5.0 ENHANCING CAPABILITIES TO MEASURE AND MONITOR EMISSIONS

5.1 HIERARCHICAL MM OBSERVATION SYSTEM

Technology Description

Introduction

- The primary focus of measuring and monitoring (MM) is to develop technologies for the measuring and monitoring of gross and net CO_2 and other GHG emission and sinks. MM must be a component of each mitigation technology option to assure that ***net*** emission reduction is occurring and that the integrity of sinks is verifiable. Measures of performance within each mitigation option, which are quantifiable and support evaluation of progress and possible future financial transactions, must be developed.
- Technology-specific profiles have been developed; but, in addition, there will be new sensor and controls needed to help each mitigation technology improve its performance – those are addressed in those sections.
- An effective MM capability will require a hierarchical structure that can address scales from in situ soil carbon measurements, to emissions from vehicles, to large point sources, and area sources ranging from a landfill to large spatial regions (up to countries).
- Assuring integrity of sinks is another key component of the system. As sequestration (all methods) is implemented, quantitative changes and leakage rates (<<1%?) must be verifiable or else leaks alone could result in emissions exceeding those of today.
- There is significant connection between observations and modeling related to emissions, sinks, and carbon stocks, and climate change mediated biogeochemical feedbacks that will be accomplished with the CCSP and the MM portion of the Climate Change Technology Program (CCTP). CCTP will utilize the Climate Change Science Program (CCSP) advances to the maximum extent.

System Concepts

- Sensors and associated information technology systems that provide an ability to determine carbon stocks, emissions, and sinks in a nested approach that can integrate point source information (e.g., leakage from geologic repository) with regional measurements or indicators of all GHG emissions to allow analysis at the scale-up to countries.
- Systems must be designed to be additive and comparable so that information from one "layer" is verified and used by the next layer. It is probable that some locations will be needed as validation sites to illustrate MM approaches. These sites will have intensive measurement at the ground-based scale and thus verify the ability of remotely sensed systems to accurately estimate carbon stocks and fluxes.
- Integrated MM measures will provide needed data for calculating net CO_2 and other GHG emissions per unit of economic activity.

Representative Technologies

- Inventory reporting methods and emissions factors for activities that provide for full life-cycle accounting of net CO_2 and other GHG inventories, emissions, and sinks.
- Platforms include satellites, buoys, aircraft, ground-based networks, and global arrays, which can house the typically broad spectrum of sensors.
- Innovative chemical or isotopic markers to track sources and sinks at the process level detail that would facilitate regional tracking of GHG emissions.
- Sensors include such items as continuous emission monitors, laser-based technologies (e.g., LIBS), mass spectrometers, lidar, radar, imaging spectroscopy, etc.
- Data technologies include networked transmission (wired and wireless), data archiving technology, and computational platforms for distribution and analysis.

Technology Status/Applications

- Emergence of new sensing technologies – e.g., chemical, laser, infrared, radar, light detecting and ranging (LIDAR), multispectral video, imaging spectrometers, mass spectrometers – and computing power capable of handling large amounts of data has spawned a new generation of instruments, databases, and computer models that can be adapted to MM challenges. However, integrated systems of data collection, management, and processing at the scale needed for MM do not exist.

- NASA's Aura, Aqua, and Terra satellites (part of the Earth Science Enterprise mission) host a suite of scientific instruments that measure atmospheric trace gases, including ozone, aerosols, and greenhouse gases. These instruments are already delivering useful data on aerosols, water clouds, methane, and carbon monoxide. Future missions, e.g., Glory, will continue to enhance the data record of aerosols, clouds, solar irradiance, and other GHGs.
- NASA's Orbiting Carbon Observatory, to be launched in late 2007, is designed to map atmospheric CO_2 on a global basis.
- Simultaneous, high-precision measurements of O_2 and CO_2 and isotopes for estimating the role of various processes within the carbon cycle at regional scales.
- Soil carbon analysis instruments are under development, but not ready for deployment.
- Area-scale CO_2 flux measurement systems are available and under improvement.
- Continuous emission monitors (CEM) are available, but remain too expensive for full deployment and are not linked to data systems to be effective.
- Satellite- and aircraft-based sensors for estimating biomass have been demonstrated and are being improved.

