Policy Recommendations for Selection & Development of Offshore Geologic Carbon Sequestration Projects Within Texas State Waters

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Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect:
Environmental Risks and Regulatory Considerations for Site Selection

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Abstract:

This report evaluates the potential environmental impact of geologic carbon sequestration projects in the state waters of Texas and makes recommendations for decisions that can be followed during the site selection phase to alleviate risk and mitigate potential harm. This report also makes related recommendations for consideration during the project development and operations phase related to site-specific monitoring, verification, accounting and reporting, and response planning.

DISCLAIMER

Environmental Defense Fund (EDF) prepared this report to support the University of Texas Bureau of Economic Geology's Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect project, related to identifying and choosing a suitable sequestration site or site(s), and as funded by the U.S. Department of Energy.

This report is intended to serve as a decision making tool for use when evaluating and selecting potential sites to develop the infrastructure and operations necessary to achieve geologic storage of carbon dioxide in the offshore environment of the Texas state waters. Although the document makes the case that CCS is a recognized and necessary tool for climate change mitigation, and development of offshore resources for CCS is likely key to that effort, this document is not meant to serve as a blanket recommendation for commercial scale development of CCS in the Texas state waters. Rather, prior to the development of any commercial scale CCS industry, in particular in the offshore environment, attention to, and coordination with existing and planned competing uses must be performed.

The views expressed herein are those of Environmental Defense Fund and not those of the University of Texas or the Department of Energy. Neither the United States Government nor any agency thereof, nor any of their employees, agents, contractors or volunteers makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, finding, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

As projects are developed or more information is collected, both in the Texas waters and beyond, the views and recommendations offered herein may be changed. As more information is developed, EDF reserves the right to update the findings, conclusions and recommendations of this paper in the future.

EXECUTIVE SUMMARY

Environmental Defense Fund (EDF) has prepared this analysis and recommendations as part of the Texas Bureau of Economic Geology's (BEG) evaluation of the suitability of geologic carbon sequestration projects within the offshore submerged lands inside the Texas state waters boundary. This analysis is part of BEG's larger research agenda associated with the Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect project.

Global climate change is a serious threat to the health and well-being of the planet. The effects of climate change include increased global temperatures, increased extreme weather events, degraded air quality and sea level rise. Carbon capture and geologic sequestration (CCS)[1] is one of many strategies that, if deployed correctly, can have a significant impact on reducing atmospheric concentrations of greenhouse gases (or at least the rate of their increase) that contribute to climate change. Examples that constitute correct deployment of CCS are well identified in the academic literature and from present day real-world operations. This combined experience with CCS suggests that with appropriate site selection, operational safeguards, and compliance with existing regulatory requirements and best practice methodology, long-term offshore sequestration can be performed safely and effectively and with manageable risk to the coastal environment.

Notwithstanding current experience however, CCS - perhaps particularly in the offshore environment - is not without risk. Accordingly, successful implementation will depend on the use of best industrial practices and safeguards by project developers and operators, and institutional capacity and integrity related to project oversight, precautionary management, monitoring, and adaptive management. For context, the BP Deepwater Horizon disaster appears to be attributable in large part to failures in both operational practices and institutional capacity and integrity – a result which must be avoided.

The purpose of this document is to assist BEG, prior to and during the process of selection of a geologic carbon sequestration site, to anticipate the environmental risks associated with long-term offshore carbon sequestration (including the processes required to do so) and to detail policy scenarios, recommendations and technical methods to avoid or minimize those risks. Issues and considerations associated with the site selection for carbon capture processes, the upstream component of CCS operations, are referred to only in passing, as are not a main point of reflection for this report. Accordingly, this paper focuses on geologic carbon sequestration and the necessary infrastructure to achieve it, including pipelines and offshore platforms.

This report also makes recommendations for consideration during the project development and operations phase related to site-specific monitoring, verification,

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[1] This paper follows common practice and uses the term CCS interchangeably with the term "geologic carbon sequestration." Consideration of the carbon capture process at an emissions source is generally outside the scope of this research assignment.

[2] The Sleipner Project is perhaps the most well-known of any CCS project in the world due to its age and the

accounting and reporting (MVAR), and impact mitigation response planning. The authors reflect that the operational aspect of MVAR and impact mitigation response planning is outside the scope of the original task related to site selection. However, since the availability of particular MVAR strategies and mitigation responses to a particular site is necessarily considered during the site selection phase, those sections are included herein.

This report is divided into six main sections discussing considerations of CCS in the waters offshore of Texas with a final section describing ten key recommendations derived from EDF's research. Highlights from each section are summarized below.

In Section I, a brief introduction to the research assignment and paper is given.

In Section II, the report analyzes the environmental and economic attributes of the Texas coastal region, both offshore within the 10-mile state waters boundary and onshore in close proximity to the tidal zone. In general, the Texas coastal region is a series of connected ecosystems that are comprised of diverse flora and fauna and support a thriving tourism and fishing industry. In addition to bringing upwards of $48 billion of economic activity to the Texas economy every year, the coastal region supports a significant number of threatened and endangered species and overlays several aquifers which serve as an important drinking water source for 73 counties. Because of Texans' reliance on the coastal zone for tourism, fisheries, and drinking water, it is essential that this resource be protected for future generations.

In Section III, the report assesses lessons learned from offshore (and onshore) CCS operations ongoing in other parts of the world and draws conclusions related to the Offshore CCS in Texas. While CCS off the coast of Texas will be the first of its kind not only in the Gulf, but also off the shores of the United States, the skills and significant experience from both on and offshore oil and gas drilling operations, and onshore and offshore waste injection projects, are directly transferrable to undertaking a CCS project in Texas. For example, offshore projects, such as Statoil's Sleipner and Snovit CCS operations, can deliver valuable insight for implementing CCS in the Gulf. In addition, significant experience in onshore operations, both for oil extraction and CCS provide valuable examples.

In Section IV, the report evaluates the general benefits associated with offshore CCS as both a climate change mitigation tool and in comparison to onshore operations. In general, widespread deployment of CCS can have a near term and substantial impact on GHG levels impacting climate change. Although it have not been used widely, when compared to other methods to sequester CO_2 in the subsurface, offshore CCS project development may hold many benefits other locations do not. Potential benefits include improved public acceptance, reduced likelihood of human interaction with CO_2 leaks if they should occur, greater clarity over legal requirements and property rights, and improved leak detection capabilities.

In Section V, the report details the potential environmental and public health risks associated with offshore CCS projects. The pathways for these risks to become actual injury are also evaluated. These risks are identified both from existing project development experiences as well as from extrapolated experiences from offshore oil and gas development and operations. As discussed, with proper management and maintenance by the project developer and operator, much of these risks can be managed or minimized, but must be considered during the site selection and development phase. As discussed, the institutional capacity for oversight of project operations is also critical.

In Section VI, the report details the existing legal and regulatory landscape for offshore CCS and installation of associated infrastructure for use in formulating policy recommendations related to site selection. Although more exhaustive accounts of legal and regulatory requirements may be found, this analysis presents the main body of regulatory restrictions associated with project development for protection of the offshore environment. As the discussion of regulatory requirements shows, while there is room for significant benefit from CCS operations in reducing greenhouse gas emissions, it is imperative that existing best management practices and regulatory requirements are followed in implementing CCS. Further, based on this set of regulatory requirements, it is apparent that much of the regulatory framework necessary to protect the offshore environment is currently in place.

In Section VII, this report takes the information presented and formulates ten key policy recommendations for use in siting and developing a project in the offshore environment of Texas. A summary of those recommendations is provided below. These recommendations are characterized both for use in the site selection phase of the research project associated with the Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect, and also for use when considering larger-scale commercial deployment of geologic sequestration of CO_2 in the offshore environment. Where differences exist between the two uses for this report (informing the project as a research effort, and informing commercial deployment policies), the report identifies and discussed those differences.

