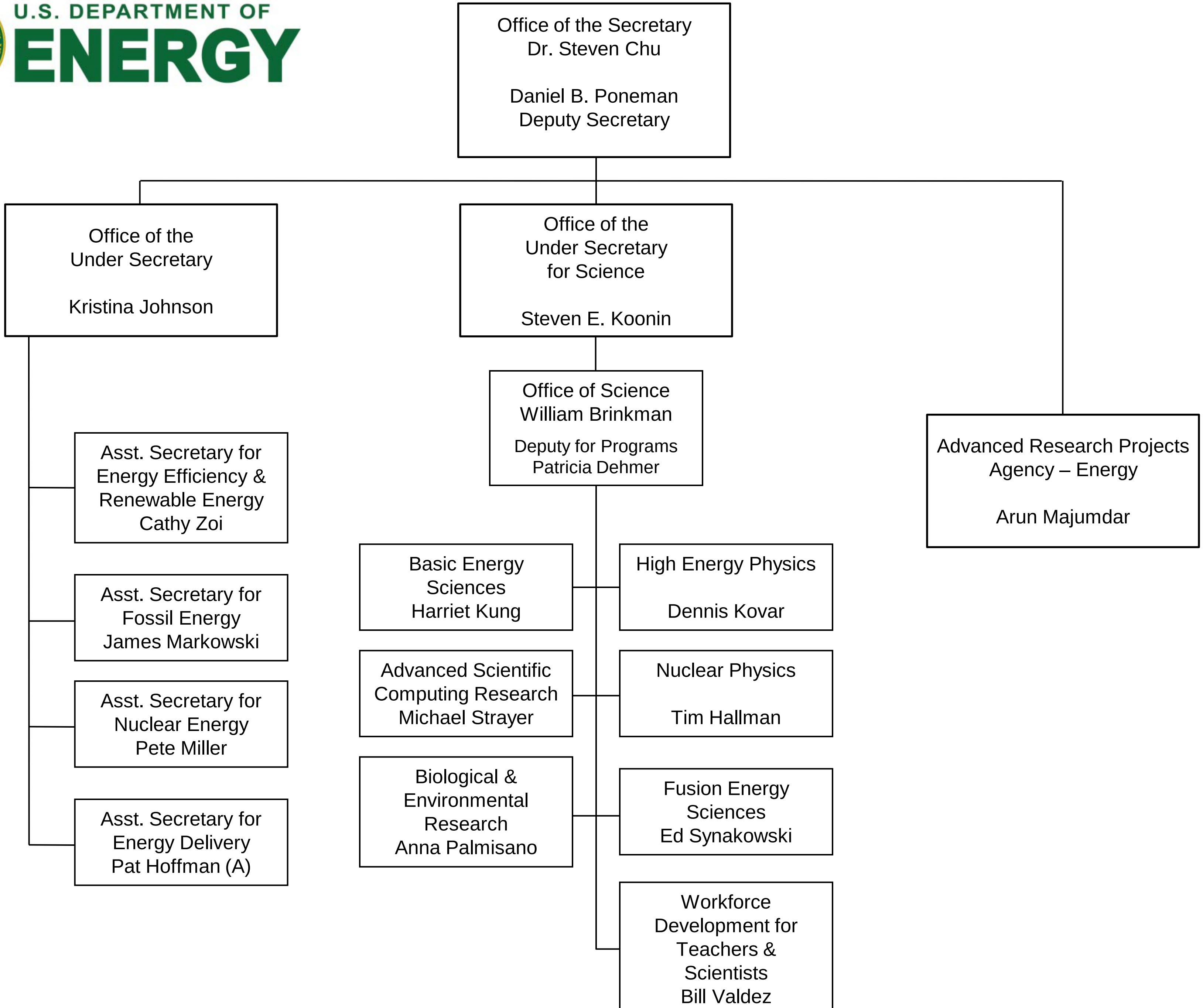
U.S. DEPARTMENT OF ENERGY | Office of Science

Our Energy Challenges

Council of Energy Research and Education Leadership

January 20, 2010

Dr. William F. Brinkman
Director, Office of Science
U.S. Department of Energy



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DOE's Energy Priorities and Goals

Priority: Science and Discovery: Invest in science to achieve transformational discoveries

- Organize and focus on breakthrough science
- Develop and nurture science and engineering talent
- Coordinate DOE work across the department, across the government, and globally

Priority: Change the landscape of energy demand and supply

- Drive energy efficiency to decrease energy use in homes, industry and transportation
- Develop and deploy clean, safe, low carbon energy supplies
- Enhance DOE's application areas through collaboration with its strengths in Science

Priority: Economic Prosperity: Create millions of green jobs and increase competitiveness

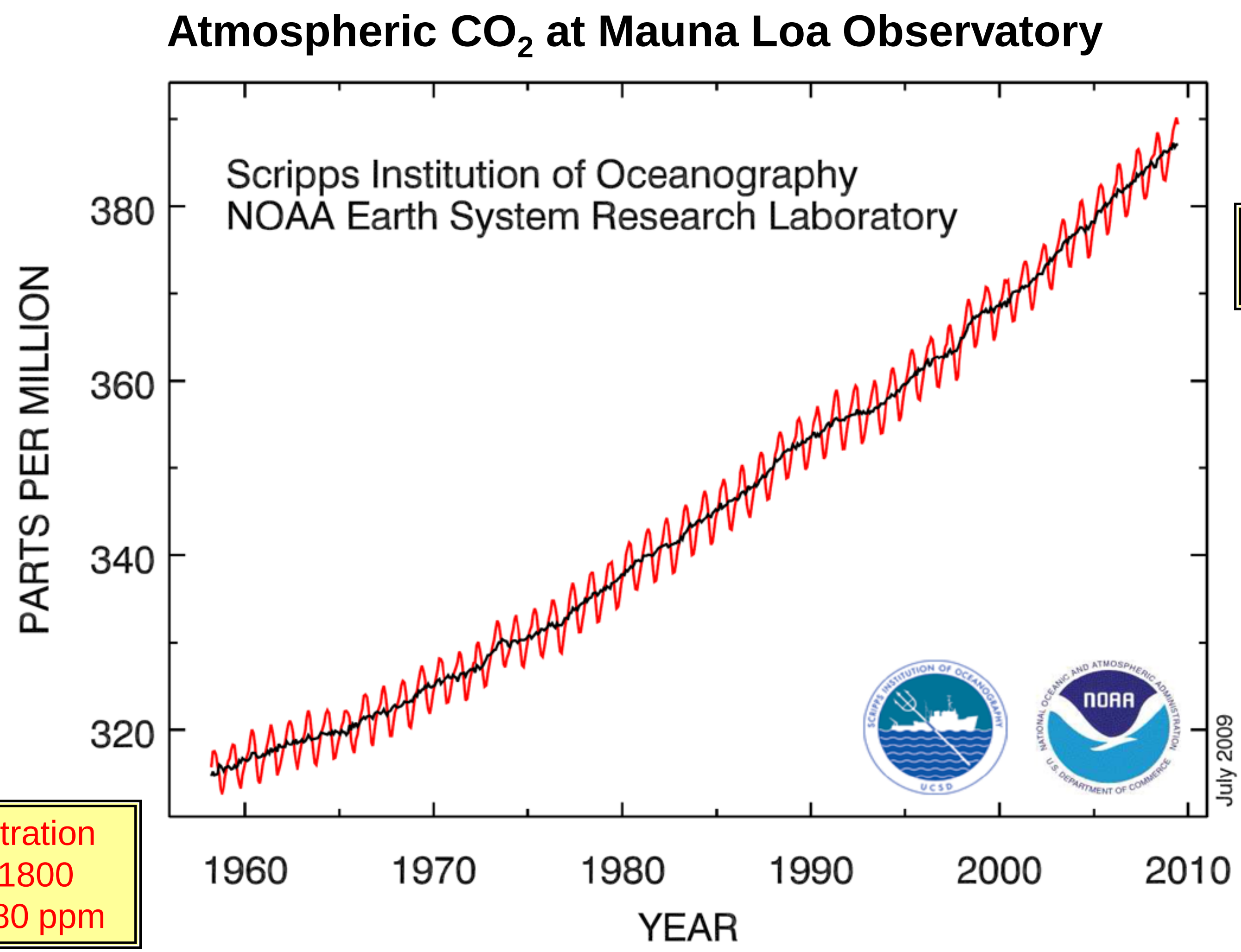
- Reduce energy demand
- Deploy cost-effective low-carbon clean energy technologies at scale
- Promote the development of an efficient, "smart" electricity transmission and distribution network
- Enable responsible domestic production of oil and natural gas
- Create a green workforce