Current Research, Development, and Demonstration

RD&D Goals

- Develop an integrated system that meshes observations (and estimations) from point sources (e.g., power plant or geologic storage site), diffuse sources (e.g., from commercial and agricultural systems), regional sources (e.g., city/county), and national scales so that checks and balances up and down these scales can be accomplished. The system should be able to attribute emissions/sinks to both national level activities and individual/corporate activities and provide verification for reporting activities.
- Inexpensive and easily deployed sensors for a variety of applications (stack emissions, N_2O emissions across agricultural systems, CO_2 fluxes across forested regions, CO_2 and other GHG emissions from transportation vehicles.
- Accurate "rules-of-thumb" (reporting/accounting rules) for practices that reduce emissions or increase sinks where comprehensive and accurate measurement is not feasible. Such rules must be based on sound scientific principles.
- A high-resolution system that captures process-level details of sources and sinks (e.g. O_2 or CO_2, isotopes) and a methodology to scale it up reliably.
- Data archiving and analysis system-to-integration observations and reporting information.

RD&D Challenges

- Alter current remotely based sensors (satellite and aircraft) from a focus on measuring atmospheric constituents to a focus of measuring CO_2 and other GHG stocks and net fluxes.
- Ground-based biomass and soil carbon measurement methods that are rapid, inexpensive, and accurate – and can address heterogeneity issues.
- Methods to detect leakage rates from geological storage systems that may be small and may be highly variable over space and time.
- Methods to measure ocean CO_2 sinks and leakage rates.
- Sensors that could be placed on individual emission sources (e.g., stack or vehicle exhaust) to provide data for new or modified MM technologies to aid emissions reduction by energy production systems.
- Development of specific sensors, and their application to vertical integration of net emissions across all scales.
- Formalized data and information systems that capture and distribute data, and that provide protocols for reporting results.
- Framework under which measuring and monitoring are linked in a functional manner – and also work within a regulatory system for carbon credits or incentives.
- Simultaneous measurements of many chemical/isotopic variables to capture process details.
- Explore the use of current remotely based sensors (satellite and aircraft) for measuring CO_2 and other GHG stocks and net fluxes.

RD&D Activities

- Scientific research on climate and the carbon cycle are resulting in new sensors and methods to estimate stocks and fluxes.
- Newly funded R&D on sequestration options is resulting in new measurements systems for net ecosystem exchange of carbon, soil carbon and biomass changes, leakage indicators from geological systems, and ocean CO_2 exchange methods.
- Geophysical methods to determine integrity of geologic storage systems are under development and can be tested as large-scale demonstrations come on-line.
- By 2010-2012, current plans will deploy satellites capable of measuring greenhouse gases in columnar samples of the atmosphere. With focused development and data-handling systems, such a sampling regime could be used to estimate a region's or nation's emissions. The Integrated Earth Observation System (IEOS) will facilitate these developments.

Recent Progress

- Ongoing demonstrations of geologic storage systems are helping to define the needs for characterizing particular geological structures and constant monitoring.
- Global networks of greenhouse gas monitoring stations, in conjunction with advanced modeling techniques, have continually improved the understanding of greenhouse gas concentrations.
- Laser-induced breakdown spectroscopy instrument to measure soil carbon in situ for less than 10% of the lab costs of other methods with comparable reliability.
- Mid-range infrared spectroscopy to measure soil carbon and chemical composition.
- Ocean buoys that can measure and transmit data from multiple depths are being used in scientific studies, but are not ready for cost-effective deployment.
- Recent research shows coupling of interannual variability of trace gases (CO_2, CO, and CH_4) and biomass burning. (Van der Werf et al. *Science* Vol 303, Issue 5654, 73-76, 2 January 2004).