KEY RECOMMENDATIONS

Recommendation 1: Any project for offshore CCS should be sited, designed and operated to avoid direct and significant impacts on human health or coastal natural resources (as defined by the Texas Natural Resources Code). To ensure adverse and / or unexpected environmental impacts are avoided, any offshore CCS project in Texas state waters must utilize the full range of precautions and safeguards available in all phases of the project timeline – including, but not limited to, site characterization, site selection, development, operation, monitoring, and closure. CCS site selection must evaluate whether the full range of precautions and safeguards are available at the target site or sites selected for development recommendation.

Recommendation 2**:** The siting of an initial project or projects to develop CCS in the offshore environment of the Texas coastal region must take a precautionary approach to prevent impacts on environmental attributes of concern. A similar approach should be taken during the development and operation phase of the project. A precautionary approach should be used for offshore CCS deployment until such time as commercial scale deployment of CCS is achieved or a regulatory framework for managing offshore projects is adopted into law.

Recommendation 3: Prior to site selection, a proposed site must undergo a site specific evaluation of its potential for geologic sequestration to cause significant environmental impacts, including an evaluation of whether the full range of monitoring and mitigation techniques will be available to minimize impacts both at the point of injection and throughout the area of review / full zone of impact. Such a review should include a full characterization of potentially significant direct and indirect impacts prior to initiating development.

Recommendation 4: If the project must choose between two or more similar or equally situated sites for ensuring long term sequestration of injected CO_2, the CCS project site should be located in the geologic formation which has the least amount of potentially transmissive pathways (pathways capable of allowing leakage of CO_2 from the confining reservoir) through the caprock formation.

Recommendation 5: Regardless of regulatory applicability, strict application of the site characterization and control requirements of U.S. EPA UIC Class VI well regulations should be performed to ensure permanent retention of injected material is achieved. Future offshore GSC projects, should be sited and operated where the best geology and site characterization exists, and with strict application of U.S. EPA UIC Class VI requirements as required by law or as necessary to ensure permanent retention of injected material.

Recommendation 6: All offshore CO_2 sequestration projects associated with the UT project should, to the extent feasible, be located at the maximum feasible distance from the shoreline and existing aquifers, but in no case closer than a distance where the zone of influence / area of review will overlap with resources of concern. This recommendation should also be followed for all projects, not just those associated with the BEG project, until further commercialization of offshore CCS occurs. Distance from the shore, aquifers or areas of concern should be built into the determination of site suitability, though must not undermine the paramount need to have a site that represents the best geology for long-term sequestration.

Recommendation 7: All offshore CO_2 sequestration project sites should be evaluated for whether their proximity to existing infrastructure and right-of-ways would allow for re-use or co-location of new equipment so as to reduce the potential environmental footprint of any new project.

Recommendation 8: Recommendation 8: The overall UT project should thoroughly evaluate several potential candidate sites for project development, allowing for critical evaluation of multiple locations and geologic characteristics by qualified experts prior to making a final determination. Assuming suitable conditions exist for sequestration, projects that are located in close proximity to another suitable site capable of acting as a back-up site for contingency purposes should be preferred.

Recommendation 9: An up-front site characterization for project site selection must evaluate the set of monitoring and mitigation options available at a proposed project site prior to making the determination of its suitability. All offshore CO_2 sequestration projects must utilize an MVAR plan that is able to detect migration or leakage of CO_2 from the target confining zone early on in the formation of a non-conforming condition. In addition to monitoring injection conditions as required under federal law, the MVAR plan must also include a regime of water, biological and sediment monitoring and testing, and must be operationalized both onshore and offshore prior to the start of operations. Further, a specialized gas leakage detection regime must be overlaid onto the MVAR as a whole.

Recommendation 10: All offshore CO_2 sequestration projects should, prior to selecting a project site, evaluate the availability of contingency and remediation measure available at the site in the event an undesired impact is observed. A contingency and remediation plan should thereafter be finalized and published prior to commencement of the project.

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I. INTRODUCTION

EDF has prepared this analysis and recommendations as part of the Texas BEG's evaluation of the suitability of CCS projects within the offshore submerged lands inside the Texas state waters boundary. This analysis is part of BEG's larger research agenda associated with the Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect project.

Today, offshore CCS projects exist in only a small set of locations around the world, though none yet in conjunction with a major power-generating facility. The most well known example of an offshore CCS project has been operating since 1996 and involves two facilities owned by Statoil of Norway: 1) a platform-based CCS facility at the Sleipner West natural gas field, roughly 155 miles off the Norwegian coast in the North Sea[2], and 2) a similar project in the Snøhvit natural gas field in the Barents Sea. Major new offshore CCS operations are also in various stages of development in Western Australia, (Gorgon Gas Project at Barrows Island), off the coast of Brazil (Petrobras' Lula oil field), and in Western Norway (Mongstad refinery).[3]

Whereas offshore CCS has few project examples worldwide, onshore research, development and project operation is more prevalent, consisting of projects ranging in size from demonstration and pilot scale to much larger commercial sizes. According to the U.S DOE National Emissions Technology Lab (NETL) CCS project database, there were about 250 onshore CCS projects in various stages of planning and development worldwide in the summer of 2011.[4] Therefore, although currently operating offshore CCS examples provide a minimum level of guidance and assurances that CO_2 risks can be effectively managed offshore, significant onshore examples do provide much more insight.

Given the significant number of industrial CO_2 point sources near the Texas coast, a wealth of information and experience in oil extraction including enhanced oil recovery, and the proximity to potential sites for geologic sequestration (i.e. a close "source-sink match"), the region presents a significant opportunity to utilize CCS to achieve emissions reductions. CCS utilization though is not without risks, and should not be performed without adequate accounting for, and mitigation of those risks. In this document, EDF addresses what it sees as the principal environmental concerns with expanded CCS operations in Texas offshore state waters, including public health issues, risks to flora, fauna, and ocean chemistry from development, operations and infrastructure. Evaluating historical examples and industry experience are central to this analytical effort.

In addition to evaluating potential environmental impacts and ways to minimize risks in the site selection phase, EDF's participation in this project involves an analysis of the

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[2] The Sleipner Project is perhaps the most well-known of any CCS project in the world due to its age and the amount of gas sequestered (roughly 1 $MMTCO_2E$/year since 1996).
[3] The decision of whether to fund CCS at Mongstad has been delayed until 2016
[4] U.S. Department of Energy, *NETL's Carbon Capture and Storage Database*, http://www.netl.doe.gov/technologies/carbon_seq/global/database/index.html (2011).

applicability of current legal and regulatory frameworks within state, federal and international law that could impact offshore CCS operations in Texas state waters, and an evaluation of how these existing regulations present opportunities to protect against environmental harm. EDF also offers recommendations related to the site operations phase for context and future planning, even though this phase may be beyond the scope of this focused project.

The conclusion made though this research assignment can generally be distilled down to the point that with appropriate site selection, operational safeguards, regulatory oversight, and compliance with existing regulatory requirements and best practice methodology, offshore CCS can be performed in Texas state waters safely and effectively, and with limited risk to the coastal environment and human population. Of course, this conclusion is built on the understanding that 1) meaningful opportunities for public participation will exist throughout the siting and environmental review process, and 2) rigorous independent regulatory oversight of project operations, including leak detection and leak mitigation, are present throughout the life of the project. To the extent that either or both of these mechanisms of participation and oversight break down, the risk of environmental harm increases and the stated conclusion may not hold.

In support of EDF's conclusion, ten discrete recommendations are made to manage and mitigate environmental risks from offshore CCS operations. In general, EDF's policy recommendations fit into the construct of ensuring rigorous site selection and characterization, followed by use of best in class monitoring and reporting practices to safeguard against environmental risks. Put more broadly, this policy framework can be thought of as promoting up front site selection work that 1) prevents problems from occurring, 2) creates mechanisms to identify problems if they arise, and 3) facilitates rapid response to problems if they should occur. Adopting these recommendations, in part or whole, are not trivial undertakings for project developers engaged in site selection. However, the application of the recommendations included in this document serve as the basis for EDF's finding that environmental risks can be effectively managed, and the recommendations therefore should be adopted in their entirety.

