Class VI Underground Injection Control
Curriculum for Regulators
5/18/2022

Disclaimer

This document presents a curriculum for the training of regulatory staff who will review and approve Class VI permit applications and monitor Class VI projects. It is intended to provide regulators with information about the underground injection of carbon dioxide (CO_2) for long-term storage. The curriculum focuses on areas of regulatory management of CO_2 injection and storage that are not typically part of existing underground injection control programs. Note that the training envisioned by the curriculum is not designed to qualify someone to fully review a Class VI project or permit application or to regulate Class VI operations where in-depth training in specific areas of expertise is needed. In addition, the curriculum is intended to supplement, and not duplicate training prepared and in preparation by EPA.

Background

Carbon Capture and Storage (CCS) is seen as an essential tool in reaching national and international greenhouse gas emission reductions targets. In the U.S., CCS as an effective strategy to address climate change will demand wide acceptance and use of Class VI storage wells regulated under the provisions of the Underground Injection Control (UIC) program. Class VI regulatory programs build on knowledge and skills developed in oversight of other UIC classes but will inevitably require new perspectives, expertise, skills, and capacity to effectively oversee Class VI projects that differ in significant respects from other types of underground injection. This curriculum does not attempt to cover Class II activities such as CO_2 EOR.

Why this Curriculum?

The objective of this curriculum is to provide high-quality, technical training to new and seasoned regulators alike, and to foster the development of efficient programs improve the understanding and competence of the CCS community. Informed and knowledgeable preparation, review, approval, and oversight of Class VI permits is foundational to the integrity and quality of CCS projects. However, the demands of permitting geologic sequestration of CO_2 may also come with high costs, delays, and inefficiencies – a particular challenge where Class VI permits are relatively novel for permitting staff. The development of high-quality CCS regulatory programs does not have to conflict with economic and efficiency needs of the regulated CCS project development community.

Curriculum content development and use

Initial Curriculum content was developed collaboratively with a panel of technical and regulatory experts. As needed, this modular course can be adapted by the instructor(s) for user needs and audience demographics. A combination of in-person and virtual sessions are envisioned to be taught by qualified experts.

Who should attend?

UIC regulatory staff responsible for existing or future Class VI permitting programs, including both EPA and state permitting staff, particularly those states that have applied for, are contemplating, or have obtained primary enforcement (primacy) delegation. The course can provide training to new staff to bring them up-to-speed quickly, as well as to refresh and supplement more seasoned staff.

What will be covered?

The Curriculum is designed to provide in-depth background, technical training, and practice exercises aimed at supplementing – not replacing – existing rules, guidance, and training. The content and format are designed specifically to familiarize regulators with issues unique to CCS in the Class VI permitting context. This includes:

- Context, background, and foundational documents and resources on CCS, UIC, and broader greenhouse gas mitigation strategies and programs
- Compiled and annotated reference "bookshelf" for Class VI permit writers
- Review of permit-relevant properties and characteristics of CO_2
- Assessing the sufficiency of storage site characterization data and model inputs
- Evaluating fluid flow modeling and assessing proposed area of review
- Understanding and reviewing site-specific risk analyses
- Assessing, reviewing, and enhancing monitoring plans
- Evaluating monitoring and model results toward assessing long-term secure storage
- Preparing for contingencies with corrective action and remediation plans
- Closure and post-injection site care considerations
- Comparison of storage in EOR, depleted fields and saline formations
- Overview of financial assurance issues for geologic storage

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Table of Contents with Module Summaries

In this module instructors presenst a high-level introduction to the goals of climate change mitigation and greenhouse gas emissions reduction, and explore the significance of this UIC program, including background on the various types of drivers that may influence the approach taken by project operators. Course instructors and students will interact to better target the course content.

This module introduces a "bookshelf" of introductory and advanced materials (indexed and annotated, noting specifically what is considered industry best practice for commercial-scale

applications and what is R&D-oriented). Reference materials (mostly digital) for students to refer to during course and afterward will be provided. This module will be of short duration during the course. An investment will be made during course preparation to collect, annotate, and index many sources of information for attendees to refer to after course completion.

3. A review of permit-relevant properties and characteristics of CO_2

This module provides a review the properties of carbon dioxide (CO_2) - focusing on the information needed to review permit applications and permits. The role of CO_2 in the carbon cycle is relevant for understanding CO_2 monitoring options; dynamic reservoirs of carbon in near surface environments contribute actively to CO_2 flux, and this must be factored into monitoring plans. Understanding the impact of pressure and temperature on CO_2 in pipelines, wells, and when released into the subsurface, groundwater, or air is essential background to explain related handling and infrastructure needs, as well as HS&E issues. Understanding CO_2 interactions with rock, water and materials is important in Class VI to manage tubular corrosion, wellhead engineering, and geochemical monitoring. The basics of dense phase CO_2 interactions with initially water-filled porous media will be introduced with technical detail; this is an essential element of fluid flow modeling for a CO_2 injection.

4. Assessing the sufficiency of storage site characterization (description and static model)

The geologic system, which is fundamental to assuring CO_2 containment, is considered in detail in this module. The focus in this module will be on how the properties of the geologic system interact with the injected CO_2 and what is needed to achieve containment and protect underground sources of drinking water (USDW). In this course we assume that site selection and characterization was previously completed and documented in the submitted permit application, and that the permit writer will evaluate the sufficiency of the application documents. The focus will be primarily on the need to quantify properties for input into a fluid flow model and less on the descriptive parts of storage site characterization (which are well-laid out in Class VI). Even in well-characterized sites uncertainties in geologic system features, events, and processes remain. Sensitivity of computational model forecasts to these parameter uncertainties should be explored to understand their impact on assessed Area of Review (AoR) and long-term containment of injected CO_2.

Participants will gain a robust understanding of how to assess the geologic system characteristics needed to assure containment effectiveness, which includes assessment of the quality and continuity of the confining system. The geologic inputs that must be characterized with sufficient quantitative rigor so that they can be represented in a computational fluid flow model are described.

