screen.pdf DOE 2003. Facilities for the Future of Science: A Twenty-Year Outlook (48 pages) . There are 42 major existing facilities and 28 future facilities and upgrades listed in this 2003 report on facilities maintained and operated by the DOE Office of Science. The lists and locations of Basic Energy Science facilities are on viewgraph 8 of http://www7.nationalacademies.org/bpa/BPA_Apr2005_Presentations_Dehmer.pdf P. Dehmer, 2005 Meetiing of the NRC Board on Physics and Astronomy (19 pages). The BES facilities include four synchrotron radiation light sources, four high-flux neutron sources, four electron beam microcharacterization centers, three special-purpose centers, and five nanoscale science research centers. There are five research facilities under Biological and Environmental Research, two network/centers under Advanced Scientific Computing Research, and twenty other facilities for fusion/high energy physics/nuclear physics.

[55] http://www.nap.edu/books/0309090849/html/167.html NAS 2004. Setting Priorities for Large Research Facility Projects Supported by the National Science Foundation (237 pages). NSF has the Major Research Equipment and Facilities Construction (MREFC) account for large facilities, with nine projects in FY2007 requests www.nsf.gov/about/budget/fy2007/tables/MAJORRESEARCHEQUIPMENT&FACILITIESCONSTRUCTION/MREFC-02.xls - 2006-02-06, including Earthscope and NEON (to be discussed in Section 4.4).

For carbon sequestration, laboratory studies can improve storage capacity estimates of the fraction of pore space that can be used for CO_2 storage, better understanding of multiphase flow, the kinetics of solubility and mineral trapping, the role of microbial processes on geochemical interactions, CO_2 adsorption and CH_4 desorption on rock media. A laboratory for synthesis and evaluation of manmade materials in subsurface environments is needed. There are many applications in which the durability of manmade materials in the subsurface environment is an important element of overall system performance. A dedicated laboratory is needed where existing materials could be tested under realistic subsurface conditions, including pressure, temperature, moisture, stress, geochemical and microbial community composition, failure modes could be evaluated, new materials could be designed for long-term durability, performance specifications could be evaluated and used for systems analysis[26].

In addition to individual laboratories, advanced and large user-facilities are valuable for many laboratory studies. The following subsections summarize several facilities as examples for applications in material characterization, process understanding, and biological studies: two synchrotron radiation light sources, one new high-flux neutron source, nanoscale science research centers for basic energy science, and two facilities for biological and environmental research.

4.1.1. Basic Energy Science Facility Examples—ALS, APS, SNS, Nanoscale Centers

The Advanced Light Source (ALS) is a national user facility located at Lawrence Berkeley National Laboratory (Berkeley, California). The ALS generates intense light for scientific and technological research—light in the x-ray region of the electromagnetic spectrum that is one billion times brighter than the sun. As one of the world's brightest sources of ultraviolet and soft x-ray beams—and the world's first third-generation synchrotron light source in its energy range—the ALS offers unprecedented opportunities for state-of-the art research in materials science, biology, chemistry, physics, and the environmental sciences. ALS was constructed in 1987–1993 at a cost of $99.5 million[56]. The potential upgrade includes the installation of a full complement of power boosters in the ALS storage ring, the replacement of conventional bend magnets with superconducting bend magnets, and full instrumentation of the insertion devices and superbend beamlines[54]. The upgrade would increase the brightness in the soft x-ray region 10 to 100 times, and extend the high energy range to between 10 keV and 20 keV.

The Advanced Photon Source (APS) at Argonne National Laboratory (Argonne, Illinois) provides this hemisphere's most brilliant x-ray beams for research. These x-rays allow scientists to pursue new knowledge about the structure and function of materials. The potential knowledge gained from this research can, for example, impact the evolution of combustion engines and microcircuits, aid in the development of new pharmaceuticals, and pioneer nanotechnologies. These studies promise to have a far-reaching impact on technology and our fundamental knowledge of materials. APS construction started in

[56] http://www-als.lbl.gov/als/ The Advanced Light Source.

1990, and research started in 1995, with a construction cost of $467 million[57]. The potential upgrade will create a super storage ring to further increase performance in the hard x-ray region of the spectrum, x-ray photon correction spectroscopy, coherent scattering, inelastic scattering, and x-ray nanoprobe microscopes[54].

The Spallation Neutron Source (SNS) is an accelerator-based neutron source being built at Oak Ridge National Laboratory (Oak Ridge, Tennessee). The construction of SNS was carried out as a partnership of six U.S. Department of Energy national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge. This collaboration was one of the largest of its kind in U.S. scientific history and was used to bring together the best minds and experience from many different fields. The SNS will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. At a total cost of $1.4 billion, construction began in 1999 and was just recently completed in 2006[58]. The current target station (with a 60 Hz frequency) is optimized for experiments in condensed matter, materials sciences, magnetic materials, and engineering. The SNS design also accommodates a power upgrade to support a second neutron beam and a second target station (at 10 Hz frequency) for study of soft matter[54] (e.g., polymers and biological materials).

Five new Nanoscale Science Research Centers are built, with initial operations begun in 2006[59]. They are the Center for Nanoscale Materials at Argonne (Argonne, Illinois), the Center for Functional Nanomaterials at Brookhaven (Upton, New York), the Molecular Foundry at Lawrence Berkeley (Berkeley, California), the Center for Nanophase Materials Sciences at Oak Ridge (Oak Ridge, Tennessee), and the Center for Integrated Nonotechnology at Sandia/Los Alamos (Albuquerque, New Mexico). The centers form an integrated network, and are part of DOE's contribution to the National Nanotechnology Initiative. The centers will focus on different areas of nanoscale research, such as materials derived from or inspired by nature; hard and crystalline materials, including the structure of macromolecules; magnetic and soft materials, including polymers and ordered structures in fluids; and nanotechnology integration. Each Center is housed near one or more existing Office of Science facilities, to take advantage of the complementary capabilities of other large scientific facilities, such as the Spallation Neutron Source at Oak Ridge, the synchrotron light sources at Argonne, Brookhaven, and Lawrence Berkeley, and semiconductor, microelectronics and combustion research facilities at Sandia and Los Alamos.

4.1.2. Biological and Environment Research Facility Examples – EMSL and JGI

The William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) at Pacific Northwest National Laboratory (Richland, Washington) provides integrated experimental and computational resources for discovery and technological innovation in the

[57] http://www.aps.anl.gov/ Advanced Photon Source.
[58] http://www.sns.gov/ Apallation Neutron Source.
[59] http://www.science.doe.gov/Sub/Newsroom/News_Releases/DOE-SC/2006/nano/index.htm with each of the five Centers described in http://nano.anl.gov/ , http://www.cfn.bnl.gov/default.asp , http://foundry.lbl.gov/ , http://www.cnms.ornl.gov/ , and http://cint.lanl.gov/ .

environmental molecular sciences. The EMSL equipment and capabilities are used to determine molecular information about processes occurring at surfaces and interfaces of solids, liquids, and gases. High-field magnetic resonance resources (300 to 900 MHz) high-performance mass spectrometers (7 to 12 telsa) are among the equipment used for studies of microbe and mineral surfaces, structural biology, solid-state materials, catalysis, synthesis, imaging, proteomics, and nanoscale science. EMSL construction began in 1994 and was completed in 1997[60].

