United States Environmental Protection Agency

Geologic Sequestration of Carbon Dioxide

Underground Injection Control (UIC) Program Class VI Well Plugging, Post-Injection Site Care, and Site Closure Guidance

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Disclaimer

The *Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells* (75 FR 77230, December 10, 2010), referred to as the Class VI Rule, establishes a new class of injection well (Class VI).

The Safe Drinking Water Act (SDWA) provisions and EPA regulations cited in this document contain legally-binding requirements. In several chapters, this guidance document makes recommendations and offers alternatives that go beyond the minimum requirements indicated by the Class VI Rule. This is intended to provide information and recommendations that may be helpful for UIC Class VI Program implementation efforts. Such recommendations are prefaced by the words "may" or "should" and are to be considered advisory. They are not required elements of the Class VI Rule. Therefore, this document does not substitute for those provisions or regulations, nor is it a regulation itself, so it does not impose legally-binding requirements on the EPA, states, or the regulated community. The recommendations herein may not be applicable to each and every situation.

EPA and state decision makers retain the discretion to adopt approaches on a case-by-case basis that differ from this guidance where appropriate. Any decisions regarding a particular facility will be made based on the applicable statutes and regulations. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The EPA is taking an adaptive rulemaking approach to regulating Class VI injection wells. The agency will continue to evaluate ongoing research and demonstration projects and gather other relevant information as needed to refine the Rule. Consequently, this guidance may change in the future without a formal notice and comment period.

While the EPA has made every effort to ensure the accuracy of the discussion in this document, the obligations of the regulated community are determined by statutes, regulations, or other legally binding requirements. In the event of a conflict between the discussion in this document and any statute or regulation, this document would not be controlling.

Note that this document only addresses issues covered by the EPA's authorities under the SDWA. Other EPA authorities, such as Clean Air Act (CAA) requirements to report carbon dioxide injection activities under the Greenhouse Gas Reporting Program, are not within the scope of this document.

Executive Summary

The *Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide Geologic Sequestration Wells* are codified in the U.S. Code of Federal Regulations [40 CFR 146.81 et seq.] and are referred to in this document as the Class VI Rule. The Class VI Rule establishes a new class of injection well, Class VI, and sets minimum federal technical criteria for Class VI injection wells that are protective of underground sources of drinking water (USDWs). This guidance is part of a series of technical guidance documents that the United States Environmental Protection Agency (EPA) is developing to support owners or operators of Class VI wells and UIC Program permitting authorities in the implementation of the Class VI Rule. Examples or recommendations in this or any other guidance are intended to illustrate potential approaches to meeting or exceeding the SDWA requirements and are not legally binding. To assist readers in differentiating between recommendations and requirements in this document, requirements are followed by a bracketed regulatory citation e.g., [40 CFR 146.91]. The Class VI Rule and related documents are available at https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-co2.

The Class VI Rule includes requirements for well plugging [40 CFR 146.92] and post-injection site care (PISC) [40 CFR 146.93] that are designed to ensure that after injection ceases, the geologic sequestration (GS) project will not endanger USDWs. Pursuant to these provisions, owners or operators must properly plug the injection well, monitor the site for a timeframe established in the permit (i.e., 50 years or an alternative approved timeframe), demonstrate to the UIC Program Director that USDWs are not being endangered, and complete the plugging of monitoring wells to enable site closure. The activities to be conducted during these stages of the project must be detailed in the Injection Well Plugging Plan [40 CFR 146.92(b); 40 CFR 146.82(a)(16)] and the PISC and Site Closure Plan [40 CFR 146.93(a); 40 CFR 146.82(a)(17)] and documented through well plugging reports [40 CFR 146.92(d)], non-endangerment demonstrations [40 CFR 146.93(b) and (c)], and a site closure report [40 CFR 146.93(f)]. This *UIC Program Class VI Well Plugging, Post-Injection Site Care, and Site Closure Guidance* provides information to help owners or operators perform the necessary activities to successfully transition from the operational phase of a Class VI GS project to the PISC phase and, ultimately, to site closure.

After injection ceases at a Class VI GS project, the injection well must be plugged to ensure that the well does not become a conduit for fluid movement into USDWs [40 CFR 146.92]. Required injection well plugging activities include flushing the well with a buffer fluid, testing the external mechanical integrity of the well, and emplacing cement into the well in a manner that will prevent fluid movement that may endanger USDWs [40 CFR 146.92(a) and (b)]. Additionally, materials used for injection well plugging must be compatible with the injectate [40 CFR 146.92(b)(5)].

This document provides information on performing mechanical integrity testing prior to well plugging; preparing the well for plugging; and selecting plugging materials, plug depths, and emplacement methods [40 CFR 146.92(b)(4)-(6)] that may help owners or operators meet these requirements, but it does not create new legally binding requirements. Other relevant guidance documents are referred to as appropriate. The document also provides guidance on preparing the required notices of intent to plug and plugging reports. Owners or operators are encouraged to consider using similar procedures when plugging monitoring wells.

The PISC phase involves monitoring as specified in the UIC Program Director-approved PISC and Site Closure Plan [40 CFR 146.93(a); 40 CFR 146.82(a)(17)]. This monitoring is an extension of the monitoring conducted during the operational phase of the project to ensure that USDWs are protected from endangerment. The EPA anticipates that it will be similar to operational phase monitoring; however, changes to the frequency and types of monitoring may be made during the PISC phase (e.g., a decrease in monitoring frequency). Changes in PISC monitoring after permit issuance must be made through approved amendments to the PISC and Site Closure Plan [40 CFR 146.93(a)(4)].

PISC must continue for a timeframe established in the permit (i.e., 50 years or an alternative approved timeframe established based on site-specific data, modeling, and other required lines of evidence as described at 40 CFR 146.93(c) demonstrating non-endangerment). During PISC, an owner or operator may be able to demonstrate non-endangerment of USDWs in advance of the 50-year period or alternative timeframe established in the permit [40 CFR 146.93(b)(2)]. Under such circumstances, the owner or operator may submit non-endangerment information to the UIC Program Director to support site closure, and the UIC Program Director may, with substantial evidence that the geologic sequestration project no longer poses a risk of endangerment to USDWs, subsequently authorize early site closure. This guidance document includes considerations and recommendations to help owners or operators obtain approval of an alternate PISC timeframe (i.e., other than the 50-year default) during permitting; revise the PISC timeframe; and make a non-endangerment demonstration to obtain approval for site closure.

The guidance also discusses the information that the owner or operator must submit to demonstrate non-endangerment [40 CFR 146.93(b)(3)] and show that no additional monitoring is needed before the UIC Program Director authorizes site closure. Once the non-endangerment demonstration is approved by the UIC Program Director and site closure has been authorized, a notice of intent to close must be submitted 120 days prior to site closure [40 CFR 146.93(d)]; following site closure, a site closure report must be sent to the UIC Program Director within 90 days [40 CFR 146.93(f)]. The types of documentation to be included in the notifications (e.g., well plugging records, notification to authorities, records regarding the injectate) are described at 40 CFR 146.93(f). This document includes guidance on providing the information the UIC Program Director will need to make a decision regarding site closure, as well as guidance on completing requirements for the site closure report. This guidance should be interpreted as providing recommendations on how to meet the Class VI requirements. Examples provided in this guidance are purely illustrative and do not create additional regulatory requirements.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AoR	Area of Review
API	American Petroleum Institute
AWWA	American Water Works Association
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
CFR	Code of Federal Regulations
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EPA	United States Environmental Protection Agency
GS	Geologic Sequestration
MIT	Mechanical Integrity Test
NETL	National Energy Technology Laboratory
PISC	Post-Injection Site Care
QA/QC	Quality Assurance/Quality Control
RCRA	Resource Conservation and Recovery Act
SC	Specific Conductivity
SDWA	Safe Drinking Water Act
TDS	Total Dissolved Solids
TVD	True Vertical Depth
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USEPA	United States Environmental Protection Agency

Definitions

Key to definition sources:

1: Source: 40 CFR 144.3.
2: Class VI Rule Preamble.
3: Source: 40 CFR 146.81(d).
4: This definition is included for the purposes of this document.
5: Source: 40 CFR 144.6(f) and 144.80(f).

Administrator means the Administrator of the United States Environmental Protection Agency, or an authorized representative.[1]

Annulus means the space between the well casing and the wall of the borehole; the space between concentric strings of casing; or the space between casing and tubing.[2]

Area of review (AoR) means the region surrounding the geologic sequestration project where USDWs may be endangered by the injection activity. The AoR is delineated using computational modeling that accounts for the physical and chemical properties of all phases of the injected carbon dioxide stream and displaced fluids, and is based on available site characterization, monitoring, and operational data as set forth in 40 CFR 146.84.[3]

Bottomhole pressure means the pressure at the bottom of the well bore within the injection zone. It may be measured directly with a downhole pressure transducer, or in some cases estimated from the surface pressure and the height and density of the fluid column.[4]

Brine means water that has a quantity of salt, especially sodium chloride, dissolved in it. Large quantities of brine are often produced along with oil and gas.[4]

Carbon dioxide plume means the extent underground, in three dimensions, of an injected carbon dioxide stream.[3]

Carbon dioxide stream means carbon dioxide that has been captured from an emission source (e.g., a power plant), plus incidental associated substances derived from the source materials and the capture process, and any substances added to the stream to enable or improve the injection process. This subpart [Subpart H of 40 CFR 146] does not apply to any carbon dioxide stream that meets the definition of a hazardous waste under 40 CFR part 261.[3]

Casing means pipe material placed inside a drilled hole to prevent the hole from collapsing. The two types of casing in most injection wells are (1) surface casing, the outermost casing that extends from the surface to the base of the lowermost USDW, and (2) long-string casing, which extends from the surface to or through the injection zone.[2]

Cement means material used to support and seal the well casing to the rock formations exposed in the borehole. Cement also protects the casing from corrosion and prevents movement of injectate up the borehole. The composition of the cement may vary based on the well type and purpose; cement may contain latex, mineral blends, or epoxy.[2]

Class VI wells means wells that are not experimental in nature that are used for geologic sequestration of carbon dioxide beneath the lowermost formation containing a USDW; or, wells used for geologic sequestration of carbon dioxide that have been granted a waiver of the injection depth requirements pursuant to requirements at 40 CFR 146.95; or, wells used for geologic sequestration of carbon dioxide that have received an expansion to the areal extent of an existing Class II EOR or EGR aquifer exemption pursuant to 40 CFR 146.4 and 40 CFR 144.7(d).[5]

Computational model means a mathematical representation of the injection project and relevant features, including injection wells, site geology, and fluids present. For a Class VI GS project, site-specific geologic information is used as input to a computational code, creating a computational model that provides predictions of subsurface conditions, fluid flow, and carbon dioxide plume and pressure front movement at that site. The computational model comprises all model inputs and predictions (i.e., outputs).[4]

Confining zone means a geologic formation, group of formations, or part of a formation stratigraphically overlying the injection zone(s) that acts as barrier to fluid movement. For Class VI wells operating under an injection depth waiver, confining zone means a geologic formation, group of formations, or part of a formation stratigraphically overlying and underlying the injection zone(s).[3]

Corrective action means the use of Program Director-approved methods to ensure that wells within the AoR do not serve as conduits for the movement of fluids into USDWs.[3]

Corrosive means having the ability to wear away a material by chemical action. Carbon dioxide mixed with water forms carbonic acid, which can corrode well materials.[2]

Enhanced Oil or Gas Recovery (EOR/EGR) typically means the process of injecting a fluid (e.g., water, brine, or carbon dioxide) into an oil- or gas-bearing formation to recover residual oil or natural gas. The injected fluid thins (decreases the viscosity) and/or displaces extractable oil and gas, which is then available for recovery. This is also used for secondary or tertiary recovery.[2]

Fluid means any material or substance which flows or moves whether in a semisolid, liquid, sludge, gas, or any other form or state.[1]

Formation or geological formation means a layer of rock that is made up of a certain type of rock or a combination of types.[2]

Geologic sequestration (GS) means the long-term containment of a gaseous, liquid, or supercritical carbon dioxide stream in subsurface geologic formations. This term does not apply to carbon dioxide capture or transport.[3]

Geologic sequestration project means an injection well or wells used to emplace a carbon dioxide stream beneath the lowermost formation containing a USDW; or, wells used for geologic sequestration of carbon dioxide that have been granted a waiver of the injection depth requirements pursuant to requirements at 40 CFR 146.95; or, wells used for geologic sequestration of carbon dioxide that have received an expansion to the areal extent of an existing Class II EOR or EGR aquifer exemption pursuant to 40 CFR 146.4 and 144.7(d). It includes the subsurface three-dimensional extent of the carbon dioxide plume, associated area of elevated pressure, and displaced fluids, as well as the surface area above that delineated region.[3]

Geophysical surveys refers to the use of geophysical techniques (e.g., seismic, electrical, gravity, or electromagnetic surveys) to characterize subsurface rock formations.[2]

Injectate means the fluids injected. For the purposes of the Class VI Rule, this is also known as the carbon dioxide stream.[2]

Injection zone means a geologic formation, group of formations, or part of a formation that is of sufficient areal extent, thickness, porosity, and permeability to receive carbon dioxide through a well or wells associated with a GS project.[3]

Mechanical integrity means the absence of significant leakage within the injection tubing, casing, or packer (known as internal mechanical integrity), or outside of the casing (known as external mechanical integrity).[2]

Mechanical integrity test (MIT) refers to a test performed on a well to confirm that a well maintains internal and external mechanical integrity. MITs are a means of measuring the adequacy of the construction of an injection well and a way to detect problems within the well system.[2]

Model means a representation or simulation of a phenomenon or process that is difficult to observe directly or that occurs over long timeframes. Models that support GS can predict the flow of carbon dioxide within the subsurface, accounting for the properties and fluid content of the subsurface formations and the effects of injection parameters.[2]

Mud refers to a generic term for a wide range of drilling fluids, usually water or oil but occasionally synthetically based, with high concentrations of suspended solids.[4]

Packer means a mechanical device that seals the outside of the tubing to the inside of the long-string casing, isolating an annular space.[2]

Parameter means a mathematical variable used in governing equations, equations of state, and constitutive relationships. Parameters describe properties of the fluids present, porous media, and fluid sources and sinks (e.g., injection wells). Examples of model parameters include intrinsic permeability, fluid viscosity, and fluid injection rate.[4]

Plug means a watertight, gastight seal installed in a borehole or well to prevent movement of fluids; it may be mechanical or composed of cement or other materials capable of zonal isolation.[4]

Portland cement refers to a hydraulic cement made by reacting a pulverized calcium silicate hydrate material (C-S-H), which in turn is made by heating limestone and clay in a kiln with water to create a calcium silicate hydrate and other reaction products.[4]

Post-injection site care (PISC) means appropriate monitoring and other actions (including corrective action) needed following cessation of injection to ensure that USDWs are not endangered, as required under 40 CFR 146.93.[3]

Pressure front means the zone of elevated pressure that is created by the injection of carbon dioxide into the subsurface. For GS projects, the pressure front of a carbon dioxide plume refers to the zone where there is a pressure differential sufficient to cause the movement of injected fluids or formation fluids into a USDW.[3]

Site closure means the point/time, as determined by the Director following the requirements under §146.93, at which the owner or operator of a GS site is released from post-injection site care responsibilities.[3]

Supercritical fluid means a fluid above its critical temperature (31.1ºC for carbon dioxide) and critical pressure (73.8 bar for carbon dioxide).[4]

Total dissolved solids (TDS) refers to the total dissolved (filterable) solids as determined by use of the method specified in 40 CFR part 136.6.[1]

Transmissive fault or fracture means a fault or fracture that has sufficient permeability and vertical extent to allow fluids to move between formations.[3]

Tubing refers to a small-diameter pipe installed inside the casing of a well. Tubing conducts injected fluids from the wellhead at the surface to the injection zone and protects the long-string casing of a well from corrosion or damage by the injected fluids.[4]

Underground Injection Control (UIC) Program refers to the program the EPA, or an approved state, is authorized to implement under the Safe Drinking Water Act (SDWA) and that is responsible for regulating the underground injection of fluids by well injection.[4]

Underground Injection Control (UIC) Program Director refers to the chief administrative officer of any approved state or tribal agency or the EPA Region that has been delegated to operate an approved UIC Program.[4]

Underground Source of Drinking Water (USDW) means an aquifer or its portion which supplies any public water system; or which contains a sufficient quantity of ground water to supply a public water system; and currently supplies drinking water for human consumption; or contains fewer than 10,000 mg/l total dissolved solids; and which is not an exempted aquifer. [1]

Well bore refers to the hole that remains throughout a geologic (rock) formation after a well is drilled.[4]

Well plugging refers to the act of sealing off a well so that all USDWs and producing zones are zonally isolated and the well bore, casings, and annulus can no longer act as a conduit for fluids. Plugging typically involves the injection of alternating layers of mud and cement into the well bore, casings, and annulus.[4]

Workover refers to any maintenance activity performed on a well that involves ceasing injection and removing the wellhead.[4]

1 Introduction

The Underground Injection Control (UIC) Program of the United States Environmental Protection Agency (EPA) is responsible for regulating the construction, operation, permitting, and closure of injection wells that place fluids underground. The EPA's *Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells* [40 CFR 146.81 et seq.], referred to as the Class VI Rule, created a new UIC injection well class, Class VI, specifically for the injection of a carbon dioxide stream for the purpose of geologic sequestration (GS).

1.1 Guidance Scope and Purpose

The potential for endangerment of underground sources of drinking water (USDWs) during the operation of a Class VI GS project increases during the injection phase as carbon dioxide is injected and subsurface pressures increase. Following cessation of injection, the potential for endangerment of USDWs will likely decrease as the carbon dioxide plume begins to dissipate and subsurface pressures decline. Each project will behave uniquely, governed by site-specific factors, which determine the actual magnitude of and change in USDW endangerment potential across the phases of a Class VI GS project, from injection through post-injection, to site closure.

To address the potential for USDW endangerment following the cessation of injection (i.e., during the post-injection site care (PISC) phase), the Class VI Rule at 40 CFR 146.92 and 146.93 includes requirements that owners or operators must meet to properly plug their injection well or wells, monitor the site until a satisfactory demonstration of non-endangerment is made, and close the Class VI GS site. Well plugging is performed as described in an Injection Well Plugging Plan required at 40 CFR 146.92(b), and post-injection site care and site closure activities are implemented pursuant to the Class VI PISC and Site Closure Plan, required at 40 CFR 146.93(a). These provisions of the Class VI Rule require that the owner or operator submit, and the UIC Program Director approve, the plans for each Class VI well.

The purpose of this guidance is to explain these requirements for Class VI well owners or operators and UIC Program Directors through the use of non-binding suggestions and examples of project activities related to the post-injection phase and site closure (as indicated by the use of "may" or "should" when describing activities). The EPA encourages communication between the owner or operator and the UIC Program Director throughout the process of planning for and executing all aspects of the Class VI GS project, including well plugging and PISC. Further, while this document addresses later-phase activities at Class VI projects (i.e., well plugging, post-injection site care and site closure), owners or operators may find it useful when developing their permit application and relevant plans as it contains guidance supportive of those efforts and associated requirements.

1.2 Injection Well Plugging Requirements

Well plugging refers to the activities associated with removing well components, flushing the well, and installing plugs. Proper well plugging is important for ensuring that the well is properly abandoned and does not provide a conduit for fluid movement that might endanger USDWs.