Priority: Climate Change: Position U.S. to lead on climate change policy, technology, and science

- Provide science and technology inputs needed for global climate negotiations
- Develop and deploy technology solutions domestically and globally
- Advance climate science to better understand the human impact on the global environment

Modern CO_2 Concentrations are Increasing

The current concentration is the highest in 800,000 years, as determined by ice core data



Concentration now ~388 ppm

Concentration prior to 1800 was ~280 ppm

Greenland Ice Mass Loss – 2002 to 2009

Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE (Gravity Recovery and Climate Experiment) satellite:

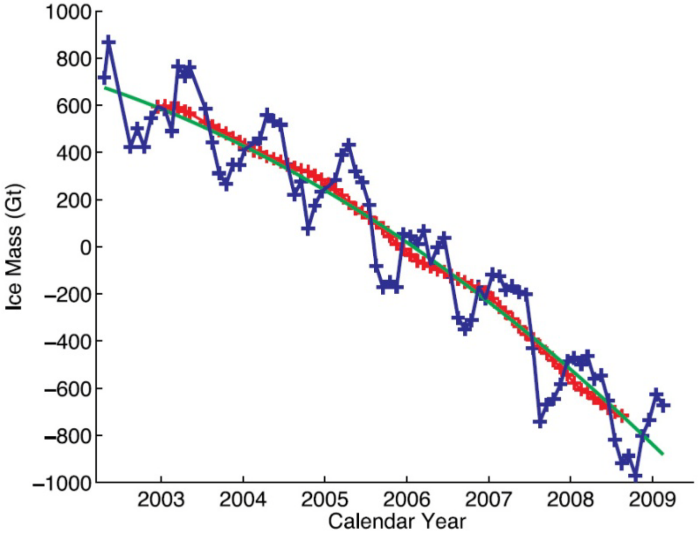
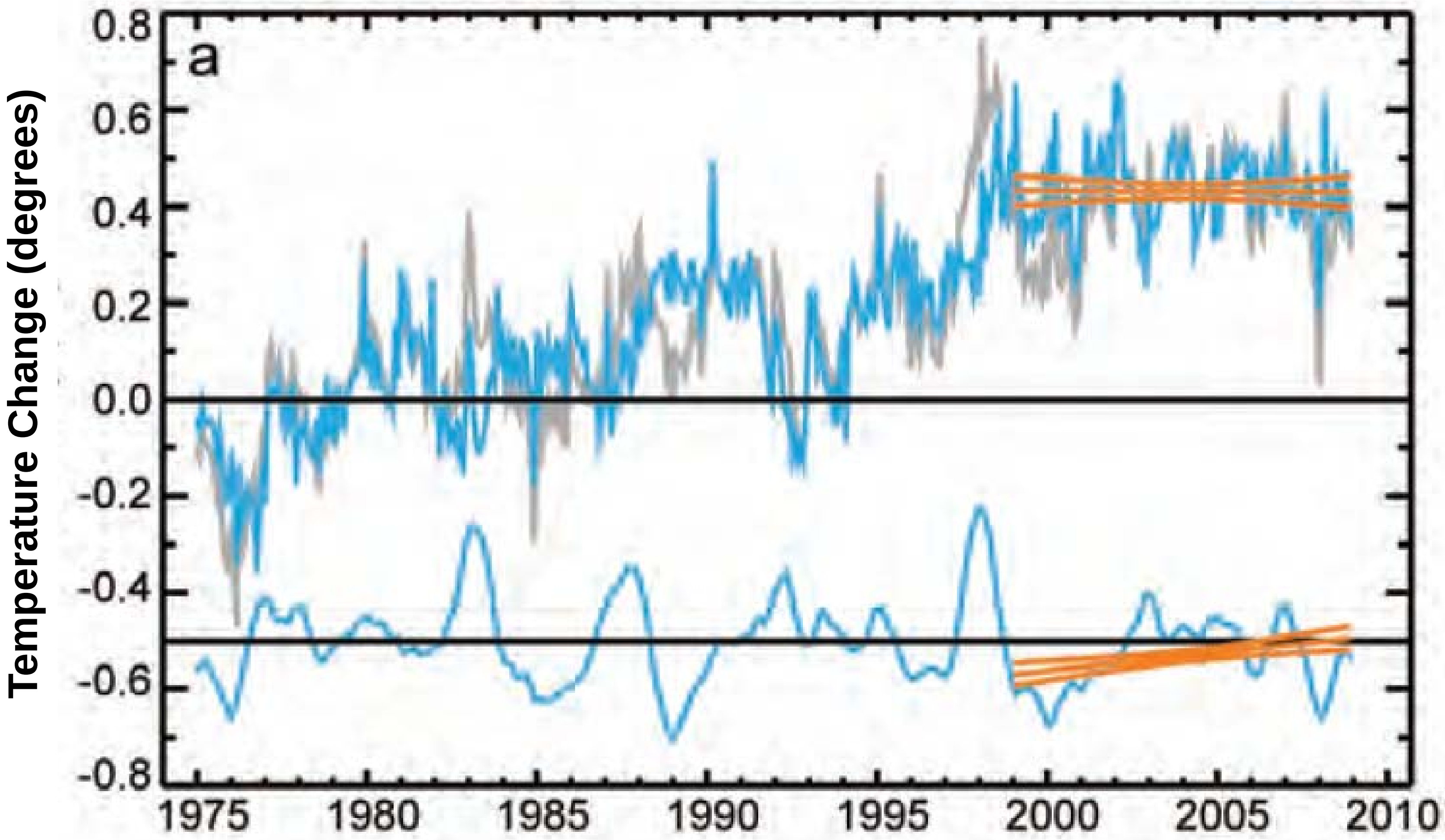


Figure 1. Time series of ice mass changes for the Greenland ice sheet estimated from GRACE monthly mass solutions for the period from April 2002 to February 2009. Unfiltered data are blue crosses. Data filtered for the seasonal dependence using a 13-month window are shown as red crosses. The best-fitting quadratic trend is shown (green line). The GRACE data have been corrected for leakage and GIA.