The Joint Genome Institute (JGI) brings the expertise of four national laboratories—Lawrence Berkeley, Lawrence Livermore, Los Alamos, Oak Ridge and the Stanford Human Genome Center—to bear on the frontiers of genome sequencing and related biology. The JGI was created in 1997 to unite the expertise and resources in genome mapping, DNA sequencing, technology development, and information sciences pioneered at the DOE genome centers. In 1999, JGI was moved to Walnut Creek, California, to consolidate activities. JGI sequencing targets encompass a rapidly expanding range of microbes, animals, and plants. Sixty percent of JGI sequencing is for the new Community Sequencing Program (CSP). The vast majority of sequencing as part of these programs is related to the DOE mission areas of bioremediation, bioenergy, and carbon sequestration[61].

4.2. Numerical Modeling and the Use of Supercomputing Centers and Networks

For modeling and analysis, it is important to test whether joint inversion of different kinds of data and simultaneous use of hard and soft information will generate more reliable models, if multiscale modeling provides a sound basis for upscaling processes and parameters, if it is possible to define a chemically representative elementary volume for reactive flows in geologic media, and if modeling of natural analogs in conjunction with engineered systems can reduce uncertainty[62].

Fundamental studies and geoscience applications of reaction rates, coupled processes, multiphase flow and transport span the full range of spatial and temporal scales, from the molecular to the mountain scale and the millisecond up to millions of years. Bridging these ranges of scales will require novel concepts and computational approaches. Only by developing dedicated programs that bring together computer scientists, earth and biological scientists, mathematicians, and engineers will real progress on the most important and intractable problems be realized, e.g., the multiscale problems[63]. Simulation models for storage design, optimisation and long-term performance prediction could be enhanced by better integration between data collection and models, including real-time synthesis of hydrogeological, geophysical, geological, and geochemical data.

[60] http://www.emsl.pnl.gov/ Environmental Molecular Sciences Laboratory.
[61] http://www.jgi.doe.gov/ DOE Joint Genome Institute.
[62] Karsten Pruess summarized the discussions in the Numerical Modeling breakout session.
[63] http://www.math.colostate.edu/~estep/doe_multiscale/IIDOEWMP_final_report_v8.pdf Final Report Second DOE Workshop on Multiscale Problems (52 pages).

Access to high-performance computing would enable making calculations with the appropriate spatial and temporal resolution.

The energy group advocated the use of multiple geophysical data and encourages the development of joint inversion of these data to construct a consistent and efficient Earth description. For oil and gas, the current methodology of reservoir modeling uses little of the available data—so little that the only real benefit of seismic data is basically the initial drilling locations. Repetitive seismic imaging has sufficient sensitivity to show regions within the reservoirs that might have been bypassed or that lacked connectivity to existing production volumes. The exploitation of these additional volumes is very important, in that integration of reservoir modeling and characterization with field production efforts is a real opportunity for new findings in collaborative research, with the possibility of real economic benefits. To support this integration, the geophysical data need to be collected, processed in a cooperative manner (joint inversion), and used effectively within the modeling and management processes.

Reservoir codes up-scale their parameter fields by enlarging the grid cell sizes, a process that virtually does away with the ability to use the fine scale of well logs (e.g., the Vertical Seismic Profiles (VSP) of three-dimensional seismic data). Using data in a cooperative manner requires that chemical, physical, and mathematical relationships be developed to a much higher level than exist today. For example, Biot theory is basically our only approach to fluid interactions with waves in a solid, and must be enhanced, replaced, or improved.

The tremendous success of two-dimensional seismic processing methods clearly illustrates the benefits of improving our understanding of the Earth's interior. These data-driven processes require a systemic investigation and data collection at the Earth surface. The data are collected with regularly spaced energy sources placed on the surface. The activation of the source propagates waves into the Earth, and as these waves reflect back to the surface, signals are recorded by uniformly spaced sensors. These elastic data are used as inputs for full waveform algorithms. Full waveform inversion uses both the kinematical wave travel-time information and the detailed information in the wave to adjust model parameters. This "gradient" like method creates model parameter updates that are used to generate new model data sets. These data are compared with the actual data, and the process is repeated until the residual errors are reduced to an acceptable level. The practitioners of these two-dimensional inverse methods are producing impressive results using both synthetic data and real data. The extension of these full waveform methods to three dimensions has significant advantages: the real 3-D data has significant amplitude decline, with multiples substantially contaminating the recorded wave field, thus and must be treated very carefully. The comparison of two dimension model data with real three-dimensional data requires a rescaling to get a reasonable match. Building a truly three-dimensional integrated reservoir/geophysical system will overcome these data rescaling requirements. However, the complexity increase to 3-D is significant[17].

The environmental group discussed the inability to model contaminant transport. Three-dimensional models are insufficient for characterization and prediction of flow in the subsurface. Roadblocks include insufficient data, the inability to collect appropriate data to fulfill the requirements of the computationally complex mechanistic (3-D, coupled reactive transport) models, data of poor quality, scaling issues, and computational insufficiencies. No strong commitment exists within the earth science community to make essential databases related to earth science available to all scientists and the public. We have limited understanding and less than adequate theoretical models for the processes in the Earth's subsurface, an environment upon which we have become extremely dependent, but for which we find exceedingly difficult to sample and characterize. For example, contaminant remediation technologies are nonexistent for the deep vadose zone in the western U.S. The detection of high-risk contaminants (e.g. ^{99}Tc) and the use of surrogates (e.g., short-lived radioisotopes) for modeling the behavior of these contaminants is a major environmental issue. A better understanding of horizontal gene exchange among microbes in subsurface environments is critical to developing models for subsurface evolution of microbial consortia. Models of microbial community dynamics must also consider predation, the interactions between the free-living and attached communities, viral influence, and evolution of subsurface communities[33].

Supercomputers tailored to subsurface earth sciences applications with dedicated and/or purpose-built computing facilities are needed to develop coupled hydrologic/geochemical/microbial/geomechanical simulators needed for energy and environmental problems. The following subsections summarize two facilities for advanced scientific computing research and additional initiatives for rapidly growing advanced computing needs.

4.2.1. Advanced Scientific Computing Research – NERSC

The National Energy Research Scientific Computing Center (NERSC) is the flagship scientific computing facility for the DOE Office of Science. Associated with Lawrence Berkeley National Laboratory and located in Oakland, California[64], NERSC provides high-performance computing tools and expertise that enable computational science on a grand scale, supporting large, interdisciplinary teams in attacking fundamental problems in science and engineering for discoveries through computation. These fundamental problems include global climate modeling, combustion modeling, magnetic fusion,

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[64] http://www.nersc.gov/ National Energy Research Scientific Computing Center. NERSC resources include: Seaborg - a 6,656-processor computer with a peak performance of 10 teraflop/s (trillion operations per second) and a Global Parallel File System with 44 terabytes (TB) of storage; Bassi - a 976-processor system with 111 compute nodes (8 processors per node) available for scientific computing, with a peak performance of 6.7 teraflop/s and 100 terabytes of disk storage; Jacquard - a 640-processor cluster with a peak performance of 2.8 teraflop/s and 30 TB of disk storage; PDSF - a 700-processor cluster with 100 TB of disk storage; and HPSS mass storage – with a capacity of 16 petabytes (PB).

astrophysics, and computational biology. The NERSC upgrade will use grid technology to meet the expanding needs of an integrated science environment[54].

4.2.2. ESNet and Networks

The Energy Sciences Network (ESnet) provides a high-speed, effective, and reliable communications network infrastructure that enables thousands of DOE, university, and industry scientists and collaborators worldwide to make effective use of unique DOE facilities and computer resources, independent of time and geographic location. User demand to ESnet has grown 100% every year since 1990. ESnet is managed and operated by Lawrence Berkeley National Laboratory[65]. The ESnet upgrade will enhance existing network services and add fast interconnections to 100 other networks[54].