II. ENVIRONMENTAL ATTRIBUTES OF THE TEXAS COASTAL REGION

A. ECOLOGICAL ASSETS

The BEG Miocene CO_2 Site Characterization project focuses on the selection of potential CCS sites within state offshore lands, which extend three marine leagues, or about 10.35 miles from the Texas coast.[5],[6] The Texas coast is 367 linear miles long, running from Mexico to the Louisiana border.[7] When counting barrier islands, bays, estuaries, and lagoons, the Texas coastline includes approximately 3,300 miles of shoreline and is characterized by a wide variety of ecosystems and economic activities. All together, the state waters represent an area of yielding a prospective area of approximately 6,400 square miles. (Figure 1)

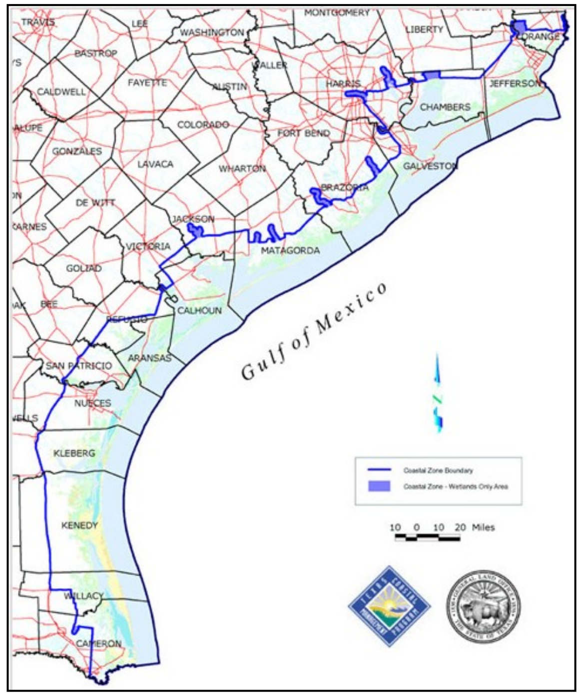

Figure 1: Texas Costal Zone
Source: Texas Parks and Wildlife

The coast plays a central role in the Texas economy, generating an estimated $48 billion in revenue through tourism, sport fishing, commercial fishing, and other economic activity at the coast's 16 ports.[8] The coast's estimated $7.2 billion in annual tourism revenue comes in significant part from visitors to Texas' popular beaches, which are major destinations for bird-watching and fishing.[9]

In general, any existing environmental resource in the coastal zone may be impacted by expanded development and use of surface impoundments necessary to facilitate a CCS project. Examples of activities that have the potential to impact environmental resources

[5] J.T. Litynski et al., U.S. Department of Energy, *Carbon Capture and Sequestration: The U.S. Department of Energy's R&D Efforts to Characterize Opportunities for Deep Geologic Storage of Carbon Dioxide in Offshore Resources,* http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2011/SelectedPubs/OTC-21987-PP%20-%20Litynski%20Offshore%20CCS%20Manuscript_Final.pdf (2011).
[6] State Submerged Lands Act, 43 U.S.C. § 1331.
[7] As discussed below, due to source-sink matching, suitability of injection formations and proximity to environmental attributes of concern, the upper third of the coast is the most likely site for an offshore CCS project in Texas state water.
[8] Texas Ports Association, *Benefits: Texas Ports Stimulate Texas Economy*, http://www.texasports.org/benefits/
[9] Oxford Economics, *Potential Impact of the Gulf Oil Spill on Tourism*, at 4, http://www.ustravel.org/sites/default/files/page/2009/11/Gulf_Oil_Spill_Analysis_Oxford_Economics_710.pdf

include, but are not limited to, installation and operation of pipelines, floating and fixed platforms, floating and fixed vessel docking facilities, injection and extraction wells, as well as increased vehicle, vessel and aircraft traffic in and around the coastal zone. Additionally, accidental and intentional releases from storage sites, surface impoundments and vessels may also impact environmental resources in the coastal zone.

Determining whether a specific project or site for offshore CCS is likely to cause significant deleterious impacts on the environment is a highly fact-specific inquiry (explored in more detail in Section IV). Such an evaluation must not only take into account impacts from new development, but also the context of the ecosystem into which the project is performed. That individualized ecosystem evaluation however cannot fully be developed in a document such as this since it is highly fact specific to each and every development site and will require in depth site specific evaluations.

In a general sense, as detailed below, while the Gulf of Mexico near shore ecosystem remains fairly productive, it is also likely to, in places, be compromised with respect to overall resilience to new external stressors because of the cumulative impacts of many existing activities, some of which are resulting in large scale modification of the processes that maintain the ecosystem. These large scale drivers include flow and sediment modifications, nutrient input, habitat fragmentation, chronic oil pollution, the lingering effects of the BP Deepwater Horizon disaster, and regular hypoxic and anoxic events associated with mass marine mortality. The risks of any new project therefore, should be evaluated in the context of a compromised ecosystem that may not be very resilient to additional impact. Moreover, depending on the site, the surrounding ecosystem may already to be subject to high loadings of carbon in various forms - including chronic leakage from oil operations and organic carbon from mass mortality events and from nutrient-fueled algal blooms.

In addition to evaluating the ecosystem context for any development site, it is also important to evaluate the suitability of mitigation options available to a particular site to reduce the potential for impacts some mitigation options will be more readily available at some sites over others.

In the brief overview that follows, we attempt to characterize, at a macro-level, the types of environmental attributes that may be affected by offshore CCS developments in the study-region. This overview is not meant as a comprehensive set of findings on environmental impact potential, (as would be required to satisfy National Environmental Policy Act (NEPA) requirements). However, by providing a summary of the key issues that would need to be evaluated in a full site characterization process and Environmental Impact Statement (EIS) under NEPA, we attempt to offer a brief list of issues that should be considered by BEG when selecting a proposed site - prior to any NEPA requirements actually maturing.

1. FAUNA

   a. Amphibians

The shorelines, wetlands and brackish waters of the Texas coast are inhabited by a number of amphibians, including seven species of salamander, and several varieties of newts, frogs and toads. These include several endangered and threatened amphibians: the Houston toad is listed on both the Texas and U.S. Endangered Species list.[10] Threatened amphibians include the Mexican tree frog, White Lipped frog, Sheep frog, and Mexican burrowing toad. Amphibian habitat is particularly fragile and susceptible to disturbance by development activity.

   b. Reptiles

Eight species of sea turtles live along the shoreline, seven of which are threatened or endangered. These include the Kemp's Ridley sea turtle, the Atlantic Hawksbill sea turtle, the Leatherback sea turtle, and the Loggerhead sea turtle.[11] Turtle nesting habitat is particularly fragile and susceptible to disturbance by development activity.

   c. Fish

The Texas coastline can be thought of as comprising several comingled fisheries ecosystems, each influenced by the geomorphological formations nearby including bays, estuaries and barrier islands. (Figure 2)

Open waters off the Texas coast, both within and outside the state waters boundary, are inhabited by more than 300 species of fish[12] including sharks, rays, and many species sought after by commercial and sport fishermen such as Red snapper, Tarpon and Black drum. Of the fish that reside off the Texas coast, the Smalltooth sawfish is listed as a federally endangered species under the federal Endangered Species Act (ESA), while the Opossum pipefish, River goby, and Mexican goby are listed at the state level as threatened.[13]