Commercialization and Deployment Activities

- Limited application within various technology areas is occurring, but no vertically integrated system is being tested at this time.

5.2 MM FOR ENERGY EFFICIENCY

Technology Description

Introduction

If measuring and monitoring (MM) for energy efficiency must be able to estimate impacts from mitigation actions at the level of corporations or sectors of usage, then MM must have the ability to quantify reductions in emissions at the point of energy usage through measurement or rules-of-thumb. The primary targets are transportation, buildings (commercial and residential), and industrial processes. The MM challenges significantly overlap needs in other technology areas. For example, the challenges in point and diffuse sources MM as part of "Other GHG" applies to energy efficiency, but with a focus on CO_2. The point sources are industrial facilities, while the diffuse sources are primarily vehicles.

System Concepts

- Continuous emission monitors (CEM) for point sources with data transmission and archiving complemented by inventory-based reporting so as to be able to evaluate the success of specific actions to improve efficiency.
- For transportation, the systems could include: (1) testing at point of production and applying assumptions to actual performance, (2) on-board emission sensors with data transmission, and (3) local-scale sensors that function autonomously with data transmission so as to homogenize emissions in an area (must also have sensors to track number/type of vehicles).
- Testing of equipment for residential and commercial usage (appliances, HVAC) at point of production; possibly with future sensors to monitor actual performance with data transmission (used for some installations, not feasible for all homes).
- Testing of equipment for industrial processes (e.g., industrial boilers and furnaces) at point of production; possibly with wireless sensors and data transmission capability.

Representative Technologies

- CEM for CO_2 (linked with energy use statistics at a facility).
- Direct measurement, or indirect measurement via tracer studies, over landscapes (for vehicle emissions); infrared, lidar, etc.
- Test systems at point of production, complemented by testing actual use for some percentage of installed systems.

Technology Status/Applications

- CEM are well developed, but improvements in performance, longevity, autonomous use, and data transmission are needed.
- Local-scale systems generally not available, although concepts are being developed and tested at the research stage (e.g., isotopic indicators of CO_2 sources).
- Testing at point of production well established; methods to track actual performance autonomously not available.

Current Research, Development, and Demonstration

RD&D Goals

- Develop sensors and data transmission systems that allow quantification of emission reductions resulting from energy efficiency improvements.

RD&D Challenges

- Develop CEM that are robust, inexpensive, accurate, and operate autonomously with data transmission.
- Demonstrate tower- or satellite-based sensors to measure CO_2 and other GHG at local scales.
- Data fusion with remotely sensed imagery and Geographic Information Systems (GIS).
- Determine whether tracer/isotopic methods can identify source of CO_2 and other GHG at local-to-regional scales.
- Develop sensors for vehicles and appliances to measure energy use and emissions with data transmission.
- Develop emissions estimates from the combustion of noncommercial fuels (propane, wood, landfill gas).

RD&D Activities
• High-temperature NO_x, O_2, ammonia, and other sensors are under development. • Engine diagnostics and controls. • Fast-response mass spectrometers are being developed. • A field laboratory that uses state-of-the-art FM-AM-LIDAR for remote monitoring of truck emissions (NOX, PM) and engine performance has been established in Knoxville, Tennessee.
Recent Progress
• Examples of new R&D results related to sensors, estimation methods. • Development of robust, wireless sensors and data transmitters for use in high-temperature, caustic industrial environments (e.g., steel mills, pulp and paper industry). • Development of the International Measurement and Verification Protocol for estimating energy savings.
Commercialization and Deployment Activities
• Activities are focused on deployment of new technologies, and measures of performance are typically comparisons of energy used. Limited use of sensors and data transmission directly for MM purposes.