- In Greenland, the mass loss increased from 137 Gt/yr in 2002–2003 to 286 Gt/yr in 2007–2009
- In Antarctica, the mass loss increased from 104 Gt/yr in 2002–2006 to 246 Gt/yr in 2006–2009

I. Velicogna, GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L19503, doi:10.1029/2009GL040222, 2009

Accounting for Stagnation of Global Average Temperature: The Role of Climate Model Variability



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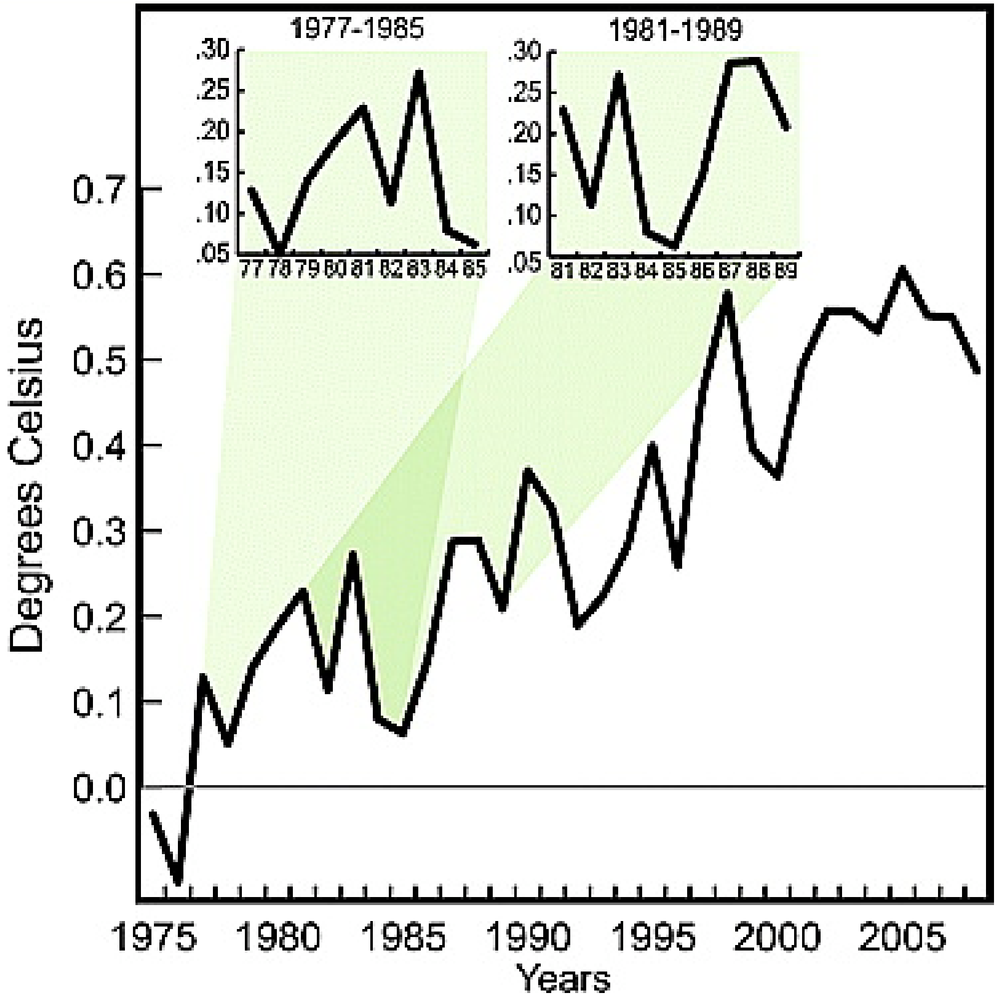

1977-1985
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77 78 79 80 81 82 83 84 85
1981-1989
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.20
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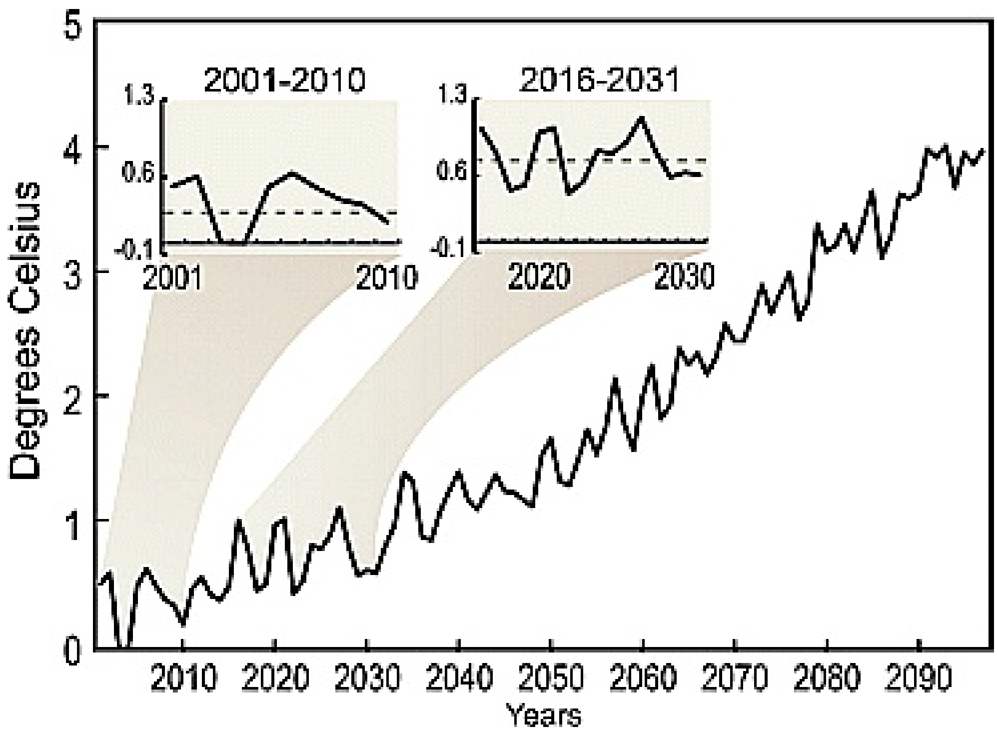
Degrees Celsius
1975 1980 1985 1990 1995 2000 2005
Years



Degrees Celsius
Years
2001-2010
2016-2031

Tackling Energy Challenges

Examples of Key Science Challenges:

- Biofuels and Microbes
- Solar PV and Fuels
- Advanced Fission and Fusion Energy Systems
- Electrical Energy Storage
- Carbon Capture and Sequestration

The DOE Bioenergy Research Centers

Revolutionizing Discovery of Future Energy Solutions

- New paradigm for research—single focus, multi-disciplinary, team-based science
- Transformational science
- Building on DOE's investments in user facilities and fundamental research programs
- Focus on
  - Feedstock characterization & development
  - Feedstock deconstruction
  - Feedstock conversion to liquid fuels

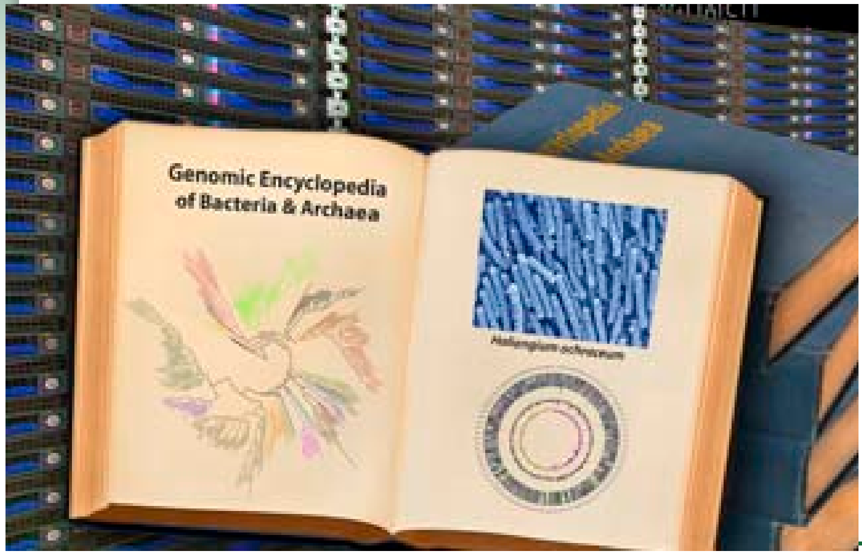
jbei Joint BioEnergy Institute

GLBRC Great Lakes Bioenergy Research Center

BESC BioEnergy Science Center

Studying the Blueprint: Genome Sequencing of Carbon Cycling Microbes

The DOE Joint Genome Institute (JGI) is sequencing a broad array of bacteria, fungi, and microbial communities that mediate major carbon cycle processes



Led by JGI, the Global Encyclopedia of Bacteria and Archaea (GEBA) Project catalogues broad genomic diversity of microbes, providing new insights into functional properties of organisms in the environment and their evolution and adaptation.