5. Evaluating the fluid-flow modeling and assessing the proposed areas of review

This module prepares permit writers to evaluate multiphase fluid flow modeling which serves as the basis for determining the appropriateness of the proposed AoR delineation, and for assessing the need for revision of the AoR and any corrective actions within the AoR during injection or Post-Injection Site Care (PISC). To become sufficiently proficient in multiphase fluid flow modeling to

appropriately build and run a model requires extensive training. In this course, we provide sufficient background to enable a non-modeler to evaluate model assumptions and results, ask key questions of the operator, and supervise a modeling specialist or contractor.

This module provides a framework to evaluate the assessment of risk at the site with a focus on events and processes that can lead to migration of brine or CO_2 to the USDW or surface, or result in unacceptable levels of seismicity and provides input data into the monitoring plans in modules 7, 8, and 9

The site monitoring plan for Class VI is not prescriptive; it must align with site-specific risks that potentially could be triggered by the planned injection operations. This module explores the strategy for designing monitoring systems that systematically collect information to mitigate the risk from the project or to put in place suitable management strategies to reduce the likelihood or consequences of risks. An overview of the possible monitoring tools that may be proposed for monitoring at a geologic storage site will be provided. Practical considerations for deployment of these technologies at depth, in the USDW, at or above the earth's surface, will be provided - highlighting strengths and limitations of candidate monitoring technologies, and identifying key questions to ask the operator as permit writers reviewing monitoring plans.

This module focuses on the data that are collected in conjunction with well construction after the permit is granted. Data collected during the drilling, construction, and testing of an injection well is essential to the permit-writer's evaluation of whether to modify the permit or grant authorization to inject.

This module discusses assessing reported monitoring and testing results, Monitoring data are rarely immediately interpretable. It is important to critically compare the monitoring results with model predictions to determine if changes in plume or pressure indicate a need for change in AoR or other modifications, and to determine if a project is on track for successful long-term containment after closure. Near surface data require different interpretation approaches to assess if USDW non-endangerment and long-term containment criteria are being met.

A successfully designed and operated project will protect against loss of CO_2 from the intended injection and confining zones, prevent leakage of brine into USDW or to the surface, and avoid triggering unacceptably high magnitude and frequency of seismic events. This module prepares for

the contingencies of: 1) discovery of a problem that may occur in the future or, 2) CO_2 loss, brine leakage, or an unacceptable seismicity occures.

Long-term containment of CO_2 is implicit in the term storage. For a well-selected, well-operated site, it can be reasonably expected that safe, long-term containment will be achieved. At the end of injection, the operator must collect any data that is needed to demonstrate that long-term containment will be assured and that the USDW is protected. This module outlines the steps needed to approve and understand when to update the PISC monitoring plan, review the data collected, and assess the case that the site will satisfy the PISC goals.

Commercial-scale CO_2 injection for enhanced oil recovery (CO_2-EOR) is a mature technology with several decades of demonstrated performance. There are relevant practices and valuable insights that can be drawn from the CO_2-EOR experience to benefit Class VI implementation. EOR experience informs the decision of many prospective Class VI operators. This module presents a high-level overview of the CO_2-EOR process and experience for Class VI permit writers.

An overview of the financial assurance elements of Class VI, especially those that relate to geotechnical considerations are presented in this module. This is an overview for non-specialists on the CO_2-specific case.

Curriculum content
Red = hands-on activity for class practice
Blue= case study presentation

1. **Introduction: Background and foundation documents on CCS, UIC, and broader greenhouse gas mitigation strategies and programs**

In this module instructors present a high-level introduction to the goals of climate change mitigation and greenhouse gas emissions reduction, and explore the significance of this UIC program, including background on the various types of drivers that may influence the approach taken by project operators. Course instructors and students will interact to better target the course content.

1.1. Goals of this course
    1.1.1. Support state and federal agencies in their review of permits or permit applications provided by others including:
        1.1.1.1. Providing a critical review of content provided by operators
        1.1.1.2. Developing skills to support follow-up dialog and requests for clarifications (how to ask a question that motivates high quality operator response)
        1.1.1.3. Developing skills to oversee the agency's third-party contractors
    1.1.2. Raise standards in CCS community to efficiently prepare and review permit applications and other data to regulate high quality CCS projects. Minimize risk of non-compliance and cost of permitting, while reducing delay.
    1.1.3. Class VI permitting process
        1.1.3.1. Stakeholders and roles: Federal and Regional EPA, state, applicant, contractors for applicant and for agencies, stakeholders, relationship with other agencies
        1.1.3.2. Scheduling, staging, iterative processes, requirements, and best practices conducted
            1.1.3.2.1. Before drilling (application review and permitting, if applicable)
            1.1.3.2.2. During drilling (testing and monitoring)
            1.1.3.2.3. After drilling (authorization to inject – permit modification)
            1.1.3.2.4. Testing and monitoring update during injection (could trigger permit modifications)
            1.1.3.2.5. Closure and post closure
            1.1.3.2.6. Transparency, consulting and Environmental Justice
                1.1.3.2.6.1. Roles (e.g., EPA as direct implementation (DI) or oversight) Phasing Transparency
                1.1.3.2.6.2. Record building
1.2. How does the UIC program fit into climate change mitigation strategies?
    1.2.1. Emissions of Greenhouse Gasses (GHGs) are regulated by the US EPA under the Clean Air Act (CAA); deep CO_2 injection operations are regulated by the US EPA under the Safe Drinking Water Act
        1.2.1.1. Class discussion with instructor review sheet

        1.2.1.2. Difference/overlap between groundwater protection in UIC and GHG programs

        1.2.1.3. Accounting for mitigation of air release under CAA

    1.2.2.Motivations for projects are variable and evolving. Understanding other needs to be met by project design include the:

        1.2.2.1. Business context

        1.2.2.2. Policy context

        1.2.2.3. ISO standard 27914 and 27916

        1.2.2.4. Funding mechanisms for CCS: overview of IRS 45Q, Clean Air Act, 40 CFR Part 98, subpart RR, CA LCFS, voluntary markets, funding mechanisms as they develop.