5.3 MM FOR GEOLOGIC CARBON SEQUESTRATION

Technology Description

Introduction

Storing CO_2 in geological reservoirs (oil/gas reservoirs, coal beds, saline formations, etc.) requires that concentrated CO_2 streams be available[1]. These will result from separation and capture at fossil-fuel power plants and advanced concepts such as fuel cell or hydrogen facilities. Methods to fully account for carbon sequestration in these systems will require analysis of energy costs and full GHG accounting for separating, capturing, and transporting CO_2 as well as during the injection to below-ground reservoirs. In addition to direct injection, there are concepts being proposed that involve storage of other carbon sources in deep reservoirs that would promote the generation of CH_4 for energy. These concepts face many of the same challenges as injection and storage of concentrated CO_2 streams. Once stored, the focus is on methods to measure and monitor (MM) for long-term storage or leakage. The challenge is to be able to detect the transport or small releases of carbon dioxide from great depths that may be highly variable in space and time.

System Concepts

- Separation and Capture: Dual focus of (1) methods based on process knowledge to fully account for energy penalties and carbon costs to obtain CO_2 streams and (2) sensors to monitor fugitive emissions around the facility.
- Transportation: Leak detection from pipelines or other transportation systems will include mass balance methods (in/out measurements), pressure transducers, remote detectors, and addition of specific gaseous tracers enabling remote leakage detection.
- Geologic Storage: Multiple approaches will be necessary and include (1) direct detection of surface leakage (probably requires area or remotely sensed approach due to heterogeneity of release pathways), (2) indicators of leakage based on natural and induced tracers, (3) seismic/ electromagnetic (EM)/electrical resistivity (ER)/pressure monitoring networks, (4) intensively monitored validation sites (with those known to be leaky) may be required to confirm monitoring methods. For enhanced oil/gas recovery systems, robust measurements need to be made on both the injected CO_2 and on the produced hydrocarbons to get an accurate carbon change balance because of measurement challenges on gases that are changing pressures/temperatures along their production pathways.

Representative Technologies

- For leak detection from capture/separation, pipelines, and surface leaks from reservoirs there are options within traditional leak-detection technologies, advanced technologies (e.g., hand-held infrared remote imaging spectrometer, portable tracer gas detectors, inexpensive time averaged activated carbon traps for tracer gases), and aircraft or satellite-based sensors for CO_2. Improved leak detection needed in produced hydrocarbon streams as well.
- Indirect indicators for subsurface performance could include (1) observable effects on soil gas compositions and ecosystems (microbial and vegetation systems), although it is likely that changes would be observable only under high leakage rates, (2) deviations from model-predicted biogeochemical conditions of the subsurface fluids using either naturally occurring tracers/indicators or tracers induced during injection that have a well-predicted behavior pattern, (3) geophysical methods (pressure transient tests, seismic, EM, ER, etc.) to detect pressure changes and map migration pathways, (4) altered geochemistry of candidate receptor formations, and (5) detection of added tracers in control sites at various depths and within formation fluids from depth to the near surface.

Technology Status/Applications

- Leak-detection technologies are available but are too labor-intensive for routine use at a global scale.
- Even excellent leak detection technologies currently provide spot measurements over very small parts of very large geographic sampling areas.

[1] The discussion of separation, capture, and transportation of CO_2 here also applies to the option for direct injection of CO_2 into deep ocean regions.

- Time-averaged traps that absorb and retain tracer gases that have been added to the sequestered CO_2 could be readily developed/deployed for quarterly or annual verification procedures.
- Process flow information is evolving that should result in accurate estimates of CO_2 costs associated with capture and separation.

Current Research, Development, and Demonstration

RD&D Goals

- Develop ability to assess the continuing integrity of subsurface reservoirs using integrated system of sensors, indicators, and models.
- Improve leak detection from separation and capture and pipelines systems (many opportunities to take advantage of accomplishments from other technology development efforts).
- Apply remote sensors for other purposes to fugitive emissions from reservoirs and capture facilities.
- Improve/develop/implement tracer addition and monitoring programs.
- Evaluate microbial mechanisms for monitoring and mitigating diffuse, wide-area GHG leakage from geologic formations.
- Determine "acceptable" leakage percentages since dissolution of CO_2 into shallower formation fluids through a "diffusion grating" sequestration horizon enhances sequestration capacities many fold.
- Document dissolution/mineral trapping potential that will remove CO_2 from the formation fluids.