Class VI well owners or operators must prepare, maintain, and comply with an Injection Well Plugging Plan [40 CFR 146.92(b)] that comports with the regulations and includes conditions regarding the approach the owner or operator will take to meet the requirements at 40 CFR 146.92(a) and 146.92(b)(1) through (b)(5), including the following steps: flush each injection well with a buffer fluid, determine bottomhole pressure, perform a final external mechanical integrity test (MIT), and plug the well with materials that are compatible with the carbon dioxide stream. The requirements for plugging Class VI injection wells are included in the Class VI Rule at 40 CFR 146.92 and are discussed in detail in Section 2 of this guidance. The EPA recognizes that injection wells may be converted for use as monitoring wells after injection ceases and that, consequently, injection well plugging may not occur immediately after the cessation of injection. Where an injection well is to be used as a monitoring well during the PISC phase of a Class VI project, the well must be plugged (once it is no longer being used as a monitoring well) following procedures outlined in the UIC Director-approved Injection Well Plugging Plan and at 40 CFR 146.92.

The procedures required at 40 CFR 146.92 apply specifically to injection wells. However, owners or operators may consider employing the same well plugging procedures when plugging monitoring wells (i.e., that have not also been used for injection) at the end of the PISC phase (see Section 4.2). Performing such activities on monitoring wells will help to demonstrate non-endangerment to USDWs [40 CFR 146.93(b)(2)] and help ensure that the wells do not allow movement of injection or formation fluids [40 CFR 146.93(e)].

1.3 Post-Injection Site Care Requirements

The PISC phase is the time period immediately following cessation of injection until site closure is authorized. During the PISC phase, an owner or operator must conduct monitoring and other actions needed to ensure that USDWs are not endangered as required at 40 CFR 146.93. It is expected that subsurface pressure will decline during PISC and the risk of endangerment to USDWs will also decrease. However, during this period, the injected carbon dioxide stream can remain mobile and elevated subsurface pressures can persist. Monitoring continues during PISC to ensure that USDWs are not endangered.

Owners or operators of Class VI wells must prepare, maintain, and comply with a PISC and Site Closure Plan [40 CFR 146.93(a)]. The plan, which must be submitted with the permit application, must be site-specific and relate to factors that may endanger USDWs. Specifically, owners or operators must monitor the site to show the position of the carbon dioxide plume and pressure front and demonstrate that USDWs are not endangered during the approved PISC monitoring timeframe [40 CFR 146.93(b)]. The purpose of these requirements is to ensure that any endangerment to USDWs is detected quickly and appropriate remediation/corrective action is taken promptly.

Section 3 discusses PISC, including monitoring, the default and alternative PISC timeframes, the evaluation of the reduction of endangerment to USDWs during the PISC phase, and the non-endangerment demonstration that are required during this phase of the Class VI GS project.

1.4 Site Closure Requirements

Site closure refers to the procedures and period immediately following PISC, when an owner or operator must plug and abandon all monitoring wells to enable the end of the Class VI project and conclusion of the permit [40 CFR 146.93(e)]. Site closure commences only when all monitoring wells have been properly plugged, a non-endangerment demonstration has been successfully made, and site closure is authorized by the UIC Program Director. Because 40 CFR 146.93(e) expressly requires the owner or operator to plug all monitoring wells as part of the site closure process, the regulations preclude the continued use of monitoring wells associated with a Class VI permit after site closure. If an entity wants to perform other monitoring (such as shallow ground water monitoring), that entity must conduct any such activity outside of and separate from activities associated with the UIC Class VI permit.

Site closure requirements are established to ensure that all PISC monitoring wells are plugged appropriately and to the UIC Program Director's satisfaction, that all project records are maintained, and that future land owners are made aware of the project and previous land use. Accordingly, the owner or operator must provide the UIC Program Director with a notice of intent for site closure at least 120 days prior to site closure [40 CFR 146.93(d)], plug all monitoring wells [40 CFR 146.93(e)], submit a site closure report within 90 days of site closure [40 CFR 146.93(f)], and record a notation in the deed or similar document [40 CFR 146.93(g)]. Note that following site closure, the owner or operator is responsible for any remedial action deemed necessary to prevent USDW endangerment caused by the injection operation (see Section 4.4). Site closure requirements are discussed in further detail in Section 4.

1.5 Relationship of This Guidance to Other Guidance Documents

This document is part of a series of technical guidance documents intended to provide information and possible approaches for addressing various aspects of permitting and operating a UIC Class VI injection well. Other UIC Program GS guidance documents that owners or operators performing injection well plugging, PISC, and site closure activities may find useful are available on the UIC Program's website at https://www.epa.gov/uic/class-vi-wells-used-geologic-sequestration-co2.

2 Well Plugging

Class VI well owners or operators must develop [40 CFR 146.92(b)] and implement [40 CFR 146.92(a)] Injection Well Plugging Plans that support plugging of injection wells in a manner that ensures USDW protection. This section includes a discussion of the UIC Class VI injection well plugging requirements and practices that may be used to help meet the plugging requirements for injection wells associated with a Class VI GS project. Additionally, the EPA recommends that owners or operators apply similar well plugging practices when plugging monitoring wells to ensure that these wells do not become conduits for fluid movement that can endanger USDWs. Some information in this document has been incorporated from other UIC Program guidance documents (USEPA, 1982; USEPA, 1989). This Section references guidance from the American Petroleum Institute (API, 1993) as well as more recent literature on specialty plugging materials (e.g., Englehardt and Wilson, 2001; Clark and Salsbury, 2003; Meyer 2007; Liversidge and Agarwal, 2006; Le Roy-Delage et al., 2000; Nagelhout et al., 2005) that may be suitable for the unique aspects of a Class VI GS project (i.e., carbon dioxide-bearing fluids in the injection zone). In addition, the *UIC Program Class VI Well Testing and Monitoring Guidance* describes, in detail, several testing activities that are discussed briefly below (e.g., mechanical integrity testing).

2.1 Purpose of Well Plugging

Proper plugging of injection and monitoring wells is a long-standing requirement of the UIC Program, designed to ensure that wells do not serve as conduits for fluid movement into USDWs following cessation of injection and site closure. Just as requirements and best practices for primary cementing are designed to produce properly constructed wells with mechanical integrity, the Class VI well plugging requirements [40 CFR 146.92; 40 CFR 146.93(e)] are intended to ensure that an abandoned well maintains integrity and will not pose a threat to USDWs. For this reason, well plugging activities must be described in the Injection Well Plugging Plan [40 CFR 146.92(b); 40 CFR 146.82(a)(16)], properly performed per 40 CFR 146.92(b), and documented in plugging reports [40 CFR 146.92(d)] and the site closure report [40 CFR 146.93(f)(1)] to the satisfaction of the UIC Program Director.

2.2 Timing of Well Plugging

Plugging activities may begin upon cessation of injection. However, the immediate plugging of the injection well is not a requirement, as some owners or operators may elect to convert an injection well to a monitoring well either for a brief or extended period. In either scenario, once injection has ceased, the owner or operator may choose to: plug the well and complete all plugging activities, perform some of the preparatory activities (e.g., mechanical integrity testing, well cleaning) and recomplete the well for monitoring purposes, or, maintain the original well configuration provided the well retains mechanical integrity and USDW protection is ensured. The EPA recommends that any recompletion take place as soon as practical to allow continued acquisition of pressure data. In the case of recompletion of the injection well, the owner or operator will be required to plug the well once it is no longer being used as a monitoring well and/or upon demonstration of non-endangerment made for site closure [40 CFR 146.93(e)]. Regardless of the timing of injection well plugging, the plugging must be done in a manner pursuant to requirements at 40 CFR 146.92 to ensure that the well does not become a conduit for fluid movement into USDWs. The plugging must be performed according to the approved Injection Well Plugging Plan.

The Class VI Rule, at 40 CFR 146.92(c), requires that the owner or operator notify the UIC Program Director in writing at least 60 days before plugging the injection well (an example template of a notice of intent to plug is available for download from the GS Data Tool, or GSDT). At this time, if any changes have been made to the original approved Injection Well Plugging Plan, the owner or operator must also provide the amended Injection Well Plugging Plan [40 CFR 146.92(c)]. This 60-day time period allows for an ongoing dialogue between the owner or operator and the UIC Program Director regarding planned well plugging activities. Once well plugging procedures have been finalized, or confirmation is made through owner or operator-UIC Program Director coordination that no changes to the Injection Well Plugging Plan are necessary, well plugging may proceed. The owner or operator must submit a well plugging report to the UIC Program Director within 60 days of plugging the injection well [40 CFR 146.92(d)].

Monitoring wells must also ultimately be plugged [40 CFR 146.93(e)]. Some (if not all) monitoring wells will need to remain in use during PISC to perform required monitoring; the locations to be sampled will be specified in the approved PISC and Site Closure Plan [40 CFR 146.93(a)(2)(iii)]. However, if any monitoring wells will not be used in the post-injection monitoring program, or if the PISC and Site Closure Plan is amended during the PISC phase of the project [40 CFR 146.93(a)(4)], the EPA recommends that the owner or operator plug monitoring wells that will no longer be used for sampling to eliminate the potential that they become conduits for fluid movement. Thus, the plugging schedule for monitoring wells may be adjusted as appropriate in consultation with the UIC Program Director and reflected in changes to the PISC and Site Closure Plan.

Because improperly abandoned monitoring wells may become conduits for fluid movement into USDWs (similar to improperly abandoned injection wells), the EPA recommends that owners or operators plug their monitoring wells in a manner similar to that used to meet the requirements for injection well plugging, as discussed in Sections 2.5 and 2.6. Section 4.2 of this guidance document includes a more detailed discussion of monitoring well plugging.

At the end of PISC, and after the UIC Program Director has authorized site closure, the owner or operator must demonstrate that all monitoring and injection wells have been plugged in a manner that will not allow movement of injection or formation fluids that endangers a USDW [40 CFR 146.93(e); 40 CFR 146.93(f)(1)].

2.3 Development and Submittal of Injection Well Plugging Plan

The Class VI Rule at 40 CFR 146.82(a)(16) requires owners or operators to prepare and submit a proposed Injection Well Plugging Plan with the permit application for approval by the UIC Program Director. The UIC Program Director-approved plan is incorporated into the Class VI permit as an enforceable condition. Flexibility exists to modify the plan at a later date based on information generated during the operational phase of the project; however, the Class VI Rule requires submission of the plan as part of the permit application.

The Injection Well Plugging Plan must include a description of how the owner or operator will meet the Class VI injection well plugging requirements at 40 CFR 146.92. Details regarding activities related to the plan are described below and in the following Sections 2.4 through 2.7. The plan must include the following information:

- Appropriate tests or measures for determining bottomhole reservoir pressure [40 CFR 146.92(b)(1)] (to help determine the appropriate plugging fluid density);
- Appropriate testing methods to ensure external mechanical integrity as specified at 40 CFR 146.89 [40 CFR 146.92(b)(2)] (to help demonstrate that the long-string casing and cement that are left in the ground after the well is plugged will maintain their integrity);
- The type and number of plugs to be used for plugging the injection well [40 CFR 146.92(b)(3)];
- The placement of each plug, including the elevation of the top and bottom of each plug [40 CFR 146.92(b)(4)] (the EPA recommends that elevations be submitted along with schematics and drawings, if appropriate);
- The type, grade, and quantity of material to be used in plugging. The material must be compatible with the carbon dioxide stream [40 CFR 146.92(b)(5)]; and
- The method of placement of the plugs [40 CFR 146.92(b)(6)] (e.g., the balance method, retainer method, or two-plug method can be used).

Stratigraphic information for the GS site, such as the location and thickness of the injection zone and USDW-containing formations, their geochemistry, well construction details, and the composition of the carbon dioxide stream are important factors to consider while developing an Injection Well Plugging Plan. For this reason, the UIC Program Director will evaluate the plan in conjunction with other information in the permit application, including site characterization data and other proposed plans, such as the Well Construction Plan and proposed operating conditions. Therefore, submittal, evaluation, and approval of the Injection Well Plugging Plan may be an iterative process, and the EPA encourages ongoing communication between the owner or operator and the UIC Program Director.

Although the Class VI Rule does not require periodic reviews and amendments to the Injection Well Plugging Plan throughout the operation/injection phase, the EPA recommends that owners or operators evaluate how any changes in facility operation, any new data collected during monitoring and/or area of review (AoR) reevaluations, or any adverse events that required an emergency response may warrant amendments to the various plans, including the Injection Well Plugging Plan. Such revisions to the Injection Well Plugging Plan may be made at any time during the life of the project, but must be submitted when notifying the UIC Program Director of the intent to plug the well at least 60 days prior to conducting the plugging activity [40 CFR 146.92(c)]. Owners or operators are encouraged to also update the value of financial responsibility instruments to ensure adequate coverage of well plugging costs; refer to the *UIC Program Class VI Financial Responsibility Guidance* for additional information.

The *UIC Program Class VI Well Project Plan Development Guidance* further describes Injection Well Plugging Plan development, including details on: what specific information must be included in the plan, how the plan should be structured, how the amendments to the plan should be made, and what underlying data must be submitted with the plan. An example template of an Injection Well Plugging Plan is available for download from the GSDT; however, use of the template is not required.

2.4 Tests to Perform Prior to Plugging

Prior to injection well plugging, the Class VI Rule requires that the owner or operator flush each Class VI injection well with a buffer fluid (discussed in Section 2.5), determine bottomhole reservoir pressure, and perform a final external MIT [40 CFR 146.92(a)]. Determination of bottomhole pressure and mechanical integrity are needed to plan any remedial activities and to ensure that plugging materials and procedures are selected correctly.

2.4.1 Determination of Bottomhole Reservoir Pressure

Bottomhole pressure refers to the pressure of the fluids at the location of the perforations (i.e., screened interval) of the injection well. Prior to plugging a Class VI well, the owner or operator is required to determine bottomhole pressure pursuant to requirements at 40 CFR 146.92(a), using the tests or measures described in the approved Injection Well Plugging Plan [40 CFR 146.92(b)(1)]. The purposes of testing bottomhole reservoir pressure prior to plugging are to: (1) determine the density of fluid that should be used during flushing and well cleaning; (2) determine the density of plugging (buffer) fluid needed to establish static equilibrium prior to plug emplacement; and (3) obtain a measurement of pressure at the injection well that should be used in calculations of pressure decay within the injection zone.

After injection ceases and the well is shut in, bottomhole pressure can be estimated from downhole pressure transducers or, in some cases, wellhead (i.e., surface) pressure measurements. If a single fluid phase is present in the well bore, wellhead pressure measurements may be used with knowledge of the average fluid density and the true vertical depth (TVD) of the well. Bottomhole pressure is equal to wellhead pressure plus the hydrostatic pressure from the weight of the fluid column between the wellhead and well bottom (Figure 1). However, when separate fluid phases are present in the well bore (e.g., gas and supercritical fluid), more complex thermodynamic modeling methods will be needed to estimate bottomhole pressure from wellhead pressure (see, e.g., Nurafza and Fernagu, 2009).

A more direct and more robust approach for determining bottomhole pressure is to obtain actual measurements with a dedicated downhole pressure transducer or with a pressure gauge lowered into the borehole. Although not required by the Class VI Rule, downhole pressure gauges collect direct measurements of reservoir pressure rather than inferring bottomhole pressure through other measurements. The *UIC Program Class VI Well Testing and Monitoring Guidance* includes additional information regarding measurement of well pressures.

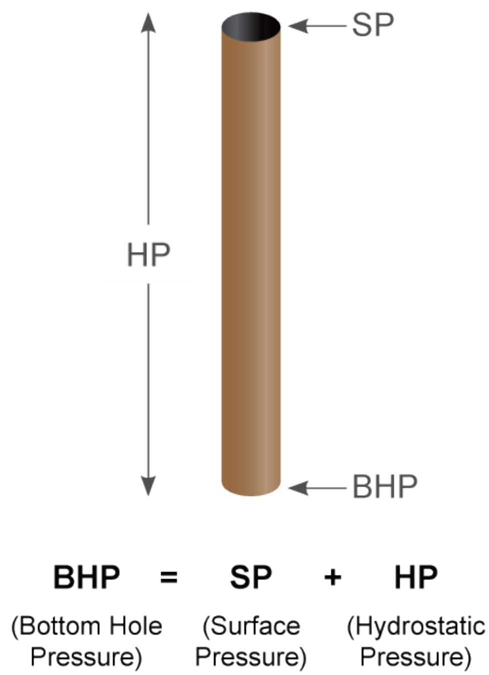


Figure 1. Relationship Between Bottomhole Pressure and Surface Pressure.
Adapted from: Drilling Formulas and Drilling Calculations (no date).

2.4.2 Mechanical Integrity Testing

Prior to injection well plugging, the owner or operator must perform a final external MIT as required at 40 CFR 146.92(a). The purpose of conducting a final MIT is to verify the absence of leakage through channels adjacent to the well bore or the well's long-string casing that may result in significant fluid movement into a USDW [40 CFR 146.89(a)]. The testing methods must be specified in the UIC Program Director-approved Injection Well Plugging Plan, which must describe testing methods to ensure external mechanical integrity as specified in 40 CFR 146.89 [40 CFR 146.92(b)(2)]. Unless an alternative test is approved by the EPA Administrator and the UIC Program Director under 40 CFR 146.89(e), the Class VI Rule at 40 CFR 146.89(c) requires that the owner or operator use either an approved tracer survey such as an oxygen activation log; or a temperature or a noise log.

A Class VI well has external mechanical integrity if there is no significant fluid movement into a USDW through channels adjacent to the injection well bore. A demonstration of external mechanical integrity indicates that the cement and casing that are left in the ground after well plugging and site closure will retain integrity over time. If a loss of external mechanical integrity is detected within the well, appropriate corrective action must be taken during or prior to well plugging pursuant to 40 CFR 146.88(f)(4), as described in Section 2.5. Further information regarding external MITs is available in the *UIC Program Class VI Well Testing and Monitoring Guidance.*

2.5 Preparation of Well Prior to Plugging

Preparation of the injection well for plugging is important for ensuring the establishment of solid plugs and long-term protection of USDWs. Several activities are necessary at this preparatory stage: well cleaning, remedial operations, and the establishment of static equilibrium within the well. The EPA emphasizes that injection zone pressure should be controlled at all times to prevent flow out of the injection zone. Pressure control is accomplished through the use of workover and plugging (buffer) fluids that are correctly weighted and compatible with the injectate and formation fluids. Because an improperly abandoned monitoring well can pose a risk of endangerment to USDWs, the EPA recommends that monitoring wells be similarly prepared for plugging.

2.5.1 Well Inspection and Initial Preparation

Prior to well plugging, the EPA recommends that the owner or operator identify details on well construction, geologic information in the vicinity of the well bore, and information on the dominant geochemistry around the well bore and of formation fluids. This information may support decisions on the placement of each plug and the type, grade, and quantity of material to be used in plugging. Information on well construction, geology, and geochemistry will also allow an assessment of compatibility of the materials with the environment in the vicinity of the well, including the formation fluids. The Class VI Rule requires that information on the plugging materials be specified in the Injection Well Plugging Plan [40 CFR 146.92(b)(5)]; if the information identified in this initial preparation stage suggests that changes are needed, an amended Injection Well Plugging Plan will need to be submitted with the notice of intent to plug [40 CFR 146.92(c)].

2.5.2 Well Cleaning

2.5.2.1 Flushing of Well

Prior to well plugging, the well must be flushed [40 CFR 146.92(a)]. This is done with workover fluids, specially prepared brines or muds that are circulated through the well to remove any remaining fluids or fine debris (USEPA, 1982). To reduce the potential for corroding well materials, the workover fluid should be chemically compatible with both formation fluids and solids in the downhole environment. In the case of a Class VI GS project, the workover fluid must be compatible with carbon dioxide and carbon dioxide-rich brines and must, therefore, be buffered against low pH conditions that might be encountered downhole [40 CFR 146.92(a)].

All sections of the well that will be left intact after plugging and have been in contact with injection or annular fluids should be flushed. These components include the annular space (between the tubing and the casing), long-string casing, perforated zone, and possibly the injection packer. Flushing is done using fluids with sufficient density to prevent fluid movement up the wellbore (IEAGHG, 2009). After the well has been killed, the packer can be removed and unseated and flushing fluid circulated through the tubing. Alternatively, packer and tubing may be removed and flushing done with a separate tubing. If the packer cannot be removed, the tubing can be cut and a separate tubing can be used to flush the well.