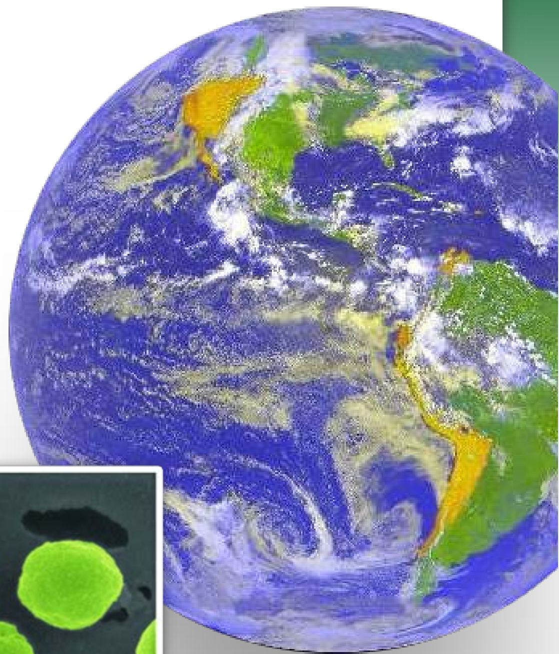
Microbes and Global Climate

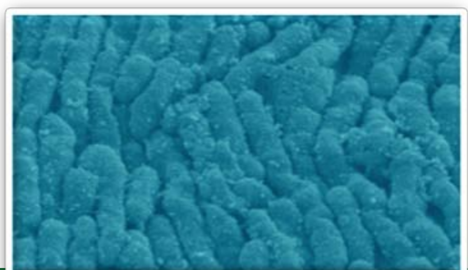
In terms of both numbers and total biomass, microbes are the dominant form of life on Earth.

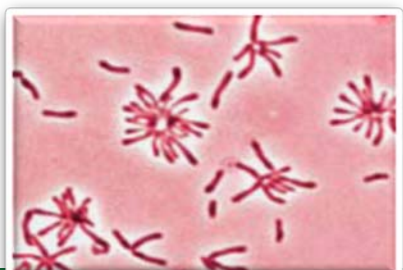
Photosynthesis and decomposition by microbes are major drivers of the global carbon cycle, which in turn regulates atmospheric CO_2 concentrations.

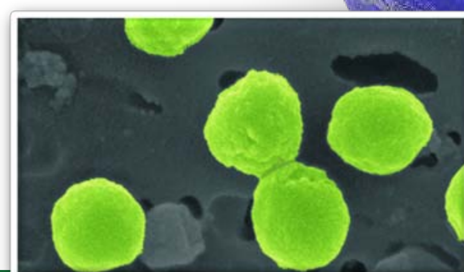
We still understand very little about:

- The diversity of microbes that mediate major global biogeochemical processes
- The full array of microbial metabolic processes that influence carbon cycling
- How the rate and magnitude of these processes will be affected by climate change









Genomic Sequencing of Microbes leads to Enzyme Discovery for Biofuel Production

Leaf-Cutting Ant Symbionts

Tropical Forest Soils

Terrestrial Hot Springs

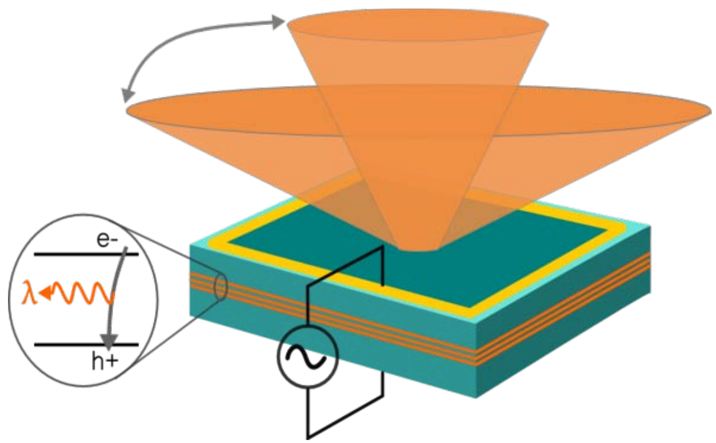
Wood-Degrading Fungi

Termite Symbionts

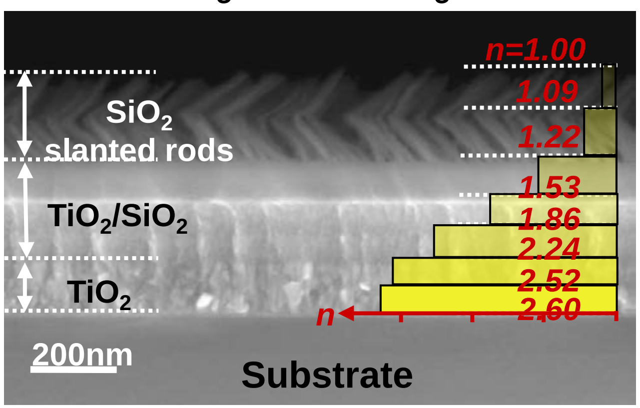
Sequencing of the genomes of microbial communities from environments with high rates of biomass degradation has led to discovery of more efficient enzymes for the deconstruction of biomass for biofuel production.

Solar Cells

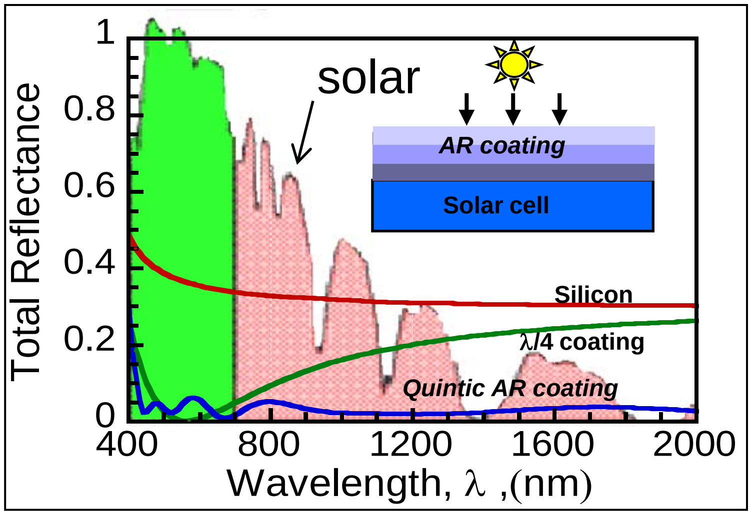
Fundamental Photon Management to Achieve a Near-Perfect Antireflection Coating - the Darkest Matter Ever



Molding the flow of light: a novel photonic design for antireflection coatings for multiple wavelengths and light incident angles



SEM Image of a 7-layer graded anti-reflection coating structure



Scientific Accomplishments/ Energy Impacts

- A new architectural design for antireflection coating that solves, for the first time, both the multiple wavelength and incident light angles critical for efficient solar collection.
- The multi-layer nanostructure can produce a >20% solar efficiency enhancement and is universally applicable to many type of solar cells, including Si, III-V and organic cells.