RD&D Challenges

- Low leakage rates occurring at spatially separated locations makes full detection difficult (this applies to both pipelines and reservoirs) likely requiring time averaged detection of added tracers.
- Heterogeneity of leakage pathway and probable alteration over time makes detection and quantification difficult for reservoirs (local vs. large area measurement capability).
- Indicators (e.g., seismic, EM, tracers) need further development for quantitative application or time averaging.
- Null results are expected, but this makes it difficult to "prove" that sample frequency and locations are not missing leak emanations.

RD&D Activities

- Significant efforts are ongoing for separation and capture technology development.
- Demonstration tests for geologic storage are ongoing and planned, which should provide test beds for MM options.
- Seismic testing methods are well-developed for exploration, and can be deployed for evaluating integrity of geologic formations for long-term storage of CO_2.
- Geochemical studies in deep formation environments are investigating the evolution of potential mineral trapping of CO_2.

Recent Progress

- Seismic methods are being used at the Sleipner test to map the location of the injected CO_2 gas phase, but such methods are not capable of aiding mass balance over the long-term performance periods.
- Geophysical methods need to be developed to track supercritical CO_2 in a diffuse (fingered) configuration that will be most typical of extended injection.
- Models, geophysical methods, and tracer indicators are being developed through the GEO-SEQ project.
- Development of innovative coatings for activated carbon particles within beads that may improve passive time-averaged sampling.
- Detection of CO_2 emission from natural reservoirs has been investigated by researchers at the Colorado School of Mines, University of Utah, and the Utah Geological Survey, including attempting isotopic discrimination of biogenic CO_2 from microbial respiration.
- Fundamental research on high-resolution seismic and electromagnetic imaging and on geochemical reactivity of high pCO_2 fluids is ongoing in basic science programs.
- ORNL application of PFT tracer gases to Frio tests and NETL PFT testing at surface during injection (Frio and New Mexico).

Commercialization and Deployment Activities
• Sleipner demonstration ongoing – seismic methods in qualitative mapping of CO_2 volume and integrity of geological formations. • Insala, Algeria, gas field CO_2 reinjection project (similar to Sleipner, but on land) being initiated with MMV a component of the research. • GEO-SEQ field tests at Frio site. • SNL-LANL field tests. • Australian demonstrations. • Canadian demonstration at Weyburn, Saskatchewan, in collaboration with the North Dakota gasification plant. • A system of CO_2 capture and geologic reservoirs has a vast potential for storing CO_2. Demonstrations are in place or planned and offer outstanding opportunities for early development and testing of MM methods, so that wide-scale implementation of the technology will be acceptable to the public in the future.

5.4 MM FOR TERRESTRIAL CARBON SEQUESTRATION

Technology Description

Introduction

Terrestrial ecosystems (forests, pastures, grasslands, croplands, etc.) offer significant near-term and low-cost options to sequester carbon. Of course, such lands also can contribute to emissions through normal operations (e.g., tillage practices, fertilizer use, fires, and pests). Measuring and monitoring (MM) technologies must address both aspects so that a full accounting of changes in carbon stocks and fluxes of CO_2 or other GHG can be determined.

System Concepts

- A hierarchical system will integrate carbon sequestration (CS) measurements of different system components (e.g., soils, ecosystems) and for a range of scales (e.g., plot, landscape, regional) to provide a net accounting of CO_2 (and other GHG) inventories, emissions, and sinks.
- Routine reporting and measurement systems must be complemented with intensive monitoring on multiscale experimental sites to ensure validation of the methods.
- A system for analysis of the large quantities of data must be developed, as data alone will be insufficient to assess changes in stock, emissions, and sinks.