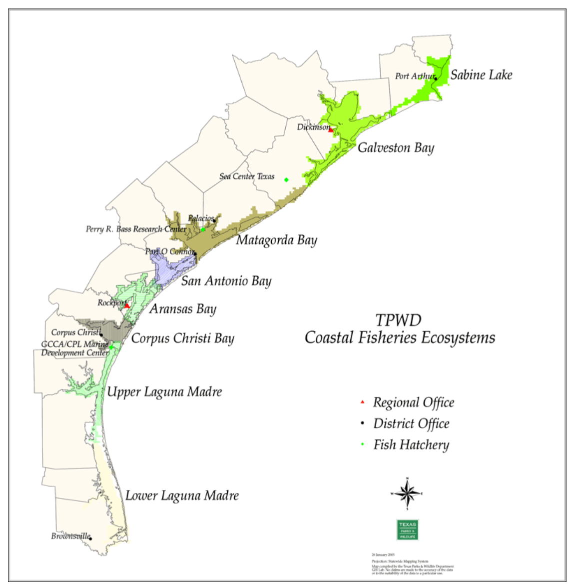

Figure 2: Texas Coastal Fisheries Ecosystems
Source: Texas Parks and Wildlife

[10] Texas Parks and Wildlife, *Endangered and Threatened Reptiles and Amphibians in Texas and the United States*, http://www.tpwd.state.tx.us/huntwild/wild/species/endang/animals/reptiles_amphibians/ (2009).
[11] *Id*.
[12] *Galveston Bay, Galveston & Gulf of Mexico*, http://www.ship468.org/seal/galveston.htm (2011).
[13] Texas Parks and Wildlife, *Endangered and Threatened Fish in Texas and the United States*, http://www.tpwd.state.tx.us/huntwild/wild/species/endang/animals/fish/ (2011).

d. Invertebrates

A number of invertebrates live in the coastal waters of Texas, including the Atlantic Bay scallop, lightning whelk, several species of crab, shrimp, beetles and spiders. Probably the most famous and economically important invertebrate in Texas waters is the oyster, American commercial oyster *Crassostrea virginica*, commonly referred to as the Eastern oyster, a highly commoditized invertebrate sought after by commercial fishermen. The American commercial oyster generally thrives in the bays and estuaries behind barrier islands separating the Texas mainland from the Gulf of Mexico.[14] In particular, Galveston Bay is home to 60-70 percent of the oyster crop in the state.[15] No coastal invertebrates are listed as threatened or endangered at this time.

e. Mammals

The Texas coastal zone and open water are home to several species of mammals, some of which are endangered or threatened. In fact, there are more endangered and threatened mammals in the Texas coastal zone than any other animal sub-group. There are two endangered land mammals that reside close to the coast, the Jaguarundi and the Ocelot, and three endangered marine mammals that are occasionally found in the coastal waters, the Finback whale, Humpback whale, and the West Indian manatee.[16] Additionally, there are 10 threatened marine mammals that either reside in or pass through the Texas coastal waters, including the Black right whale, Sperm whale, Atlantic spotted dolphin, Gervais-beaked whale, Goose-beaked whale, Killer whale, Pygmy killer whale, Rough-toothed dolphin, and the Short finned pilot whale.[17]

f. Bird Life

Bird life is abundant throughout the coastal zone, particularly in one of Texas' six national wildlife refuges. Of the nature reserves in the coastal zone, the Aransas National Wildlife Refuge is the world's largest migration ground for Whooping cranes, a U.S. and State-listed endangered species.[18] The area is also home to the state listed endangered Brown pelican, and three state listed threatened species of water birds: the Reddish egret, White-faced ibis, and Wood stork.[19]

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[14] Texas Department of Agriculture, *About Texas oysters*, http://www.texasoysters.org/about.html (2011).
[15] Texas Parks and Wildlife, *Endangered and Threatened Mammals in Texas and the United States*, http://www.tpwd.state.tx.us/huntwild/wild/species/endang/animals/mammals/ (2011).
[16] *Id.*
[17] *Id*.
[18] Texas Parks and Wildlife, *Whooping crane (Grus americana)*, http://www.tpwd.state.tx.us/huntwild/wild/species/endang/animals/birds/whooper.phtml (2011).
[19] Texas Parks and Wildlife, *Endangered and Threatened Birds in Texas and the United States,* http://www.tpwd.state.tx.us/huntwild/wild/species/endang/animals/birds/ (2011).

2. FLORA

a. Wetlands

A large portion of the Texas coast is characterized by wetlands, which the Clean Water Act defines as "areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs and similar areas."[20] Wetlands provide a variety of critical ecosystem services, including water filtration, flood buffering, erosion control, and habitat for developing and mature wildlife. (Figure 3)

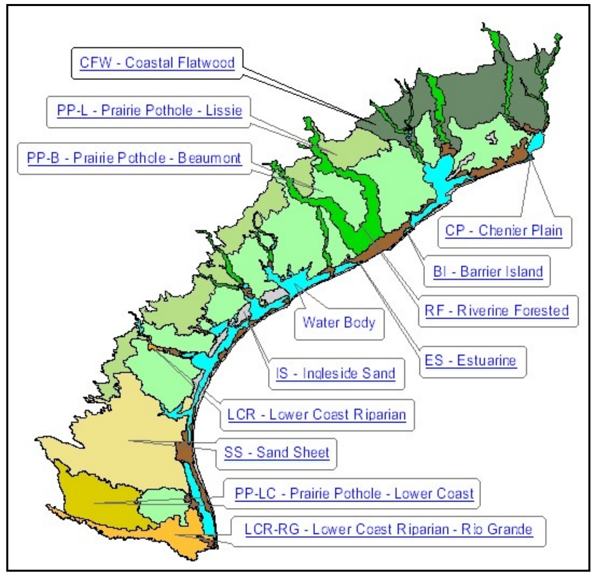

Figure 3: Seven major wetland categories for the Texas Gulf. Source: Jacob et. al., Texas Costal Wetlands Guidebook

Seven wetland areas are classified as either National Preserves or National Wildlife Refuges. As a nursery for fish, crab, and other shellfish, coastal near-shore wetlands support the commercial fishing industry throughout the Texas state waters which at the wholesale level is valued at more than $400 million annually and employs about 30,000 coastal residents. The total economic impact of saltwater sport fishing in Texas is almost $2 billion annually, employing about 25,000 coastal residents.[21]

Currently, the main threat to Texas' wetlands is from subsidence, hurricanes and resulting flooding. Together, these processes imbalance the freshwater/saltwater equilibrium and can result in wetland drowning (long term or permanent submersion). According to Jacobs et al., subsidence causes the land surface to drop, which can then become flooded if the surface is already very near to sea level.[22] However, since CGS results in additional material sequestered below the surface, it is not expected to have a profound impact on this phenomenon.

[20] 40 CFR § 230.3(t) http://water.epa.gov/lawsregs/guidance/wetlands/definitions.cfm (2009).
[21] *Id*.
[22] Although subsidence-induced flooding has drowned many wetlands, especially in and around large coastal cities such as Houston, and can be caused by multiple factors such as groundwater pumping, oil and minerals extraction, or surface removal, it is unlikely that injection of new material, by itself, into the subsurface would have an appreciable impact on subsidence.

b. Submerged Aquatic Vegetation

Submerged Aquatic Vegetation (SAV), which includes seaweeds and seagrasses, plays a central role in the Gulf of Mexico's offshore coastal ecosystem. These plants convert sunlight, water and nutrients into food for many fish, crustacean, invertebrate and bird species. In addition, they provide nursery grounds for many species sought after by commercial and recreational fishermen, such as shrimp, Black drum, Red snapper, Grouper, Spotted sea trout, Southern flounder, and others.[23]

Although abundant throughout the Gulf of Mexico, robust seagrass beds and their accompanying marine biodiversity only occur in two locations in the near-shore waters of Texas, covering roughly 37,000 acres: the Laguna Madre and the Copano-Aransas Bay complex. These are valuable, rare ecosystem resources that thrive due to a complex combination of environmental factors including temperature, water depth, turbidity, salinity, turbulence and substrate suitability.[24] Seagrass conditions in these areas are fragile and can easily be disrupted by industrial activity or environmental damage.