        1.2.2.5. Public funding incentives and R&D

        1.2.2.6. Public acceptance and social license to operate – drivers within and outside of Class VI program

  1.3. Where are class participants working within the Class VI UIC structure?

    1.3.1.Federal

    1.3.2.State with Primacy/applying for Primacy/considering Primacy

    1.3.3.State without Primacy

    1.3.4.Participant activity: Each participant will fill out questionnaire of his/her job duties, background, and current state of knowledge, needs and expectations from the course. (Suggest using real time poll for quick feedback)

2. Compiled and annotated reference "bookshelf" for permit writers.

This module introduces a "bookshelf" of introductory and advanced materials (indexed and annotated, noting specifically what is considered industry best practice for commercial-scale applications and what is R&D-oriented). Reference materials (digital) for students to refer to during course and afterward will be provided. This module will be of short duration during the course. An investment will be made during course preparation to collect, annotate, and index many sources of information for attendees to refer to after course completion.

  2.1. Background materials on CCS including:

    2.1.1. National Petroleum Council Dual Challenges 2019 report, Chapter 7

    2.1.2. University of Edinburg CCS course

    2.1.3. UNFCC reports – 1.5 degree C

    2.1.4. IPCC special report on GS 2005.

    2.1.5. WRI CCS Guidelines, WRI CCS Stakeholder Engagement Guidelines

    2.1.6. GCCSI global project resources

    2.1.7. Several books that are most useful to regulators

    2.1.8. DOE resources (include BMP's)

    2.1.9. IEAGHG R&P program reports

    2.1.10. Link to completed Class VI permits at EPA and states (potentially as hosted website)

    2.1.11. Information on relevant global projects

  2.2. Regulatory documents including:

2.2.1. State Primacy on Class VI (will potentially need updating as a hosted website) and will include:

2.2.1.1. EPA guidance

2.2.1.2. North Dakota

2.2.1.3. Wyoming

2.2.1.4. Louisiana

2.2.1.5. Others in progress

2.2.2. Relevant EPA rules including:

2.2.2.1. Class VI rules online

2.2.2.2. Preamble breakdown

2.2.2.3. Class VI indexed word version

2.2.2.4. Class VI guidance documents (annotations needed, cite as needed through slide deck)

2.2.2.5. EPA webinars and other CCS resources

2.2.3. Clean Air Act GHG reporting rules including:

2.2.3.1. UU, RR W and others as needed

2.2.3.2. Link to completed subpart RR MRV plans

2.2.4. IRS – 45Q Tax Credit

2.2.5. ISO standards 27914 and 27916 (must be purchased but can provide the class with a synopsis of major elements relevant to Class VI)

2.2.6. ISO Technical Reports (must be purchased but can provide the class with a synopsis of major elements relevant to Class VI)

2.2.7. Data submission requirements to State Primacy Agencies and US EPA

2.3. Additional supporting documents on project development, permitting, and approval

2.3.1. DOE FECM released a set of Best Management Practices for GCS (U.S. DOE, NETL 2020)

2.3.1.1. Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects

2.3.1.2. Public Outreach and Education for Geologic Storage Projects

2.3.1.3. Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects

2.3.1.4. Risk Management and Simulation for Geologic Storage Projects

2.3.1.5. Operations for Geologic Storage Projects

2.3.1.6. Geologic Formation Storage Classification

2.3.2. DOE NETL NRAP Recommended Practices for Containment Assurance and Leakage Risk Quantification (2022)

2.3.3. Van Voorhees, B., S. Greenberg, and S. Whittaker, 2021, Observations on Class VI permitting: Lessons learned and guidance available: Illinois State Geological Survey, Special Report 9

2.4. Indexed resources for both basic and more in-depth information on CCS project components including:

2.4.1. Properties of CO_2 – Phase changes, solubility in water vs. salinity, impact of impurities basic/expert (WinProp and equation of state)

2.4.1.1. CO_2 sources and volumes

2.4.1.2. Energy requirements for separation, transportation, and injection

2.4.2. Geology – just what permit-writers needed to know such as:

2.4.2.1. Petrophysics 101-reservoir/types of barriers to flow, porosity, permeability, and saturation, mineralization, dissolution, capillary trapping

2.4.2.2. Geometries of flow units. Basic/ case studies, focus on input to models.

2.4.2.3. References on 2-D and 3-D seismic imaging

2.4.2.4. References on wireline log types, analysis, extracting porosity, other properties, time lapse logs, esp. pulsed neutron

2.4.3. Multiphase flow characteristics, basic, literature on current edge of research

2.4.4. Trapping mechanisms

2.4.5. Fluid flow modeling basics/expertise including:

2.4.5.1. Introduction to fluid flow models

2.4.5.2. Case studies of fluid flow models

2.4.6. Monitoring – IEAGHG Monitoring tool overview

2.4.7. 4-D geophysics

2.4.8. Monitoring CO_2 groundwater and soil gas

2.4.8.1. Sampling techniques, preservation, and laboratory methods

2.4.9. CO_2 HS&E data, MSDS, ecosystem, groundwater. Heavy metals consideration.

2.4.10. Induced seismicity basics and advanced resources

2.4.10.1. Overview of the state oil and gas regulatory exchange guide on induced seismicity for regulators

2.4.10.2. NRAP Recommended Practices for Induced Seismicity Risk Management

2.4.10.3. Stanford's Center for Induced and Triggered Seismicity "SCITS"

2.4.10.4. Appendix H from the GWPC document Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection

2.4.10.5. LCFS rules on induced seismicity

2.4.10.6. Determination of tectonic stress conditions

2.4.10.7. Proximity to crystalline basement rock

2.4.11. Site remediation reference materials

2.4.12. CO_2-EOR cases and background Including Denbury, Oxy, Core energy and others

2.5. Provide guidance as to where to find ongoing and updated reference material.

2.6. Participant activity: Briefly review 5 of the provided resources (at least the annotation) and make notes on how you think this might be used in your work. If time allows, you will give a brief "book report" to the class.

3. A review of permit-relevant properties and characteristics of CO_2

This module provides a review the properties of carbon dioxide (CO_2) focusing on the information needed to review permit applications and permits. The role of CO_2 in the carbon cycle is relevant for understanding CO_2 monitoring options; dynamic reservoirs of carbon in near surface environments contribute actively to CO_2 flux, and this must be factored into monitoring plans. Understanding the impact of pressure and temperature on CO_2 in pipelines, wells, and when released into the subsurface, groundwater, or air is essential background to explain related handling and infrastructure needs, as well as HS&E issues. Understanding CO_2 interactions with rock, water and materials is important in Class VI to manage cement and tubular corrosion, wellhead engineering, and geochemical monitoring. The basics of dense phase CO_2 interactions with initially water-filled porous media will be introduced with technical detail; this is an essential element of fluid flow modeling for a CO_2 injection.