2.5.2.2 Removal of Well Components and Obstructions

The removal of well equipment prior to plugging is necessary to open the well for access. In general, uncemented and non-permanent components of the well should be removed. This includes downhole monitoring devices, such as pressure transducers, and the downhole shut-off device if installed. Injection tubing is almost always removed because it serves no purpose after the operational phase of the project (USEPA, 1989); removal is done with a workover rig. The packer may be retrievable, or it may be permanent. If it is permanent and cannot be removed, it may be drilled through (USEPA, 1989) or used as a platform for the first cement plug. If the tubing and packer cannot be removed, the tubing should be cut directly above the packer.

At this stage, larger debris such as metal pins and tools can be removed using a junk basket/retriever or a "fishing" magnet. In some cases, it may not be possible to remove all pieces of larger debris from the well. Pieces of equipment inadvertently lodged downhole may need to be milled or drilled through if they cannot be retrieved.

Casing that is not cemented to the formation poses a fluid migration risk. Because the surface and long-string casings in a Class VI injection well will be cemented to the surface [40 CFR 146.86(b)(2) and (3)], they will generally not be removed. For monitoring wells that predate the project, however, there may be sections of uncemented casing. Wells that were converted to Class VI from other types of wells, and where the UIC Program Director approved alternative cement configurations as being protective of USDWs, could conceivably also have uncemented casing sections. If so, the free casing should be removed, or the owner or operator may need to squeeze cement behind portions of the casing to ensure zonal isolation and prevent fluid migration that could endanger USDWs.

2.5.3 Remedial Operations

Deficiencies found during well inspections at any phase of a Class VI GS project (e.g., during injection or in preparation for well plugging) may include cement channeling, casing leaks, corroded sections of casing, and collapsed sections of casing (USEPA, 1989). Owners or operators are required to repair any deficiencies to ensure that the casing does not leak during or after well plugging and potentially endanger USDWs [40 CFR 146.88(f)]. The owner or operator should take into account the results of external mechanical integrity testing, as well as historical MIT data and records of any remedial work done during the lifetime of the well, to locate areas of concern when planning remedial operations. As information on potential remediation needs emerges, the EPA encourages owners or operators to include planned remedial activities in any amendments to the Injection Well Plugging Plan.

In the case of a buckled or collapsed casing, the casing may be opened up using a casing roller or swaging tool (USEPA, 1989). Squeeze cementing, however, is the most common remedial measure, and it is used in cases of channeled or absent cement behind the casing. This procedure serves to protect against fluid movement behind the casing, and it is considered an important step in ensuring the long-term protection of USDWs.

Squeeze cementing involves placing a cement slurry across a leaking section of casing. Hydraulic pressure is used to force the cement through leaks or perforations in the casing to provide a cement seal between the casing and the formation. Cement squeezes can also be used in well plugging as discussed in Section 2.6.4. If a section of the well bore requires cementing behind the casing (e.g., due to defects from primary cementing), but the casing does not have leaks or perforations, it may be necessary to perforate the casing first. If a portion of casing is uncemented (e.g., in a monitoring well), and the casing is to be left in place, it may be necessary to circulate cement behind the casing through perforations to provide a new cement sheath.

Owners or operators should ensure that the squeeze pressure and cement slurry are correctly selected. The pressure should be sufficient to force the cement into the desired zone without fracturing the formation or compromising casing integrity. The cement slurry will need to be compatible with the formation and should be formulated to control filtration of water from the cement solids (formation of filter cake). Owners or operators may wish to consult with the UIC Program Director regarding squeeze cementing and will need to demonstrate to the UIC Program Director that the remedial squeezing was appropriate in preventing the endangerment of USDWs. More detailed discussion of the basics of squeeze cementing can be found in references such as Smith (1976), Nelson (2006), and IEAGHG (2009). Additional information on cement types is provided in the *UIC Program Class VI Well Construction Guidance, NPC Paper 2-25 (2011),* and below in Section 2.6.2.

2.5.4 Establishment of Static Equilibrium

The last stage of well preparation prior to plugging is to establish static equilibrium within the well bore. This involves introducing a plugging fluid in a way that does not promote excessive fluid mixing and which controls flow into and out of the well. Because at least one long-string casing in a Class VI injection well must extend to the injection zone, effectively creating separation from USDWs and other formations [40 CFR 146.86(b)(3)], loss of fluid to formations along the well bore will not be a significant concern during injection well plugging. However, the plugging fluid should be able to control injection zone pressure. If there are sections of the well bore for which casing has been removed (e.g., in a monitoring well), the plugging fluid must be able to control pressure from high-pressure formations or prevent loss of fluid to low-pressure formations.

The plugging fluid should allow placement of cement plugs at the desired depth and should be suitable to remain as a fluid between the cement plugs, maintaining physical and chemical stability indefinitely (USEPA, 1982). The fluid should have uniform weight and produce minimal movement during the setting and hardening of the cement. Excessive fluid movement during setting can contaminate the slurry or cause it to migrate, resulting in a non-sealing plug with reduced strength (API, 1993; USEPA, 1989; Smith, 1976). Drilling mud and bentonite are often selected as plugging fluids (NPC, 2011); the selected fluid should be formulated to be compatible with the cement and control pressure where necessary. The needed mud weight (density) can be estimated from bottomhole pressure (determined as required at 40 CFR 146.92(a)) and the vertical depth. The formula for estimating the necessary density is:

$$\rho = \frac{P * 19.25}{d}$$

Where ρ is the density in pounds per gallon, P is the downhole pressure in psi, and d is the depth in feet.

A suggested plugging fluid might contain: (1) fresh water or brine; (2) bentonite (gel or clay); (3) attapulgite (a type of clay); and (4) lost circulation material (as needed) (USEPA, 1989). A weighting material such as barite, sand, or hematite may be needed to produce a fluid with greater density. In some areas, KCl, $CaCl_2$, and other brines are common components. The plugging fluid will replace the fluid used for flushing, and it may require several circulations to complete the replacement. After circulation of the fluid, the fluid level in the well should be observed visually to note if there is fluid movement. Adequate circulation and establishment of static conditions with a plugging fluid of appropriate weight and viscosity will help ensure quality cement plugs. USEPA 1989 provides additional information.

2.5.5 Preparation for Recompletion of Injection Well

If a well is to be recompleted for use as a monitoring well, well preparation will be needed. However, steps may be modified as appropriate to prepare for installation of any necessary monitoring hardware. Flushing of the well should be done, small debris should be circulated out, and larger debris should be removed. The injection tubing should be pulled, and any necessary remedial actions should be performed to address casing leaks or defective cement, including those steps outlined in this guidance. After well preparation, recompletion with hardware for monitoring (e.g., downhole fluid sampling systems, sensors) may be done. If needed, new packers may be installed to isolate the injection zone and/or other zones that will be monitored.

An owner or operator who wishes to convert an injection well and has not previously provided plans for doing so must update the monitoring well schematic and the PISC and Site Closure Plan for the UIC Program Director's approval within 30 days of such a change [40 CFR 146.93(a)(4)]. This will allow time for the UIC Program Director to evaluate the conversion and associated specifications. Any injection well that is recompleted to function as a monitoring well remains subject to the well plugging provisions at 40 CFR 146.92, as outlined in the Injection Well Plugging Plan, once use as a monitoring well is terminated.

2.6 Performing Well Plugging

Establishing secure plugs pursuant to 40 CFR 146.92 is a crucial step in ensuring long-term protection of USDWs after a well is no longer in use. Plugging is achieved through the use of mechanical and cement plugs. Mechanical plugs help in isolating high pressure zones such as the injection zone. A series of strategically placed cement plugs, however, provides the primary means of ensuring long term zonal isolation in an abandoned well bore. Issues an owner or operator should consider in planning the plugging activities include: (1) the locations of USDWs; (2) the locations of any previously remediated portions of the well; (3) the design of the cement slurry; and (4) the best method of cement emplacement. At all stages, control of pressure in the injection zone will need to be maintained. If there are any uncased sections, control of exposed high- or low-pressure zones should also be maintained. Although the Class VI Rule requirements at 40 CFR 146.92 apply to plugging of the injection well and there are no specific requirements for monitoring well plugging procedures, the EPA recommends the same considerations for plugging of injection wells be applied to plugging of monitoring wells.

2.6.1 Mechanical (Bridge) Plugs and Inflatable Packers

A mechanical or bridge plug is a downhole tool that is used to isolate a pressurized zone such as the injection zone (Figure 2). The plug is formed around a mandrel and consists of a push sleeve with expandable nitrile elements, which seal off the wellbore. A plug shoe allows cement to be pumped through the plug to seal off areas below the plug. These plugs are often placed in the casing above the injection zone or above other equipment such as a packer or tubing that cannot be removed. They are available in models made with corrosion-resistant alloys. This is important for plugs used to isolate the injection zone in a Class VI well, where the plug will be exposed to carbon dioxide and carbon dioxide-rich fluids. Bridge plugs may be permanent or temporary, and they should be made of strong but sufficiently brittle material, such that they can be drilled through, if necessary, to re-enter the well bore. Those set for the plugging of Class VI wells will likely be permanent, and cement plugs should be emplaced above them. Alternatively, if the owner or operator intends to cement across the perforated injection zone, a cement retainer may be placed at the top of the injection zone, beneath which cement will be squeezed (see Section 2.6.4). Some bridge plugs can also serve as cement retainers.

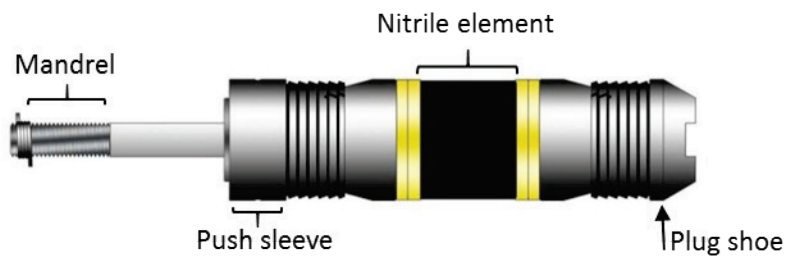


Figure 2. Bridge Plug.
From: Wyoming Completion Technologies (no date).

Inflatable packers, which have rubber and steel components, are a potential alternative to mechanical bridge plugs (e.g., Vaucher and Brooks, 2010). They can pass through restrictions and inflate to several times their original outside diameter. At this time, data are lacking on the performance of these devices in a carbon dioxide-rich environment. However, given their potential utility, interested owners or operators may wish to consult with the UIC Program Director regarding their use to ensure they are appropriate for the given site-specific conditions.

2.6.2 Cement Plugging Materials

The type, grade, and quantity of material to be used in plugging must be specified in the Injection Well Plugging Plan and be compatible with the carbon dioxide stream [40 CFR 146.92(b)(5)]. The cement used for plugs should form a bond with the casing and should be compatible with the plugging fluid. The owner or operator might also consider cement and material compatibility with carbon dioxide-formation fluid mixtures. In addition, the cement slurry needs to be able to be pumped into place and to set and gain strength in a reasonable amount of time (Calvert and Smith, 1994). The cement slurry should also have certain properties with respect to the plugging fluid; it should have a higher yield strength and plastic viscosity. However, differences in the densities of the cement and plugging fluid should be carefully coordinated to allow the cement to be placed at the desired depth (USEPA, 1982; IEAGHG, 2009).

Bottomhole pressure and temperature affect the properties and setting time of the cement and should be taken into account when designing the slurry (Smith, 1976; IEAGHG, 2009). For example, high pressures decrease the setting time, while high temperatures cause cement to lose strength and gain permeability. Depth is also important for determining the necessary placement time, and retarding agents or accelerators may be needed to control the setting time (API, 1993). Table 1 presents some of the additives used to control cement properties, generally in API cement classes. See Smith (1976), Kosmatka et al. (2003), or IEAGHG (2009) for a more comprehensive list of additives and their uses.

Table 1. Examples of Common Cement Additives.
Modified from: Nelson and Guillot (2006).

Additive Type/Category	Examples/Composition	Use/Benefit
Accelerator	Calcium (Ca) chloride Sodium (Na) chloride Na and Ca formates Nitrates Nitrites Sodium silicates	Shorter thickening time; Greater early compressive strength
Retarder	Lignosulfonates Hydroxycarboxylic acids Cellulose derivatives Organophosphonates Certain inorganic compounds	Longer thickening time
Extender	Bentonite Sodium Silicates Pozzolans Gilsonite Powdered coal Microspheres Nitrogen	Lower slurry density; Greater slurry yield
Weighting agent	Barite Hematite Ilmenite Manganese tetraoxide	Higher slurry density
Dispersant	PNS PMS Lignosulfonates Polystyrene sulfonate Polycarboxylate	Lower slurry viscosity

Additive Type/Category	Examples/Composition	Use/Benefit
	Hydroxylated polysaccharides Hydroxycarboxylic acids	
Fluid-loss additive	Cellulosic polymers Polyamines Sulfonated aromatic polymers PVP PVA AMPS copolymers and terpolymers Bentonite Latexes Crosslinked PVA	Reduced slurry dehydration
Lost-circulation control agent	Gilsonite Granular coal Cellophane flake Nut shells Fibrous additives Gypsum Certain soluble sulfate salts Bentonite Crosslinked cellulosic polymers	Prevention of loss of slurry to formation
Antifoam agent	Polyglycol ethers Silicones	Reduced air entrainment during slurry mixing
Strengthening agent	Glass and polymer fibers Metallic microribbons Ground rubber	Increased tensile strength, flexural strength, and toughness
Radioactive tracers	${}_{53}I^{131}$ ${}_{77}Ir^{192}$	Easier determination of cement location behind casing

USEPA (1982) and IEAGHG (2009) suggest that most plugging needs can be met with a cement such as API Class A, G, or H. API Spec 10 provides details on the specifications for cements and materials for well cementing (API, 2002), and ASTM C150 - 11/C150M - 11 gives the standard specifications for Portland cement. Because of the corrosive nature of wet supercritical carbon dioxide and carbon dioxide-rich fluids, owners or operators of Class VI GS projects should consider cements that offer resistance to carbonic acid. This may entail use of non-Portland cements or Portland cements with additives. In particular, additives that reduce the percentage of carbon dioxide-reactive material (calcium hydroxide) in the cement will reduce susceptibility to carbonic acid (Moroni et al., 2009). Pozzolans, such as fly ash or silica fume, may be added to boost the portion of silica in a Portland-containing mixture and provide better resistance to carbon dioxide. Also, dispersants reduce the water content in the slurry and produce cement with lower permeability and reduced vulnerability to degradation (Calvert and Smith, 1994).

Non-Portland cements, which are non-reactive or less reactive with carbonic acid, include pozzolan-lime cement, gypsum cement, microfine cement, expanding cements, calcium aluminate cement, latex cement, resin or plastic cements, and sorel cements (Meyer, 2007). In particular, calcium aluminate cement (also referred to as high aluminate cement) blended with additives has been found to be resistant to carbon dioxide-rich environments (Meyer, 2007).

ASTM International (ASTM) standards exist for some specialty cements (e.g., ASTM C1438 - 99 (2005)e1: Standard Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar; ASTM C1707 – 10: Standard Specification for Pozzolanic Hydraulic Lime for Structural Purposes). The *UIC Program Class VI Well Construction Guidance* contains additional discussion of cements that may be suitable for carbonic acid-rich environments. For example, Section 2.5.3 of that guidance provides more information on the compatibility of Portland cements with the carbon dioxide stream, and Section 3.2.2 of that guidance provides information on considerations when selecting downhole materials in a potentially corrosive environment. Also, newer commercial cements now available in the oil and gas industry are designed specifically for carbon dioxide-rich environments such as those associated with GS or enhanced oil recovery (EOR) operations. Stresses due to variation in downhole pressure and temperature are known to contribute to cement defects, including the formation of microannuli and loss of zonal isolation (Goodwin and Crook, 1992; Thiercelin et al., 1998). Although downhole pressure and temperature conditions will be more stable after plugging than during the injection phase of a project, cement properties should be suitable for any anticipated tests and downhole conditions.

More recent literature (e.g., Liversidge and Agarwal, 2006; Le Roy-Delage et al., 2000; Nagelhout et al., 2005) has explored the use of flexible, expanding cements for plugging operations, including offshore projects. These cements include expanding agents (e.g., calcium oxide-based) and additives to increase flexibility. The resulting systems have increased elasticity and decreased compressibility and permeability, and they maintain strength. In a GS setting, the superior sealing and decreased permeability of these cements may be beneficial in providing protection from degradation of cement and resulting fluid migration. Owners or operators may wish to consider the costs and benefits of such materials and, if interested, discuss their use with the UIC Program Director.

Bentonite nodules have been studied as a plugging material for deep wells (e.g., Englehardt and Wilson, 2001; Clark and Salsbury, 2003). Compressed sodium bentonite provides good plugging capability because it hydrates (thereby providing swelling), and it has lower permeability than cement. It can also be emplaced without the need for a rig and can be easily drilled out if the well needs to be reentered. Bentonite nodules (1 to 6 inches in size) have been found to form a good plug even in high salinity conditions. Compressed bentonite in the shape of bullets has been found to improve pressure containment as well (Towler et al., 2008). Compressed bentonite is also flexible and can adjust its shape if the casing moves, reducing the risk of formation of microannuli. However, research may still be needed on emplacement methods.

Because bentonite pellets cannot be pumped into the well, they need to be dropped through the fluid. Care needs to be taken to avoid bridging of the pellets above the desired plug depth resulting in potential improper plug placement. Shaping the pellets into bullets may help to minimize the bridging problem (Towler et al., 2008). Compressed bentonite plugs also have poor compressive strength and have limited pressure capabilities (USEPA, 2002). Compatibility of bentonite plugs with carbon dioxide or carbon dioxide-rich brine remains to be evaluated. Choices of plugging material will ultimately be addressed in the Injection Well Plugging Plan in consultation with the UIC Program Director [40 CFR 146.92(b)(5)].

Other materials studied for use in well plugs include pumpable fluorsilicone and perfluoro-ether silicone elastomers (e.g., Bosma et al., 2000). Although the compatibility of these materials with a carbon dioxide-rich environment has not been established, they may be sandwiched between conventional cement plugs to provide extra sealing capability. The EPA will continue to monitor research and developments in cement and material compatibility as more data become available.

2.6.3 Locations of Cement Plug Placement

The type and number of plugs to be installed, as well as the placement of each plug (top and bottom), must be specified in the Injection Well Plugging Plan [40 CFR 146.92(b)(3) and (4)]. In most cases, a continuous column of cement is not necessary, but plugs should be placed at critical locations to prevent communication between the injection zone and USDWs (Figure 3). The EPA recommends that owners or operators emplace plugs: (1) above any production or injection zones; (2) above, below, and/or through each USDW; (3) at the bottom of intermediate and surface casings; (4) across any casing stubs (pulled casing sections); and (5) at the surface (USEPA, 1989). Owners or operators may also consider emplacing cement across the injection zone's perforated interval by squeezing cement below a retainer set above the injection zone. Plugs may also be placed at other depths and locations at the UIC Program Director's discretion. Schematics and drawings of the top and bottom of plug placements are recommended, as part of the Injection Well Plugging Plan.