In the Facilities for the future report[54], Priority 2 in the plan is an UltraScale Scientific Computing Capability (USSCC), to be located at multiple sites, which would increase by a factor of 100 the computing capability available to support open scientific research. Most existing supercomputers have been designed with the consumer market in mind; USSCC's new configurations will develop computing capability specifically designed for science and industrial applications. The USSCC will involve long-term relationships with U.S. computer vendors and an integrated program of hardware and software investments, designed to optimize computer performance for scientific and commercial problems by creating a better balance of memory size, processor speed, and interconnection rates. The USSCC is motivated by the development of the Japanese Earth Simulator[66].

NSF has a plan for the establishment of a computing community consortium (CCC) for the design of a global environment for networking innovations (GENI), to be submitted to the major research equipment and facilities construction (MREFC) account[67]. The NSF Directorate for Computer and Information Science and Engineering is calling for the computing research community to unite in the establishment of a CCC. The Directorate will support the CCC as a community proxy responsible for facilitating the conceptualization and design of promising infrastructure-intensive projects identified by the computing research community to address compelling scientific "grand challenges" in computing. The CCC will ensure broad community engagement in the identification of compelling research agendas and in the subsequent identification and refinement of related shared use infrastructure requirements.

4.4. Field Testing

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[65] http://www.es.net/ Energy Science Network.

[66] http://www.es.jamstec.go.jp/esc/eng/ The Earth Simulator Center. The Earth Simulator uses vector technology with 5,120 processors, with peak performance of 40 Teraflops/s, and 20 TB storage. The Earth Simulator is for research in Earth related science, simulating complex linked systems in which, for instance, the climate is modeled together with water flow on the earth and models of the ocean.

[67] http://www.nsf.gov/pubs/2006/nsf06551/nsf06551.htm Computing Community Consortium (CCC): Defining the large-Scale Infrastructure Needs of the Computing Research Community NSF 06-551 (12 pages).

Field experiments are absolutely essential for developing a viable technology for deployment. We believe that a two-pronged approach will be most cost-effective. Initial field experiments can be carried out in a SECUREarth field facility, shared among subsurface applications (CO_2 sequestration, geothermal, nuclear, environment, groundwater, etc.). Specific applications may require dedicated facilities. For examples in oil and gas, an abandoned field may be ideal for testing advanced enhanced recovery methods. To the extent geothermal resources have some unique characteristics (temperatures > 200°C, crystalline host rocks), it will most likely be necessary to test the more promising ideas in one or more geothermal fields[23]. For fundamental validation of scaling models and direct validation of process understanding, the establishment of field research sites is absolutely essential[33]. In this section, we discuss the sensor development needed for field testing, surface-based borehole-testing facilities, and underground drift-testing facilities. The studies in different settings with different focuses will complement each other and generate the breakthroughs needed in all applications.

4.4.1. Sensor Development

To obtain comprehensive information about complex coupled systems (geological, mechanical, microbial, thermal, chemical, hydrological), innovative approaches will be required, such as the use of triggered sensors**,** smart tracers (nanoprobes), delivery systems (microdrilling, injection, infiltration), and data management[68].

The wide variety of geophysical methods, including gravity, magnetic, and seismic methods can be greatly enhanced by use of new technologies like nanodevices for sensors. The energy group strongly supported the development of new methods for data collection that have the promise of increasing resolution, types of data, and in particular the chemistry within the Earth[17]. Engineering of storage site design, operations, and mitigation activities could be improved by developing additives, catalysts, or novel injection schemes to accelerate immobilization of CO_2[26].

The rapid advances in integrated circuit processing and micromachining greatly lower the cost and reduce the size of sensors, motors, structures, and electronic systems to micro-centimeter scale. With self-assembling and networking capabilities through wireless communications, it is now feasible to deploy thousands of "smart" mote sensors for remote monitoring and testing[69]. With five new nanoscale science research centers inaugurated in 2006, more rapid developments in even smaller (nanoscale) sensors are ensured.

One example is the use of nuclear magnetic resonance to activate paramagnetic particles (10 nanometers) suspended in flow to determine tracer-transport, mixing, and concentration. The nanoparticles can have hydrophilic or hydrophobic coats. Many material science, biomedical, solar cell, and hydrogen-storage research findings can shed

[68] Ernie Majer presented and Andy Ward summalized the discussions in the breakout session on Sensors and Drilling.

[69] http://www.ce.berkeley.edu/sensors/ 2002. National Workshop on Future Sensing Systems.

light on how to apply nanotechnology to our subsurface energy and environmental problems. For example, the Federal Remediation Technologies Roundtable meet periodically to update the knowledge of site characterization and monitoring case studies in field demonstration and full-scale uses of innovative technologies[70].

4.3.2. Borehole and Sensor Network Facilities – CUASHI, ARM, FRC, INL/Hanford Sites, NEON, and Earthscope

The idea of testing a better method for oil and gas production is limited by our ability to perform the necessary experiments. At present, we can perform higher-quality seismic experiments, we can drill more wells, and we can enlist the owners of a producing oil field to try a new method—but only at some risk, either monetary or punitive. One of the recommendations discussed by the energy group[17] was the notion of complete access to a working oil/gas property. A working property would allow for real scientific experiments on the scale necessary for results. It is difficult to carry out scientific studies with physical assets owned by someone else. Basically, no science gets accomplished if no one is willing to provide the necessary access or relinquish control to a scientist. The energy group recommended that serious consideration be made to acquire one or more producing oil/gas properties as long-term test sites. Perhaps these sites could coexist within an existing federal property. .

For CO_2 sequestration, a dedicated experimental facility is needed for long-term, large-scale CO_2 storage experiments in a representative storage formation. CO_2 injection over a ten-year period, with injection rates on the order of 100,000 tones per year, would provide a wealth of data and monitoring opportunities and greatly facilitate addressing many of the issues. Understanding and improving the durability of manmade materials (such as cement and metal casing in the deep subsurface) would help to avoid or mitigate concerns associated with leakage from abandoned wells[26].

For water cycle evaluation, watersheds can be instrumented to understand the complete life cycle of water, to track the fate of water through the atmosphere, the trees, the soil, the streams and oceans, and back again into the atmosphere. Recent research shows that only 30 to 50% of the rain that falls on the Amazon comes directly from the ocean. The rest comes from rain that fell earlier in the season and has been recycled through trees, soil, and streams back into the atmosphere. Two California watersheds, for example, are planned (through private foundation grant) for collecting real-time data on rain, air moisture, soil water content, and stream flow via wireless network and satellite uplink[71].

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[70] http://costperformance.org/monitoring/#38 Federal Remediation Technologies Roundtable. Remediation Optimization: Site Characterization and Monitoring Technologies (41 pages).

[71] The example is a project funded by W. M. Keck Foundation to Inez Fung and her colleagues, described in http://www.berkeley.edu/news/media/releases/2006/02/23_water.shtml. Wireless sensor motes will be placed in the tops of trees, embedded in the ground, or scattered by the thousands around the watershed. These motes self-assemble into a wireless network that will send data to a central computer in the watershed, which will then relay the data via satellite to laboratories. One California watershed is along Elder Creek in the Angelo Coast Range Reserve on the South Fork of the Eel River near Branscomb. The other is at Sagehen Creek Field Station, about 20 miles north of Lake Tahoe. Other information will

Rio Grande/Bravo River basin and San Petro River basin are the foci of the SAHRA center funded by NSF[72]. Hydrological Observatories (Environmental Observatories) organized by NSF's Consortium of Universities for the Advancement of Hydrologic Science (CUASHI)[73] are aimed to address subcontinental, continental, and global water cycle questions.