B. Groundwater Assets

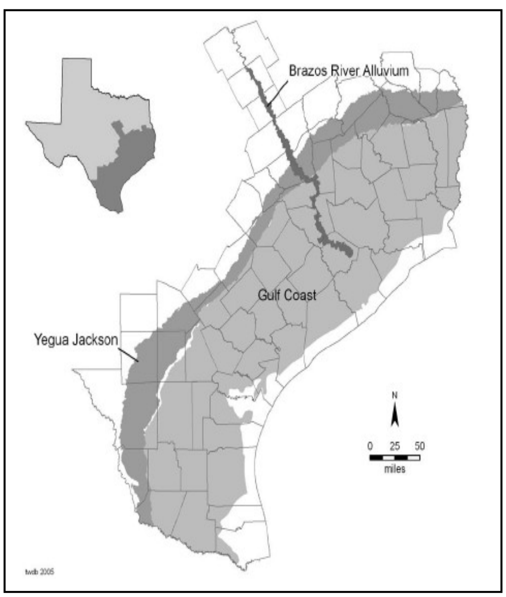

Figure 4: Locations of Major and Minor Aquifers in the Texas Coastal Area
Source: Texas Costal Wetlands Guidebook

Studies have shown there are no freshwater aquifers in the Texas offshore coastal area. (Figure 4) The onshore coastal zone does include significant freshwater aquifers that provide irrigation and drinking water for the nearly 73 counties of the Texas Gulf Coast region, and which are particularly critical for the Houston metro area.[25]

The Texas Water Development Board has designated the Gulf Coast aquifer as a main aquifer, and the Yegua-Jackson Aquifer and the Brazos River Alluvium as minor aquifers. Altogether, these three aquifers serve a population of roughly 8 million Texans. Over 1.1 million acre-feet of groundwater from the Gulf Coast aquifer are used annually in Texas. The Gulf Coast aquifer extends over 430 miles from the Texas-Louisiana border in the northeast to Texas-Mexico border in the south.[26]

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[23] U.S. Coast Guard and Maritime Administration, *Final Environmental Impact Statement, Beacon Port Deepwater Port License Application*, at 3-32, Vol. 1 (Nov. 2006).
[24] *Id*. at 3-32-33.
[25] Texas Water Development Board. *Report 365: Aquifers of the Gulf Coast of Texas*, at 1 (Feb. 2006), see also http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R365/R365_Composite.pdf.
[26] *Id*. at 81.

Groundwater quality in the Gulf Coast aquifer is generally of sufficient quality northeast of the San Antonio River but declines to the southwest due to increased chloride concentrations and saltwater encroachment near the coast. In addition, heavy pumpage has caused saltwater intrusion to occur along the coast as far north as Orange County.[27]

Much of the Gulf Coast region's freshwater resources are managed by 25 groundwater conservation districts. Following the passage of Texas House Bill 1763 (2005), as of 2010, all groundwater conservation districts are required to establish desired future conditions for the aquifers within their groundwater management area boundaries.[28] Although not enforced or monitored by the Texas Water Development Board, groundwater conservation districts must ensure that their management plans are designed to meet the newly decided conditions.[29]

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[27] *Id*.
[28] *Id.* at 173.
[29] *Id.* at 16.

III. OPERATIONS AND EVENTS IMPORTANT FOR DRAWING CONCLUSIONS RELATED TO OFFSHORE CCS IN TEXAS

Subsurface injection of gases onshore for disposal, enhanced oil recovery and / or sequestration has occurred across the globe for several decades. Additionally, injection of fluids and gases into the subsurface of the seabed (offshore) has also been ongoing at several sites across the globe for several years. This offshore work has included CO_2 injection for the purpose of sequestration, fluid injection for disposal, and also for enhanced oil recovery. Finally, research of CO_2 emissions from natural CO_2 seeps and fissures located on the sea floor has also been ongoing for many years. Together, the body of information developed from these operations and research provide insight into the risk profile of the development and use of offshore CCS in submerged lands in Texas state waters.

The summation of this research and operational experience from onshore and offshore operations, and scientific research indicates that offshore CCS can be performed in the Texas offshore waters, at specified sites, without resulting in unmitigated leakage of CO_2 from the target confining zone and without causing significant environmental impacts on ecological assets of concern. However, given the direct record of offshore CCS operations and offshore CO_2 leakage research, albeit relatively brief, it has been demonstrated with sufficient clarity that offshore CCS projects in Texas should take certain precautions (as discussed in Section V).

A. ON-SHORE CCS PROJECTS AND ENHANCED OIL RECOVERY WITH CO_2

There are approximately 250 onshore CCS projects in various stages of planning and development worldwide.[30,31] Across the globe, this proliferation and experience with CCS projects has matured the industry to the point that best practices standards have been generally identified and regulatory requirements have been developed for nearly every aspect of project monitoring, operation and reporting (including site characterization, selection, drilling and development, operation, closure and post-closure).[32]

Onshore CCS projects which do not use enhanced oil recovery (EOR) generally involve injection into either saline aquifers, depleted oil fields, coal seams, or other subsurface structures. Of the various types of structure available, saline aquifer storage is generally thought of as providing the greatest opportunity for large scale CCS deployment.[33]

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[30] NETL, http://www.netl.doe.gov/technologies/carbon_seq/global/database/index.html
[31] Global CCS Institute 2011, *The global status of CCS: 2010*, Canberra http://cdn.globalccsinstitute.com/sites/default/files/publication_20110419_global-status-ccs.pdf (2011).
[32] Forbes et al., *Guidelines for Carbon Dioxide Capture, Transport, and Storage*, World Resources Institute, http://pdf.wri.org/ccs_guidelines.pdf (2008).
[33] Herzog, H., "*Carbon Dioxide Capture and Storage*," Chapter 13 in The Economics and Politics of Climate Change, http://sequestration.mit.edu/pdf/2009_CO_2_Capture_and_Storage_Ch13_book.pdf (2009).

There are approximately 129 enhanced oil recovery projects using carbon dioxide (EOR CO_2) worldwide, with 114 of those located in the United States.[34] In general, EOR techniques allow increased recovery of oil in depleted or high viscosity oil fields. In general, CO_2 is flooded into an oil field through a number of injection wells drilled around a producing well and at a pressure equal to or above the minimum miscibility pressure (MMP). Once injected, the CO_2 and oil mix together and form a liquid that more easily flows to the production well. Pumping can also be enhanced by flooding CO_2 at a pressure below the MMP, swelling the oil and reducing its viscosity.[35] (Figure 5)

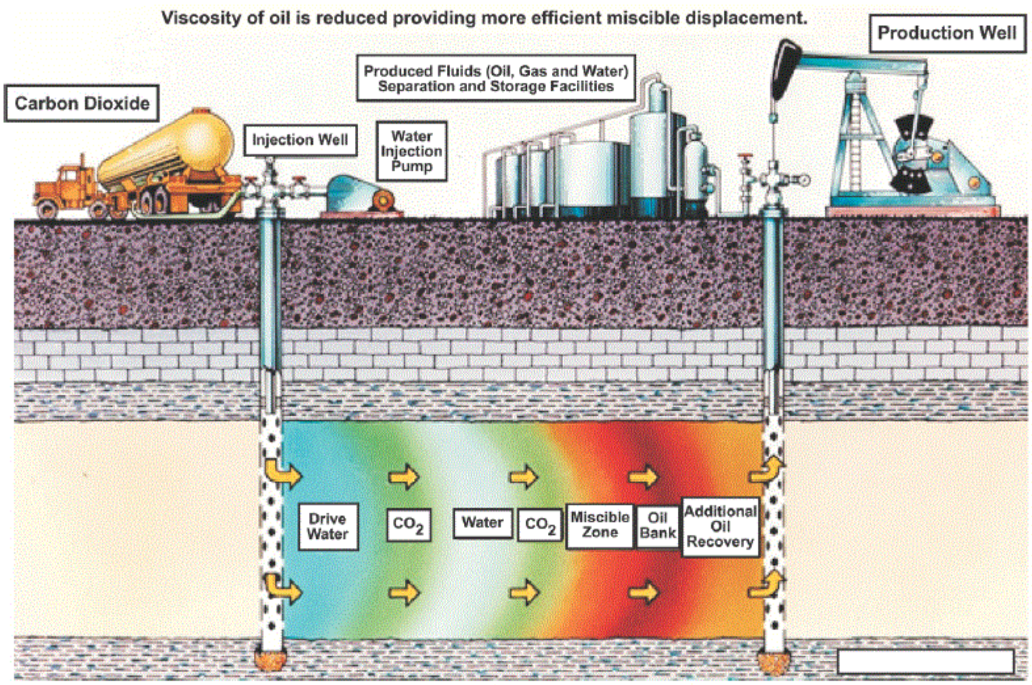

Figure 5: Simplified diagram of an onshore enhanced oil recovery with carbon dioxide operation. Source: U.S. DOE