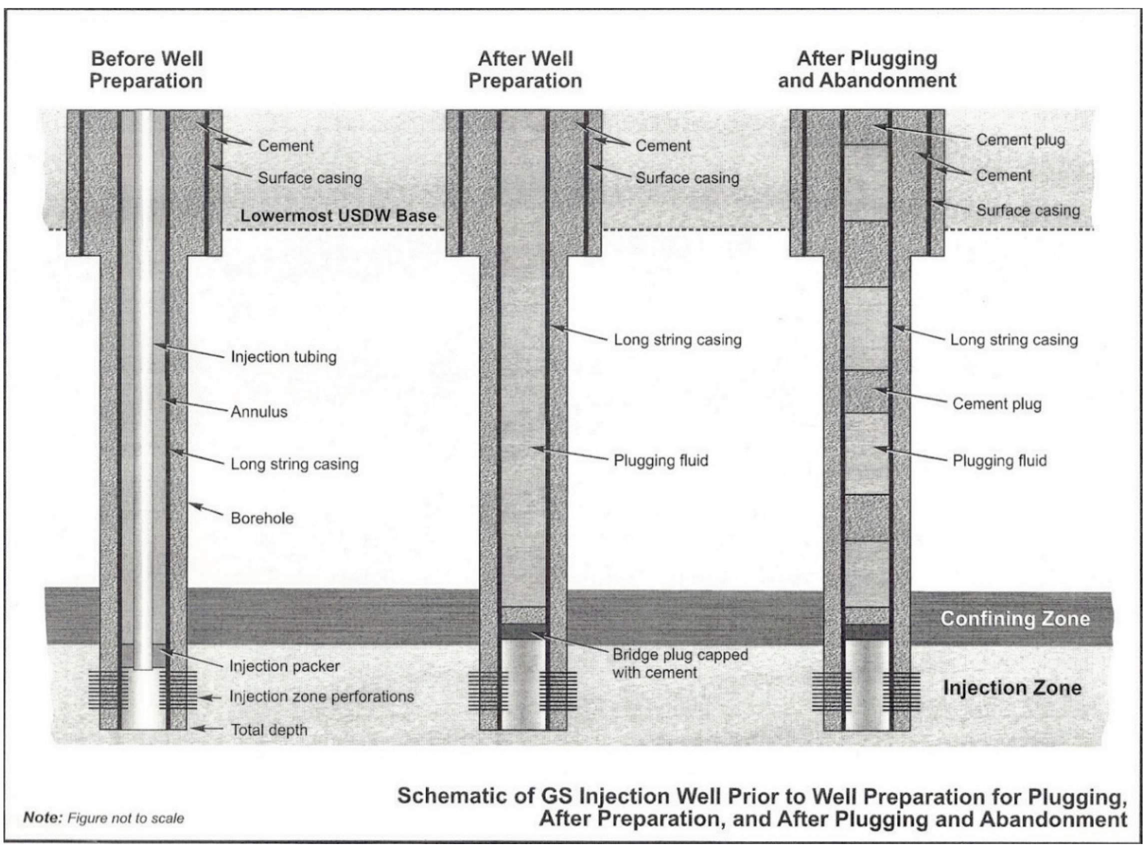


Figure 3. Schematic of Class VI Injection Well Prior to Well Preparation for Plugging, After Preparation, and After Plugging and Abandonment.

In horizontal wells, the EPA suggests that a bridge plug be installed above the kickoff point, with a cement plug on top of it. The EPA also recommends that owners or operators consider emplacing cement across perforated sections of laterals. In addition, if a vertical pilot hole has been drilled below the kickoff point into a permeable formation, that portion of the hole should be plugged as well.

API (1993) recommends that the top of a 100-foot plug be at (and extend downward from) the base of the lowermost USDW for protection of USDWs. Similarly, the EPA recommends that plugs in GS settings be at least 100 feet long and extend, at a minimum, from the base of the surface casing (required to be set at some distance below the base of the lowermost USDW) up through the base of the lowermost USDW as shown schematically in the well on the right in Figure 3. Furthermore, given the potential for the presence of carbonic acid near a Class VI well, the EPA strongly recommends that owners or operators consider longer plugs, especially in critical zones such as above the injection zone.

2.6.4 Methods and Timing for Plug Emplacement

Plugs should be set sequentially from the bottom of the well to the top, with adequate time in between to allow setting. The adequate time for setting can vary (ranging from 24 to 48 hours) and should be established through coordination between the UIC Program Director and the owner or operator. A bridge plug is recommended to isolate the injection zone. Bridge plugs may also be used to help position cement plugs at intermediate depths and prevent them from migrating. After emplacing a cement plug and allowing it to set, it may be tested by tagging, a method in which pipe is run into the well to locate the top of the plug. This indicates if the top of the plug is at the desired depth and whether it has acquired strength. It does not, however, indicate whether the cement has set properly throughout the entire plug. The EPA (USEPA, 1989) recommends tagging as an option for testing plugs that are in critical locations or are suspected to be of inadequate quality.

Accepted and established methods for the emplacement of cement plugs suitable for a Class VI GS project include the balance method, the retainer method, and the two-plug method. Brief summaries for each are included below. The dump bailer method is generally not suitable for plugging deep wells and is not discussed in this guidance. The method(s) for plug emplacement that will be used for a specific project must be specified in the Injection Well Plugging Plan [40 CFR 146.92(b)(6)].

2.6.4.1 Balance Method

The balance method is simple and commonly used, but requires a great deal of operator skill. A drillpipe or tubing is run downhole, and cement is pumped through until the level of cement outside the tubing equals the level inside (Figure 4). Tubing should be centralized to ensure even flow of cement around the pipe. The tubing is then withdrawn from the well, excess cement is circulated out of the tubing, and the cement is left in place to set (Smith, 1976; API, 1993; Nelson, 2006; IEAGHG, 2009).

As noted above, movement of the plugging fluid can compromise the integrity of the plug. Use of small-diameter tubing and slow, careful emplacement and withdrawal can help minimize disturbance. Fluid spacers or small amounts of non-chemically treated mud may be used ahead of and behind the cement in the tubing to prevent contamination with the plugging fluid if compatibility is a concern (API, 1993). Another factor in successful plugging is careful calculation of cement, water, and displacement volumes. Further details and an example of cement volume calculations are provided in USEPA (1989).

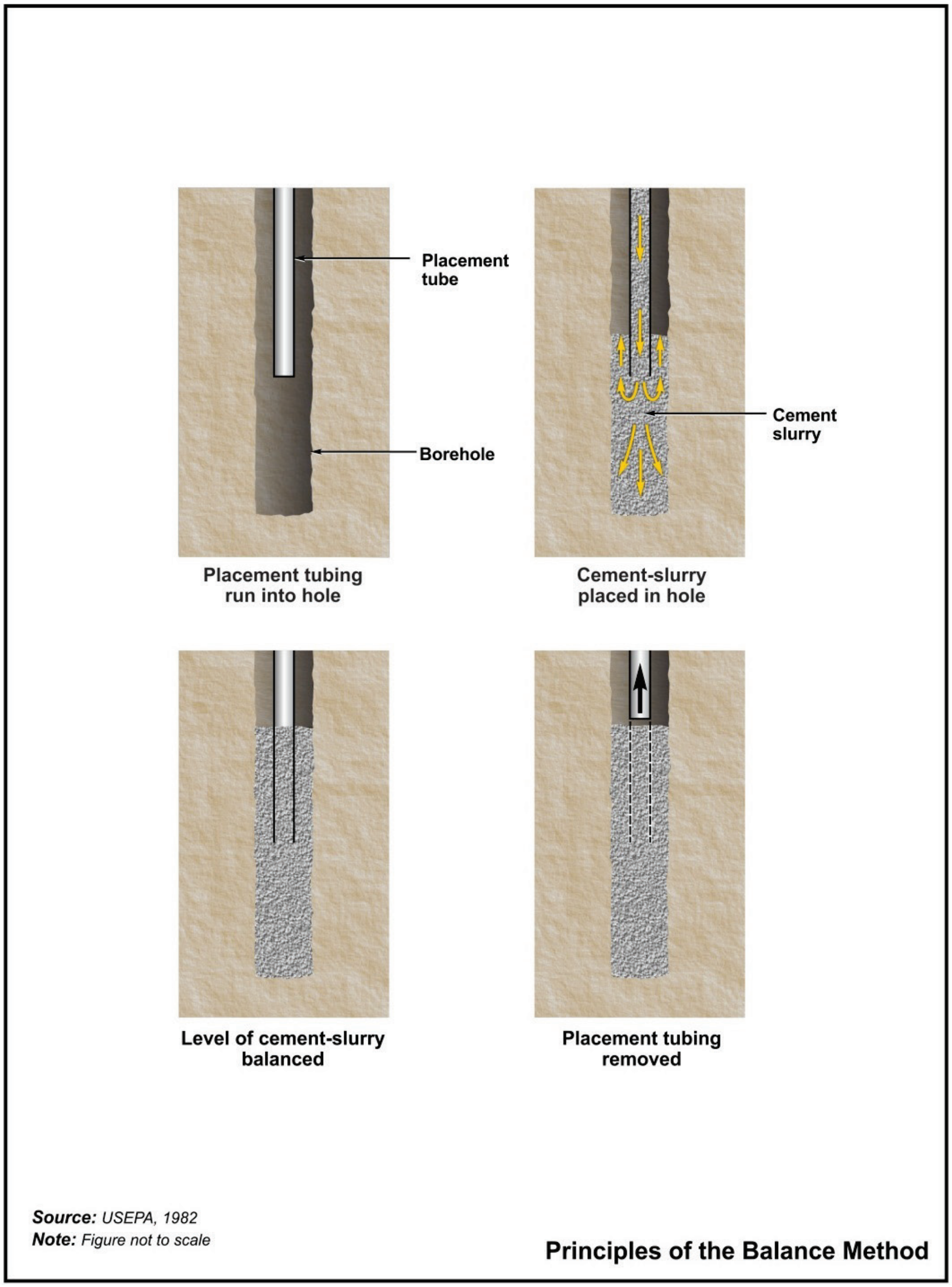


Figure 4. Principles of the Balance Method.
From: USEPA (1982).

2.6.4.2 Retainer Method

The cement retainer method is useful for setting plugs in uncased boreholes (e.g., a shallow uncased monitoring well) and can be used to cement across the perforated casing in the injection zone. For Class VI injection wells, the method may be useful in placing a plug across the injection perforations if such a plug is desired. Retainers allow cement to be emplaced beneath the packer under pressure, forcing cement into the surrounding formation. Different models of cement retainers may be emplaced by tubing, drillpipe, or wireline. Some can be converted to bridge plugs. Owners or operators should verify that any retainers used are drillable. A cement plug should be emplaced above the retainer.

Exact procedures may vary depending upon the retainer selected. In the example in Figure 5 below, the retainer is attached to the bottom of the tubing. The tubing with the retainer is lowered to the bottom of the well, and cement is pumped through the retainer. Pressure is applied to squeeze the cement through the perforation and form a good seal. Once the desired amount of cement is placed below the retainer, the tubing is removed and the retainer valve is closed. Additional cement can then be placed on top of the retainer to provide an additional seal (NPC, 2011).

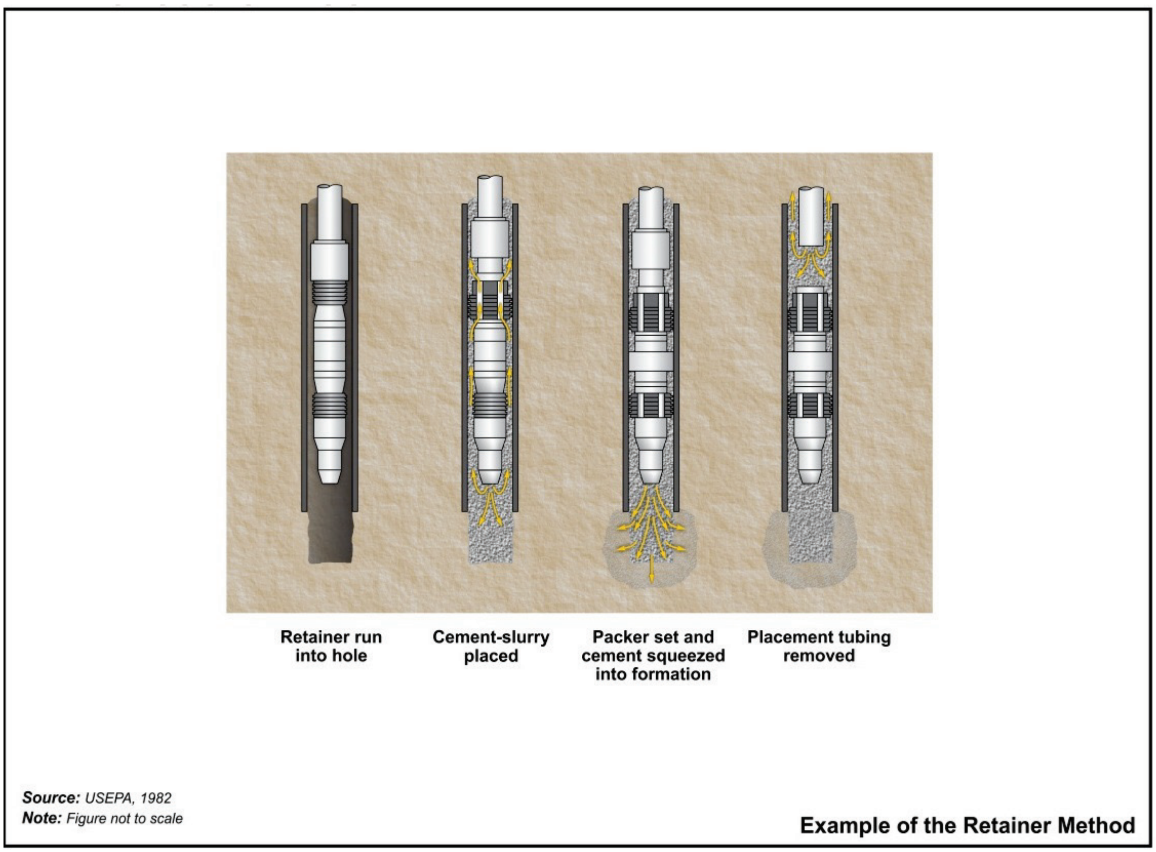
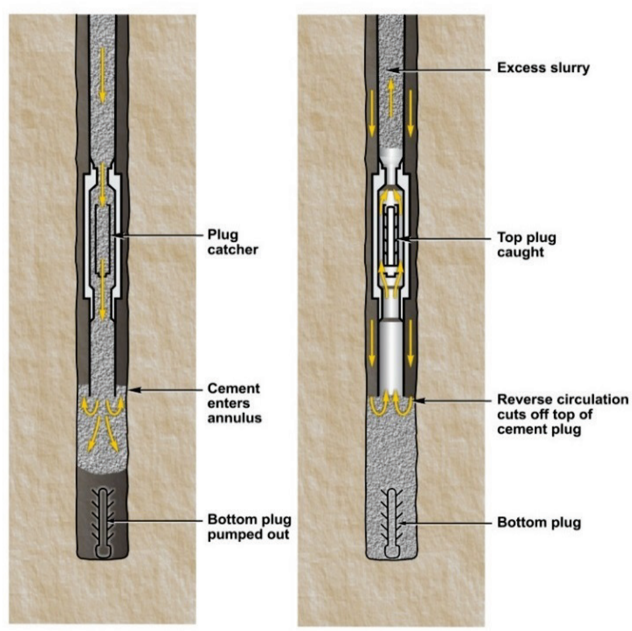


Figure 5. Example of the Retainer Method.
From: USEPA (1982).

2.6.4.3 Two-Plug Method

This method is more complex than the balance method, but provides advantages. Upper and lower tubing plugs are used to separate the plugging fluid from the cement slurry, minimizing cement contamination by the plugging fluid. It also offers good control over cement emplacement, which is especially advantageous in deep wells.

In this method, two ball plugs are used to start and stop the pumping of cement through the tubing. The lower tubing plug proceeds down the tubing, stopping at the depth of the desired cement plug. Pressure is increased and the cement slurry is then pumped through the tubing. When the desired amount of cement has been pumped, the top tubing plug follows. It is caught in a plug-catcher tool in the tubing and does not pass into the well. A latching device prevents further displacement of fluid, allowing good control over the amount of cement emplaced and the location of the top of the cement plug (Figure 6). Further details are provided in USEPA (1982), Smith (1976), and IEAGHG (2009).



Source: *USEPA, 1982*
Note: *Figure not to scale*

Principles of the Two-Plug Method

Figure 6. Principles of the Two-Plug Method.
From: USEPA (1982).

2.6.5 Considerations for Offshore Wells

Generally, plugging and abandonment of offshore injection wells will be similar to procedures for onshore wells. As with onshore wells, cement plug locations should be selected to isolate the injection zone and protect USDWs. There are, however, some additional considerations for placing cement plugs near the ocean floor in offshore environments due to the mud found at and below the sea floor. Any annuli in the well that are open to the mudline should be plugged to prevent migration of mud or other fluids down into the well or to prevent fluids in the annulus from migrating upward. Special materials and procedures may be necessary due to the lower density and unconsolidated nature of the sediment above the mudline. One recommendation is to place a top in the well within 150 feet of the mudline (Jirapongpipat, 2007).

Cementing in the mud environment near the ocean floor can be more difficult. The mud may mix with the cement, or heavier cement can displace the mud and lose its shape. Cross flow in the cementing area can also be problematic. These problems can be avoided by placing a barrier between the mud and cement such as a bentonite pill or a spacer fluid, by using circulation methods that circulate cement to the side but not vertically, and by using special cements such as lightweight cements (King, 2009). Cement evaluation logs will also be important to ensure that a proper cement job was obtained, especially above the mudline. In developing an Injection Well Plugging Plan for offshore Class VI wells, EPA recommends that owners or operators consult with professionals that specialize in well plugging for offshore projects as well as any relevant guidelines developed to implement the London Convention.

2.7 Development and Submittal of Plugging Report

Within 60 days after plugging, the owner or operator must submit a plugging report to the UIC Program Director [40 CFR 146.92(d)]. The purpose of this report is to document that the plugging activities approved in the Injection Well Plugging Plan [40 CFR 146.92(b)] or any amendments to that plan were executed to the UIC Program Director's satisfaction and that the well will not be a conduit for fluid movement. The report must be certified as accurate by the owner or operator and by the person who performed the plugging operation, and the owner or operator must retain the plugging report for 10 years following site closure [40 CFR 146.92(d); 40 CFR 146.91(f)(4)].

Although a well plugging report is not explicitly required for monitoring wells, the EPA encourages owners or operators to submit such reports. Proper plugging of monitoring wells is important for the long-term protection of USDWs, and although documentation is ultimately required at the time of site closure [40 CFR 146.93(f)(1)], prompt documentation of plugging done during the PISC phase will help to demonstrate non-endangerment of USDWs.

The well plugging report must include at least the following information, which will have been specified in the approved Injection Well Plugging Plan:

- Results of tests to determine bottomhole pressure and mechanical integrity;
- The type and number of plugs used;

- Cement type, grade, weight, and quantities for plugs;
- Method of cement plug emplacement; and
- Top and bottom of each cement plug.

A sample template of a well plugging report is available for download from the GSDT. In addition, although not required by the Class VI Rule, EPA suggests that the following information on well preparation and remediation be included to demonstrate to the UIC Program Director that the well was in good condition for the installation of the plugs:

- Well flushing activities, required at 40 CFR 146.92(a), including fluid type and volumes used;
- Notes on removal of large debris;
- Documentation of removal of downhole components (e.g., pressure transducer, packer, shut-off devices);
- Documentation of removal of injection tubing;
- Reports on remedial activities (e.g., squeeze cementing records);
- Plugging fluid type and volume used to establish static conditions; and
- Notes on any plugs that were tagged.

See the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators* for additional information on submitting the well plugging report.

3 Post-Injection Site Care (PISC)

The post-injection site care (PISC) phase of a Class VI project begins when all carbon dioxide injection ceases and ends with site closure [40 CFR 146.81].

This section addresses the following aspects of PISC:

- Development, reviews, and amendments of the PISC and Site Closure Plan throughout the life of a Class VI project (Section 3.1);
- The PISC timeframe, including a discussion of demonstrating an alternative PISC timeframe (Section 3.2);
- Monitoring during PISC to ensure USDW protection from endangerment (Section 3.3); and
- Demonstrating non-endangerment of USDWs to facilitate authorization for site closure (Section 3.4).