3.1. The Carbon Cycle including:
   3.1.1. Mantle sources
   3.1.2. Biogenic activities
   3.1.3. Carbon in atmosphere, ocean, groundwater, and soil.
   3.1.4. Weathering
3.2. CO_2 phase behaviors such as:
   3.2.1. Pressures, density, and viscosity; temperature changes of state
   3.2.2. How this relates to handling – expansion, Joule Thomson effect, buoyancy
3.3. CO_2 Health, Safety and Environment (HS&E) issues
3.4. Density in air
3.5. Dissolution in water, pH change, corrosivity, isotopes of carbon and oxygen (with respect to use in monitoring)
3.6. CO_2 reactivity with rock
3.7. CO_2 reactivity with engineered materials (steel, gaskets, cements)
3.8. Participant activity: discussion: EPA developed Class VI to consider of the "unique nature" of CO_2. In small group discussion, note the aspects of CO_2 behavior that are relevant to permit application and permit review. Provide an answer sheet before end of discussion listing PVT issues with buoyancy, density and BHP, ambient CO_2 in reservoirs, groundwater, atmosphere, how to find leaks. Relate to long-term experience with CO_2 injection for EOR.
3.9. CO_2 in water and porous media
3.10. Solubility Pressure, Temperature salinity dependence, pH Change
3.11. CO_2 diffusion processes
3.12. H_2S separation processes
3.13. Multi-phase fluid flow including:
   3.13.1. Capillary entry pressure
   3.13.2. Hysteretic curves
   3.13.3. Types of trapping and timescales for trapping – structural/dissolution/residual/mineralization

3.13.4. Viscosity and capillary-dominated flow

3.13.5. Wettability

3.13.6. Upscaling and model simplifications

3.14. Isotopies of carbon relevant to monitoring

3.15. More complex CO_2-fluid interactions – oil, methane, H_2S (diffusion and mineralization)

3.16. CO_2 stream - conditional exclusion from RCRA

4. **Assessing the sufficiency of storage site characterization (description and static model)**

The geologic system, which is fundamental to assuring CO_2 containment, is considered in detail in this module. The focus in this module will be on how the properties of the geologic system interact with the injected CO_2 and what is needed to achieve containment and protect underground sources of drinking water (USDW). In this course we assume that site selection and characterization was previously completed and documented in the submitted permit application, and that the permit writer will evaluate the sufficiency of the application documents. The focus will be primarily on the need to quantify properties for input into a fluid flow model and less on the descriptive parts of storage site characterization (which are well-laid out in Class VI). Even in well-characterized sites uncertainties in geologic system features, events, and processes remain. Sensitivity of computational model forecasts to these parameter uncertainties should be explored to understand their impact on assessed Area of Review (AoR) and long-term containment of injected CO_2.

Participants will gain a robust understanding of how to assess the geologic system characteristics needed to assure containment effectiveness, which includes assessment of the quality and continuity of the confining system. The geologic inputs that must be characterized with sufficient quantitative rigor so that they can be represented in a computational fluid flow model are described.

4.1 How elements of properties in the geologic system interact with injected CO_2 to achieve containment and protect USDWs

   4.1.1. The injection zone including:

      4.1.1.1. Geometries of the injection zone – flat lying, layered, dipping, structural and stratigraphic traps

      4.1.1.2. Multiple stacked injection zones

      4.1.1.3. Multiple injection points in the same or different zones

      4.1.1.4. How can mischaracterization of the injection zone lead to failure to retain CO_2 or brine?

   4.1.2. The confining system including:

      4.1.2.1. Confinement vs. seal – how do we know what is good enough? Confirming elements of trap and seal lateral continuity

      4.1.2.2. Pressure isolation – How permeability limits single-phase flow; capillary entry pressure relevant for multiphase flow

      4.1.2.3. Fractures, fracture systems

         4.1.2.3.1. Cubic law of flow and the importance of aperture

4.1.2.3.2. Estimation of fracture properties

4.1.2.3.3. State of stress, orientation, fracture networks

4.1.2.4. Case study – In Salah project

4.1.2.5. Faults

4.1.2.5.1. Offset, Allan diagrams

4.1.2.5.2. Fault gouge

4.1.2.5.3. Age of faulting

4.1.2.5.4. Types, amount of throw, and vertical height of faults

4.1.2.6. Wells (discussed further in module 6)

4.1.2.7. How can mischaracterization of the confining system, wells or faults lead to failure to retain CO_2 or brine?

4.2. Parts of a static model

4.2.1. Flow units (injection zone(s)) including:

4.2.2. Confining systems(s)

4.2.3. Structural framework

4.2.4. Gridding

4.2.5. Allocation of properties to cells

4.2.6. Boundary conditions

4.2.6.1. Dealing with multiple injectors or producers in the same zone or in other zones.

4.2.7. Discretizing wells

4.2.8. Quality control points – what makes a model sufficient for its purpose?

4.3. Data sources for static models including:

4.3.1. Seismic imaging to define injection zone and confining system geometries (seismic monitoring is discussed in modules 7 and 9 and seismicity in module 6)

4.3.2. A new tool in UIC, but well-developed in hydrocarbon exploration. Therefore, spend some time discussing these models. Here we are discussing a single survey; which may have added value in time lapse

4.3.2.1. When seismic imaging is needed - complexity in flow units that cannot be described by the more limited data from well penetrations. Include seismic resolution with depth, sediment type etc. as well as multiple techniques for improved stratigraphic resolution.

4.3.2.2. Structural complexity – faults and fractures, geometry of top of flow units.

4.3.2.2.1. Structural Dip's impact on well location and plume characterization

4.3.2.3. Sleipner case study showing Utsira characterization data. Compare projected and observed flow, and the impact of subtle bedding and structure on flow. Note that these are world's best images of CO_2 response to stratigraphy not typical images

4.3.2.4. Stratigraphic complexity – channels, bars, pinch out examples

4.3.2.5. 2D lines , 3-D surveys and VSP

4.3.2.5.1. Vertical and horizontal resolution

4.3.2.5.2. Time to depth conversion

4.3.2.5.3. Noise and static error

4.3.2.5.4. Fold and bin size, impact at edge of survey.

4.3.2.5.5. Impact of fluid compressibility

4.3.2.5.6. Limits of seismic detection - static error, depth, thin bed problems, multiples, poor returns, location errors.