Representative Technologies

- The USDA Forest Service's Forest Inventory and Analysis Program and the Natural Resources Conservation Services' National Resources Inventory provide the underlying data for estimating a national carbon inventory and annual changes in carbon pools for forest, pastures, and croplands.
- Airborne and space-based platforms used to remotely sense land use/cover changes and biomass (e.g., LAI, soil moisture) are in place and are undergoing use and further enhancements and validation via land-based studies.
- Eddy covariance flux towers for area-scale CO_2 flux measurements.
- Laser-induced breakdown spectroscopy for soil carbon analysis for point measurement ($<mm^2$) and neutron-scattering methods for volumetric measurement ($\sim 1\ m^3$).
- A variety of models and decision-support tools for converting observations to information that can be used to implement greenhouse gas stabilization practices are being developed.

Technology Status and Applications

- Imaging, LIDAR, and RADAR remote sensing methods are being developed and tested for 3-D imaging of forest structure. Quantification is lacking and directly coupled, land-based measurements are not able to be easily integrated with remote sensing data.
- Laboratory-based LIBS analysis is calibrated and in testing; rapid, in situ soil carbon measurement systems are under development but not ready for field implementation.
- Eddy covariance flux measurement systems are being developed, but are not ready for deployment with all landscapes and would be difficult to implement at high spatial density.
- Methods and models to process land inventory data for estimating carbon changes and attributing changes to human-caused and natural factors are being revised as more accurate data are provided by recent technologies.
- Testing of nonimaging synthetic aperture radar to estimate forest biomass.

Current Research, Development, and Demonstration

RD&D Goals

- Provide integrated, hierarchical system of ground-based and remote sensing for carbon pools and CO_2 and other GHG flux measurements.
- Reduce uncertainty on regional-to-country scale inventories of carbon stocks.
- Develop low-cost, portable, rapid analysis systems for in situ soil carbon measurements.
- Develop standard estimates that relate management practices to net changes in emissions/sinks over time (e.g., life cycle of wood products, changes in agricultural crop rotations, energy use in ecosystem management, etc.).

RD&D Challenges

- Emission/sink factors for management practices must be based on a more complete understanding and quantification of ecosystem carbon allocation and storage processes.

- The broad range of required scales, cover types, and ecosystems will require the development of (1) remote sensing integrated with other measurements at various levels of coverage, duration, and intensity and (2) low-cost, robust measurement systems that can effectively be used at different scales.
- For such data collection methods to be of value, advanced data distribution, analysis, and simulation tools will be needed for scale-up of site-specific changes in carbon stocks to regional and global estimates. Sites covered need to be expanded as part of extensive monitoring and intensive measurement systems.

RD&D Activities

- The AmeriFlux network is being completed. It will improve our understanding of carbon pools and fluxes in large-scale, long-term monitoring areas and intensive experimental sites.
- Terrestrial carbon process R&D and technology development through the North American Carbon Program (NACP) will result in an understanding of mechanisms of carbon sequestration, and will contribute to the development of standard estimates for applications of carbon management practices.
- Technology for in situ sensors is supported.
- Development of remote sensing platforms and ground-based validation of carbon stocks is underway and should lead to national-scale methods.
- Development of statistically based approaches for regionalizing the United States, based on spatially variable features such as soil, climate, and land-use characteristics.

Recent Progress

- USDA FIA and NRCS program provide information to assess the structure and condition of U.S. forests, croplands, pastures, and grasslands that is then converted to state, regional, and national carbon inventories.
- Prototype soil carbon analysis systems have been developed and are undergoing preliminary field testing.
- Satellite and low-altitude remote sensing technologies have been developed that can quantify agricultural land features at spatial resolution of approximately 0.5 m^2.
- Prototype versions of Web-based tools for estimating carbon budgets for regions.
- Increased accuracy of carbon sequestration estimates related to land management and full carbon accounting.

Commercialization and Deployment Activities

- Forest inventory measurement methods are being deployed at the project scale within the United States and other countries that will allow assessment of costs, utility, and accuracy.
- Tillage and land conservative practices are ongoing and offer test-beds for ground-based and remote sensing methods, as well as verification of rules of thumb for emissions factors.
- Opportunities for software development and support; and for development of models to support reporting under the 1605(b) program.