This section does not add requirements for the use of specific technologies beyond what is identified in the Class VI Rule; rather, it is intended to support the implementation of site- and project-specific approaches to regulatory compliance and USDW protection at Class VI projects throughout the PISC phase and the demonstration of non-endangerment, which is required prior to authorization of site closure.

3.1 PISC and Site Closure Plan

Class VI GS project owners or operators are required to prepare, maintain, and comply with a plan for PISC and site closure [40 CFR 146.93(a)]. The purpose of developing and implementing the PISC and Site Closure Plan is to: ensure the development of a site-specific strategy for PISC monitoring that will provide information on plume and pressure front behavior, which confirms USDW protection from endangerment (during PISC) and support the final non-endangerment demonstration and subsequent site closure.

The PISC and Site Closure Plan must describe the planned monitoring methods, locations, and frequencies that will be employed to ensure non-endangerment of USDWs; the duration of PISC activities; and under what conditions the frequency of PISC monitoring may be reduced [40 CFR 146.93(a)(2)]. In addition, the EPA encourages the owner or operator to include details regarding how the non-endangerment demonstration will be made on a project-specific basis and the information and conditions that the owner or operator intends to use to confirm and demonstrate non-endangerment. While this is not a required part of the PISC and Site Closure Plan, describing and agreeing upon the criteria for the non-endangerment demonstration reduces future uncertainty and helps to ensure that the operator plans to collect appropriate types and amount of data to inform a demonstration that site closure is appropriate. In this way, the activities described in the PISC and Site Closure Plan will support a non-endangerment demonstration and allow the UIC Program Director to authorize project site closure [40 CFR 146.93(b)(3)].

The Class VI Rule requires submission of a proposed PISC and Site Closure Plan as part of the permit application [40 CFR 146.82(a)(17); 40 CFR 146.93(a)]; the plan must be approved by the UIC Program Director and becomes an enforceable part of the Class VI permit. Development of the plan and the resultant coordination between the owner or operator and the UIC Program Director before the project commences will provide clarity regarding the procedures to be implemented for early detection of carbon dioxide plume and pressure front migration, which may endanger a USDW, and how the monitoring can eventually support the non-endangerment demonstration required at 40 CFR 146.93(b)(3).

However, the owner or operator may amend the plan at any time during the life of the project (e.g., during the injection or PISC phase) based on: project-specific information collected during the operational or PISC phase; AoR reevaluations; or amendments to the other plans. Subsequent amendments will support ground-truthing and updating of the Plan with project-specific information. See Section 3.1.1 for information on PISC and Site Closure Plan reviews and amendments.

For additional details about the structure of the Plan, see the *UIC Program Class VI Well Project Plan Development Guidance*.

3.1.1 PISC and Site Closure Plan Reviews and Amendments

At the cessation of injection, owners or operators are required to submit an amended PISC and Site Closure Plan or demonstrate that no amendment is necessary [40 CFR 146.93(a)(3)]. Amendments to the plan or the demonstration that no revisions are necessary should be based on monitoring data collected during injection and the most recent AoR delineation. An amendment of the PISC and Site Closure Plan would require the UIC Program Director to modify the Class VI permit, per 40 CFR 144.39(a)(5)(iv). A demonstration that no amendment to the PISC and Site Closure Plan is needed should be based on monitoring data collected during injection and the most current AoR delineation. Examples of content that could be included in the demonstration include:

- A discussion of how subsurface pressure, plume migration, and operational monitoring results have generally tracked with modeled predictions;
- A discussion of how the most recent modeled predictions compare with the predictions made at the time the approved PISC and Site Closure Plan was developed;
- Confirmation of USDW protection based on above confining zone monitoring and monitoring of any USDWs in the Area of Review;
- The most up-to-date, predicted timeframe for pressure decline within the injection zone; and/or
- A comparison of anticipated monitoring frequency with predicted rates of plume movement and pressure decay.

Box 3-1 provides an example of planned PISC monitoring at a hypothetical project and revisions based on AoR reevaluation.

The purpose of periodic plan reviews is to incorporate new monitoring data or changes to the site computational model that warrant changes in PISC monitoring, or any changes in the methodology proposed to be used to demonstrate non-endangerment of USDWs. This approach may also support the use of newer technologies that were not available or considered at the time of permitting. Owners or operators are encouraged to evaluate the necessity of amending the plan within one year of an AoR reevaluation (for details regarding AoR reevaluation, see the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance*), following any significant changes to the facility such as an increase in the number of injection or monitoring wells in the project AoR, or on a schedule to be determined by the UIC Program Director. Note that an amended PISC and Site Closure plan would be needed for each well with a Class VI permit given that area permits are not permitted for Class VI wells [40 CFR 144.33]. However, the EPA acknowledges that projects with multiple Class VI wells may have plans that look substantively similar.

While amending the PISC and Site Closure Plan during the injection phase is not required, the EPA encourages owners or operators to consider whether a PISC and Site Closure Plan amendment is warranted concurrent with amendment of other project plans to ensure consistency across all the approved plans. In particular, PISC and Site Closure Plan amendments may be appropriate when amendments are made to the Testing and Monitoring Plan (for details regarding the Testing and Monitoring Plan reevaluation, see the *UIC Program Class VI Well Testing and Monitoring Guidance*).

3.1.1.1 Considerations for Injection and Post-Injection Adjustment of the AoR Delineation Computational Model

The owner or operator is required to reevaluate the AoR periodically to compare model predictions to monitoring results [40 CFR 146.84(e)]. Depending on the level of agreement between computational model predictions and site monitoring data (and depending on the criteria specified in the project's approved AoR and Corrective Action Plan), this reevaluation may result in re-delineating the AoR to account for all available site/monitoring information and actual operational conditions. This process may involve calibration of the existing model or, if necessary, making more substantial changes to the modeling approach. (See the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance.*)

Following an AoR reevaluation, if the AoR and Corrective Action Plan is amended, EPA encourages the owner or operator to submit an amended PISC and Site Closure Plan that describes how changes to the model affect modeling results, predictions of pressure dissipation, plume migration rates, trapping, and additional processes that need to be accounted for in the non-endangerment demonstration for the alternative PISC timeframe demonstration. While amending the PISC and Site Closure Plan is not required during the injection phase, the EPA encourages owners or operators to consider whether any updates are needed to ensure consistency across all of the plans for the project.

Where the AoR and Corrective Action Plan is amended as a result of an AoR reevaluation, it is expected that the alternative PISC timeframe: 1) will also be adjusted based on the new AoR delineation and model calibration efforts; or 2) a confirmation will be made that no modification of the timeframe is needed. The EPA expects that an updated alternative PISC timeframe demonstration would be reported to the UIC Program Director as part of the amended PISC and Site Closure Plan. Using this information, the UIC Program Director may review the alternative PISC timeframe following model calibration and may approve the modified timeframe (whether lengthened or shortened), accordingly. For information on demonstrating an Alternative PISC Timeframe, see Section 3.2.2.

Box 3-1. Hypothetical Example of PISC Monitoring Plan and Revision.

This box presents an example summary of a PISC monitoring plan for a hypothetical Class VI GS project. This example is based on the hypothetical Class VI GS project used throughout the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance*. The PISC monitoring plan is a component of the PISC and Site Closure Plan, and it describes proposed monitoring techniques and frequencies (Section 3.1). The hypothetical project consists of three injection wells, and injection is planned for 30 years (Figure 7).

The PISC monitoring program submitted with the PISC and Site Closure Plan in the initial permit application and approved as a permit condition called for an initial continuation of monitoring conducted during the injection phase, as follows:

- Fluid sampling and pressure monitoring using a series of 18 monitoring wells; some are screened within the injection zone, and others are screened above the primary confining zone:
  - Monitoring wells MW-4, MW-6, MW-13, MW-16, MW-17, and MW-18 were proposed to be constructed after injection begins, and the remaining wells were proposed to be constructed prior to injection. All wells were proposed to be constructed prior to PISC.
  - Fluid geochemical and pressure monitoring were proposed to be conducted once every six months at the beginning of PISC and to decrease over time based on pre-defined criteria that are listed in the plan for each monitoring well. The number of monitoring wells used will decrease over time as the potential for endangerment decreases.
  - Monitoring wells will be plugged/closed in accordance with site closure requirements when they are taken out of use.
- Indirect geophysical surveys are to be conducted initially once every two years, with frequency decreasing in future years based on repeat surveys demonstrating that the carbon dioxide plume is migrating at rates less than those in pre-defined criteria.
- The internal integrity of the monitoring wells will be assessed via a pressure test during every sampling event. External integrity of all monitoring wells will be evaluated at least once every three years during PISC while each well is active.

Box 3-1. Hypothetical Example of PISC Monitoring Plan and Revision.

The initial approved PISC and Site Closure Plan also describes the site-specific PISC timeframe and monitoring criteria that will be used to demonstrate non-endangerment of USDWs. In this case:

- The PISC timeframe is assumed to be 50 years (for a total project timeframe of 80 years). The Plan does not include a demonstration that would allow for an alternative PISC timeframe other than 50 years.
- Several risk-based site-specific criteria that will be used to demonstrate non-endangerment of USDWs. These include:
    - Return of pressure within the injection zone to pre-injection conditions at all monitoring wells that remain in use.
    - Stable or decreasing levels of carbon dioxide in sampled fluids.
    - Stable or increasing pH in sampled fluids above the confining zone.
    - Levels of any drinking water contaminants are below baseline levels and are stable or decreasing over time for at least two years in any fluids sampled above the primary confining zone.
    - The results of at least three consecutive geophysical surveys that demonstrate the separate-phase carbon dioxide plume is no longer growing in size, either laterally or vertically, in a manner that may endanger any USDW.
    - All artificial penetrations, including former injection and monitoring wells, within one mile of the extent of the separate-phase plume and pressure front, have been evaluated and determined to not endanger USDWs. This may include monitoring of USDWs and soil gas in the direct vicinity of all artificial penetrations and confirmation of the mechanical integrity of all wells.

The UIC Program Director approved of these specifications as described in the initial PISC and Site Closure Plan that was submitted with the permit application. These specifications were incorporated as permit conditions. After the commencement of injection, the AoR was reevaluated every 5 years. During the first three AoR reevaluations (5 years, 10 years, 15 years), the owner or operator demonstrated that the initial AoR delineation was adequate, and no model calibration was necessary. At 20 years, based on comparison of modeling and monitoring data, the owner or operator determined that the computational model should be recalibrated, and a revised AoR resulted. The revised AoR extended further towards the east than the initial AoR (Figure 7).

Box 3-1. Hypothetical Example of PISC Monitoring Plan and Revision.

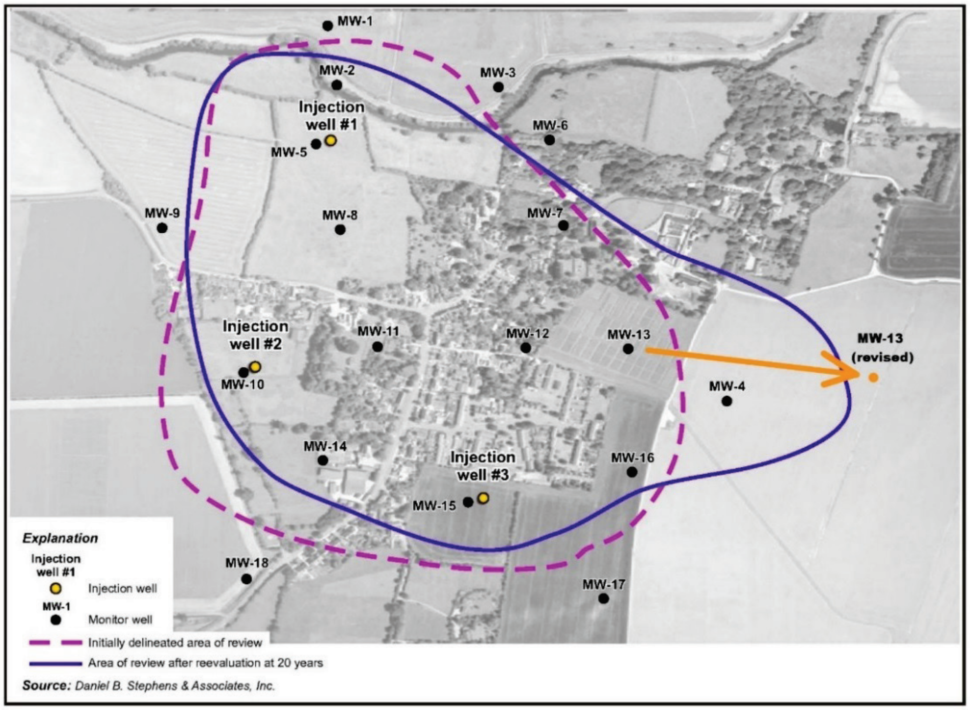


Figure 7. Hypothetical Class VI GS Project Showing Initial and Revised AoR.
The location of MW-13 is revised after AoR reevaluation, as shown by the orange arrow.

Upon reevaluation of the AoR at 20 years, the PISC and Site Closure Plan was also amended and the permit modified to incorporate the amendment. The following major changes were made to the plan:

- MW-13 had not been constructed as of 20 years after injection. The location of MW-13 was revised to be located in the predominant direction of plume migration and outside of the revised AoR (Figure 7). The plan specifies that MW-13 will remain an active monitoring well until final site closure.
- Artificial penetrations in the newly identified area of eventual plume migration were identified, and a plan was outlined for assessment and monitoring of those penetrations.
- New criteria for the USDW non-endangerment demonstration were added for MW-13. Non-endangerment criteria include no detection through direct and indirect monitoring of separate-phase carbon dioxide fluids from MW-13, no presence of elevated pressure, and no change in geochemistry that indicates fluid changes beyond allowable levels. If any of these criteria are not met, the owner or operator has committed to reevaluation of the PISC and Site Closure Plan at that time and establishment of updated non-endangerment criteria.

3.2 PISC Timeframe

3.2.1 Duration of PISC

The Class VI Rule specifies a default PISC monitoring timeframe of 50 years after the cessation of injection [40 CFR 146.93(b)(1)]. However, the Rule provides the flexibility for the owner or operator to propose an alternative timeframe other than 50 years based on operational, monitoring, and AoR delineation modeling information about the Class VI GS project [40 CFR 146.93(c)].

An alternative timeframe can be proposed as part of the permit application or may be incorporated as an amendment to the Post-Injection Site Care and Site Closure Plan during the operation or post-injection phases of a Class VI project [40 CFR 146.93(a)(3)]. If an owner or operator submits an alternative timeframe request as part of their Class VI permit application, they must include all of the information at 40 CFR 146.93(c); see Section 3.2.2. Furthermore, the EPA recommends that, if an owner or operator submits an alternative timeframe request as part of a PISC and Site Closure Plan amendment, they include all of the information at 40 CFR 146.93(c) to facilitate the UIC Program Director's evaluation. If the UIC Program Director approves the alternative PISC timeframe, it will be incorporated into the PISC and Site Closure Plan and the Class VI permit. Such a change would require the UIC Program Director to modify the Class VI permit [40 CFR 144.39(a)(5)(iv)].

Regardless of the PISC timeframe defined in the plan, the owner or operator must continue PISC monitoring until he or she can demonstrate, based on monitoring and other site-specific data, that no additional monitoring is needed to ensure that the Class VI GS project does not pose an endangerment to USDWs. The UIC Program Director must approve this non-endangerment demonstration [40 CFR 146.93(b)(3)]. If the owner or operator can demonstrate non-endangerment of USDWs prior to the end of the permitted PISC timeframe with substantial evidence that the geologic sequestration project no longer poses a risk of endangerment to USDWs [40 CFR 146.93(b)(2)], the UIC Program Director may authorize site closure. Alternatively, if at the end of the pre-defined PISC timeframe there is evidence that endangerment to USDWs can still occur, the UIC Program Director may require PISC to continue until a non-endangerment demonstration can be made [40 CFR 146.93(b)(4)]. See Section 3.4 for information on demonstrating non-endangerment.

Because changes to the PISC duration may affect the cost of activities described at 40 CFR 146.85(b)(2)(iii), owners or operators should also refer to the *UIC Program Class VI Financial Responsibility Guidance* for information on demonstrating that monitoring costs and any potential leakage encountered during PISC can be covered financially.

3.2.2 Alternative PISC Timeframe Demonstration

The demonstration that an alternative PISC timeframe is appropriate must be based on site-specific data and evidence that the project will no longer pose a risk of endangerment to USDWs at the end of the timeframe [40 CFR 146.93(c)]. Several analyses are required under the Class VI Rule to support this demonstration. These analyses include:

- The results of the current AoR delineation modeling (conducted in compliance with 40 CFR 146.84) including predicted pressure and plume migration, and immobilization due to site-specific trapping mechanisms;

- Any site and project information verifying AoR modeling predictions;

- Identification and characterization of any potential conduits (e.g., fractures/faults, wells); and

- Any other site-specific factors, such as the distance between the injection zone and the nearest USDW.

EPA encourages the owner or operator to consult with the UIC Program Director regarding information that should be submitted based on site-specific conditions and how best to conduct the required analyses. The information and strategy to meet these criteria will depend upon available project data and the phase of the project at the time the demonstration is submitted or updated (as part of the amended PISC and Site Closure Plan).

The Class VI Rule requires that the predictive models used for the alternative PISC timeframe demonstration be based on site conditions and calibrated where sufficient site/project data are available [40 CFR 146.93(c)(2)(iii) and (iv)]. For example, if the demonstration is submitted with an amended PISC and Site Closure Plan during or after injection, the AoR delineation modeling used should be evaluated and calibrated (if needed) using the injection and site conditions, and existing testing and monitoring data. Furthermore, the AoR delineation modeling results used for this demonstration must be based on conservative values and assumptions, and include a sensitivity analysis to identify the parameters that most contribute to the uncertainty in the demonstration [40 CFR 146.93(c)(2)(v) and (vi)].

The EPA acknowledges that some owners or operators of Class VI wells may plan to eventually produce the carbon dioxide from the injection zone or might be interested in preserving this option (e.g., to sell the carbon dioxide for EOR/EGR). Owners or operators are encouraged to consider the planned withdrawal of the carbon dioxide as a factor in developing an alternative PISC timeframe or revising their PISC timeframe during the life of the GS operation. The EPA recommends that owners or operators plan a post-injection monitoring period and strategy that extends for at least as long as a quantity of the injected carbon dioxide is to remain in the ground and until a demonstration of non-endangerment can be made. As withdrawal of the carbon dioxide proceeds and the system conditions show a trend toward reduced potential for endangerment of USDWs (e.g., subsurface pressures begin to decline), the owner or operator may choose to discuss modifying the monitoring schedule (or plans for conducting the non-endangerment demonstration) with the UIC Program Director. However, pursuant to 40 CFR 146.93(b)(1), PISC must continue until non-endangerment can be demonstrated.

The EPA encourages the owner or operator and the UIC Program Director to coordinate and discuss monitoring and operating data and other information about the facility if the owner or operator seeks to amend the PISC timeframe (e.g., to modify the monitoring schedule or approach). See Section 3.1.1 of this document and the *UIC Program Class VI Well Project Plan Development Guidance* for additional information on preparing and updating the PISC and Site

Closure Plan and the *UIC Program Class VI Implementation Manual for State Directors* for additional information about the procedures for modification of Class VI permits and the related plan amendments. For additional information on reporting an alternative PISC timeframe demonstration to the EPA's electronic reporting system, see the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators.*

Sections 3.2.2.1 through 3.2.2.8 below provide guidance on evaluating and complying with the requirements at 40 CFR 146.93(c)(1) and (2).