4.3.2.5.7. Quality of seismic inversion to reported properties

4.3.2.5.7.1. Alternate approaches for inversion

4.3.2.5.7.2. QC metrics for results

4.3.2.5.8. Quality control on seismic data for static modeling

4.3.2.6. Wireline logs

4.3.2.6.1. Widely used tool for subsurface characterization

4.3.2.6.2. Quick poll -- how do you use logs?

4.3.2.6.3. Brief overview of wireline logs

4.3.2.6.4. What is sufficient quality and density?

4.3.2.6.5. How to QC log data including:

4.3.2.6.5.1. Picks (geologic tops) Log quality – reading log headers

4.3.2.6.5.2. Calibration of logs with core data

4.3.2.6.5.3. Parameter extraction for calibration to porosity and permeability; Indirect measurements of rock properties.

4.3.2.6.5.4. Evaluation-quality of data (QC metrics for interpretation of flow unit(s), confining system and log transform to reservoir properties)

4.3.2.6.5.5. Advanced logs (ADT, NMR, formation micro-scanner or borehole imager)

4.3.2.6.5.6. Correlation and extrapolation of rock data

4.3.2.6.5.7. Importance of fluids in log analysis

4.3.2.6.6. Quick exercise – judging is there enough data?

4.3.3. Core requirements in Class VI including:

4.3.3.1. Core analysis and petrophysics – what is needed and why.

4.3.3.1.1. Whole core vs. sidewall

4.3.3.1.2. When will offset cores be sufficient?

4.3.3.1.3. Porosity and permeability

4.3.3.1.4. Petrophysical analysis

4.3.3.2. Special core analysis (SCAL) – relative permeability, rock strength measurements Youngs modulus, bulk modulus, Poisson's ratio, etc.

4.3.3.3. Capillary entry pressure, reading the diagram for CO_2

4.3.3.4. How to spot bad data.

4.3.4. Hydrologic testing (pressure measurement, pressure transient testing, build-up, fall-offs, interference testing, mini-frac tests, injectivity testing, etc.)

4.3.5. Quantification of reservoir properties including:

4.3.5.1. Phase of CO_2, bottom hole pressure

4.3.5.2.   Thermal stress of formation near wellbore

4.4. Evaluation of all existing wells

4.4.1. Many UIC regulators are already experts

4.4.1.1. Class discussion of problem wells

4.4.2. Most deep wells were constructed to provide barriers to inter-formational flow such as:

    4.4.2.1. Surface casing to protect USDWs

    4.4.2.2. Cement from Total Depth (TD) to reservoir seal

    4.4.2.3. Drilling mud across other zones

    4.4.2.4. Real world challenges and methodologies to identify top of cement

        4.4.2.4.1. Very old – pre groundwater protection regulations in jurisdiction

        4.4.2.4.2. Inadequate records

        4.4.2.4.3. Cement bond logs – variable density logs

        4.4.2.4.4. Caliper logs and records of amount of cement sufficient to lift to reservoir seal.

        4.4.2.4.5. Injection into a zone above the original reservoir - no cement in zone

    4.4.2.5. Damage to well during operations such as corrosion and annular voids

4.4.3. Will existing wells be damaged by CO_2 flood?

4.5. Other leakage risks – what are they? How can we define them? Eliminate them? Reduce impact from them?

4.6. Boundary conditions for the model – the hidden peril

    4.6.1. Why boundary conditions matter – significant impact on AoR and PISC

    4.6.2. Case studies of open and closed boundary conditions

    4.6.3. Characterization of boundary conditions such as:

        4.6.3.1. Geologic models – faults, channels

    4.6.4. Evidence of pressure support or lack thereof

    4.6.5. Arbitrary limits (lease lines, limits of data, etc.)

    4.6.6. Model options for boundary conditions such as:

        4.6.6.1. Constant head, closed, constant pressure, limited volume aquifers, and variations in between

        4.6.6.2. Dealing with uncertainty in boundary condition assumptions

4.7. Seismicity basics including:

    4.7.1. Source of energy

    4.7.2. Ground motion

    4.7.3. Detection

    4.7.4. State of knowledge, USGS assessment

    4.7.5. Case study Oklahoma water disposal experience

    4.7.6. Case study LCFS approach for managing seismicity

    4.7.7. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection

4.8. Overburden, groundwater, unsaturated zone, surface characterization.

    4.8.1. Near surface characterization - reasonable expectations. What is sufficient? What is unacceptable surface characterization?

    4.8.2. Need for data on groundwater including:

        4.8.2.1. Base of USDWs

        4.8.2.2. Geochemical characterization for baseline

4.9. What questions to ask of operator about static characterization/ QC approaches

4.10. Diverse other types of CO_2 geologic storage not covered in this course

    4.10.1. Carbonated water in saline formations, CO_2 in gas phase, injection in coal and shales, basalts, acid gas disposal (See guidance in Class VI preamble)

4.11. Use of multi-zone injection

4.12. Potential impact of vertical vs. horizontal wells for injection

5. **Evaluating the fluid-flow modeling and assessing the proposed areas of review**

This module prepares permit writers to evaluate multiphase fluid flow modeling which serves as the basis for determining the appropriateness of the proposed AoR delineation, and for assessing the need for revision of the AoR and any corrective actions within the AoR during injection or Post-Injection Site Care (PISC). To become sufficiently proficient in multiphase fluid flow modeling to appropriately build and run a model requires extensive training. In this course, we provide sufficient background to enable a non-modeler to evaluate model assumptions and results, ask key questions of the operator, and supervise a modeling specialist or contractor.

5.1. Basics of fluid flow modeling including:

    5.1.1. Types of models, assume cellular models (Regulatory required models review)

    5.1.2. Gridding - discretization

    5.1.3. Times step discretization

    5.1.4. Model fit-to-purpose

5.2. How did operator build a fluid flow model? How does it work? What can we expect it to tell us? What can we not expect from a model? Reconciling models.