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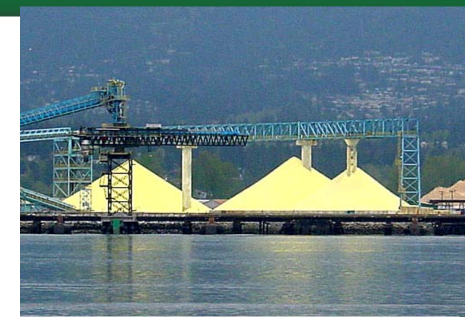
(Kuo and Lin et. al. *Optics Letters,* Nov. 2008)

Shawn-Yu Lin, RPI

Fundamental studies of unconventional sulfide semiconductors for cost-effective and environmentally-benign thin film photovoltaics

Thin film photovoltaics: efficient and cost-effective

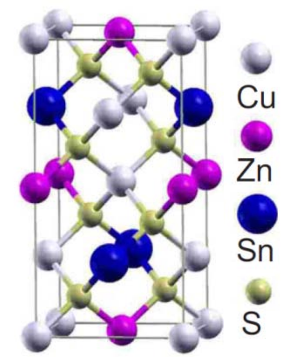
- First Solar: production CdTe modules at $0.96/W_p
- Thin film ~50% of all PV modules sold in 2009
- NREL: $CuIn_{1-x}Ga_xSe_2$ (CIGS) cells η=20% efficiency
- Electronic defects govern efficiency



Semiconductors of benign commodity elements Cu_2ZnSnS_4 (CZTS) and $Cu_2Si_{1-x}Sn_xS_3$ (CSTS) may allow unhindered scale-up to >GW_p/yr photovoltaic manufacturing

Current research focuses on CZTS & CSTS thin film synthesis & defect studies

- Chemical derivatives of CIGS, similar electronic & crystal structures
  - CSTS: no prior thin film growth
  - CZTS: 6.7% efficient cells to date (Katagiri group)
- Electronic effects of intrinsic point defects unknown
  - CIGS: Defects are electronically benign allowing η=20%
  - Are CZTS & CSTS similar?



Leaner and Cheaper, *The Economist* 10/22/09; Bär et al., *APL 052106* (2009); www.firstsolar.com
Wadia et al., Environ. Sci. Tech. **43** 2072 (2009); Chen et al., APL **94** 041903 (2009);
Raulot et al., JPCS **66** 2019 (2005); Zhang et al., PRB 57 9642 (1998)

Solar Fuels

Prospects for Solar Fuels Production

Two Limits

What we can do today:

$12/kg H_2 @ $3/pW PV
(BRN on SEU 2005)

PV cell

balance of system

current

electrolyzer

gas

fuel storage

H_2 compression

High capital costs

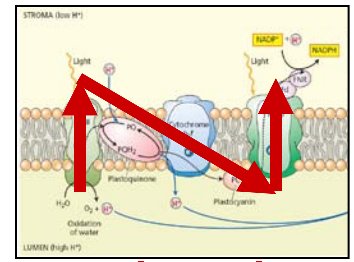
We do not know how to produce fuels in a cost effective manner.

Low capital costs

Chemists do not yet know how to photoproduce O_2, H_2, reduce CO_2, or oxidize H_2O on the scale we need.

Ultimate goal:

solar microcatalytic energy conversion



liquid

fuel storage

gas

fuel storage

compression

Energy Innovation Hub – Fuels from Sunlight

Part of a significant new DOE initiative - one of three Hubs funded at $22M each in the FY 2010 appropriation.

Key Dates:

- **December 22, 2009: Funding Opportunity Announcement (FOA) issued**
- **January 29, 2010: Letters of intent due (but not required)**
- **March 29, 2010: Full applications due**
- **June, 2010: Award announcement**
- **August 2010: Award initiation**

The objective of the Fuels from Sunlight Hub is to develop an effective solar energy to chemical fuel conversion system. The system should operate at an overall efficiency and produce fuel of sufficient energy content to enable transition from bench-top discovery to proof-of-concept prototyping.

For information on DOE Energy Innovation Hubs see: http://www.hubs.energy.gov/

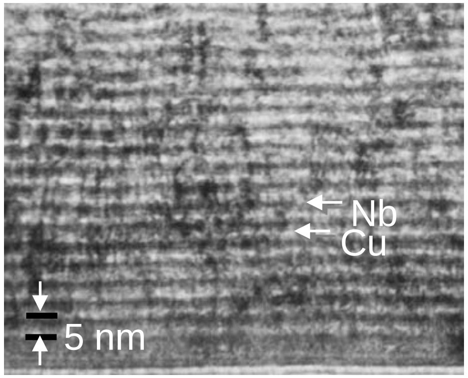
Advanced Fission & Fusion Energy Systems

Materials Science for Advanced Fission & Fusion Energy

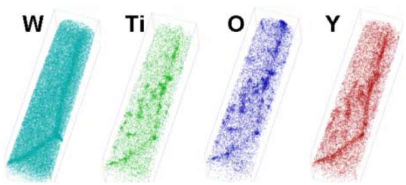
- Materials performance at high temperatures: Advanced fission and fusion reactors will operate at much higher temperatures than typical operating ranges of most materials today. High temperatures are known to degrade strength over long time periods, especially when combined with other extreme conditions.
- Neutron exposure: Materials have to be able to withstand fluences of ~ 100 atomic displacements due to neutron bombardment without severe degradation of physical, functional, and mechanical properties.
- Interfaces with harsh environments are common in current and advanced reactors. Interactions with high-temperature gases and plasmas, liquid metals and steam are all potentially detrimental to the long-term behavior of materials.
- New FY 2009 BES research on these issues includes three Energy Frontier Research Centers at $9.6M/yr and $2.6M/yr for new core projects.

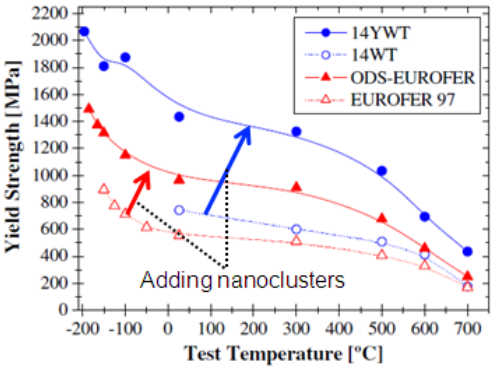
Nanostructured Materials for Strength and Radiation Resistance

5 nm multilayer structures of Cu-Nb exhibit high strength and resistance to radiation damage



En-Gang Fu et al., *Mat. Sci and Eng. A*, 493, 283 (2008)





Stable nanoclusters (~2-4 nm in size) are found in ferritic alloys prepared by mechanical alloying and serve to increase strength even after long times at high temperatures

Xu et al, *Phys Rev. B*, 79 (2) 020204 (2009)

- **Materials with nano-scale features such as multi-layers (e.g. Cu-Nb) or oxide-based nanoclusters have been found to posses remarkable strength, even at high temperatures, and resist changes due to radiation far better than their conventional counterparts.**

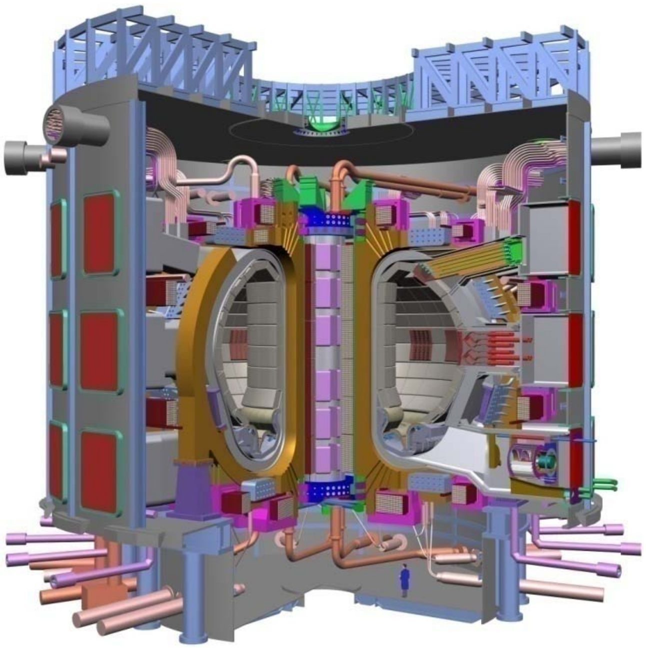
- **Research is ongoing to better understand how interfaces can lead to these improvements, which may result in structural materials that retain their properties in the extreme environments found in advanced nuclear energy systems.**

Fusion Energy: Controlling the Burning Plasma State

- **Burning plasmas**: Energy released by fusion exceeds the energy required to heat and control it: The required basis of any future fusion reactor.