For climate studies, the Southern Great Plains site at Okalahoma is the first (since 1992[74]) and largest field site of DOE's Atmospheric Radiation Measurement (ARM) research program. The central facility is located on cattle pasture and wheat fields, enabling observations of a wide variety of cloud types and surface flux properties. The site is heavily instrumented (including with infrared thermometers) for studying the effects and interactions of sunlight, radiant energy, and clouds, to better understand their impact on temperatures, weather, and climate.

For environmental studies, the Field Research Center (FRC) of DOE's Office of Biological and Environmental Research at Oak Ridge is an example of a field site with lysimeters and other equipment, installed within the FRC at several contaminated sites and one uncontaminated background area. The majority of the contaminated area is open, and the background area is heavily wooded, with perennial and ephemeral streams crossing through the area[75]. Additional FRCs are being evaluated for natural and accelerated bioremediation research.

The Vadose Zone Research Park at INL[76] and the Vadose Zone Transport Field Study sites at Hanford[77] are used for flow and transport research to validate conceptual models and test equipment for unsaturated flow and contaminant detection. Advanced tensiometer and water-flux meters are among instruments being deployed for vadose-zone plume detection and waste site drainage monitoring.

The National Ecological Observatory Network (NEON) of NSF was incorporated in 2005[78] for continental-scale ecological research with a geographically distributed infrastructure, networked via state-of-the-art communications. The grand challenges for NEON include biodiversity, biogeochemical cycles, climate change, hydroecology, and

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come from monitors that measure total rainfall and collect samples throughout a rainstorm that can be chemically analyzed to determine where water that fell in a particular area originated from. The presence of chloride from sea-salt would indicate that the water came from the ocean. A high concentration of carbon, nitrogen, or iron would indicate the water came from surface soil. Other elements would indicate a long residence time in the rock.

[72] http://www.sahra.arizona.edu/ SAHRA – Sustainability of Semi-Arid Hydrology and Riparian Areas, funded by NSF.

[73] http://www.cuahsi.org/hos.html Consortium of Universities for the Advancement of Hydrologic Science: Hydrologic Observatory.

[74] http://www.arm.gov/sites/sgp.stm Southern Great Plains.

[75] http://www.esd.ornl.gov/nabirfrc/ Oak Ridge Field Research Center. http://www.sc.doe.gov/ober/berac/field_site_report.pdf 2004. Need for Additional Field Research Sites (17 pages).

[76] http://www.inl.gov/geosciences/vadosezone.shtml Vadose Zone research Park.

[77] http://vadose.pnl.gov Vadose Zone Transport Studies.

[78] http://www.neoninc.org/ National Ecological Observatory Network.

land use. Field stations and *in situ* terrestrial and aquatic sampling platforms are among earth science facilities and infrastructure needed for the network. The Long Term Ecological Research (LTER) network is another ecology project, with 26 sites[79] and a program established in 1980 by NSF to support research on long-term ecological phenomena in the United States.

NEON and the Earthscope Project are the two earth science projects funded by NSF's Major Research Equipment and Facilities Construction (MREFC) account. Earthscope, our last example for this section, contains both deep borehole and sensor network facilities. This project is an unprecedented undertaking in solid earth science, both in its interdisciplinary approach and in its scope, with approximately $200 million in funding. EarthScope is developing a comprehensive systems approach to understanding the tectonics of the North American continent at all scales—from the active nucleation zone of earthquakes, to individual faults and volcanoes, to deformation along the plate boundary, and to the structure of the continent[80].

A 3.2 km deep borehole is being drilled through the San Andreas Fault Zone near the hypocenter of the 1966 M~6 Parkfield earthquake for the establishment of the San Andreas Fault Observatory at Depth. Arrays of Global Position System (GPS) receivers and strainmeters are used in the Plate Boundary Observatory to measure the deformation across the active boundary zone between the Pacific and North American plates in the western United States. The USArray component of the EarthScope experiment is a continental-scale seismic observatory with both transportable arrays (400 portable seismographs and 2,000 recorders) and permanent stations for integrated studies of continental lithosphere and deep Earth structure.

SECUREarth Initiative can interface with EarthScope's activities for the mitigation of risks from geologic hazards, the development of natural resources, and the understanding of the dynamic Earth and the forces that shape the landscape.

4.4.1. Underground Drift Facilities—WIPP, Yucca Mountain ESF, DUSEL

There is a need for a facility that permits science to be extrapolated to larger temporal and spatial scales, and that would permit the investigation of coupled processes. Synergy can be developed at such a facility between investigators that work at different scales and use different techniques, but who focus on the same environments. For example, we need more opportunities for biogeochemists and geophysicists to work together to develop remote methods for characterizing biogeochemical processes[33]. For CO_2 sequestration, a facility dedicated to understanding the sealing properties of faults and the fault interaction with CO_2 would provide valuable new information. This facility would ideally be located in an underground laboratory, where the fault would be accessible at multiple depths[26].

[79] http://www.lternet.edu/ Long Term Ecological Research Network.
[80] http://www.agu.org/meetings/fm05/?town_hall=town_hall_h&pageRequest=activities#thm Townhall meeting on EarthScope. http://www.earthscope.org/ Earthscope.

Substantial progress have been achieved in underground research associated with nuclear waste repositories, both at the Waste Isolation Pilot Plant (WIPP)[81], Carlsbad, New Mexico, and at the Exploratory Studies Facility (ESF) at Yucca Mountain[82], Nevada. WIPP is the world's first underground repository licensed for disposal of transuranic radioactive waste left from production of nuclear weapons, in operation since 1999. The disposal rooms and early research area are located in a single level at the depth of 655 m (2,150 ft) in salt. Since the mid-1990s, the ESF has had two drifts with alcoves and niches excavated for hydrological tests and a drift-scale heater test, ~300 m deep in tuff. While both WIPP and ESF facilities can be evaluated for other scientific and technical research, their primary mission is nuclear waste storage.

The planned NSF Deep Underground Science and Engineering Laboratory (DUSEL) will be accessible at multiple levels to a depth of over 2 km. SECUREarth experiments in flow/geochemistry/biology delineation and manipulation, coupled process testing, geotechnical studies, and deep geophysical monitoring could be conducted in DUSEL. We advocate as one possibility the use of DUSEL for SECUREarth research, and not for any storage.

Development of DUSEL has progressed substantially since 2004, with a site-independent study nearly completed and site conceptual design studies initiated at two underground mine facilities (Homestake, South Dakota, in metamorphic rock and Henderson, Colorado, in granite). A DUSEL would provide science and engineering communities with a unique and dedicated facility for fundamental and applied multidisciplinary research at depths. Current development of DUSEL is sponsored by NSF, with physics, geoscience, engineering, education and outreach components. Earth science investigators are at present exchanging information and ideas on important questions associated with depths and effects of site-specific characteristics. The availability of and access to potential experimental sites, and the development of potential experiments and common infrastructure, have been discussed in a series of workshops and meetings. Current effort is on the coordination of earth science studies with underground physics experiments, with the earth science focus on deep life search and on design of coupled-process experiments taking place over decades. With high stress at great depths, large excavations for physics detectors, and elevated temperatures anticipated in deep boreholes, ample opportunities exist to design field-testing programs to solve geoscience problems. Like SECUREarth, DUSEL is actively developing interactions with other national initiatives[83].

[81] http://www.wipp.energy.gov/ Waste Isolation Pilot Plant.
[82] http://www.ocrwm.doe.gov/about/pm/programbrief/pg09.htm The Scientific Studies at Yucca Mountain.
[83] http://www.agu.org/meetings/fm05/?town_hall=town_hall_a&pageRequest=activities#thm Townhall meeting on DUSEL – Deep Underground Science and Engineering Laboratory.