5.3. Evaluating components of a model including:

    5.3.1. Static models-- Model extent (ensuring that model domain extends beyond the extent of the expected plume and pressure-affected area), input of geotechnical features, gridding, upscaling, representation of wells, boundary conditions (See module 4)

    5.3.2. Dynamic (fluid flow models) selection of software, inputting static model into dynamic model software, managing input files – boundary conditions, injection and extraction wells. The art and science of calibration and history matching.

5.4. Evaluating capacity

    5.4.1. Dealing with multiple injectors or producers in one or more injection zones

5.5. Extracting plume areas from model results

5.6. Determining AoR from model results

    5.6.1. The distinction between hydrostatic or initially underpressured injection zones and initially overpressured injection zones.

5.7. Holistic approaches to multiple well projects - collectively considering all wells in a field will ensure that the site is evaluated and operated in a holistic manner and that all aspects of the project that may impact USDWs have been evaluated and addressed

5.8. Projecting future migration of water with CO_2 in solution

5.9. Case study, - what does model look like – how do we assess CO_2 plume and pressure changes. Relating reservoir pressure to AoR.

5.10. Updating static and fluid flow models with new data – evaluating concordance between model predictions and monitoring observations and assessing the adequacy of history match. Describe how concordance observed over time constrains uncertainty in prediction based on models where history match time is short.

5.11. What are costs/values? How to decide if and when the models are reasonably well calibrated and can be used to predict absence of leakage in the future?

    5.11.1. Setting confidence intervals

5.12. Examples of model failures – how to spot them

5.13. What questions to ask of the operator?

5.14. Assessing the qualifications of a modeling contractor who advises the regulator

5.15. See also updating models after data collection in section 9.

6. **Reviewing site-specific risk analysis**

This module provides a framework to evaluate the assessment of risk at the site with a focus on events and processes that can lead to migration of brine or CO_2 to the USDW or surface, or result in unacceptable levels of seismicity and provides input data into the monitoring plans in modules 7, 8, and 9

6.1. Goals and components of risk analysis

6.2. Risk is the product of probability and consequence

6.3. Evaluating potential leakage, mechanisms, pathways, and processes.

    6.3.1. Find the risks exercise.

6.4. Geomechanical risks –changes to state of stress from injection operations may cause reactivation of existing faults or opening of fractures in the sealing caprock. Targeted data collection can substantially constrain uncertainty (stress polygon)

    6.4.1. Microseismicity as a tool

6.5. Microseismicity for risk evaluation

6.6. Case studies and industry examples (Decatur, Anneth, Cogdell)

    6.6.1. Linking CO_2 projects with your agency's other seismicity concerns in brine disposal and geothermal work (response plans etc.…, GWPC guide, LCFS information)

6.7. Lifecycle well risk, Discussion of risk assessment around well construction

6.8. Using models in risk analysis

6.9. Using risk analysis to inform design of an effective and adaptive monitoring plan

6.10. Using risk to determine applicable financial assurance and liability insurance

6.11. Industry concept of bow tie management of risk

6.12. Quantitative risk assessment from NRAP

6.13. What questions to ask of operator?

6.14. Using risk management for permitting conditions

7. Assessing and reviewing a monitoring plan prior to execution

The site monitoring plan for Class VI is not prescriptive; it must align with site-specific risks that potentially could be triggered by the planned injection operations. This module explores the strategy for designing monitoring systems that systematically collect information to mitigate the risk from the project or to put in place suitable management strategies to reduce the likelihood or consequences of risks. An overview of the possible monitoring tools that may be proposed for monitoring at a geologic storage site will be provided. Practical considerations for deployment of these technologies at depth, in the USDW, at or above the earth's surface, will be provided - highlighting strengths and limitations of candidate monitoring technologies, and identifying key questions to ask the operator as permit writers are reviewing monitoring plans.

7.1. Goal setting for monitoring
    7.1.1. Leakage pathway analysis and assessment
    7.1.2. Targeting monitoring to increase confidence that storage is secure and will continue to be secure far into the future (through injection and PISC, and into the post-closure phase)
    7.1.3. Design for termination of monitoring activities
7.2. Individual pre-survey - where would you monitor? Self-evaluate exercise during lecture.
7.3. Monitoring to validate and update model (see module 9 on model updating).
    7.3.1. Assessment of consequential uncertainty in model
        7.3.1.1. Examples of consequential uncertainty of determining AoR and plume extent
    7.3.2. Designing monitoring to reduce/eliminate consequential uncertainties.
    7.3.3. Dealing with multiple injectors or producers in the same or other zones
7.4. Aligning monitoring tool selection and monitoring plan with risks – can the risk be detected? Can it be detected sufficiently early to take preventative actions?
    7.4.1. The critical aspect of attribution – how to tell if a change is a response to injection or something else?
        7.4.1.1. Issues of false positives and false negatives
    7.4.2. Role of baseline/background - what does baseline allow you to do, what are limitations?
7.5. Methods – evaluating operator's plans, how to tell if they will they collect the data you need to oversee the project?
7.6. Monitoring tool deployment – spatial density and frequency of sampling, Instrument installation and calibration
7.7. Limits on use of geochemical tools, need for physics and pressure-based methods.
7.8. Special issues for CO_2
    7.8.1. CO_2 abundance in reservoir, groundwater, soil, atmosphere, role of isotopes
    7.8.2. Meters -- mass vs. volume measurement
7.9. Project-wide holistic multi-well monitoring
7.10. Monitoring tools at depth
    7.10.1. What tools are available? What can you expect them to do? What tools are not fit-to-purpose? Basics, new tools, special-needs tools.
    7.10.2. Interpretation of monitoring data - export to modeling

7.10.3. Time lapse geophysics – value, risk, and evaluation of how this is used.

    7.10.3.1. Seismic types, time lapse, how it works, what it can and cannot measure including:

        7.10.3.1.1. 2D, 3D, VSP, new uses of fiber

        7.10.3.1.2. Criticality of obtaining repeatability for time lapse implies different collection standards than characterization data