3.2.2.1 Results of Computational Modeling Performed for Delineation of the AoR [40 CFR 146.93(c)(1)(i)]

The alternative PISC timeframe demonstration must be based in part on the results of the computational modeling performed to delineate the current and calibrated (if needed and data are available) AoR, per 40 CFR 146.84. It is important to note that the Class VI Rule requires that the AoR be delineated using computational modeling that accounts for all phases of carbon dioxide (e.g., supercritical, dissolved, etc.) and that accounts for site-specific and proposed/actual operational conditions. The results of the AoR delineation modeling to consider under this criterion should include, at a minimum, the predicted evolution of the plume and pressure (also indicating the pressure front) during the alternative PISC timeframe (including snapshots at the beginning and end) and any other results that support demonstrating the predicted system behavior (e.g., cross sections to present the evolution of upward migration during PISC). It should also include the results of a sensitivity analysis identifying the parameters that contribute to the uncertainty in model predictions associated with the PISC timeframe. For more information on AoR delineation modeling, see the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance*.

3.2.2.2 Predicted Timeframe for Pressure Decline [40 CFR 146.93(c)(1)(ii)]

A prediction of the timeframe for pressure decline, based on the current and calibrated (if needed and data are available) AoR delineation modeling, upon the cessation of injection must be included with the alternative PISC demonstration [146.93(c)(1)(ii)].

Fluid pressure impacts that may result in endangerment to USDWs and estimating a critical pressure to delineate the pressure front are discussed in detail in the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance.*

The demonstration of pressure decline is recommended to include the full spatial extent of pressure front evolution at the project site. EPA encourages the owner or operator to use plots of the pressure front (including pressure contour lines) at various time intervals presenting pressure buildup during injection and pressure dissipation during PISC until the pressure values reach a steady-state, below the critical pressure, or pre-injection pressure levels. This assessment can be supported by pressure decline profiles at specific locations, particularly at the injection well, following the cessation of injection. The EPA recommends that site-specific pressure monitoring results are also used to support these predicted assessments when available.

The sensitivity of the parameters that affect pressure decline (e.g., permeability, porosity, relative permeability) must be evaluated to understand their impact on the uncertainty associated with the demonstration [40 CFR 146.93 (c)(2)(vi)].

3.2.2.3 Predicted Rate of Plume Migration [40 CFR 146.93(c)(1)(iii)]

A prediction of the rate of carbon dioxide plume migration, and the timeframe for the cessation of migration must be included in the demonstration for an alternative PISC timeframe [40 CFR 146.93(c)(1)(iii)] and should be based at least in part on results of computational modeling performed for delineation of the current AoR.

This assessment is recommended to include the full spatial extent of plume evolution at the project site, including both the lateral and vertical extent. EPA encourages the owner or operator to use plots and cross sections of plume extent (including saturation contour lines) at various time intervals during PISC until its mobility ceases or it reaches a potential receptor (e.g., an active or abandoned well). When the plume is migrating at a rate such that this timeframe becomes exceedingly long (e.g., thousands of years), the plume migration rate may be considered sufficiently minor as to not pose an endangerment to USDWs. The plume migration assessment can also be supported by saturation profiles at specific locations, such as monitoring wells. The EPA also recommends the use of site-specific plume monitoring results (e.g., seismic surveys presenting the extent of the plume and/or actual saturation profiles or time of plume arrival at certain monitoring wells) to support these predicted assessments when available.

The sensitivity of the parameters that affect the plume mobility (e.g., permeability, porosity, relative permeability, the dip of the confining/injection zones, structural trapping by confining zone or other features also discussed below) must be evaluated to understand their impact on the uncertainty associated with the demonstration [40 CFR 146.93(c)(2)(vi)].

3.2.2.4 Trapping Processes and Predicted Rate of Carbon Dioxide Trapping [40 CFR 146.93(c)(1)(iv)–(vi)]

Specific processes leading to carbon dioxide trapping at the site must be identified, including physical entrapment and immobilization at the injection zone/confining zone interface, capillary trapping, dissolution of carbon dioxide into ground water, mineralization, and any additional relevant processes [40 CFR 146.93(c)(1)(iv)]. The trapping rate for each of these processes must also be estimated [40 CFR 146.93(c)(1)(v)]. The physical trapping effects of any structural features that may be present (e.g., domes, faults, or pinch-outs) should also be considered in predicting carbon dioxide trapping. Additionally, the results of laboratory analyses, research studies, and/or field studies used to estimate trapping rates must be identified [40 CFR 146.93(c)(1)(vi)]. See the *UIC Program Class VI Well Site Characterization Guidance* for more information on trapping mechanisms.

These predictions may be based in part on the results of computational modeling performed for the current AoR delineation and should incorporate a representative geologic conceptual model, which should be updated during injection operations as part of the AoR reevaluation required at 40 CFR 146.84(e). While the AoR delineation modeling must account for all phases, including dissolution, of the injected carbon dioxide stream [40 CFR 146.84(a)], potential mineralization due to site-specific geochemistry may need to be assessed separately. It is important to note that if the geochemical reactions are found to significantly affect carbon dioxide mobility, those processes should be accounted for during the delineation of the AoR as well. For example, detailed geochemical modeling, which is not anticipated to be part of many AoR modeling efforts (due to lack of significant impact on plume mobility), may be necessary to estimate trapping rates and evaluate trapping processes and capacity. Owners or operators may also conduct literature studies or perform laboratory tests or field-specific studies to better estimate trapping rates and evaluate governing processes. Alternatively, the owner or operator may estimate trapping rates and processes based on observations at similar projects, under similar conditions. EPA encourages the owner or operator to consult the UIC Program Director in choosing an appropriate methodology for estimation of trapping rates at the site.

Because different simulators and estimation methods have different capabilities, the format or presentation of the trapping rate estimates and processes will vary from project to project. In general, the EPA recommends that owners or operators provide a quantitative representation of the important mechanisms that will immobilize the carbon dioxide plume at the site. For example, if mineralization is predicted to take place, relevant geochemical reaction rates could be provided. If capillary trapping is predicted to be a key mechanism, then estimated trapping rates could be provided in data tables and/or graphs showing the percent of the injected carbon dioxide in the gas, aqueous, and trapped phases over time. Alternatively, where structural trapping is dominant at a specific project, representation of information in tables, maps or cross sections may be appropriate. In each case, a discussion or description of the governing processes as well as the applicable assumptions and parameters used for the estimation should be included. Additionally, the extent to which the owner or operator expects that carbon dioxide trapping will lead to changes in the potential for USDW endangerment over time should be discussed.

3.2.2.5 Confining Zone Characterization [40 CFR 146.93(c)(1)(vii)]

The owner or operator is required to present results of characterization of the confining zone, including a demonstration that it is free of transmissive faults, fractures, and micro-fractures, and that it is of appropriate thickness, permeability, and integrity to impede fluid movement [40 CFR 146.93(c)(1)(vii)]. Where relevant, the EPA recommends that structural traps (e.g., faults, domes, or pinch-outs) that can serve important roles in containing the carbon dioxide plume also be noted. EPA encourages the owner or operator to draw on information and data collected pursuant to 40 CFR 146.82(a)(3)(ii) and (iii) and 146.83(a)(2). When available, the EPA recommends that any relevant monitoring information under 40 CFR 146.90 is also used to support this assessment. As a complement to data collection and synthesis pursuant to 40 CFR 146.82, the owner or operator should consider regions of the confining zone predicted to come into contact with the carbon dioxide plume or mobilized fluids for the first time during post-injection. The owner or operator is also encouraged to explain how the data summarized in this section were used in computational modeling and demonstrations of pressure decline, plume migration, and trapping (see above).

3.2.2.6 Assessment of Potential Conduits for Fluid Movement [40 CFR 146.93(c)(1)(viii)–(ix)]

The owner or operator must identify potential conduits for fluid movement including the planned injection well(s) and project monitoring wells associated with the Class VI GS project as well as any other projects in areas that may be reasonably expected to come into contact with supercritical carbon dioxide and/or mobilized fluids [40 CFR 146.93(c)(1)(viii)]. EPA encourages the owner or operator to draw on data collected pursuant to 40 CFR 146.82(a)(4) and 40 CFR 146.90 (when available). Of particular importance are any potential leakage pathways, such as surrounding injection or production wells, that are predicted to come into contact with mobilized fluids only after the cessation of injection. The EPA encourages the owner or operator to provide a demonstration that potential conduits for fluid movement will not pose an endangerment to USDWs giving consideration to the proposed alternative timeframe.

For all abandoned wells within the current AoR, the owner or operator must present information on construction and an assessment of the quality of plugs [40 CFR 146.93(c)(1)(ix)]. EPA encourages the owner or operator to draw on data collected pursuant to 40 CFR 146.84(c)(2). The EPA suggests that this assessment confirms that the corrective action data collected for the current AoR represent all artificial penetrations that may come into contact with mobilized fluids and/or carbon dioxide injected based on AoR modeling results. The reader is referred to the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance* regarding the evaluation of abandoned wells.

3.2.2.7 Evaluation of the Distance between the Injection Zone and the Nearest USDWs [40 CFR 146.93(c)(1)(x)]

The owner or operator is required to identify the distance between the injection zone and the nearest USDWs above and/or below the injection zone [40 CFR 146.93(c)(1)(x)]. This distance is a key determinant of the potential that artificial penetrations may endanger USDWs. An evaluation of the distance between the injection zone and the nearest USDW, vertically and laterally (where applicable), should complement the pressure and plume migration analysis [see 40 CFR 146.93(c)(1)(ii) and (iii)], trapping processes and rates analysis [see 40 CFR 146.93(c)(1)(iv) through (vi)], and assessment of potential conduits for fluid movement [40 CFR 146.93(c)(1)(viii) and (ix)]. Evaluating these in a comprehensive manner will facilitate a determination of potential for USDW endangerment and confirm non-endangerment for the purposes of approving an alternative timeframe.

3.2.2.8 Additional Criteria for Alternative PISC Timeframe Demonstration [40 CFR 146.93(c)(2)(i)–(vii)]

The Class VI Rule requires that information submitted with this application meet the following criteria [40 CFR 146.93(c)(2)]:

- *All analyses and tests must be accurate, reproducible, and performed in accordance with established quality assurance standards* [40 CFR 146.93(c)(2)(i)]. EPA encourages the owner or operator to follow accepted protocols, including the use of peer-reviewed methods, to ensure that all analyses meet these criteria. Furthermore, the owner or operator is required to submit a QA/QC plan to demonstrate that all analyses meet these standards (see below).

- *Estimation techniques must be appropriate, and EPA-certified test protocols must be used where available* [40 CFR 146.93(c)(2)(ii)]. Computational modeling and the resulting interpretation to evaluate changes in endangerment potential to USDWs may be prone to uncertainty and error. EPA recommends the use of sensitivity analyses to reduce uncertainty in modeling the movement of the carbon dioxide plume and pressure front. To minimize error in ground water sample analyses, EPA encourages the owner or operator to use accepted methods, such as EPA-certified methods and standards developed or approved by ASTM, the American Water Works Association (AWWA), the Society of Petroleum Engineers, or similar entities. See the UIC Program Class VI Well Testing and Monitoring Guidance for additional information on EPA-certified analytical methods for ground water constituents.

- *Predictive models must be appropriate and tailored to the site conditions, composition of the carbon dioxide stream and injection and site conditions over the life of the Class VI GS project* [40 CFR 146.93(c)(2)(iii)]. The reader is referred to the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance* regarding model development and appropriateness using site-specific information and parameters.

- *Predictive models must be calibrated using existing information (e.g., at Class I, Class II, or Class V experimental technology well sites) where sufficient data are available* [40 CFR 146.93(c)(2)(iv)]. Model calibration refers to adjustment of model parameters in order to match model results to monitored site observations. For example, model calibration may consist of adjusting site permeability values within a reasonable range such that previously observed pressure measurements are consistent with model results. Where data that may be used for model calibration are readily available, owners or operators must perform model calibration prior to use of computational modeling results in the alternative timeframe demonstration. The reader is referred to the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance* for additional information regarding model calibration.

- *Reasonably conservative values and modeling assumptions must be used and disclosed to the UIC Program Director whenever values are estimated on the basis of known, historical information instead of site-specific measurements* [40 CFR 146.93(c)(2)(v)]. In some cases, in computational modeling or other quantitative analyses, parameter values from peer-reviewed literature sources may be used when site-specific data are not available. Typically, literature searches result in a range of reasonable parameter values. In these cases, the owner or operator must select values from the reported range that are reasonably conservative (i.e., reasonable values that may tend to estimate longer, rather than shorter, estimated PISC timeframes) and are also consistent with other data used to model site-specific information. This is of particular importance for those modeling parameters for which the model has been shown to be highly sensitive. The owner or operator must also disclose the source of all parameters used.

- *An analysis must be performed to identify and assess aspects of the alternative PISC timeframe demonstration that contribute significantly to uncertainty. The owner or operator must conduct sensitivity analyses to determine the effect that significant uncertainty may contribute to the modeling demonstration* [40 CFR 146.93(c)(2)(vi)]. Analyses used in the alternative timeframe demonstration, including computational modeling, are prone to uncertainty. Model uncertainty is a result of the uncertainties related to the underlying science of the governing equations and the uncertainty in the parameter values input to represent the actual system (USEPA, 2003). A number of factors contribute to significant uncertainty in Class VI-related modeling predictions, including:

    - Difficulties in determining the structural geology and rock properties throughout the area likely to be affected by large injection volumes;

    - A relative lack of data on the behavior of supercritical carbon dioxide in the subsurface;

    - The drastic changes in transport behavior of carbon dioxide caused by changes in pressure and/or temperature; and

    - The buoyant nature of carbon dioxide relative to native formation fluids.

  The impact of parameter uncertainty on modeling results can be characterized through a model sensitivity analysis, which consists of sequentially varying a single parameter in successive model simulations while keeping all other model features constant. Sensitivity analyses provide an indication of those modeling parameters that most affect predictions of carbon dioxide plume and pressure front movement, trapping, and pressure changes, and provide guidance regarding which parameters to focus on during data collection, parameter estimation, and model calibration.

- *An approved QA/QC plan must address all aspects of the demonstration* [40 CFR 146.93(c)(2)(vii)]. A QA/QC project plan must be submitted with the demonstration. It will describe all QA/QC standards to which the owner or operator will adhere. The purpose of the QA/QC plan is to outline all steps taken by the owner or operator during development of the demonstration to ensure that data and analyses are accurate, reproducible, and complete. The EPA encourages the owner or operator to review relevant federal EPA and state guidance regarding development of QA/QC project plans. Applicable federal EPA guidance includes USEPA (2002).

3.3 PISC Monitoring

The Class VI Rule requires PISC monitoring to track the evolution of the plume and pressure front and to demonstrate that USDWs are not being endangered during the post-injection phase of the project [40 CFR 146.93(b)]. These monitoring activities (and their associated reporting requirements) are intended to ensure that the project is continuing to conform to the permit conditions and that any unforeseen USDW endangerment is identified and mitigated.

Furthermore, PISC monitoring results are a critical component of the non-endangerment demonstration that must be made before site closure, as discussed in Section 3.4.

During the post-injection phase, the majority of the injected carbon dioxide is expected to remain as a separate-phase plume (i.e., in a carbon dioxide-rich, dense supercritical/gas phase). However, a fraction of the carbon dioxide will continue to dissolve in formation fluids, contributing to the aqueous-phase plume (which can potentially also include mobilized naturally occurring trace metals from the formation). The primary driving force for migration of both the separate-phase and dissolved-phase plumes is pressure buildup in the formation from the injection operation, particularly in the area near the injection well. However, buoyant flow (driven by the relatively lower density of carbon dioxide) also contributes to plume migration, driving the plume toward the confining zone and/or other structural traps along its trajectory. Therefore, even as pressure declines during the post-injection phase, separate- or dissolved-phase carbon dioxide and displaced formation fluids may continue to endanger USDWs, and monitoring continues to be necessary. Monitoring also provides evidence that the potential for USDW endangerment decreases as expected over time, as pressure declines in the system and immobilization/trapping of the carbon dioxide progresses.

A description of all post-injection monitoring methods and their locations is required to be submitted to the EPA as part of the PISC and Site Closure Plan, pursuant to 40 CFR 146.93(a)(2)(iii). The EPA recommends that PISC monitoring programs be designed based on site- and project-specific needs and considerations. The EPA expects these programs to be an extension of the injection-phase testing and monitoring activities, focusing on the strategies and methods that were successful during the injection phase and tailored specifically to address the anticipated system changes and risks during PISC. While designing their PISC monitoring programs, owners or operators are strongly encouraged to also consider their strategies for making the non-endangerment demonstration, to ensure that the necessary supporting data will be available to make such a demonstration and facilitate the UIC Program Director's authorization of site closure.

As required by the Class VI Rule at 40 CFR 146.93(b), the PISC monitoring program must, at a minimum, track the position of the pressure front and carbon dioxide plume and demonstrate that USDWs are not being endangered. As discussed in detail in the *UIC Program Class VI Well Testing and Monitoring Guidance,* both the plume and pressure front can be tracked using a combination of direct methods (e.g., taking fluid samples or pressure measurements at a monitoring well) and indirect methods (e.g., conducting geophysical surveys). Sections 3.3.1 and 3.3.2 below provide some guidance on the use of these methods during the post-injection phase. In addition to tracking the evolution of the plume and pressure front, the EPA recommends that PISC monitoring programs also include monitoring above the confining zone and a strategy to ensure that all potential leakage pathways are identified and addressed. Section 3.3.3 below focuses on above confining zone monitoring during the post-injection phase, and the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance* provides additional detailed information on identifying artificial penetrations and conducting corrective action.

Depending on site characteristics and the planned strategy for the non-endangerment demonstration, it may also be appropriate for the owner or operator to incorporate additional monitoring techniques into the PISC monitoring program. For example, the EPA encourages owners or operators to perform periodic mechanical integrity and corrosion testing of monitoring wells to ensure that they do not allow for fluid movement that may endanger a USDW. Other monitoring techniques, including surface air and/or soil gas monitoring or additional geophysical techniques such as passive seismic monitoring, may be used to provide additional, complementary data. The reader is referred to the *UIC Program Class VI Well Testing and Monitoring Guidance* for further details regarding each of these monitoring techniques.

The Class VI Rule requires that the PISC and Site Closure Plan include a schedule for these post-injection monitoring activities [40 CFR 146.93(a)(2)(iii)]. The appropriate frequency for PISC monitoring activities depends on site- and project-specific conditions. In general, the EPA recommends that, as long as it was proven successful, the frequency used at the end of the injection phase for each selected monitoring activity be continued through the initial stages of PISC. If new methods are being implemented, the EPA encourages the owner or operator to employ a frequency appropriate to support an understanding of the technology to ensure that the new method is successful as well as to account, where appropriate, for any potential site-specific seasonal variability; and to ensure that sufficient data are gathered to support project decisions.

In the PISC and Site Closure Plan, an owner or operator may also propose reducing the frequency of monitoring during the post-injection phase, if it can be demonstrated based on monitoring results that the potential for endangerment of USDWs has decreased over time. The EPA encourages owners or operators to consult with their UIC Program Director to determine specific, risk-based, quantitative criteria that, when achieved, will indicate that a reduced monitoring frequency is appropriate. Some examples of such criteria could include the reservoir pressure reaching a certain level relative to pre-injection conditions or steady or favorable trends in observed geochemical monitoring results over a pre-defined period. In this way, PISC monitoring frequency can be evaluated to establish the most appropriate monitoring intervals, and it may be adjusted through the post-injection phase before eventually ending with site closure (see Section 3.2).