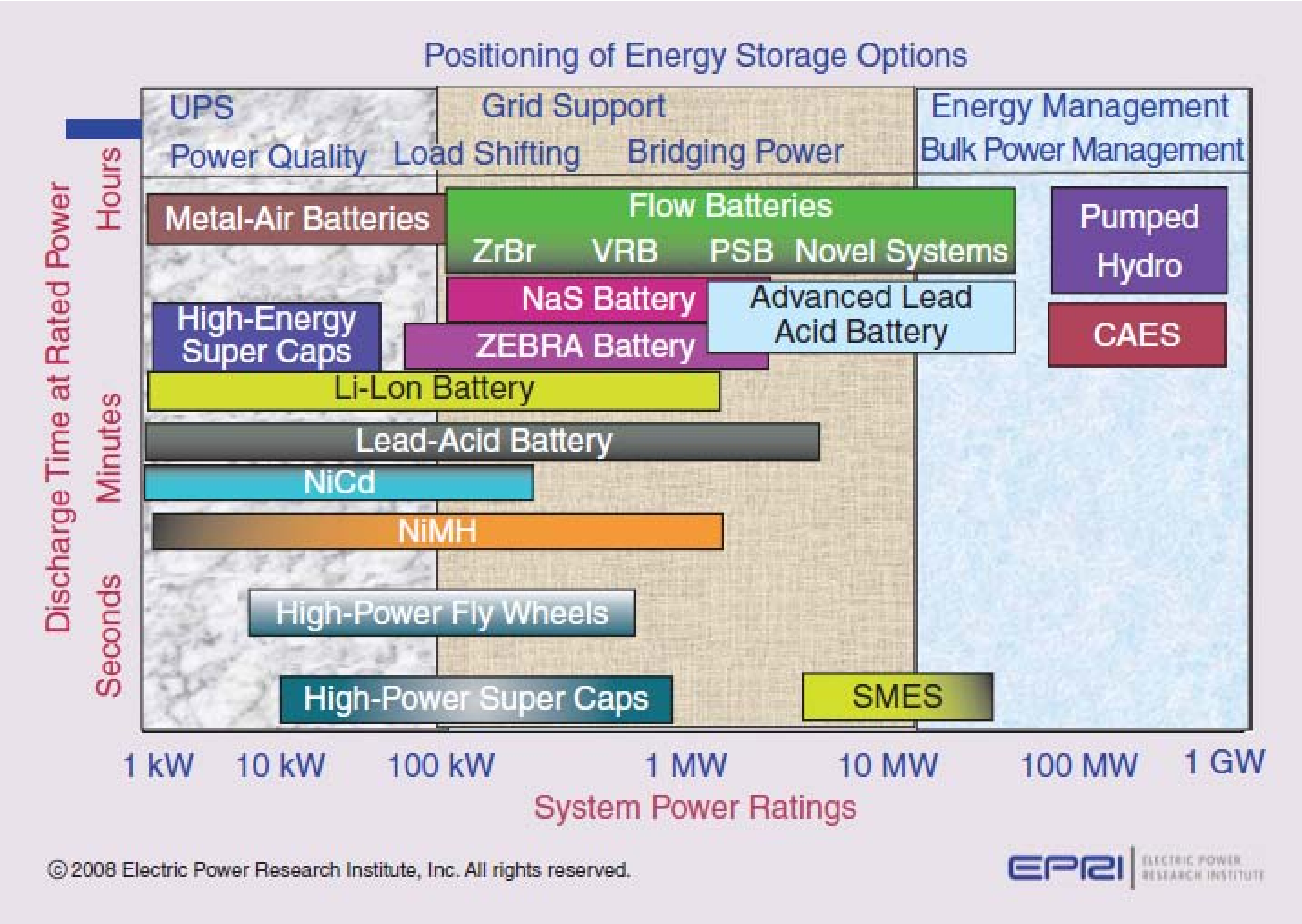
- **Science critical to fusion energy**: The nonlinear physics of a self-heated plasma: Developing a robust and predictable approach to controlling the dynamics of this plasma state.

- **Leading research tools**: ITER, an international project being built in Cadarache, France, will create the world's first sustained burning plasma in the 2020's. The U.S. magnetic fusion science program supports burning plasma research: scaled ITER simulation experiments, ITER design, fundamental understanding of the underlying plasma state.



Electrical Energy Storage

Energy Storage Challenges for the Grid and Transportation Applications



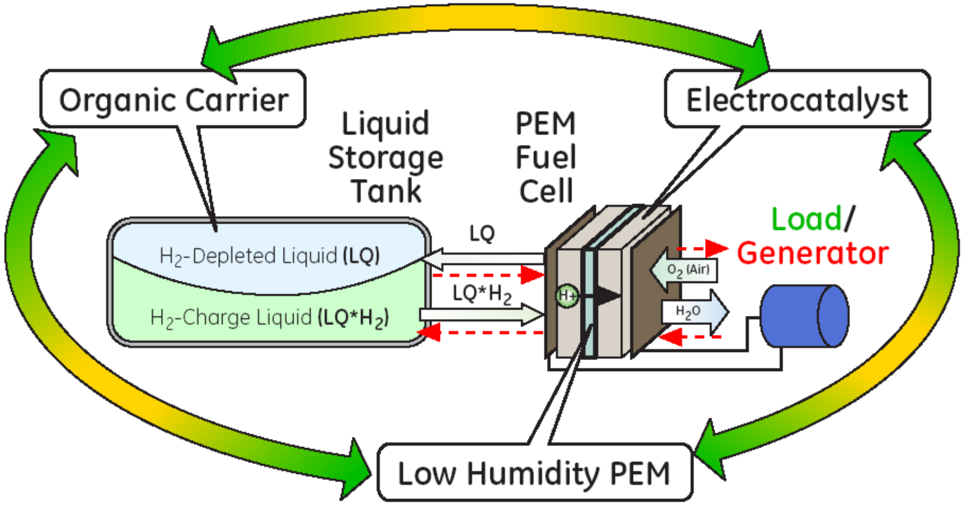
Consumer → Transportation → Grid Management

Basic Research in Electrical Energy Storage Leads to a Broad Range of Applications

- BES-sponsored basic research initiated at MIT over a decade ago led to the discovery of a new nanostructured cathode material for battery applications.
- Based on the knowledge gained, the faculty member founded a high-tech start-up company, A123 Systems in Watertown, MA, to commercialize this new battery technology.
- The development was further supported by a DOE SC SBIR starting in 2002 and by a grant from the DOE Office of Energy Efficiency and Renewable Energy starting in 2006.
- Within the last several years, the A123Systems' batteries reached the commercial marketplace in power tools, hybrid and plug-in hybrid electric vehicles, and grid-related applications.

Center for Electrocatalysis, Transport Phenomena, and Materials for Innovative Energy Storage
Dr. Grigorii Soloveichik (GE Global Research)

Electrocatalysis, transport phenomena and membrane-materials research aimed to three novel components of an entirely new high-density energy storage system combining the best properties of a fuel cell and a flow battery: organic carriers, electro(de)hydrogenation catalysts, and compatible proton exchange membrane (PEM) fuel cells.