Due to the large number and considerable degree of variability of standards and practices applicable to onshore CCS and EOR CO_2 operations, this paper does not attempt to characterize the full range of lessons learned and best practice standards developed. A more detailed discussion of requirements is included in Section VI below. When taken together however, these site selection and operation standards support the claim by the Intergovernmental Panel on Climate Change (IPCC) that geologic storage sites that are well selected, designed and managed can trap CO_2 for millions of years and are likely to retain

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[34] Dooley et al., *CO_2-driven Enhanced Oil Recovery as a Stepping Stone to What?*, Pacific Northwest National Laboratory, U.S. Department of Energy (2010); (Citing Koottungal, L., *Special Report: EOR/Heavy Oil Survey: 2010 Worldwide EOR Survey*, Oil and Gas Journal (2010).
[35] U.S. Department of Energy, *NETL EOR Factsheet*, http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf

more than 99 percent of the injected CO_2 over more than 1,000 years.[36] Accordingly, the history of onshore CCS and EOR CO_2 support the IPCC conclusion and the general conclusion of this paper that offshore CCS can be performed in a manner that 1) retains the CO_2 in the target injection zone and 2) does not cause adverse impacts on the offshore environment.

B. EXISTING OFFSHORE GEOLOGICAL CARBON SEQUESTRATION (CCS) PROJECTS

1. STATOIL – UTSIRA FORMATION (SLEIPNER PROJECT)

The first, oldest, and most well known, and offshore CCS facility in the world is located at the Sleipner natural gas field in the North Sea, roughly 155 miles off the Norwegian coast.[37] In the Sleipner gas field, carbon dioxide is injected into brine / saltwater within a sandstone formation approximately 2,600 ft (800 meters) below the sea floor and between 200 and 300 m thick.[38] (Figure 6)

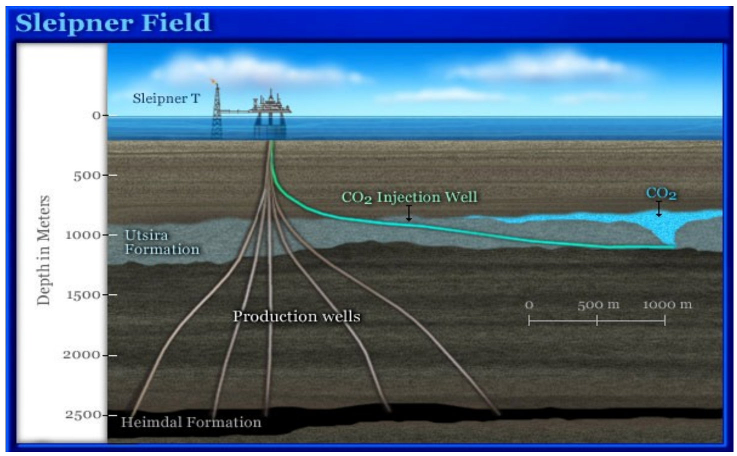

Figure 6: CCS infrastructure at the Sleipner natural gas field. Source: Schlumberger Excellence in Educational Development (SEED), Inc.)

The Sleipner project started in 1996 as a direct outgrowth of both Statoil's need to meet customer specifications for natural gas extracted from the Heimdal Formation (requiring decarbonization from 9% CO_2 content to 2.5%) and the Norwegian government's introduction of a $50/ton CO_2 tax in 1991.[39] Conventional practice of natural gas purification would have involved venting produced CO_2 into the atmosphere. However, the CO_2 tax created a financial incentive for Statoil to look for opportunities to avoid releasing the CO_2 – and instead turned to CO_2 sequestration in a nearby geologic formation (the Utsira Formation).

[36] U.S. Department of Energy, *Carbon Dioxide Enhanced Oil Recovery Untapped Domestic Energy Supply and Long Term Carbon Storage Solution,* National Energy Technology Laboratory http://www.netl.doe.gov/technologies/oil-gas/publications/EP/small_CO_2_eor_primer.pdf (2010).
[37] Bellona, *Factsheet: Security of CO_2 storage in Norway*, http://www.bellona.org/factsheets/1191928198.67
[38] Id.
[39] Statoil, *Annual Report*, http://www.statoil.com/AnnualReport2008/en/Sustainability/Climate/Pages/5-3-2-3_SleipnerCCS.aspx

To initiate the overall project, Statoil invested roughly $100 million on platform-based carbon capture technology, which captures the CO_2 during the natural gas processing phase using conventional amine scrubbing, and transports it via pipeline approximately 650 feet (200 meters) to the sea floor. (Figure 7) From there, nearly pure CO_2 is injected to a depth of about 2,600 feet (800 meters) below the sea floor into the Utsira sandstone formation – a brine aquifer. The multiple (3) layers of impermeable caprock above the Utsira Formation extend upwards approximately to the sea floor surface.

Figure 7. Sleipner A Platform. Source: Statoil

Statoil has injected roughly 1 $MMTCO_2E$ per year into the Utsira Formation at Sleipner, equivalent to the annual CO_2 emissions of a 350 MW coal-fired power plant. So far, Statoil has reported no major CO_2 leaks. [40,41]

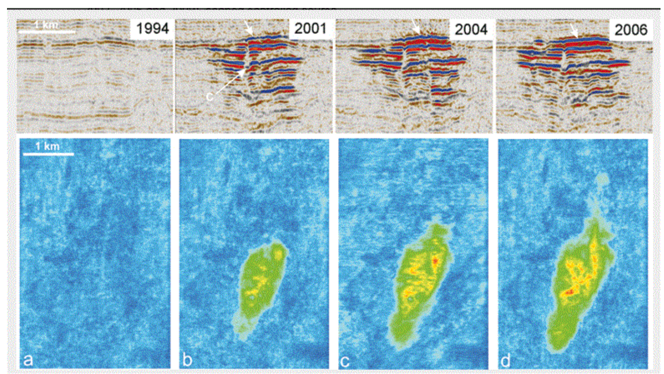

Figure 8: Time-lapse seismic images from Sleipner. Source: British Geological Survey

Research and time lapse plume monitoring similar to that shown (right) at the Sleipner site has shown that CO_2 migration from the point of injection has occurred to a lateral distance of approximately 1.6 miles (2 km), and with a vertical distance of approximately 250m.[42,43] (Figure 8)

[40] Eiken, et al., *Lessons learned from 14 years of CCS Operations: Sleipner, In Salah and Snøhvit.* 10th International Conference on Greenhouse Gas Technologies, 19-23 Sept. 2010, Amsterdam, Netherlands. www.sciencedirect.com (2010).
[41] Statoil, *Annual Report*, http://www.statoil.com/AnnualReport2008/en/Sustainability/Climate/Pages/5-3-2-3_SleipnerCCS.aspx (2008).
[42] Rutqvist et al., *Coupled reservoir–geomechanical analysis of the potential for tensile and shear failure associated with CO_2 Injection in multilayered reservoir–caprock systems*, Int J Rock Mech Mining Sci, http://www.epa.gov/climatechange/emissions/downloads/LBNL3.pdf (2007).
[43] Website British Geological Survey, http://www.bgs.ac.uk/science/CO2/home.html

2. Statoil – Tubåen Formation (Snøhvit)

Similar to the Sleipner project, Statoil also operates a major offshore CCS facility at the Snøhvit gas field in the Barents Sea, approximately 87 miles from the Norwegian coast. Statoil began sequestering CO_2 at this site in April 2008, again as a byproduct from natural gas processing. Injection occurs to a depth of approximately 2,500m, and at a water column depth of approximately 330m.[44]

Statoil produces approximately 13,000 metric tons of liquefied natural gas annually from four sub-seabed wells within the Snøhvit gas field. After extraction, natural gas is transported via pipeline to the Melkoya processing facility, just off the coast of Hammerfest. At Melkoya, the CO_2 is separated via amine scrubbing and returned to the Snøhvit field via pipeline for injection into the Tubåen Formation. Although the Tubåen Formation is relatively thin (between 65m and 87 m thickness), Statoil estimates that at full capacity it will sequester 700,000 metric tons of CO_2 per year at the site.[45]

Figure 9. Snøhvit processing facility. Source: Statoil

Unlike the Sleipner project, the Snøhvit project requires no fixed or floating ocean surface impoundments at the point of injection.[46] (Figure 9) This design allows for seabed facilities to be "over-trawlable", so that neither they nor fishing equipment will suffer any damage from coming into contact.