3.3.1 Direct Monitoring of the Plume and Pressure Front in the Injection Zone

Direct monitoring in the injection formation is an integral component of a strategy to track pressure and plume evolution in GS operations. During the injection phase, owners or operators are required to directly monitor formation pressure within the injection zone [40 CFR 146.90(g)(1)]. The EPA also anticipates that owners or operators will use direct methods to track the carbon dioxide plume in the injection formation (e.g., via fluid sampling from deep monitoring wells), especially when the UIC Program Director determines that indirect methods may not be appropriate or sufficient pursuant to 40 CFR 146.90(g)(2).

During PISC, the EPA recommends that owners or operators continue to use direct monitoring techniques as a part of their strategy to track the pressure front and carbon dioxide plume. There are several outcomes that owners or operators may want to consider when developing this strategy. For example, fluid pressures within the injection zone are anticipated to decrease over time following cessation of injection; observing a sustained decrease in fluid pressures across the system, consistent with the pressure dissipation rates predicted by computational modeling, could be a key justification for reducing and eventually ending monitoring. Conversely, an unexpected and significant decrease in pressure could potentially indicate an unanticipated leak out of the monitored zone and could trigger additional action. Importantly, the rate of fluid pressure decline may not be steady within particular zones due to heterogeneity in the subsurface, as pressure depends on the site-specific geologic properties of the rock formations. Fluid pressures may also fluctuate due to external factors, including local fluid extraction, injection, or ground water recharge. The EPA expects that the owner or operator will synthesize and interpret their direct pressure monitoring results to provide a clear picture of system behavior in their reporting to the EPA (see Section 3.3.4).

In addition to direct pressure monitoring, direct fluid sampling in the injection zone (at elevations where the carbon dioxide plume is predicted to appear/migrate) may be used to infer the presence or absence of carbon dioxide at a location and, therefore, be used to provide data on the extent and movement of the carbon dioxide plume. During PISC, the EPA recommends that owners or operators conduct direct plume monitoring to validate the migration predicted by modeling in both the lateral and vertical directions and to confirm the presence of the predicted trapping mechanisms (e.g., structural trapping, capillary trapping, and mineralization) and their effect on plume mobility. For example, as carbon dioxide saturation decreases in certain areas after injection, the EPA recommends that owners or operators determine the residual saturation in those areas to confirm that trapping is taking place as predicted by the AoR delineation modeling. Owners or operators should continue to analyze for the same target parameters monitored during the injection phase, such as carbon dioxide (dissolved and free phase), major anions and cations, organics, total dissolved solids (TDS), pH, co-injected tracers (if used), or any drinking water contaminants of concern at the site. The *UIC Program Class VI Well Testing and Monitoring Guidance* further discusses technical considerations and methods for this type of monitoring.

When owners or operators develop their direct monitoring strategies, the EPA recommends that they consider the potential for ambiguous data at the outer portions of the carbon dioxide plume (e.g., due to viscous fingering, heterogeneity, and/or very low concentrations). Concentrations of key constituents will likely be lower in these areas and more difficult to differentiate from background sources than in other locations. Additionally, the supercritical carbon dioxide plume may exhibit thin, laterally extensive zones at the top of the injection zone (i.e., gravity tongues; see, e.g., Ide et al., 2007). Fluid sampled from injection zone monitoring wells with a relatively long perforated interval may dilute carbon dioxide present in this thin zone. In such cases, an uncertainty analysis of monitoring well data may be used to support interpretations of the monitoring results. This type of analysis may include plotting historical trends for comparison to recently collected data and conducting statistical tests for significance.

Additional injection zone monitoring wells may need to be installed during PISC if there is evidence that the carbon dioxide plume or pressure front may be migrating in new directions, either vertically or laterally (see Box 3-1). Although increasing the number of monitoring wells may be costly, installation of new monitoring wells is one way to reduce uncertainty in interpretation of monitoring results (as well as to provide additional data to support the non-endangerment demonstration). Methods exist for determination of well placement to reduce uncertainty (e.g., Meyer and Brill, 1988), though the EPA recommends that owners or operators discuss proposed approaches with the permitting authority to ensure they are appropriate for plume or pressure-front monitoring. (Monitoring above the confining zone is addressed in Section 3.3.3.) Alternatively, an owner or operator may consider whether an existing monitoring well could be dually completed to monitor in multiple intervals at a Class VI project. As discussed in Section 3.3.2, geophysical methods may also be used to reduce monitoring data uncertainty and address some of these concerns.

If owners or operators determine that data from additional monitoring wells or from additional intervals within an existing well or wells are necessary to achieve the goals of PISC monitoring, the EPA recommends that they discuss their plans with the UIC Program Director before amending their PISC and Site Closure Plan and installing any new wells. In general, the EPA recommends that monitoring wells be strategically located to maximize useful data collection while minimizing the number of potential conduits for fluid migration. At the time that the owner or operator, in consultation with the UIC Program Director and following the PISC and Site Closure Plan, determines that a monitoring well is no longer needed (e.g., if pre-determined benchmarks or criteria are met), the EPA encourages the owner or operator to plug the well in a manner that will not lead to the endangerment of a USDW. All monitoring wells must be plugged prior to site closure [40 CFR 146.93(e)].

3.3.2 Indirect Monitoring of the Plume and Pressure Front in the Injection Zone

Indirect monitoring technologies include geophysical surveys and wellbore methods used to indirectly monitor subsurface conditions, often over a relatively large area using surface and/or downhole measurements. In combination with direct monitoring activities, these technologies can provide critical information on the plume and, occasionally, pressure distribution for Class VI GS projects. During the injection phase, the Class VI Rule requires the use of indirect methods for plume and pressure-front monitoring unless the UIC Program Director determines, based on site-specific considerations, that indirect methods are not suitable [40 CFR146.90(g)(2)]. Generally, these same site-specific considerations apply to the use of indirect techniques during PISC; if certain techniques have been used successfully during the injection phase of a project, the EPA encourages the owner or operator to continue their use during PISC.

Geophysical monitoring techniques provide broad, non-point measurements and can be used to estimate the extent of the separate-phase carbon dioxide plume and, in some cases, pore pressure. Although they do not provide direct measurements of target parameters and may be subject to uncertainties in interpretation, geophysical methods can complement the point data collected using monitoring wells; monitoring uncertainty is reduced when direct and indirect monitoring data are collected and interpreted in a complementary fashion. Applicable geophysical methods that may be used for PISC monitoring include seismic, electromagnetic, and gravity surveys, as well as, in some cases, ground displacement methods such as interferometric synthetic aperture radar (InSAR). More information on these methods can be found in the *UIC Program Class VI Well Testing and Monitoring Guidance*.

Time-lapse application of geophysical surveys involves repeat measurements in the same locations over time to evaluate changes in subsurface conditions. Comparison among sequential surveys is contingent upon geophysical methods being geo-referenced and, in some cases, being located at exactly the same coordinates. Changes in near-surface conditions such as soil-water saturation may also have a large impact on comparability among geophysical surveys. Due to the potentially long duration of the post-injection phase, repeatability and comparability of geophysical surveys may be challenging at Class VI GS projects, though consistency of the methods used in the geophysical surveys will increase the value of comparing results through time. The EPA encourages "truthing" of geophysical data with direct monitoring results to help reduce error from changes in near-surface conditions and aid in comparison of repeat geophysical surveys.

These geophysical monitoring techniques are used in many applications including the injection of carbon dioxide for EOR and enhanced gas recovery (EGR). Additionally, the EPA recognizes that application and interpretation of geophysical monitoring techniques will improve during the lifetime of Class VI GS projects. As with other injection well technologies and UIC well classes, the EPA encourages owners or operators to consider adopting improved geophysical techniques that develop during the lifetimes of their Class VI projects, including during PISC, in consultation with their UIC Program Directors.

3.3.3 Above Confining Zone Monitoring

The Class VI Rule requires periodic monitoring of ground water quality and geochemical changes above the confining zone(s) during injection [40 CFR 146.90(d)]. Geochemical and/or pressure monitoring above the confining zone is an important method for identifying potential injectate leakage and/or native fluid displacement from the injection zone. Results from direct above confining zone monitoring, along with some indirect monitoring activities and well logs, may be used to support a demonstration of plume confinement and a lack of leakage at a GS site.

For the purposes of detecting potential leakage through the confining zone(s) during PISC, the EPA recommends that owners or operators continue the same monitoring strategy as implemented during the injection phase, until the leakage potential is reduced (e.g., with declining pressure). However, it is important to note that buoyant separate-phase carbon dioxide may still migrate through a pathway (e.g., a well with loss of integrity) even after pressure decline. The EPA recommends that the owner or operator continue to rely on MITs for monitoring wells and/or targeted above confining zone monitoring to demonstrate that no leakage out of the injection zone occurred.

More information on above confining zone monitoring can be found in the *UIC Program Class VI Well Testing and Monitoring Guidance.*

3.3.4 Reporting of PISC Monitoring Results

Owners or operators will submit PISC monitoring results according to the schedule established in the approved PISC and Site Closure Plan, pursuant to 40 CFR 146.93(a)(2)(iv). The EPA encourages owners or operators to select a reporting schedule that involves submitting monitoring results on an annual basis or more frequently, depending on site conditions.

Unlike the semi-annual reports of testing and monitoring results submitted during the injection phase, the Class VI Rule does not include specific requirements for the content of post-injection phase monitoring submissions. While these submissions will necessarily be site- and project-specific, the EPA recommends that owners or operators follow the general recommendations outlined below. The EPA has also developed a template for post-injection monitoring reports, which can be downloaded from the GSDT and used to guide the preparation of submissions. In addition, owners or operators are encouraged to cross-reference previous submissions where applicable/appropriate, to avoid the need for duplicative reporting.

In general, the EPA recommends that the following information be submitted with all reports:

- A list of all monitoring events that have taken place during the reporting period and the associated dates;
- A brief description of sampling/testing/analytical locations, elevations/depths, equipment, and procedures, indicating whether (and why) there were any departures from the procedures specified in the PISC and Site Closure Plan;
- Identification of any planned changes to the monitoring program that took place during the current reporting period (e.g., closure of monitoring wells, changes in the frequency of monitoring activities based on criteria established in the PISC and Site Closure Plan);
- Synthesis and interpretation of the results in the context of existing data from the injection and post-injection phases (e.g., describing trends, comparing results to predictions from computational modeling, identifying any anomalous or unexpected results, describing progress toward criteria for non-endangerment, highlighting any evidence of endangerment of USDWs, etc.);
- One or more map(s) and cross section(s) showing the AoR, monitoring locations, and the interpreted extent of the separate-phase carbon dioxide plume and the pressure front; and
- Any necessary changes to the project PISC and Site Closure Plan to continue protection of USDWs.

More specifically, for direct ground water quality and geochemistry monitoring results (including results from both the injection zone and any over- or underlying formations subject to fluid sampling), EPA recommends that owners or operators submit:

- Tabular and/or graphical representations of the entire body of monitoring results for the site (e.g., tables that show the results of each target parameter from pre-injection baseline sampling through the current reporting period);
- An interpretation of any trends, a comparison of results to predictions made during AoR computational modeling, and an evaluation of fluid leakage and migration, including (as appropriate) uncertainty analyses, graphs or charts, interpretive diagrams (e.g., Piper and Stiff diagrams), etc.;
- An evaluation of data quality for each sampling event, which may include the results of QA/QC analyses (examples may include duplicate analyses, matrix spikes, or blanks), instrument calibration information, and any other QA/QC details specified in the QASP; and

- If required by the UIC Program Director and/or specified in the PISC and Site Closure Plan, copies of all laboratory analytical reports.

For direct pressure monitoring (including results from both the injection zone and any over- or underlying formations where pressure is monitored), the EPA recommends that owners or operators submit:

- Tabular and/or graphical representations of pressure monitoring results at the site (e.g., measured depth to fluid or pressure transducer readings in all wells, with related parameters such as fluid density and fluid temperature);

- If using pressure transducers, records of the most recent calibration or verification of the measurement instruments;

- Calculated or measured bottom-hole pressure in all wells;

- Time-series graphs and pressure or head maps used in interpretation of pressure data; and

- A description, supported by graphics, comparing the newly acquired pressure data to AoR modeling predictions.

For geophysical surveys and other indirect plume and pressure front monitoring methods, the EPA recommends that owners or operators submit:

- A description and technical justification of all survey techniques and methodologies used (or references to previously submitted documentation);

- A map showing the location of all survey equipment positions during the test(s);

- A description of all data processing steps taken and the major assumptions used during data processing;

- An interpretation of results in the context of plume and/or pressure front location and fluid leakage, including relevant information on method sensitivity and any out-of-zone anomalies that may require follow up; and

- A description, supported by one or more map(s) and cross section(s) comparing results to relevant AoR modeling predictions.

For information on using the GSDT to submit PISC testing and monitoring results, see the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators.*

3.4 Demonstration of USDW Non-Endangerment

Prior to receiving authorization for site closure, the owner or operator must submit a demonstration, based on monitoring and other site-specific data, that no additional monitoring is needed to ensure that the project does not pose an endangerment to USDWs [40 CFR 146.93(b)(3)].

Based on site- and project-specific conditions, a non-endangerment demonstration may be submitted to the UIC Director for review and approval at various times during the PISC phase of a Class VI project.

- An owner or operator may submit a demonstration of non-endangerment of USDWs at the end of the PISC timeframe established in the permit;

- Alternatively, an owner or operator may choose to submit a demonstration before the end of the PISC timeframe established in the permit where he or she has substantial evidence that the geologic sequestration project no longer poses a risk of endangerment to USDWs pursuant to 40 CFR 146.93(b)(2). Under this scenario, an alternative PISC timeframe need not have been in place.

If the UIC Program Director approves the non-endangerment demonstration, site closure is authorized pursuant to requirements at 40 CFR 146.93(d). If, after review of a non-endangerment demonstration, the UIC Program Director determines that the demonstration cannot be made at the site (at a given time), he/she may extend PISC beyond the previously established PISC timeframe [40 CFR 146.93(b)(4)], through an amendment to the PISC and Site Closure Plan (see Section 3.1.1).

The non-endangerment demonstration should take the form of a detailed report submitted to the UIC Program Director which synthesizes site- and project-specific information and demonstrates a current understanding of system behavior at the time of the non-endangerment demonstration. Pursuant to 40 CFR 146.93(b)(3), the report should, at a minimum, reflect consideration of the following:

- ***Operational and post-injection phase monitoring data and information:*** A summary and synthesis of all testing and monitoring data collected during the injection and PISC phases of the project should be submitted to help demonstrate non-endangerment. The EPA recommends owners or operators focus on monitoring results of pressure and carbon dioxide plume tracking supplemented by other data confirming the absence of any USDW endangerment. Sections 3.4.1 and 3.4.2 provide more information on these analyses. The summary of monitoring information is expected to be in a narrative form including an explanation of monitoring activities, the dates of all monitoring events, changes to the monitoring program over time, and an explanation of all monitoring infrastructure that has existed at the site. The EPA anticipates that the owner or operator will rely on previously submitted semi-annual reports and/or submittals of testing and monitoring results to support this summary; all previous submittals can be cited in the text using the date and name of the submittal to the EPA's GS Data Tool.

- ***A current AoR evaluation:*** The results of computational modeling used for the current AoR delineation and (if applicable) the demonstration of an alternative PISC timeframe may be used by the owner or operator to support the demonstration of USDW non-endangerment. The EPA expects that the modeling results, verified (and/or calibrated) by the actual field data, would be supplementary to the monitoring information used in this demonstration and are a critical component of presenting a detailed characterization of system behavior. EPA encourages the owner or operator to provide a detailed comparison of site and monitoring data collected during the injection and post-injection phases with AoR delineation modeling predictions of plume and pressure evolution, and trapping of carbon dioxide. The objective of this comparison is to assess if modeling predictions have been reasonably valid and support an understanding of system behavior during injection and post-injection, and to validate the non-endangerment demonstration. If monitoring results and model predictions agree well, this suggests that modeling results may be useful for supporting the non-endangerment demonstration. If modeling predictions are to be used in support of a non-endangerment demonstration, the EPA encourages the owner or operator to additionally submit all model documentation and supporting data or refer to relevant, previous submissions made to the GSDT. See the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance* for examples of the comparison of monitoring results and model predictions, discussion of model uncertainty analysis, and reporting of model predictions.

- ***The status of potential conduits for fluid movement within the AoR:*** Potential conduits for fluid movement, or leakage pathways, include active and abandoned wells, faults, and fractures. The EPA recommends that the non-endangerment demonstration include an assessment of all potential conduits for fluid movement including artificial penetrations (e.g., injection, monitoring and other wells) and faults and fractures that may endanger USDWs within the AoR (the area of USDW endangerment potential as confirmed by monitoring and project data). This assessment should provide a confirmation on these conduits' disposition –including wells associated with the project that have been or will be plugged and abandoned as outlined in the PISC and Site Closure Plan following the UIC Director's authorization of site closure. The demonstration may include a narrative explanation of the analyses conducted to identify potential conduits (i.e., aeromagnetic surveys, records reviews), a listing of all potential conduits, and an explanation of why each conduit will not pose an endangerment to USDWs, supplemented by monitoring data confirming no existing leakage. This demonstration may reference previously submitted information (e.g., information on corrective action, MITs conducted). Relevant supporting analyses may include assessment of the proximity of conduits to USDWs, monitoring for carbon dioxide in the region around potential conduits, and well integrity testing.

- ***Any other site-specific data or information that may support a demonstration of USDW protection and non-endangerment.***

Box 3-2 below describes example data that may be used in demonstrating non-endangerment and a sample template of a Class VI non-endangerment demonstration is available for download from the GSDT. See the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators* for more information on how to submit a non-endangerment demonstration.

3.4.1 Evaluation of Reservoir Pressure

Evaluation and demonstration of pressure decline to a level that it no longer poses potential endangerment of USDWs is integral to a Class VI non-endangerment demonstration. Pressure, along with buoyancy, is one of the primary drivers of fluid movement that may endanger a USDW. While pressure differentials will decay over time after injection ceases, the rate of pressure decay will be project-specific, influenced by factors including: injection zone and confining zone properties (e.g., porosity, permeability, compressibility); the injection pressure and volume; the areal extent and thickness of the formation; and the presence of lateral stratigraphic confining features.

This analysis should take into consideration the most recent AoR delineation/modeling results and pressure monitoring data. Data from direct pressure monitoring in the injection zone (e.g., using downhole pressure transducers) provides the most reliable metric of pressure decline over time. More detailed discussion on pressure monitoring during PISC can be found in Section 3.3.1. For the purposes of this demonstration, monitoring data should be compared against modeled predictions to confirm pressure has declined such that it will not induce fluid migration up any natural or artificial conduits. Models, including robust numerical simulators and simpler analytic or semi-analytic methods, can be used to estimate pressure decay. However, the EPA recommends using the same model that supported the delineation of the current AoR, as it is expected to be verified (or calibrated) by actual monitoring and operational data via AoR reevaluations. Additionally, modeling may be used to supplement monitoring data in order to estimate pressure in areas with little or no monitoring data as well as to estimate future trends.

3.4.2 Evaluation of the Carbon Dioxide Plume

Evaluation of the carbon dioxide plume in support of a non-endangerment demonstration should consider both the separate-phase plume (i.e., where the carbon-dioxide-rich gas phase, such as the supercritical phase, exists in pore spaces) and the aqueous-phase or dissolved-phase plume (i.e., dissolved in other formation fluids). Some factors that affect the mobility of these plumes are: (1) the presence or lack of a stratigraphic trap; (2) the presence or lack of a structural trap and existence of regional ground water flow; (3) movement up-dip at the injection zone/confining zone interface; (4) the presence of significant highly permeable pathways that lead to preferential plume migration; (5) the effect of geochemical mechanisms; and (6) the persistence of a pressure differential (e.g., due to other near-by operations) that results in fluid movement.