5. SECUREarth Implementation and Focused Themes

The technical challenges for SECUREarth can be addressed with effective organization, efficient management, and realistic funding prospective. Some specific suggestions are presented to initiate and turn this SECUREarth grassroots effort into a national initiative.

5.1. Collaboration Teams for Focused Themes

We advocate that we start the SECUREarth initiative with four basic multidisciplinary teams, focusing on flow delineation, physical modification, geochemical alteration, and microbial control (as outlined in Section 3). Team members are investigators with substantial background and knowledge in one or more of the energy and environmental programs: enhanced fossil fuel recovery, geothermal heat extraction, groundwater resource management, carbon sequestration, nuclear waste disposal, and environment remediation (as outlined in Section 2). The team will use advanced facilities for laboratory measurements, supercomputers for multiscale modeling and coupling of processes, and field facilities for validation, upscaling, and demonstrations (as outlined in Section 4).

The SECUREarth multi-disciplinary teams include investigators with interests and experience in subsurface research and with shared concerns on common energy and environmental problems. With knowledge of the status and approaches of ongoing and planned activities in geosciences, SECUREarth teams collectively then select specific themes for focused studies to achieve breakthroughs. The focused themes will have specific goals set and tasks identified to measure progress. The teams can be expanded as additional themes or other urgent needs are identified. All theme projects will have a finite duration to reach the specified goals. New topics for SECUREarth will be aggressively pursued to update and replace the original goals and themes.

The approach with coordinated research programs that cut across programmatic lines is essential for the SECUREarth major campaign. Traditional approaches within each program are primarily driven by given missions, with scientific advances achieved mainly as pleasant surprises and byproducts after long-term investigations. For example, both innovation in hydrocarbon production technology and environmental restoration led to the drive towards higher-resolution geophysical imaging and development of multiphase flow and transport modeling. In the SECUREarth approach, we advocate that we adopt a non-traditional approach by tackling directly cross-cutting themes and accelerating focused research crossover multiple programs.

The SECUREarth teams can tackle focused themes such as checking the mass balance in delineating and controlling subsurface flow and transport paths, bridging the gap between laboratory and field-scale studies of fractured rocks or heterogeneous blocks, focusing on the use and fate of injected carbon dioxide in different geological media with residual oil or other mineral resources, and responding to both long-term geological and catastrophic disasters. The themes can change to address emerging energy and environmental issues, but the teams will stay together and evolve effectively following the vision of SECUREarth. The SECUREarth approaches optimize the use existing research

infrastructures and develop new concepts and facilities if needed for revolutionary advances. The SECUREarth initiative contributes to American competitiveness and advanced energy by addressing subsurface problems for urgent solutions common to both the energy and environmental problems.

5.1.1. Theme 1: Mass Balance in Field Evaluation

”Trying to obtain a mass balance in the field would be, at best, very difficult.” “Field tests are expensive, are difficult to control, offer many challenges to achieving good scientific measurements, and represent only a single set of conditions which are not readily controlled.” These quotes are from a study on oil spill in ocean[84]. Mass balance is also explicit in a Lake Michigan study[85] and implicit in many pollution removal and environmental remediation studies. For subsurface studies, mass balance is certainly recognized to be a crosscutting, major challenge for field testing. The suggested goals and tasks are:

Goals:

- Explicitly impose mass balance requirements in subsurface studies in the field
- Quantify leakages through the domain boundaries at all times
- Determine interactions and distributions of different fluid and solid components within the flow domains.

Tasks:

- Develop and couple geophysical imaging methods with fluid phases and reactive transport
- Design injection and monitoring schemes to enhance sensitivities and minimize leakages
- Incorporate fluid collection devices and nest of withdrawal ports to account for injected masses.

5.1.2. Theme 2: Constitutive Relationships of Fractured Rocks

The majority of subsurface studies are based on laboratory measurements of core properties and then on empirical scaling to determine the effective parameters for reservoir filed-scale modeling. There is a gap in the fundamental knowledge over the intermediate range between core size and field scale. Blocks of fractured rocks or heterogeneous media over the range of decimeters to decameters can be systematically instrumented and tested for coupled physical, chemically, and biological processes. This range of scales is amenable in a large laboratory testing facility to tackle the scaling problem and to validate the models. Such a macroscopic facility can be co-located at a field research center or near a major microscopic science center or institution.

Goals:

[84] http://darwin.nap.edu/books/030909562X/html/279.html NRC 2005. Oil Spill Dispersants: Efficacy and Effects (396 pages).

[85] http://www.epa.gov/glnpo/lmmb/ EPA. Lake Michigan Mass Balance Study.

- Develop scaling laws and constitutive relationships to relate effective field-scale parameters to core measurements
- Determine the degree of influence from pore geometry, fracture network characteristics and heterogeneity correlation structure on macroscopic properties
- Establish rigorous criteria for model representation for large-scale engineering applications

Tasks:

- Select and design block tests for a range of block sizes, rock types, heterogeneity characteristics, fluid components and mixtures
- Instrument and measure physical, chemical, and biological responses to controlled injections and withdrawals
- Develop theoretical and numerical models for data analyses and interpretations for processes under subsurface conditions.

5.1.3. Theme 3: Interactions of CO_2 with Residual Oil

We can have a major campaign and focus on CO_2 to measure its flow, transport, and distribution in the subsurface, to determine whether CO_2 EOR can indeed increase oil reserves by a factor of more than five[86], whether CO_2 can effectively displace coal-bed methane, whether CO_2 can be an effective heat exchange fluid for enhanced geothermal systems, whether CO_2 can be converted to CH_4 effectively with microbial processes, etc. The SECUREarth team can investigate all these potentials to address both energy production and greenhouse gas environmental concerns in a focused, concerted effort. In this theme, we can start by focusing on interaction between CO_2 and residual oil.

Goals:

- Optimize the displacement of residual oils with CO_2 flooding
- Determine mechanisms and efficiencies of CO_2 conversion to calcite, methane, and other mineral or organic components in subsurface environment and conditions
- Contribute to carbon neutral renewable energy supply strategy.

Tasks:

- Image CO_2 and organic oil phases in rock samples under different viscous conditions
- Conduct large scale control experiments in underground research facilities
- Design and conduct field demonstration projects.

5.1.4. Theme 4: Response to Disasters Like Katrina

[86] http://www.fossil.energy.gov/news/techlines/2006/06015-Oil_Recovery_Assessments_Released.html
DOE FE 2006. New CO2 Enhanced Oil Recovery technology Could Greatly Boost U.S. Oil Supplies.

We envision that multidisciplinary teams for crosscutting fundamental research can also respond to cataclysmic events. Hurricanes, tsunamis, earthquake, volcano eruption, land slides, forest fires, etc., are disasters that can have a dramatic impact on energy supplies and environmental conditions. New Orleans was discussed as an example. Present population and demographic profiles suggest that future events like the Katrina and Rita hurricanes, and the Sumatra Tsunami, will occur with greater frequency and have greater environmental impact. We need to be able to respond quickly to these issues with scientifically sound and multidisciplinary characterization and mitigation strategies.

The SECUREarth teams can respond and provide the comprehensive scientific foundation needed to tackle complex energy and environmental problems, such as those associated with the Katrina disaster. The potential roles of SECUREarth can include: environmental remediation of New Orleans contaminants, assessment of Gulf Coast ecosystem vulnerability and, and the sustainability of urban centers. For longer-term responses, environmental assessment and remediation may take several years, with salinization of wetlands a 5-year goal[87].