5.5 MM FOR OCEAN CARBON SEQUESTRATION

Technology Description

Introduction

There are two approaches for carbon sequestration in the ocean – direct injection and fertilization. These require somewhat different measuring and monitoring (MM) strategies. For direct injection, the separation, capture, and transportation of CO_2 must be addressed as well.[2] Sequestering CO_2 in the deep ocean below the main thermocline (depths of >1,000–1,500 m) should result in extended residence times, and the main measure of performance will be quantities of CO_2 injected and then tracking the dispersion of the concentrated CO_2 plume. MM systems are needed to monitor spatial and temporal CO_2 concentration histories. For fertilization strategies, the primary measure of performance will be the quantity of carbon exported deeper in the water column and its longevity. Sensors for direct measure augmented by remotely sensed indicators for the surface ocean and water column will be required.

System Concepts

- Injection: MM systems are needed to provide histories of CO_2 concentration profiles near the injection sites and track the dispersion and potential release of CO_2 to the atmosphere.
- Fertilization: MM systems should address both direct measurements of CO_2 concentration as well as indirect measures of performance that might be easier to accomplish.
- Alternatively, models of ocean circulation and biogeochemistry could be used to provide projections of CO_2 leakage rates and representative small volumes of the ocean would be intensively monitored for validation of model accuracy.

Representative Technologies

- Measurement of comprehensive trace gas parameters [Total CO_2 (TCO_2), Total Alkalinity (TALK), partial pressure of CO_2 (pCO_2), and pH] that represent an amount of CO_2 concentration in seawater (measurement of any two of these four parameters could result in calculation of other pair); extensive use of floats that cover various depths and report data back directly to data handling systems.
- Indirect indicators of fertilization effectiveness may be possible (phytoplankton biomass, pH, particulates, etc) rather than CO_2 measurements; satellite-based sensors may be able to provide quantitative indicators with selective validation via physical measurements.
- CO_2 sensors that "track" the dissolved CO_2 plume from injection locations.

Technology Status/Applications

- Extensive use of floats and buoys is ongoing for studies of the carbon cycle, but these are expensive and ship-intensive.
- Determining CO_2 concentration via comprehensive measurement is ongoing, but costs and complexity are prohibitive from an MM viewpoint.

Current Research, Development, and Demonstration

RD&D Goals

- Develop integrated MM concepts that include direct measurement, model analysis, and indirect indicators that can be used across the scales needed to verify process information and ocean-wide observations.
- Data transmission and analysis systems that avoid expensive ship time.
- Quantitative satellite-based sensors for surface ocean indicators of sequestration effectiveness.
- Determine whether direct measurement of plume dispersion or model analysis with selective validation is needed for direct injection MM.

RD&D Challenges

- Development and testing of robust sensors working at the pressure of deep oceans are still needed.
- Develop the ability to track the fate of direct injected CO_2.

[2] MM strategies for separation, capture, and transport of CO2 are addressed in technology Profile 5.3 MM for Geologic Carbon Sequestration.

- Develop sensors to provide robust measurements of CO_2, and other species introduced by impurities with CO_2 in seawater under a range of temperature and pressure conditions, from the deep ocean to the surface.
- Calibrate and test the sensors using the inter-comparison with proven equipment method in the laboratory and at sea conditions.
- Reduce uncertainty in measurements.
- Develop the ability to transfer measurements via satellite systems to centralized data collecting stations.

RD&D Activities

- For more than 10 years (1990-2000) the U.S. DOE and NOAA have sponsored the ocean carbon dioxide survey during the World Ocean Circulation Experiment (WOCE), monitoring the carbon concentration in the Indian, Pacific, and Atlantic oceans from the research oceanographic ships. The global WOCE carbon data set includes ~23,000 oceanographic stations.
- Low-cost discrete measurement sensors are under development. These sensors will be used in conjunction with the conductivity, temperature, depth (CTD), and oxygen sensors to measure the ocean profile on oceanographic stations.
- Development of floats with CO_2 sensors (SOLO) is underway through the NOPP program.
- Remote sensors are being developed to measure indicators of CO_2 parameters.