        7.10.3.1.3. Dealing with noise

        7.10.3.1.4. Static errors

        7.10.3.1.5. Pressure vs. fluid substitution

    7.10.3.2. Detection of CO_2 and pressure with time-lapse (Snøhvit case)

7.10.4. Gravity

    7.10.4.1. Value as a direct measure

    7.10.4.2. Limits, tool evolution

7.10.5. ERT, EM

    7.10.5.1. Value as a direct measure

    7.10.5.2. Limits, tool evolution

7.10.6. Surface uplift for pressure area detection

    7.10.6.1. Satellite based

        7.10.6.1.1. Intelligent Laser Ranging and Imaging Systems (ILRIS)

        7.10.6.1.2. Interferometric Synthetic Aperture Radar (InSAR)

        7.10.6.1.3. Global Positioning Systems (GPS)

    7.10.6.2. Ground based

        7.10.6.2.1. Tilt meters, reflectors, base stations, broadband surveys

7.10.7. Other geophysics in development

    7.10.7.1. Example cases of various tools

    7.10.7.2. Assessing new tools including:

        7.10.7.2.1. Practical detection thresholds

        7.10.7.2.2. Single to noise, repeatability

        7.10.7.2.3. Reliability and durability of sensors in context

7.11. Well-based methods

7.11.1. Bottom hole pressure, wellhead pressure, loading of well as measure of fluid type based on density

7.11.2. Time lapse logging (PNC, cased-hole neutron, other)

7.11.3. What does CO_2 breakthrough look like?

    7.11.3.1. Change in compressibility

    7.11.3.2. Thermal effects

7.11.4. Roles for CO_2 soluble tracers including:

    7.11.4.1. Tracer types

    7.11.4.2. Input and extractions, non-contamination protocols

    7.11.4.3. Limitations, strong GHG

7.12. Expect innovation and updates – how to manage baseline.

7.13. Quality Control (QC)

7.13.1. Example of forward model limits of detection, bin size, source characteristics.

7.13.2. Processing workflows

7.13.3. Detection thresholds

7.14. Monitoring in overburden including:

7.14.1. Pressure, seismic, chemical methods

7.14.2. Value of matching modeled risk to observed

7.14.3. Detection of out-of-zone leakage

7.14.4. Pressure, temperature, geomechanical responses, microseismicity, detection at surface

7.14.5. Examples from model and real cases: In Salah, Cranfield, Frio-as-a-leak

7.15. Monitoring tools in groundwater, surface water, soil, atmosphere, ecosystem

7.15.1. Groundwater

7.15.1.1. Direct detection of CO_2 and brine in groundwater with chemical methods

7.15.1.1.1. Sampling for dissolved gas is difficult. Sampling techniques, preservation and laboratory methods

7.15.1.1.2. Isotopic difference measurements from sidewall core samples

7.15.1.1.3. Analytical options

7.15.1.2. Flow, transport, mixing, rock water reaction

7.15.1.3. Endangerment standard vs. demonstration of storage permanence

7.15.1.3.1. Role of geochemical and reactive transport modeling in groundwater assessment.

7.15.1.4. Complexities in groundwater system that limit detection and add noise.

7.15.1.5. Expectations of transients in groundwater

7.15.1.6. Monitoring design for attribution

7.15.1.6.1. Unique signifiers of deep sources of CO_2 and brine

7.15.1.6.2. Monitoring of first permeable formation above geologic barrier above injection zone

7.15.1.7. Case study – is this water contaminated? game

7.15.2. Soil gas

7.15.2.1. Soil gas principles

7.15.2.2. Atmosphere/in-soil processes, allochthonous inputs (leakage?)

7.15.2.3. Concentration-based methods

7.15.2.4. Chemical signal-based methods such as:

7.15.2.4.1. LICOR and other tools

7.15.2.4.2. Geometry and sampling

7.15.2.5. Process -based methods

7.15.2.6. Need for attribution

7.15.2.6.1. Interpretation of data via modeling

7.15.2.7. Learning from controlled release and natural analogs

7.15.3. Atmospheric monitoring including:

7.15.3.1. Eddy covariance

7.15.3.2. Samplers

7.15.3.3. Various Light Detection and Ranging (LIDAR) systems

7.15.3.4. CO_2 cameras

8. Pre-injection testing and characterization during well construction

This module focuses on the data that are collected in conjunction with well construction after the permit is granted. Data collected during the drilling, construction, and testing of an injection well is essential to the permit-writer's evaluation of whether to modify the permit or grant authorization to inject.

8.1. Class VI specific construction requirements for injection wells (review)

   8.1.1. Discuss cement

8.2. Discussion of monitoring wells

8.3. Reasons for deviation from the initial injection well design

8.4. Review of implementation of the approved formation testing program

8.5. Completion report -- Reviewing well testing results cement bond, MIT's, surface casing,

8.6. Updating and revaluating characterization data including:

   8.6.1. Injectivity

   8.6.2. Verify other critical parameters, e.g., pressure.

   8.6.3. Logs and log interpretation

   8.6.4. Needed update to AoR delineation model?

8.7. Determine whether major permit modifications are necessary to bring permit and plans in line with new data

8.8. Granting authorization to inject

9. During injection operation evaluation of monitoring and testing results (as they are reported)

This module discusses assessing reported monitoring and testing results, Monitoring data are rarely immediately interpretable. It is important to critically compare the monitoring results with model predictions to determine if changes in plume or pressure indicate a need for change in AoR or other modifications, and to determine if a project is on track for successful long-term containment after closure. Near surface data require different interpretation approaches to assess if USDW non-endangerment and long-term containment criteria are being met.

9.1. What is required? in Class VI, RR

9.2. Review of schedules and triggers for updates of monitoring and other plans – link measurements made to risk reduction

    9.2.1.AoR and corrective action plan

        9.2.1.1. In-reservoir monitoring for conformance/to validate or update models

    9.2.2.Well plugging and abandonment (P&A) plan

9.3. How do you decide to approve reports (based on monitoring results, etc.…) and when to require various mid-course corrections during operations? Adaptive monitoring and ending some activities

9.4. Exercise: Idealized (model based) case studies of nonconformance. Workflows to spot the problems

9.5. How do you decide that storage is secure AND will continue to be secure far into the future?

9.6. Using monitoring outcomes to assess conformance or update model

9.7. Case study with examples – "turning knobs" to match pressure, plume area, saturation

9.8. Challenges to validating key model results

    9.8.1.Examples of how a measurement can validate a model

9.9. If above-zone or surface changes observed.

    9.9.1.The need for attribution – what has caused a change? Is it the project or unrelated event?