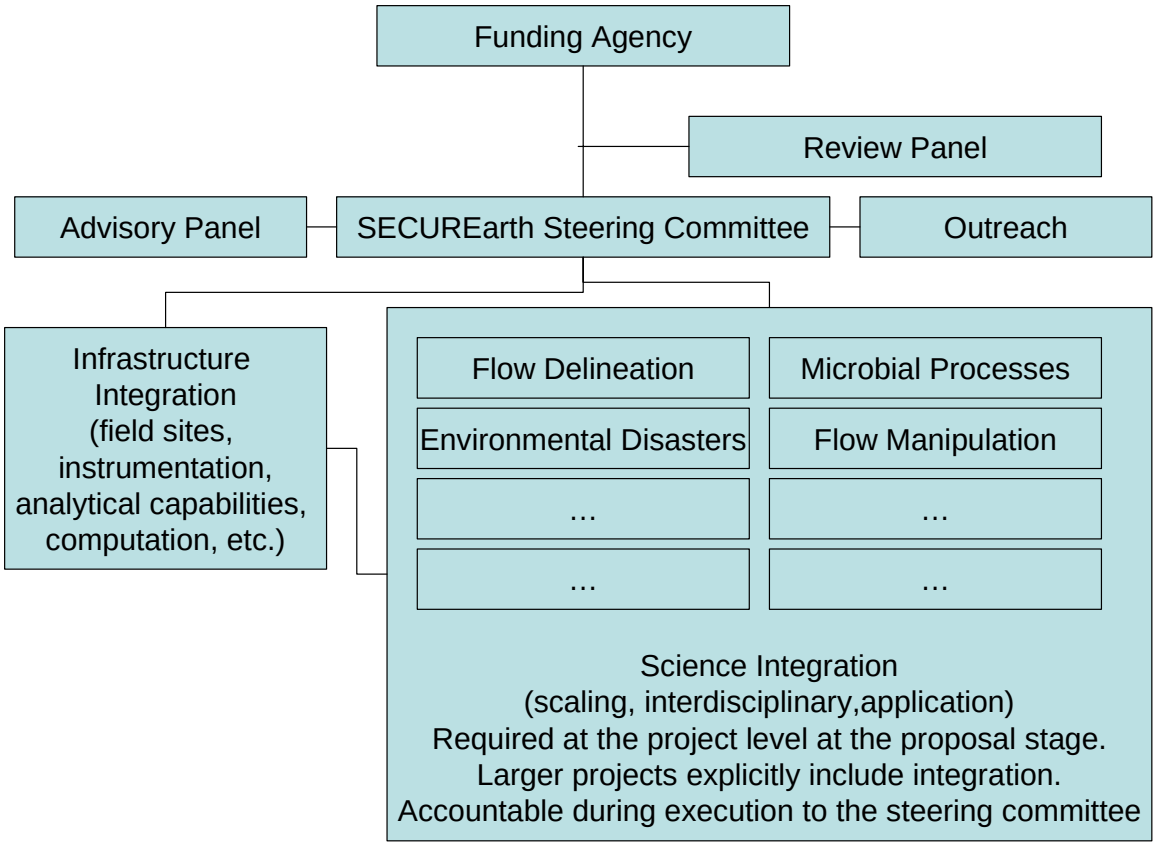
The devastation wrought by Katrina and Rita demonstrated the risks that many coastal areas face from hurricanes and associated flooding. Prior to these storms, ongoing land losses in the coastal regions of Louisiana had contributed to widespread concern regarding the vulnerability of the region to storms and coastal flooding[88]. To the extent that wetlands can offset a significant degree of storm impact, large-scale wetlands restoration projects can be an important component of national efforts to reduce future hazards from hurricanes.

Specific goals and tasks can be developed for specific disaster response.

5.2. Management

The formation of multidisciplinary research teams requires a strong “top-down” structure modeled after the Ocean Drilling Project, with an upper tier defining the major campaigns and a lower tier defining individual projects. Explicit requirements of a major campaign include public outreach, regulator inputs, and end-user interactions. The facilities can be established following DOE’s Natural and Accelerated Bioremediation Research—Field Research Center model (Section 4.3.2). The role and responsibility of SECUREarth is depicted in the following schematic diagram[89]:

[87] Susan Hubbard summarized and presented the plan developed for the New Orleans theme.
[88] http://www.nap.edu/catalog/11476.html NRC 2006 Drawing Louisiana's New Map: Addressing Land Loss in Coastal Louisiana (206 pages).
[89] Bob Smith presented the discussions in the Management breakout session.



SECUREarth, with its mission for solving urgent energy and environmental problems, should actively find creative ways to capture the public's interest—by continuously advocating scientific findings and solutions, and by disseminating real-time scientific information about Earth systems. One good example is the earthquake displays created by the Incorporated Research Institutions for Seismology (IRIS) and the USGS in five U.S. museums. Real-time seismic data from three remote locations, displays of locations of current and past earthquakes overlain on satellite images of the world, and earthquake listings are presented to the public as signals of geological forces rather than of destructive events. Surveys indicated that the displays were effective because they reached out to their audience in a clear way, increasing understanding of an obviously important issue that the displays were popular by connecting with visitors, increased understanding, and expanding the outreach[90].

5.3. Funding Potential

SECUREarth seeks commitment on the national level for dedicated and concerted effort to focus on subsurface flow path delineation and modification, geochemical alteration, and biological conversion with specific thrusts on mass balance in field testing, basic research in macro-scale constitutive laws, and CO_2 in fossil and bio-fuel recovery, methane production, and calcite precipitation to fulfill the demand for clean energy and

[90] "Real-Time Seismic Displays in Museums Appeal to the Public", EOS, 87(8), February 21, 2006.

improvements in the environment. With a Manhattan Project-scope, SECUREarth is envisioned to reach an annual $20 M operating budget for a few hundred scientists conducting research in existing and established facilities. In addition, the requirements and approaches for dedicated facilities will be developed by the SECUREarth teams for fundamental crosscutting research. The infrastructure and management of dedicated facilities are estimated to require on the order of $50 M. The SECUREarth request is envisioned to be independent of the funds for existing programs, but will use the findings and existing research capabilities to launch a concerted effort to address our nation's energy needs and environmental challenges.

It is informative to compare the SECUREarth funding estimate to federal funding profiles of previous years. National geosciences research program funding in FY2004, summarized by Nicholas Woodward (DOE BES Geosciences), was as follows: Total FY2004 geosciences funding was $687.7M. The bulk of geoscience funding ($593.3 M) was for directed research distributed among 11 USGS programs, 9 NSF programs, and 11 DOE programs. For basic science research, DOE had the additional BES program of $21.5 M for atomic-to-continuum-scale studies of Earth processes and properties, and NSF had the additional individual investigator program of $72.9 M for geology and paleontology, geophysics, hydrological sciences, petrology and geochemistry, and tectonics. The NSF individual investigator program was the largest (10.6%) among all geosciences programs, including both directed research and basic science.

The SECURearth scope of $70 M is equivalent to ~10% of current geoscience funding.

In additional to federal funding (see Section 6.1.1 on American competitive initiative and advanced energy initiative for additional information and prospective), the SECUREarth will seek industrial and foundation support. Cost sharing is an effective mechanism by which to ensure that research is problem-driven and solutions will be used. Many of the SECUREarth goals, such as improvement in imaging methods and permeability changes can greatly reduce exploration and production costs. Changes in tax laws to encourage alternative energy productions (e.g., extension of Production Tax Credit to geothermal energy, a Renewable Portfolio Standard, etc.) should result in additional incentives to support SECUREarth research.