The evaluation of the carbon dioxide plume for non-endangerment should rely on monitoring data including geochemical and geophysical analyses (see Sections 3.3.1 and 3.3.2 for more information on direct and indirect plume and pressure tracking during PISC) and the most recent AoR modeling results. Monitoring information can provide evidence of plume location, mobility/immobility, migration rates, and support an understanding of trapping mechanisms (e.g., structural trapping, capillary trapping, and mineralization). Direct measurements of the plume in monitoring wells screened within the injection zone as well as the results of geophysical surveys may be used to confirm plume location and demonstrate plume migration rates. Geochemical analyses can support conclusions about trapping and plume immobilization.

The comparison of monitoring data against the most recent modeling results can corroborate model predictions. EPA expects that these modeling results may be used to supplement monitoring data in order to assess plume behavior in areas with little or no monitoring data as well as to estimate future trends. Modeling may be used to estimate and demonstrate the phase-state and degree and processes of carbon dioxide trapping over time. If a demonstration can be made, in conjunction with monitoring data, that a vast majority of the injected carbon dioxide stream has been immobilized via trapping mechanisms, this is strong evidence that the potential for USDW endangerment posed by the carbon dioxide plume has decreased. Modeling results, including sensitivity analyses, may be used to demonstrate that plume migration rates are negligible based on available site characterization, monitoring, and operational data.

Modeling may also be used to estimate future plume migration in cases where the plume is not completely immobilized (e.g., where structural traps are not present). If plume migration rates are extremely slow, and/or if a demonstration can be made that no conduits for fluid movement/leakage pathways exist in the direction(s) of plume migration within long timeframes (e.g., hundreds to thousands of years) until the plume reaches a potential receptor, USDW-endangerment potential may be determined to be low.

Separate-Phase Plume Analysis

The separate-phase plume will preferentially migrate upward due to density-driven buoyancy. Therefore, the potential for endangerment to USDWs will decrease when the extent of separate-phase carbon dioxide ceases to grow either laterally or vertically at a location where no leakage pathways exist. This condition may be met if the vast majority of carbon dioxide is trapped via trapping mechanisms which prevent buoyancy- or pressure-driven migration. In the case of relatively non-dipping formations, the decrease in pressure differentials will also result in plume immobilization where buoyancy is controlled.

An analysis of the separate-phase plume should confirm migration rate and the degree of immobilization or trapping that has occurred. The analysis should rely upon monitoring data such as down-gradient monitoring wells screened within the injection zone (at an elevation within the trajectory of plume movement). The results from such monitoring, over an extended period (as outlined in the PISC and Site Closure Plan), should indicate the absence of the separate-phase carbon dioxide plume. This can be used as evidence that the plume has not migrated into that area, and upper and lower bounds of the plume migration rate can be estimated and/or separate-phase plume immobilization confirmed. Plume migration rates should be compared against the most current modeled predictions and evaluated in the context of potential conduits for fluid movement within the AoR for the purpose of demonstrating model-monitoring data agreement and that the separate-phase plume will not migrate in a manner that it intercepts any potential conduits.

Aqueous-/Dissolved-Phase Plume Analysis

Following the cessation of injection, the aqueous-phase carbon dioxide plume (and mobilized constituents) will migrate in response to increased pressure and, once pressure declines to background levels, migration will continue via advection with regional ground water flow and diffusion away from the separate-phase source. As carbon dioxide concentrations decrease further from the separate-phase source, endangerment potential associated with the plume concomitantly decreases.

In a manner similar to the analysis of the separate-phase plume, the aqueous-phase plume analysis should support an understanding of migration rate, trapping and the disposition of potential migration pathways or conduits within the AoR relative to the aqueous-phase plume location. Monitoring wells screened above the confining zone may be used to determine aqueous-phase concentrations of carbon dioxide and mobilized constituents in order to assess USDW endangerment potential and should be compared against the most recent modeling results. A comprehensive evaluation of monitoring and modeling results of the aqueous-phase plume within the AoR will validate modeled predictions, identify uncertainties and support a confirmation that the aqueous-phase will no longer pose an endangerment to USDWs within the project AoR.

Box 3-2. Demonstration of USDW Non-Endangerment.

This box provides an example of a USDW non-endangerment demonstration, based on the hypothetical project presented earlier in Box 3-1 and the *UIC Program Class VI Well Area of Review Evaluation and Corrective Action Guidance*. This example is intended only for discussion purposes and does not create any additional regulatory requirements.

The owner or operator identified a PISC timeframe of 50 years in the PISC and Site Closure Plan. However, 40 years after the cessation of injection (70 years total from the beginning of injection), the owner or operator has determined that sufficient data exist to demonstrate non-endangerment of USDWs. The operator provided operational and post-injection phase monitoring data, information supporting the current AoR delineation, and the status of potential conduits for fluid movement.

Operational and post-injection phase monitoring data

Historical pressure measurements are plotted versus time in years from the beginning of injection. Model results are also plotted, and are based on the most recently calibrated model. As can be seen, model predictions and observed pressure data agree reasonably well, increasing confidence in use of the model for evaluating future trends.

At 40 years after the cessation of injection, pressure has declined to pre-injection levels in all three wells (Figure 8). Based on risk-based criteria listed in the PISC and Site Closure Plan, pressure decline to pre-injection levels is one factor indicative of USDW non-endangerment. Importantly, elevated pressure has not been observed in MW-13, consistent with the AoR reevaluation that occurred 20 years after the beginning of injection (see Box 3-1). Determination of non-endangerment cannot be made solely on the basis of pressure curves; however, this data may be presented alongside other data as part of a non-endangerment demonstration.

Current AoR evaluation

Model results from the most recent reevaluation of the AoR confirm that pressures will continue to decline or be steady at levels that do not pose an endangerment to USDWs.

Potential conduits for fluid movement

At 40 years after the cessation of injection, three monitoring wells remain in use at the project: MW-9, MW-12, and MW-13 (see Figure 7). The operator confirmed, based on the results of MITs, that all three wells are in good condition and plans to plug them following authorization of site closure.

Box 3-2. Demonstration of USDW Non-Endangerment.

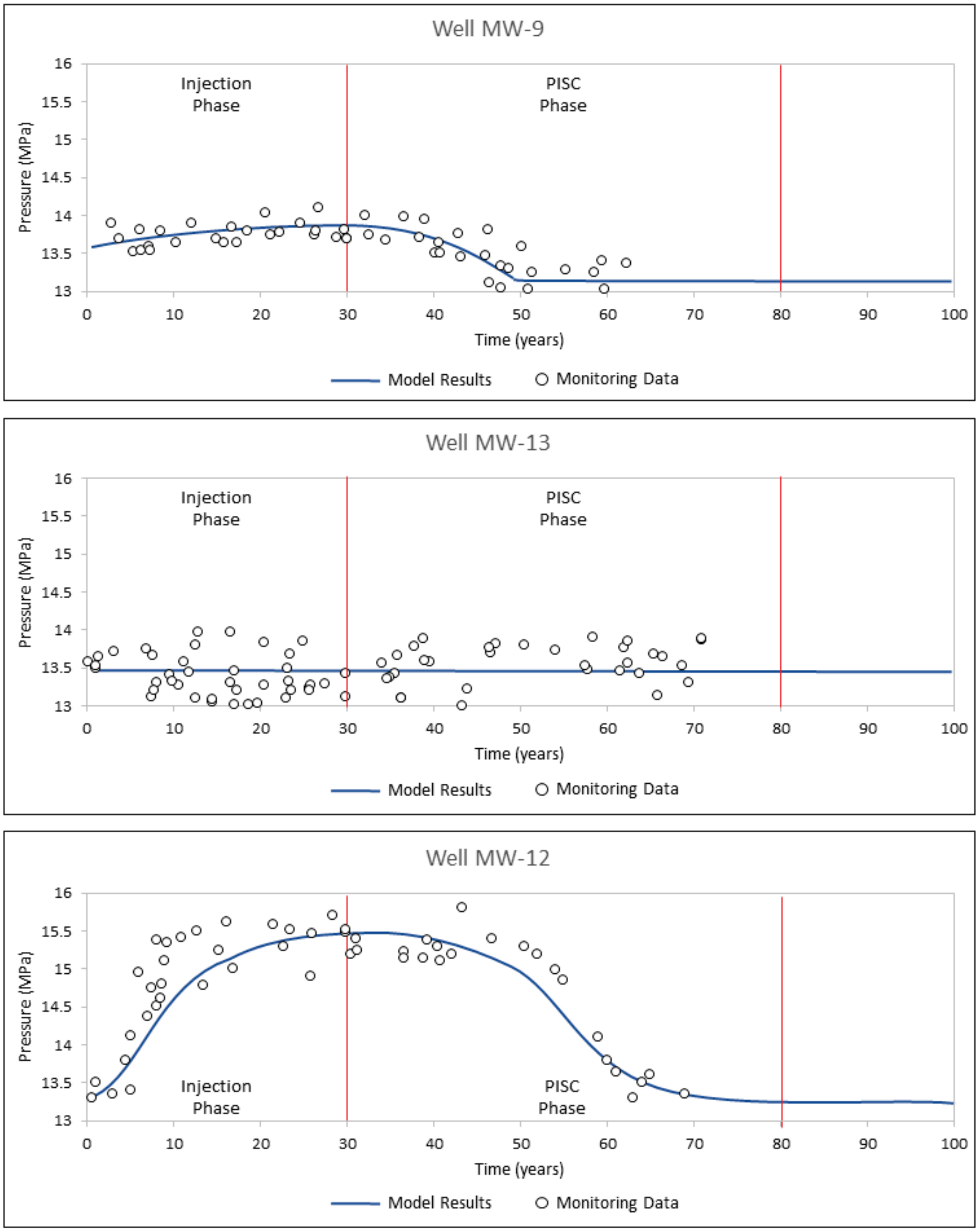


Figure 8. Historical Reservoir Pressure Data within the Injection Zone and Model Predictions for Three Monitoring Wells at Hypothetical Class VI GS Project.

4 Site Closure

Site closure activities required at 40 CFR 146.93(d) through (h) include notifying the UIC Program Director of intent to close the site, plugging all monitoring wells, submitting a site closure report, and recording a notation on the deed to the facility or other documents that the land has been used to sequester carbon dioxide. Additional site closure activities may include removing all surface equipment and restoring the site to its prior land surface condition (e.g., site restoration, site grading, and planting vegetation) or to a condition approved by the UIC Program Director.

Site closure requirements are established to ensure that all monitoring wells are plugged appropriately and to the UIC Program Director's satisfaction, that all Class VI GS project records are maintained, that necessary documentation is provided to the UIC Program Director, and that future land owners are made aware of the injection operation and that carbon dioxide is stored under the surface. Site closure may only occur after the UIC Program Director releases the owner or operator from PISC responsibilities following a non-endangerment demonstration pursuant to requirements at 40 CFR 146.93(b); see Section 3. Additionally, at the conclusion of site closure, the owner or operator will be released from financial responsibility requirements associated with the Class VI GS project [40 CFR 146.85(b)(1)]; see the *UIC Program Class VI Financial Responsibility Guidance.*

While not required, the EPA recommends that owners or operators describe in their PISC and Site Closure Plan how they plan to conduct site closure following the conclusion of the PISC phase (particularly the procedures for plugging monitoring wells). This can document agreements and provide certainty for how the site closure requirements of the Class VI Rule will be met. Site closure activities should be carried out in fulfillment of the requirements at 40 CFR 146.93(d) through (h). See the *UIC Program Class VI Well Project Plan Development Guidance* for more information regarding the preparation of the PISC and Site Closure Plan and Section 3.1 of this guidance document for how to amend the Plan. Except where noted with a rule citation, none of the recommendations in this section should be interpreted as regulatory requirements; they are provided only to illustrate potential pathways to fulfill the requirements of the Class VI Rule.

4.1 Site Closure Notification

Owners or operators are required to notify the UIC Program Director in writing at least 120 days prior to planned site closure [40 CFR 146. 93(d)]. At this time, if any changes have been made to the original PISC and Site Closure Plan, the owner or operator must also provide the amended plan. A notification period shorter than 120 days may be allowed by the UIC Program Director prior to a planned site closure. For details on submitting the notification and the amended plan to the EPA electronic reporting system, see the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators.*

A site closure notice submitted by the owner or operator of a Class VI well to the UIC Program Director may include:

- Facility information, such as the facility name and location;

- A list of contact personnel (e.g., names, titles, business phone numbers, business email addresses) for allowing timely direct communication to resolve any pressing issues; and

- A projected closure date, no less than 120 days following the site closure notification submission, unless the UIC Program Director has approved a different period prior to notice submission.

The EPA envisions that this notification would take the form of a letter from the owner or operator to the UIC Program Director with all of the information described above. A sample template of such a letter is available for download from the GSDT.

The EPA recommends that upon receipt of this notification, the UIC Program Director and the owner or operator discuss the planned site closure activities to ensure that all parties agree on the activities that must be performed.

4.2 Monitoring Well Plugging

The primary activity during site closure will be plugging of all monitoring wells at the site in a manner that prevents movement of injection or formation fluids that would endanger a USDW [40 CFR 146.93(e)]. Proper plugging of injection and monitoring wells is a long-standing requirement in the UIC Program, designed to ensure that injection or monitoring wells do not serve as conduits for fluid movement following cessation of injection and site closure, to ensure protection of USDWs.

Because improperly abandoned monitoring wells may become conduits for fluid movement into USDWs (similarly to improperly abandoned injection wells), the EPA recommends that owners or operators plug their monitoring wells using procedures similar to those used to plug injection wells, particularly regarding the use of plugging materials that are compatible with the injected carbon dioxide stream and carbon dioxide-water mixtures. While advance notification of monitoring well plugging is not explicitly required (i.e., as is required for injection wells at 40 CFR 146.92(c)), the EPA recommends that the owner or operator notify the UIC Program Director in advance of plugging monitoring wells. A template for a letter that can be used for notification of plugging the injection well is available for download from the GSDT.

If the injection well has not been plugged (i.e., because it is used as part of Director-approved post-injection testing and monitoring), well plugging must follow all requirements under 40 CFR 146.92 as outlined in the Injection Well Plugging Plan for injection wells. The requirements at 40 CFR 146.92 for plugging a Class VI injection well are discussed in Section 2 of this guidance document.

Owners or operators may consider the same types of information when selecting methods for monitoring well plugging as they do for injection well plugging. Relevant information includes well depth and construction, borehole diameter, location, well type, subsurface formations penetrated by the well, and how the composition of the injected carbon dioxide stream may affect plugging materials. This information will help determine the type and number of plugs that are necessary for monitoring wells, the method of emplacement, and the type, grade, and quantity of material to be used. See Section 2 above for additional information and appropriate well plugging methods. Information on plugging monitoring wells is also provided in "Region V Guidelines for Class I Well Monitoring Plans," available at: https://www.epa.gov/sites/production/files/2015-09/documents/r5-deepwell-guidance4-plugging-abandoning-injection-wells-19941222.pdf.

4.3 Site Closure Reporting and Recordkeeping

The Class VI Rule requires the owner or operator to submit a site closure report to the UIC Program Director within 90 days of site closure [40 CFR 146.93(f)]. The purpose of the report is to document appropriate closure procedures as well as provide information about the operation that may be of interest to future land owners and planners. Such information is needed to help authorities impose appropriate conditions on subsequent drilling activities that may penetrate the injection or confining zone(s).

The site closure report must document appropriate injection and monitoring well plugging as specified in 40 CFR 146.92 and described in Sections 2 and 4.2 of this guidance document [40 CFR 146.93(f)(1)]. The report should include a description of pre-plugging activities and the plugging procedures used to demonstrate that plugging requirements have been met.

The report must also contain a copy of a survey plat that has been submitted to the local zoning authority designated by the UIC Program Director [40 CFR 146.93(f)(1)]. The survey plat must indicate the location of the injection well relative to permanently surveyed benchmarks. In addition, the EPA recommends that the plat also identify the locations of all monitoring wells. The owner or operator must submit a copy of the survey plat to the Regional Administrator of the appropriate EPA regional office within 90 days of site closure.

The site closure report must also include documentation of appropriate notification and information to state, local, and tribal authorities that have authority over drilling activities [40 CFR 146.93(f)(2)]. This notification will enable them to impose appropriate conditions on subsequent drilling activities that may penetrate the injection and confining zone(s) to avoid compromising the containment of the injected carbon dioxide stream and potentially endangering USDWs. Such documentation may include:

- The names of entities being informed;
- Copies of letters sent to accompany the information;
- Maps of the AoR indicating the location of the injection well, plume, and pressure front;
- Important dates (e.g., operation phase, PISC phase, site closure); and
- Site characterization information.

Although not required by the Class VI Rule, owners or operators may also wish to notify other stakeholders, such as nearby drinking water utilities and agencies with primacy for drinking water regulations.

The site closure report must also include records reflecting the nature, composition, and volume of the injected carbon dioxide stream [40 CFR 146.93(f)(3)]; this may take the form of historical analyses of the injectate. The EPA recommends that the results of any other geochemical analyses conducted at the site also be submitted. Although not required by the Class VI Rule, the report may also include other information related to the carbon dioxide stream such as plume and pressure front modeling and monitoring data.

The site closure report submitted to the UIC Program Director must be retained by the owner or operator for 10 years following site closure [40 CFR 146.93(f)]. Concurrently, a copy of the report will be submitted to the EPA and will be retained in the EPA electronic reporting system [40 CFR 146.91(e)]. The UIC Program Director has authority to require the owner or operator to retain any records for longer than 10 years after site closure [40 CFR 146.91(f)(5)].

A recommended template for a site closure report is available for download from the GSDT, although this specific format is not required by the Class VI Rule. More information on submitting the site closure report can be found in the *UIC Program Class VI Well Recordkeeping, Reporting, and Data Management Guidance for Owners and Operators.*

Following site closure, each owner or operator of a Class VI injection well must record a notation on the deed to the facility property or any other document that is normally examined during a title search by a potential purchaser of the property [40 CFR 146.93(g)]. The notation must include the following information:

- That the land has been used for GS;
- The name of the state agency, local authority, and/or tribe with which the survey plat was filed, as well as the address of the EPA Regional Office to which it was submitted; and
- The volume of fluid injected, the injection zone(s), and the period over which the injection occurred.

4.4 Post-Site Closure Activities

Under the final Class VI Rule, once an owner or operator has met all regulatory requirements under 40 CFR Part 146 for Class VI wells and the UIC Program Director has approved site closure pursuant to requirements at 40 CFR 146.93, the owner or operator will generally no longer be subject to enforcement for regulatory noncompliance. However, following site closure, the owner or operator is financially responsible for any remedial action deemed necessary for USDW endangerment caused by the injection operation.

As EPA explained in the preamble to the Final Class VI Rule, site closure does not eliminate any potential responsibility or liability of the owner or operator under other provisions of law. [75 Fed. Reg. 77230, 77270 (Dec. 10, 2010)]. Separate from the EPA's authority to enforce regulatory compliance, an owner or operator may be subject to a response order under Section 1431 of the Safe Drinking Water Act (SDWA) even after proper site closure is approved under 40 CFR 146.93. Under Section 1431 of SDWA, the Administrator may require an owner or operator to take necessary response measures if he or she receives information that a contaminant is present or is likely to enter a public water system or a USDW, which may present an imminent and substantial endangerment to the health of persons, and the appropriate state and local authorities have not acted to protect the health of such persons. The action may include issuing administrative orders or commencing a civil action for appropriate relief against the owner or operator of a Class VI well. If the owner or operator fails to comply with the order, he or she may be subject to a civil penalty for each day in which such violation occurs or failure to comply continues. Furthermore, after site closure, an owner or operator may remain liable under tort and other remedies, or under other federal statutes including, but not limited to, the Clean Air Act (CAA), 42 U.S.C. 7401-7671; the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), 42 U.S.C. 9601-9675; and the Resource Conservation and Recovery Act (RCRA), 42 U.S.C. 6901-6992.

Additional information related to post-closure activities is available in the *UIC Program Class VI Financial Responsibility Guidance.*

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