RESEARCH PLAN AND DIRECTIONS

Challenges: - Effective electrocatalysts for (de)hydrogenation of organic carriers
- Transport of protons and electrons
- Compatibility of cell components

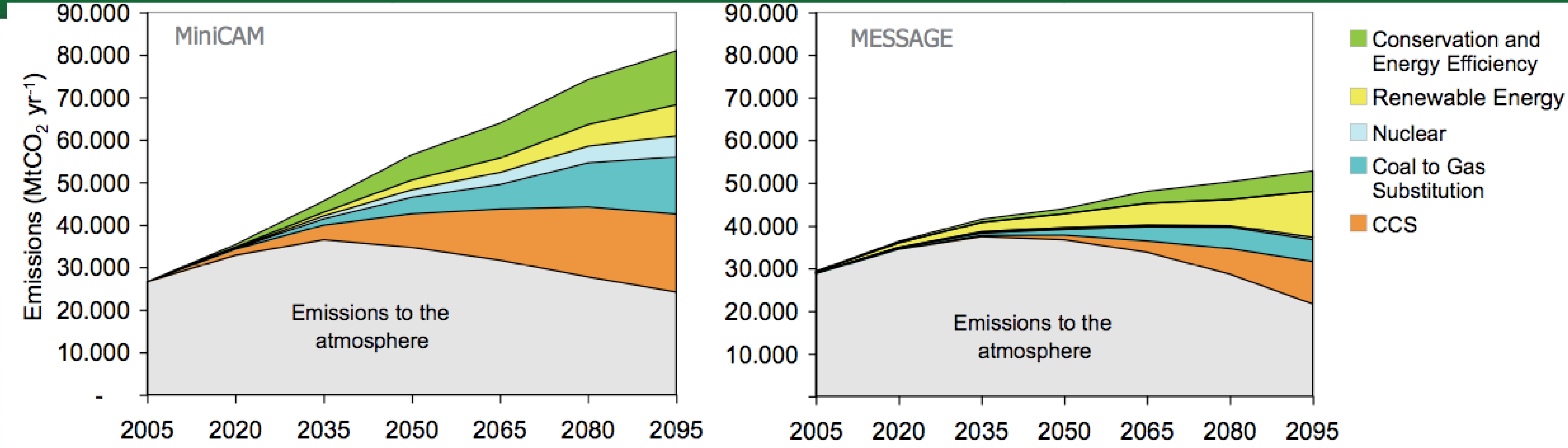
Approach: Combination of modeling, synthetic chemistry and electrochemistry

Unique Aspects: Using PEM fuel cell with organic carriers instead hydrogen gas

Potential Outcome: High-density mobile and stationary energy storage systems

Carbon Capture and Sequestration

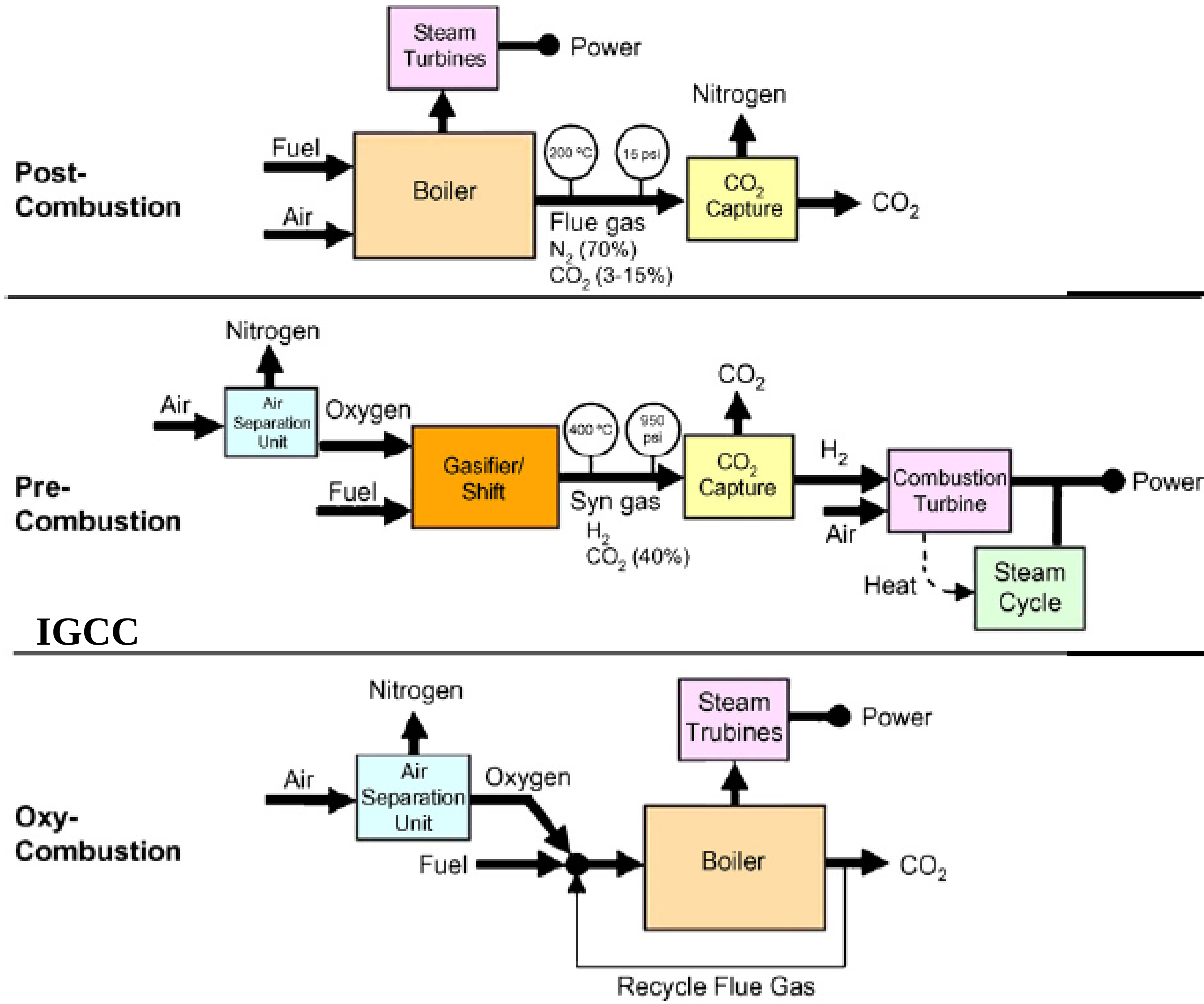
Carbon Capture and Sequestration



Two scenarios for reducing carbon dioxide emissions to keep atmospheric concentrations at 450-750 ppmv. Left: high-emission scenario, where nuclear plays an important role. Right low-emission scenario. In both cases, carbon capture and storage (CCS) – the orange wedge - plays a critical role. (IPCC report, 2007)

- Continued use of fossil fuel while capping the atmospheric concentration of carbon dioxide to about double the pre-industrial level requires the sequestration of ~10 GT of CO_2 per year.
- Current technologies for the post-combustion capture of CO_2 are too expensive.
- “Underground” as a long-term storage container
  - Advantages: Enormous volume; distance from subsurface environment; pre-made container
  - Disadvantages: Designed by nature, only approximately fits the design criteria for containment; complex materials and processes; difficult to see and monitor; uncertainty about long-term performance

Today's Carbon Capture Options



Challenges

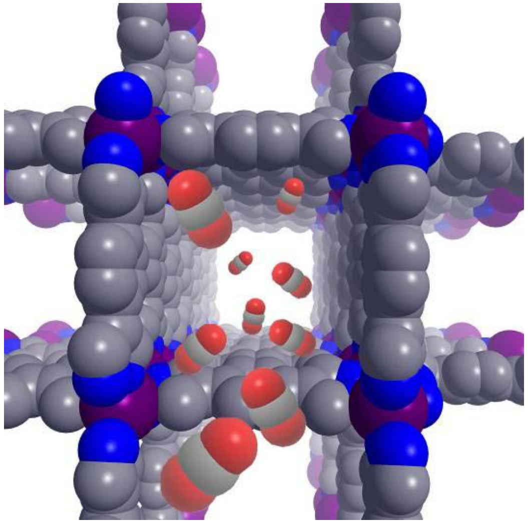
- Low CO_2 Concentration
- High energy for regeneration

- Mostly new plants
- Oxygen production – Air Separation Units (ASUs) have high electricity cost (chemical looping, ITMs)