Although the Snøhvit facility's environmental record has been without recorded incident since operations began in 2008, the facility and accompanying injection has faced a series of extended maintenance shut-downs, largely due to its setting in the extreme climate of the Barents Sea. The facility was closed for nearly three months in 2009 to perform unspecified maintenance.[47] From late 2010 to early 2011, the facility was closed to address leakage in the plant's cooling system.[48] No leaks have been reported from this project.

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[44] Statoil, *Presentation CSLF Interactive Workshop*, Saudi Arabia, March 2011. P. Ringrose et al, *available at* http://www.cslforum.org/publications/documents/alkhobar2011/CO2StoreProjectSleipnerandSn%C2%BFvitProjects_Session3.pdf (2011).
[45] Statoil, *Annual Report* (2010). http://www.statoil.com/AnnualReport2010/en/sustainability/Health,Safety,ClimateAndTheEnvironment/Climate/CarbonCaptureAndStorage/Pages/OurCCSProjects.aspx
[46] Statoil, http://www.statoil.com/en/ouroperations/explorationprod/ncs/snoehvit/pages/default.aspx
[47] UpstreamOnline.com, *Statoil Restarts Snohvit*, http://www.upstreamonline.com/live/article198246.ece. (2009).
[48] McLoughlin, *Statoil says Snohvit LNG output to resume H_2 Jan*, Platt news service, http://www.platts.com/RSSFeedDetailedNews/RSSFeed/Oil/8362448 (2011).

3. Petrobras – Lula Oil Field

In September 2011, Brazil's Petrobras announced it had begun production at its Lula oil field, located roughly 185 miles from Rio de Janeiro. Currently the field is pumping about 30,000 barrels a day, with a projected maximum extraction rate of 100,000 barrels per day, [49] making it potentially one of the most productive fields in the Americas.

Brazil has a national greenhouse gas emissions reduction target of 33% to 36% below business as usual emissions by the year 2020. To boost production of the field and mitigate CO_2 emissions from produced gas, Petrobas will inject and retain some percent of the total emissions from the operations and reduce the project's overall GHG emissions.[50] This mitigation consists of reinjection of CO_2 from produced gas into the field, and may be used to enhance oil recovery operations. Injection of produced gas into the field, including CO_2 likely began in April 2011.[51] Sequestration of the emissions is also consistent with Petrobas' 2009-2013 Business Plan that calls for avoiding voluntarily the emissions of 4.5 million tons of carbon dioxide equivalent (CO_2e) in 2013.[52]

C. Offshore Oil extraction

Offshore oil extraction has been occurring in the United States since the turn of the 20th century, though practices have evolved to allow for deeper wells and greater water depths. Since many of the same types of operations and pieces of equipment are utilized in CCS operations as oil extraction operations, site impact prevention and mitigation applicable to installation of oil extraction infrastructure (oil platform siting, well drilling equipment, infrastructure installation and operation, etc.) are generally applicable to CCS operations.

Similarly, environmental impact reports prepared for the purpose of complying with the National Environmental Policy Act (NEPA) for new oil extraction operations can serve as valuable tools to assess the potential for environmental impacts associated with CCS surface impoundments, processing and transport equipment. Where possible, recommendations made in this paper draw information from EIR's performed for siting of oil platforms in the near shore environment of Texas.

Although a strong correlation exists between the potential impacts from surface impoundments associated with oil extraction and offshore CCS, the differences associated with drilling for extraction of high pressure fluids (i.e. oil extraction) and drilling and operation for CO_2 injection urge caution in making direct correlation for the purposes of environmental impact evaluation from leaks.

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[49] http://en.mercopress.com/2011/09/20/petrobras-begins-pumping-natural-gas-from-first-pre-salt-field-of-santos-basin
[50] *Id.*
[51] http://www.oilonline.com/default.asp?id=259&nid=19457&name=Lula+producing+on+commercial+basis
[52] Petrobas, http://www.petrobras.com.br/rs2009/en/relatorio-de-sustentabilidade/meio-ambiente/mudanca-do-clima/

D. SUBSURFACE INJECTION OF NON-CO_2 LIQUIDS AND GASES

1. PRODUCED WATER AND ACID GAS INJECTION

In general, produced water and acid gases have been injected into the subsurface for decades and have resulted in the development of a large body of scientific understanding, industry literature and practices, and comprehensive regulations to prevent environmental damage. In fact, injection into underground formations represents the most common approach for onshore management of produced water.[53] Additionally, in 2004 and 2005, there were over 60 different wells injecting acid gases (primarily consisting of hydrogen sulfide and carbon dioxide) across the United States, with the highest numbers in Wyoming and Texas.[54]

Stringent controls that have been developed by US EPA for protection of subsurface resources such as potable groundwater, and to prevent escape and migration from the target confining zone are discussed in Section VI of this report. Together, this body of information and experience illustrates a long history with safe, long-term storage of subsurface injected high pressure materials. Additionally, this experience supports the conclusion that injection of pressurized CO_2 for the purpose of geologic sequestration can occur without deleterious impacts on the environment.

2. STATOIL – UTSIRA FORMATION (TORDIS GAS FIELD)

To date, only one example of problematic operations from offshore injection of produced water or acid gas exists. Although the Statoil project in the Tordis gas field does not entail CO_2 injection, it does involve the injection of high pressure fluids into the seabed subsurface, and therefore is relevant for the purpose of identifying potentially undesirable impacts that may occur from seabed injection of high pressure fluids, namely CO_2.

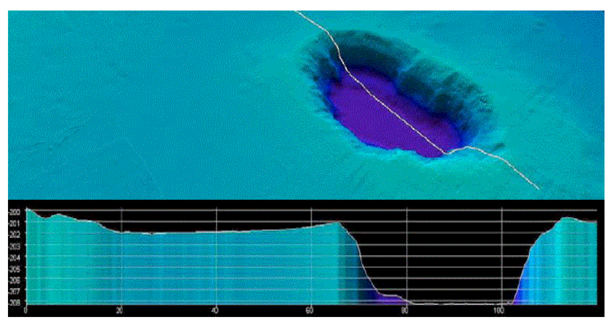

Figure 10: Illustration of the seabed crater near Tordis. The scale is in meters. Source: Statoil

The Tordis gas field is located approximately 180 miles (300 km) from the Sleipner project.[55] In 2008, Statoil began injecting produced water into the Utsira formation at Tordis, at a depth that was expected to be roughly 1000m below the sea floor. However,

[53] U.S. Department of Energy, *Produced Water Management Technology Descriptions Fact Sheet - Underground Injection for Disposal*, http://www.netl.doe.gov/technologies/pwmis/techdesc/injectdisp/index.html
[54] U.S. Department of Energy, *Acid Gas Injection in the United States,* Presentation at the Fifth Annual Conference on Carbon Capture & Sequestration (2010). http://www.netl.doe.gov/publications/proceedings/06/carbon-seq/Tech%20Session%20140.pdf
[55] Statoil, *Tordis incident 2008,* http://www.statoil.com/en/OurOperations/ExplorationProd/ncs/tordis/Pages/TordisIncident2008.aspx (2009).