9.10.Ecosystem and other near surface changes

9.11.Review and update of design proposed in the planning stages – monitoring designed for attribution

    9.11.1. Tools for assessing and approving termination of individual monitoring activities

10. Injection modification, changes in AoR, corrective action, and remediation plans

A successfully designed and operated project will protect against loss of CO_2 from the intended injection and confining zones, prevent leakage of brine into USDW or to the surface, and avoid triggering unacceptably high magnitude and frequency of seismic events. This module prepares for the contingencies of: 1) discovery of a problem that may occur in the future or, 2) CO_2 loss, brine leakage, or an unacceptable seismicity occures.

10.1. Understanding the consequences of CO_2/brine leaks.

10.2. Insipient or future loss indicators. Seismic event probabilities.

    10.2.1. Remedial actions options

    10.2.2. Closing problem sites

10.3. How bad can it get-- atmospheric release or water pollution?

10.4. Implications/consequences requiring changes in operations.

10.5. Case studies of analogs for serious failures – Aliso Canyon (gas storage) and Macondo (well blowout). CO_2 blowouts from the past. Lake Nyos story – why this is not a good CCS case study. Successful mitigations – e.g., Decatur shallower perforation.

10.6. When is remediation necessary?

    10.6.1. Moderated discussion

10.7. What goes into a remediation plan?

10.8. Review of remediation plan (ARI, others)

10.9. Monitoring success of remediation

11. Post-injection Site Care (PISC) and Closure

Long-term containment of CO$_2$ is implicit in the term storage. For a well-selected, well-operated site, it can be reasonably expected that safe, long-term containment will be achieved. At the end of injection, the operator must collect any data that is needed to demonstrate that long-term containment will be assured and that the USDW is protected. This module outlines the steps needed to approve and understand when to update the PISC monitoring plan, review the data collected, and assess the case that the site will satisfy the PISC goals.

11.1. Approaches to assessments at the end of injection and work needed to successfully manage post-injection site care and closure approaches

    11.1.1. Performance and risk based approaches

    11.1.2. Prescriptive duration based approaches

11.2. Indicators of no endangerment to USDW

    11.2.1. Modeling approaches

        11.2.1.1. Pressure stabilization/prediction

        11.2.1.2. Plume stabilization/prediction

        11.2.1.3. Rate dependent process

            11.2.1.3.1. Dissolution

            11.2.1.3.2. Rock-water-CO$_2$ reaction

            11.2.1.3.3. Change from viscous to capillary-dominated flow

    11.2.2. Design focused data collection to challenge/validate model prediction during PISC

11.3. PISC Monitoring approaches

    11.3.1. Assessment of CO$_2$ plumes and elevated pressure

        11.3.1.1. Alignment of monitoring with site-specific expectation and risk

            11.3.1.1.1. Monitoring in a geologic trap closure

            11.3.1.1.2. Monitoring migrating plume

        11.3.1.2. Time lapse geophysics in PISC

        11.3.1.3. Well-based measurements

            11.3.1.3.1. Bottom hole/wellhead pressure, relationships

            11.3.1.3.2. CO$_2$ breakthrough

            11.3.1.3.3. Logging

            11.3.1.3.4. Fluid sampling

        11.3.1.4. Limitations of measurements

            11.3.1.4.1. Detection thresholds, uncertainty in complex systems

            11.3.1.4.2. Assessing and approving termination of monitoring activities

    11.3.2. Model validation based on monitoring - When is modeling completed?

        11.3.2.1. Probabilistic approach

11.3.3. Monitoring the negative – how to design monitoring to measure the expected no change? When is monitoring completed?

11.3.3.1. Scientific methods approaches.

11.4. Real world case studies of closure - CO_2 pilots.

11.5. Example cases of plume and pressure performance during PISC (based on models)

11.6. Flag goals are not being reached and responses to achieve those goals.

11.7. Long-term management of wells, potential need for modification/corrective action

11.7.1. Open wells that are accessible for monitoring

11.7.2. P&A wells

11.7.2.1. Evaluation without reentry

11.7.2.2. Re-entry

11.8. Additional needs for well evaluation at end of injection

11.8.1. Check on well inventory in AoR as defined by elevated pressure

11.8.2. Check on well inventory that intersect plume at end of injection

11.8.3. Check on well inventory that intersect plume at stabilization

11.9. Well monitoring options in the PISC period

11.9.1. Inventory of pressure and plume data needed from wells during PISC

11.9.1.1. Pressure

11.9.1.2. CO_2 breakthrough

11.9.1.3. Logging

11.9.1.4. Wellhead/bottom hole pressure relationships

11.9.1.5. Fluid sampling

11.9.1.6. Conversion from injection to monitoring

11.9.2. Connect monitoring to modeling -- special issues during PISC

11.9.3. Well maintenance during PISC

11.9.4. P&A schedule before site closure

11.9.5. Surface-based monitoring during PISC

11.9.6. PISC surface data interpretation

11.10. Building a justification to end PISC and move to site closure

12. Comparison and contrast of storage in an EOR project, depleted field, and deep saline aquifer

Commercial-scale CO_2 injection for enhanced oil recovery (CO_2-EOR) is a mature technology with several decades of demonstrated performance. There are relevant practices and valuable insights that can be drawn from the CO_2-EOR experience to benefit Class VI implementation. EOR experience informs the decision of many prospective Class VI operators. This module presents a high-level overview of the CO_2-EOR process and experience for Class VI permit writers.

12.1. How is a depleted field or an EOR prospect different from a saline aquifer?

12.1.1. Trap and production history

12.1.2. More complex fluids

13. Financial Assurance (overview)

In module 13 we overview the financial assurance elements of Class VI; especially those that relate to geotechnical considerations in the course. This is an overview for non-specialists on the CO_2-specific case.

    13.1.4.2. Emergency and Remedial Response Plans (ERRPs) based on a risk assessment – from module 6

13.2. Costs must be estimated for third-party implementation

13.3. Acceptable financial responsibility instruments – what they are and how you can mix and match to find the right combination

  13.3.1. Bonding and bonding release

  13.3.2. Liability Insurance

  13.3.3. Trust Funds

  13.3.4. Other qualifying financial instruments

13.4. Cost elements prepared annually by permittee for corrective actions , plugging, PSC, emergency, and remedial response

13.5. Long-term stewardship

14. Wrap up, thank you, and Course Evaluation