Recent Progress

- MBARI has demonstrated the ability to inject and monitor via video camera and other sensors at depths; the challenge is to develop these into routine sensor systems.
- Experimental facilities for testing sensors in simulated seawater at representative pressure and temperature are available at ORNL.

Commercialization and Deployment Activities

- Total CO_2 is measured worldwide by use of single-operator multiparameter metabolic analyzers SOMMAs) coupled with coulometers; Total Alkalinity and pH are measured by closed-cell automated potentiometric titration system developed at University of Miami; discrete pCO_2 is measured by an automated equilibrator-IR analyzer system, developed at LDEO.

5.6 MM FOR OTHER GHG

Technology Description

Introduction

Other GHG (e.g., N_2O, CH_4, PFCs, HFCs, SF_6) are emitted from both point sources (industrial plants) and diffuse sources (open pit coal mines, landfills, rice paddies, and wastewater treatment lagoons) and offer unique challenges due to spatial and temporal variations. Measuring and monitoring(MM) technologies for both sources must include direct measurement of emissions as well as accurate reporting that is based on inventory accounting procedures or rules-of-thumb for activities or processes. Reporting methods are available and being improved.

System Concepts

- Continuous Emission Monitoring (CEM) for point sources with data transmission and archiving complemented by improved inventory-based reporting, and remotely sensed measurements.
- For diffuse sources, the system will include (1) rules-of-thumb for emissions based on known processes (e.g., agricultural practices related to N_2O emissions), (2) area-scale sensors that function autonomously with data transmission, and (3) remote sensing methods for local-to-regional scale estimation.

Representative Technologies

- CEM for a wide variety of other GHG.
- Direct measurement over landscapes.
- Indirect measurement via tracer studies.

Technology Status/Applications

- Diffuse emissions; Current technology (labor intensive) can estimate area-averaged atmospheric concentrations from diffuse emissions. New approaches are needed to quantify source and sink rates for other GHG. A more simple, reliable, and low-cost (meaning, presumably, unattended) method of measuring area-source emissions would be very helpful in producing both more accurate inventories and improving prospects for identifying low-cost reduction opportunities.
- Point sources: CEMs and inventory-based accounting and reporting provide elementary capability for estimating point sources of GHG emissions.

Current Research, Development, and Demonstration

RD&D Goals

- Point sources: Inexpensive CEM, instruments to measure from stand-off distances, satellite-based sensors capable of point-source estimation, and improved understanding of process chemistry so that accounting-based estimates are more accurate.
- Diffuse sources: New analytical tools for autonomous measurement, improved scientific understanding of processes to develop accurate rules-of-thumb, and remote sensors to quantify other GHG at multiple scales and in the vertical atmospheric profile.

RD&D Challenges

- Modeling activities that increase the accuracy of spatial estimates of N_2O and CH_4 from land management activities (e.g., nitrogen fertilizer, manure management, rice production, etc.).
- CEM systems for industrial emissions that are robust and inexpensive that are linked to data collection, distribution, and analysis systems.

RD&D Activities

- Limited scientific studies to measure or estimate emissions in systems such as landfills or agricultural practices are ongoing.

Recent Progress

- One approach involves tracer technique with Fourier transform measurement of sulfur hexafluoride tracer gas placed with emission sources. As a proxy, the tracer observations infer annual emissions, and while this procedure works, there are presently cost and logistical limitations.
- Airborne platforms effectively monitor aerial concentrations of GHGs, and have some capability with identifying emissions sources; new detection and measurement systems are being evaluated.

Commercialization and Deployment Activities
• Point source CEM methods and area-averaged concentration of GHGs can be obtained in limited applications; improved spatial resolution of measurements is needed before approaches are accepted by commerce and industry. • Methods do not exist for remote sensing of diffuse GHG emissions.