- ASUs consume considerable energy
- Expense - corrosion resistant materials

INTERNATIONAL JOURNAL OF GREENHOUSE GAS CONTROL 2 (2008) 9–20

EFRC: Center for Gas Separations Relevant to Clean Energy Technologies -- Berend Smit (UC Berkeley)

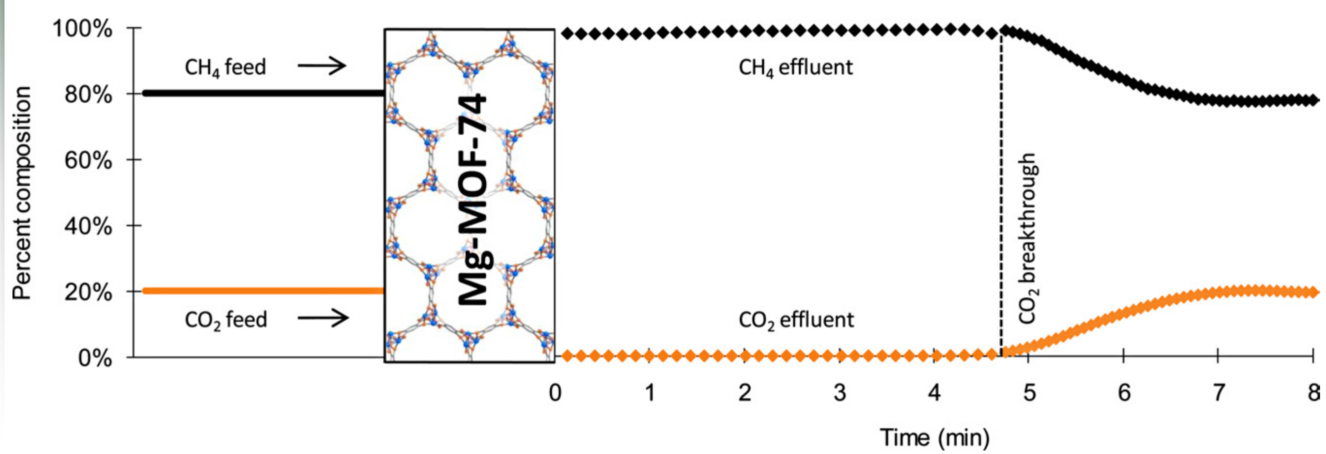


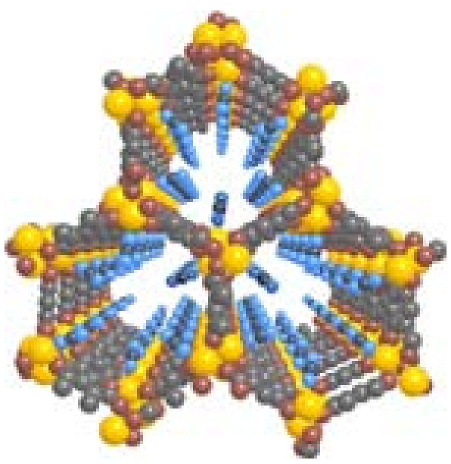
This EFRC will develop new strategies and materials that allow for energy efficient selective capture or separation of CO_2 from gas mixtures based on molecule-specific chemical interactions.

New Materials May Aid in Capturing Carbon Dioxide
Omar Yaghi, UCLA

Metal-organic frameworks (MOFs) act as “crystalline sponges” and show promise at reducing the energy penalty for CO_2 capture.

A new magnesium-based MOF is selective in capturing CO_2 in the presence of CH_4 and releases the stored CO_2 at temperatures much lower than current capture media.





Schematic structure of Mg-MOF-74

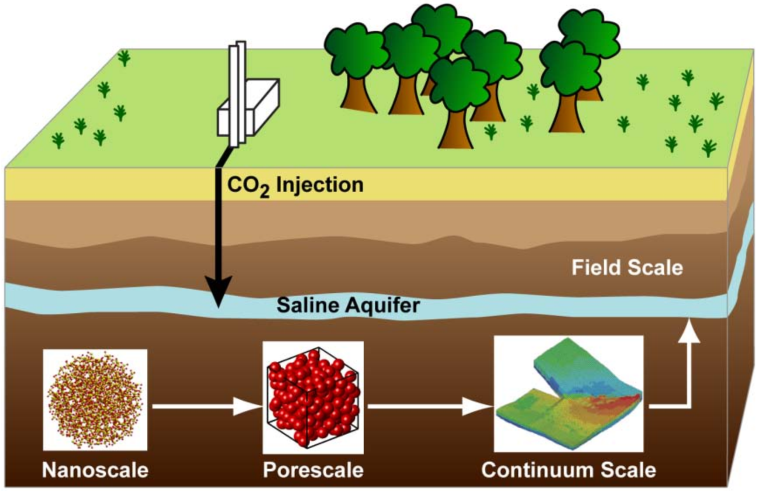
D. Britt, H. Furukawa, B. Wang, and O. M. Yaghi, PNAS 106, 20637 (2009); also featured in N.Y. Times on Dec. 8, 2009.

Geological CO_2 Sequestration

Geological Carbon Dioxide Sequestration is the deep well injection of supercritical CO_2 into porous rock formations for permanent disposal. This process initially displaces *in situ* aqueous fluid. Subsequently, the CO_2 buoyantly migrates slowly through the pores, breaking up into immobile bubbles, dissolving within the fluid, or reacting with minerals to form solid phases.

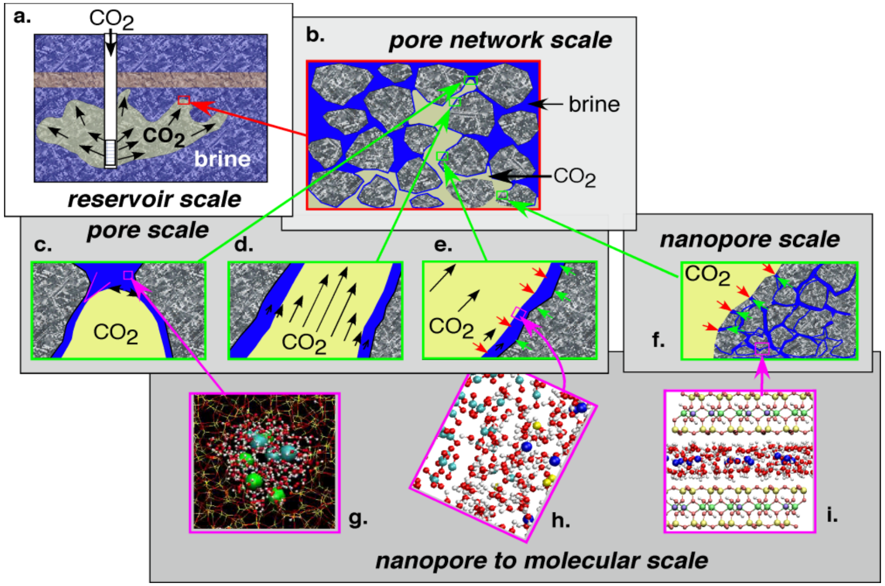
Prediction of CO_2 Sequestration effectiveness depends on understanding:
- Reactive fluid flow properties of multiphase fluids under reservoir conditions in porous and fractured media
- Geochemical stability of mineral phases within deep formations
- Improved geophysical imaging of reservoir-scale properties to track changing reservoir dynamics over long periods of time

EFRC: Center for Frontiers of Subsurface Energy Security
Gary. A. Pope (The University of Texas)



Summary statement: Our goal is scientific understanding of subsurface physical, chemical and biological processes from very small to very large scale so that we can predict the behavior of CO_2 and other byproducts of energy production that may need to be stored in the subsurface.

EFRC: Nanoscale Controls on Geologic CO_2 -- Donald J. DePaolo (LBNL)



OBJECTIVES are to (1) develop molecular, nano-scale, and pore network scale approaches for controlling flow, dissolution, and precipitation in subsurface rock formations during emplacement of supercritical CO_2; and (2) achieve a new level of prediction of long-term performance