6. Synopsis of SECUREarth Science Plan

The dependence on fossil fuel threatens our way of life in the U.S. and accelerates global warming. The geosciences can lead the research to meet the challenges facing us in this century. The SECUREarth Workshop in 2005, together with the National Research Council board meeting and other meetings in 2004, have begun the identification of broad themes in subsurface processes related to energy and the environment. This science plan calls for formation of multidisciplinary teams from national laboratories, academia, and industry—with research backgrounds in enhanced fossil energy recovery, geothermal heat extraction, groundwater resource management, carbon sequestration, nuclear waste disposal, and environmental remediation—to tackle identified crosscutting problems. The SECUREarth teams have the grand vision to achieve revolutionary breakthroughs while maintaining the flexibility to improve and refine key scientific approaches. The initial suite of crosscutting issues to be addressed by these teams is proposed on the subsurface flow delineation and modifications—physically, geochemically, and biologically.

6.1. Grand Challenges

The U.S. public is paying increasing attention to the many energy and environmental problems faced by this nation. We have seen gasoline prices increase prohibitively, enough to make it the public's No.1 concern (4/30/2006)—an even greater concern than Iran having a nuclear bomb, illegal immigration, and the war in Iraq. Energy and environment-related headlines in 2006 include Brazil becoming energy self-sufficient with the use of ethanol from sugar cane (4/10/2006), the President's State of the Union address on protecting American competitiveness and advanced energy initiatives (1/31/2006), and the tragedy at Sage coal mine (1/3/2006). SECUREarth can contribute to the grand challenges of the initiatives and the transitions to sustainable energy.

6.1.1. American Competitiveness Initiative and Advanced Energy Initiative

In the 2006 State of the Union address, President Bush announced two initiatives to support science and technology in the coming years[91]. The American Competitiveness

[91] http://www.whitehouse.gov/news/releases/2006/01/20060131-5.html on American Competitiveness Initiative. http://www.whitehouse.gov/news/releases/2006/01/20060131-6.html on Advanced Energy Initiative. FY 2007 budget request is at http://www.whitehouse.gov/omb . See News in EOS, 87(7), February 14, 2006 on summary of the FY2007 budget impact on geoscience research. In the Administration's budget request for Fiscal Year 2007, NSD, DOE Office of Science, and NIST would see significant increases if Congress approves. The budgets would double within 10 years as part of the American Competitiveness Initiative as key supporters of the physical sciences and engineering, areas of science expected to produce marketable technologies and techniques. Some of the NSF funds would be used for operational and scientific support of EarthScope, and operation of the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER). The DOE Office of Science highlights include increases for research in geosciences and environmental remediation. DOE-funded climate change research would be cut, although overall federal climate change research would be sustained. Outside the Office of Science, the DOE request includes funds for continued development of

Initiative includes doubling the federal commitment to the most critical basic research programs in the physical sciences over the next 10 years. The Advanced Energy Initiative would, among other things, increase funding for alternative fuel energy development. SECUREarth will contribute to the research and development of domestic energy supplies and the clean energy for the future. SECUREarth will meet the challenges for "Rising Above the Gathering Storm"[2] (Section 1.1).

6.1.2. Transitions to Sustainable Energy

The international InterAcademy Council (IAC) of the world's Academies of Science has launched a study in 2005 to address how transitions to sustainable energy systems can be achieved. The major energy challenge is on (1) access to affordable modern energy, and (2) mitigation of health and environmental impacts. The ongoing study will consider the projections and impacts of varying assumptions as to future energy sources and use. It will characterize the rate and direction of technological progress—including demonstration and deployment—that will be needed to substantially meet the needs for clean, affordable energy[92]. The results of this study will provide a global perspective for SECUREarth's energy and environmental solutions.

Both solar energy and hydrogen energy are in the mix of sustainable resources. In 2001, solar electricity provided less than 0.1% of world's electricity, and solar fuel from modern (sustainable) biomass provided less than 1.5% of the world's energy. However, sunlight provides the largest of all carbon-neutral energy sources. The basic research need for solar energy utilization was discussed in a Basic Energy Sciences Workshop in 2005[93]. The option of leveraging photosysthesis for sustainable solar production of biofuels will have a large impact on land use. "For biomass energy to be viable on a large scale, research will be needed that would allow the utilization of marginal land, limited water supplies, and low fertilizer use"[1]. Hydrogen is carbon-free fuel that can be generated together with electricity in the next generation of nuclear reactors. In 2003, President Bush unveiled the Hydrogen Fuel Initiative and the BES workshop addressed the basic research needs for the hydrogen economy[94]. The transportation of hydrogen is based on the use of hydrides, an earth material. In our research in nanosciences, with five new nanoscale centers on line in 2006, SECUREarth can examine other earth materials (such as zeolite) with high hydrogen sorbing capacity, to evaluate the transformational energy potential of earth materials.

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the Yucca Mountain nuclear waste repository, and large increases for solar and biomass research. However, funding for geothermal and hydropower would be eliminated

[92] The IAC is a globally-based association of the world's academies of science, located in Amsterdam, and governed by a Board of 15 Academy Presidents (elected by the complete set of academies), representing countries of all regions and levels of development. The Transitions to Sustainable Energy is described in http://www.interacademycouncil.net/studies.asp?id=5720 . The expert panel on Transitions to Sustainable Energy is co-chaired by Steve Chu, Director of LBNL (Today at Berkeley Lab, 1/6/2006).

[93] http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf 2005. Basic Research Needs for the Solar Energy Utilization (276 pages).

[94] http://www.er.doe.gov/bes/reports/files/NHE_rpt.pdf 2003. Basic Research Needs for the Hydrogen Economy (178 pages).

6.1.3. Grand Research Questions in the Solid-Earth Sciences

As a result of 2004 NRC meeting, the National Research Council, at the direction of the Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS), formed a committee to report on the "Grand Research Questions in the Solid-Earth Sciences" — a decadal study. The Committee plan is to have a series of meetings in 2006 and report to DOE, NSF, NASA, and USGS in the spring of 2007. The task of this committee is to "formulate a short list of grand research questions driving progress in the solid-earth sciences." This was done effectively for physics and astronomy in "Connecting Quarks with the Cosmos: Eleven Questions for the New Century"[95], and the Committee proposes to use that report as a model. The research priorities identified by early and recent reports (Section 1.1) provide the background for the new study.

The task of the new Grand Research Questions committee is to develop and describe "research questions that will cover a variety of spatial and temporal scales, from subatomic to planetary, and from the past (billions of years) to the present and beyond. The questions will be written in a clear, compelling way and will be supported by text and figures that summarize research progress to date and outline future challenges. The report *will not* discuss implementation issues (e.g., facilities, recommendations aimed at specific agencies) or disciplinary interests." The overriding questions formulated by the committee are[96]:

1. How did the Earth and planets form?
2. What happened during Earth's dark age? (the half billion years before the oldest known rock formed)
3. How did life begin on Earth?
4. Why is there plate tectonics?
5. How has Earth's interior evolved, and how has it affected the surface?
6. Why does Earth have a magnetic field?
7. How do life and Earth co-evolve?
8. How has Earth's climate changed and why?
9. Can we understand and predict catastrophic natural events?
10. How do material properties control planetary processes?
11. How do air, water, land, and life processes interact to shape our environment?

These are obviously broad and far-reaching issues, and there will be a critical need to employ crosscutting multidisciplinary research to address these questions.

SECUREarth provides inputs to the National Research Council committee on its deliberation in 2006 to formulate the list of grand research questions in the solid-earth sciences. There will be a critical need to employ crosscutting multidisciplinary research to

[95] http://www.nap.edu/books/0309074061/html/ NRC 2003. Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century (222 pages). Committee on the Physics of the Universe, Board on Physics and Astronomy.

[96] "Identifying Grand Research Questions in the Solid-Earth Sciences", EOS 87(9), February 28, 2006.

address broad and far-reaching issues (Section 1.1). **The broad question SECUREarth aims to answer is "What role must the geosciences play in sustaining our energy supply and protecting our environment?"** The SECUREarth is a focused implementation initiative, aimed to crosscut the physical, chemical, biological, and geological sciences to achieve breakthroughs that will be necessary to solve our coming energy and environmental needs.

SECUREarth needs to be distinctly unique, but at the same time closely integrated with advances advocated by scientific communities and programs with strong solid-earth research components. In addition to specific energy and environment problems (Section 2) and identified crosscutting issues (Section 3), there are additional examples of insightful visions documented in recent NRC reports. Global climate change research calls for improving atmosphere-land-ocean models (especially the geophysical flow model) and for improving quantification of climate forcings beyond surface mean temperature (including evapo-transpiration flux)[97]. NASA is developing a roadmap to support the earth sciences and applications from space, for the NRC Decadal Survey[98]. An NRC geoengineering committee for NSF calls for incorporation of nanotechnology, biotechnology, microelectromechanical systems, and cyber-infrastructure for engineering solutions[99].

SECUREarth represents an expansion of the traditional role for geoscientists and geoengineers for Earth systems, which will include efforts to integrate social, environmental, and scientific issues into technological solutions for Earth system problems. This expanded scope will require new types and quantities of data and new approaches. The critical problems to be addressed will include developing technology that is environmentally responsible and economically beneficial, managing the emerging critical issues of global change, and dealing with the legacy and future of energy use.

6.2. Specific Goals

Subsurface energy and environmental problems draw on the geosciences for solutions.

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[97] http://www.nap.edu/catalog/11266.html NRC 2005 Improving the Scientific Foundation for Atmosphere-Land-Ocean Simulations: Report of a Workshop (84 pages). http://www.nap.edu/catalog/11175.html NRC 2005. Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties (222 pages).

[98] http://www.nap.edu/catalog/11416.html NRC 2006 Review of Goals and Plans for NASA's Space and Earth Sciences (73 pages). http://darwin.nap.edu/books/0309096723/html/ NRC 2005 Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation (an Interim report for NRC Decadal Survey, 58 pages). http://www.hq.nasa.gov/office/apio/pdf/earth/earth_roadmap.pdf NASA 2005 Exploring Our Planet for the Benefit of Society (90 pages).

[99] http://www.nap.edu/catalog/11558.html NRC 2006. Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation (220 pages). http://www.armarocks.org/documents/igu_report ARMA 2000. Rock Mechanics and Rock Engineering: Challenges and Opportunities (28 pages). http://www.nap.edu/catalog/9690.html NRC 1999. Our Common Journey: A Transition Toward Sustainability (379 pages). http://darwin.nap.edu/books/0309100097/html/173.html NRC 1989. Geotechnology: Its Impact on Economic Growth, the Environment, and National Security (221 pages).

This SECUREarth science plan report presents a vision for the future of subsurface studies aimed at the geoscience community as a whole, including academia, industry, national laboratories, as well as program managers of agencies, companies, and other stakeholders in geoscience research. Geoscientists are poised to expand their roles and lead in finding solutions for modern Earth system problems, including emissions-free energy supply, global water supply, and environmental assessment/remediation.

6.2.1. Enhance Energy Production and Clean Up Environment

For the program needs of resource production and contaminant sequestration, the specific goals are:

(1) For oil and gas, double the recovery from 30–40% to 60–80% of maximum recovery.
(2) For geothermal systems, increase the thermal outputs ten fold.
(3) In water supply and quality, meet all our future needs of clean water.
(4) In CO_2 storage, ensure that the injected carbon dioxide remains in the reservoir over geological time scale.
(5) For nuclear waste disposal, use the natural system to meet the million-year dose standard.
(6) In environmental remediation, improve beyond natural attenuation approach and reduce new pollution in energy production.

These are the specific goals for each of the program area. SECUREarth will work with each program to evaluate the crosscutting challenges with multidisciplinary approaches.

6.2.2. Evaluate Crosscutting Issues of Flow Delineation and Manipulation

The first set of problems for SECUREarth is for SECUREarth teams to study (Section 3):

(1) Flow delineation, with geophysical imaging and fracture/fault studies.
(2) Physical modification, with improvements in hydraulic fracturing, thermal cracking, use of explosive slurry, and laser drilling.
(3) Geochemical alternation, with foam fracturing, *in situ* crystallization and precipitation, and geochemical engineering.
(4) Microbial control, with biodiversity quantification, nanowires and life under extreme condition studies, and microbial enhanced energy recovery to close the carbon cycle.

In addition to these foci, SECUREarth will tackle specific themes and respond to disasters (Section 5). For examples, we can form a CO_2 team to evaluate the roles of CO_2 in enhanced oil recovery, in displacement of coal-bed methane, as heat-exchange fluid in enhanced geothermal systems, and in converting to methane under microbial mechanism. We can also form teams to respond to disasters as in the case of Katrina. More teams can be formed as additional themes or other urgent needs are identified. Each team will set specific goals by which to measure success. All teams set finite periods of time in which to reach the specified goals. New topics for SECUREarth will be aggressively pursued to update and replace original goals and themes where needed.

6.2.3. Deploy Effective Crosscutting Approaches

The SECUREarth teams will use state-of-the-art methodologies to tackle crosscutting challenges, with a combination of (Section 4):

(1) Laboratory measurements, with the use of advanced facilities, including BES's ALS, APS, SNS, and five new nanoscale centers, BER's EMSL and JGI.
(2) Numerical modeling, with the use of DOE's and NSF's supercomputing centers and networks.
(3) Field testing, with sensor development, use of borehole and sensor network facilities of CUASHI, ARM, FRC, INL/Hanford sites, NEON, and Earthscope, and with underground drift facilities demonstrated in WIPP and Yucca Mountain ESF, and in the soon-available DUSEL.

Additional facilities will be developed if needed. Dedicated field facilities can provide the focus and synergy required for breakthroughs.

7. Summary: SECUREarth for Revolutionary Advances with Quantum Steps

The dependence on fossil fuel threatens our way of life in the U.S. and warns up the globe. Geosciences can face the challenges to lead the research and solve the problems facing us in this century**.** While SECUREarth will promote research by individual principal investigator-driven research teams, we see a critical need to expand the current mode of most research programs to encourage the formation of multidisciplinary research teams. The SECUREarth initiative is not to replace, but to build on, current research approaches, incorporating lessons learned from directed and mission-oriented programs and geoscience-related initiatives**.** To maximize the value of future geosciences, the scientific results must be tightly coupled with ultimate users and benefactors of the research. If SECUREarth is to succeed in its objectives, various industrial entities, including representatives of the oil and gas, environmental remediation, nuclear waste disposal, and geothermal industries, must help to set the goals, perform the research, and evaluate the applicability of the results. We must have the eventual users of the results be involved during the whole process of advancing geosciences for sustaining our energy resources and protecting of our environment.

The SECUREarth Workshop in 2005, together with the National Research Council board meeting and other meetings in 2004, have initiated the identification of crosscutting themes in subsurface processes related to energy and the environment. We advocate that we start the SECUREarth with four basic multidisciplinary teams with foci on flow delineation, physical engineering, geochemical alteration, and microbial control. Specific themes can be identified to address, for examples, the assessment for mass balance in field testing, the establishment of fundamental constitutive relationships of fractured network, the optimal use of carbon dioxide in EOR. More teams can be formed as additional themes or other urgent needs are identified. Each team will set specific goals to measure success. All teams have finite duration set to reach the specified goals. New topics for

SECUREarth will be aggressively pursued to update and replace the goals and themes. The teams have the grand vision to achieve revolutionary breakthroughs while maintain the flexibility to improve and refine the approaches.