due to underdeveloped geology of target reservoir that was not identified on geologic site characterization surveys, the fluid was not being injected into a target reservoir capable of handling the injection pressures and volumes.[56]

As a result of the geologic unsuitability for the injection operations, the Tordis project resulted in the Statoil operator over-pressuring the injection site and causing a direct fluid communication to the seabed which released between 48 m^3 and 175 m^3 of oil into the water column. (Figure 10) Follow-up investigation of the site revealed lack of a pressure monitoring regime capable of detecting the problems prior to the eventual total depressurization as well as lack of effective project management.[57]

E. RESEARCH OF CO_2 VENTS IN THE SEA FLOOR

A considerable amount of research has been performed on natural and induced seafloor vents and seeps. This research has yielded a range of outside-the-well detection methods that can be used to find out whether CO_2 is emanating into the water column, and also to calculate quantities and effects. However, no research has definitively characterized a fool proof single method for determining whether CO_2 is being emitted from the seafloor into the water column over a large area and in all cases. Where applicable, this paper draws from the findings of that research to propose policy solutions in Section VII related to site selection, monitoring and operations for the express purpose of detecting and mitigating leaks of CO_2.

Based on available literature, research on CO2 seeps, vents and discharges is ongoing or completed at the following sites:[58]

- Norwegian offshore CO2 storage Sleipner;
- Norwegian offshore CO2 storage Snøhvit;
- B3 field in the Polish Baltic Sea;
- Natural CO2 seeps off Italy (Panarea);
- Natural CO2 seeps off Japan (Okinawa Trough);
- Natural CO2 seeps off Germany (Salt dome Juist);
- Natural CO2 seeps off Germany (Lake Kaach); and
- Natural CO2 seeps off Norway (Jan Mayen).

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[56] T. Eidvin and J. Øverland, *Faulty geology halts project,* NPD, http://www.npd.no/Global/Engelsk/3%20-%20Publications/Norwegian%20Continental%20Shelf/PDF/10%20faulty%20geology.pdf
[57] Greenpeace, *Reality Check on Carbon Storage*, at 5 http://www.greenpeace.org/raw/content/international/press/reports/reality-check-on-carbon-storage.pdf. (2009).
[58] European Commission, *Assessing the environmental risks of sub-seabed CO2 storage, http://www.ifm-geomar.de/index.php?id=537&L=1&tx_ttnews%5Btt_news%5D=742&tx_ttnews%5BbackPid%5D=8&cHash=0a2c58583e*

IV. General Benefits of Offshore Geologic Carbon Sequestration in Texas State Waters

Near-offshore CCS has some environmental and public health advantages compared to onshore geologic storage worth briefly noting before considering its environmental risks.

A. As Enumerated by the U.S. Department of Energy

Benefits of offshore CCS have been enumerated by the U.S Department of Energy as follows:[59] (Figure 11)

Figure 11: U.S. Department of Energy Enumerated Benefits of Offshore CCS

Offshore CCS is a promising technology due to several key advantages:

- *Offshore storage provides additional* CO_2 *storage potential in the United States to supplement existing onshore capacity estimates.*
- *The formation fluid in offshore sediments is typically similar to sea water in terms of chemistry and salinity with 30,000 to 40,000 ppm total dissolved solids (TDS)….*
- *Locating sequestration sites away from heavily populated, onshore areas avoids the perception of storing waste material beneath a populated area. This also reduces the difficulty of establishing surface and mineral rights at candidate storage sites. …*
- *Offshore storage reduces the risk to underground sources of drinking water (protected groundwater).*
- *Establishing transport pipeline corridors or using existing infrastructure should be feasible based on already existing infrastructure for natural gas and oil.*
- *Offshore CCS provides storage sites in the vicinity of heavily populated areas along U.S. coastlines (like the Northeast and California).*
- *The overall economics of offshore CCS may be more favorable compared to onshore CCS, despite higher capital costs (for drilling rigs, well manifolds, etc.) typically associated with working in an offshore environment. This will be especially true if offshore storage projects prove relatively easy to permit, finance, and operate.*

[59] J.T. Litynski et al., (2011); Citing extensively Schrag, D., *Storage of Carbon Dioxide in Offshore Sediments*. Science 325, 1658, DOE: 10.1126/science.1175770 (2009).

B. SEQUESTRATION OF GREENHOUSE GASES AND CLIMATE CHANGE MITIGATION

Global climate change is a serious threat to the health and well-being of the planet. The potential catastrophic effects of climate change are well documented and include increased global temperatures, increased extreme weather events, degraded air quality and sea level rise.[60] Carbon capture and geologic sequestration is one of many strategies that, if deployed correctly, can have a significant impact on reducing atmospheric concentrations of greenhouse gases that contribute to climate change. Examples that constitute correct deployment of CCS are well identified in the academic literature and from present day real-world operations.

Although there may be roughly 250 research, development and / or deployment CCS projects world-wide at varying scales, mitigation of greenhouse gas pollution sufficient to combat climate change will require many, many more CCS sites. Rough estimates of CCS deployment needed to effectively reduce the emissions from the power sector (in combination with other emissions reduction measures) place the total number of project sites close to 3,500 projects as large as the Sleipner project[61], and with coincident technological advancements to significantly reduce the overall cost of construction and operation of the facilities.

As identified by the U.S. Department of Energy, "the University of Texas at Austin (UT–Austin) will identify one or more CO_2 injection sites within Texas' offshore state lands that are suitable for the safe and permanent storage of 30 million metric tons of CO_2 from future large-scale commercial CCS operations (NETL, 2010c)." This deployment will serve as a measured starting point for a larger effort to tap into the vast geologic sequestration potential of the Gulf of Mexico, and prove the potential for offshore CCS projects elsewhere – a critical starting point for meaningful CCS in the United States.

C. REDUCED IMPACT TO HUMANS COMPARED TO OTHER CCS SITES ONSHORE

In general, and as identified by the U.S. DOE (above), storing CO_2 in offshore geologic formations makes it less likely the CO_2 will interact with humans, either through freshwater aquifers or direct atmospheric exposure. Although contamination of underground sources of drinking water (USDWs) is a significant concern when storing CO_2 in onshore sites, and is of particular focus within federal regulations for Underground Injection Control (UIC) for Aquifer Protection, freshwater aquifers are much less prevalent under the ocean, and not observed in the area of review for this project.[62]

[60] Cambridge University Press, *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (2007).
[61] Pacala, Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, Science, Vol. 305 (2004).
[62] On-shore groundwater contamination stemming from saltwater intrusion caused by a zone of elevated pressure at lateral extent of the injected CO_2 may occur in theory, though it has not been proven in practice.

CO_2 stored in offshore formations is also 1) less impactful on the global atmosphere than releasing it directly from CO_2 sources, and 2) has far fewer chances of affecting humans (compared to onshore CCS) in the event of a storage leak to the atmosphere from the sequestration site.[63] If CO_2 were to leak from an off-shore formation, CO_2 would either dissolve in the overlying water column or rise to the surface of the water and equilibrate with the atmosphere, away from human life. On land, a remote possibility exists that CO_2 could gather in low-lying formations and create a concentration which could present a dangerous condition for humans, animals, or plants. However, this scenario is highly unlikely because a leak would likely expel at slow rate and CO_2 dissipates quickly in the atmosphere,

Overall, reduced public health risks make offshore CCS advantageous both in terms of public safety and public acceptance. Whereas communities in Europe have vociferously opposed CCS operations being built near their homes, schools, and commercial districts,[64] several surveys of community respondents have indicated less anxiety when the sequestration site is offshore.[65] While some public concerns may remain, moving storage away from human communities should significantly narrow these objections.

D. Ability to Accurately assess existing leakage pathways

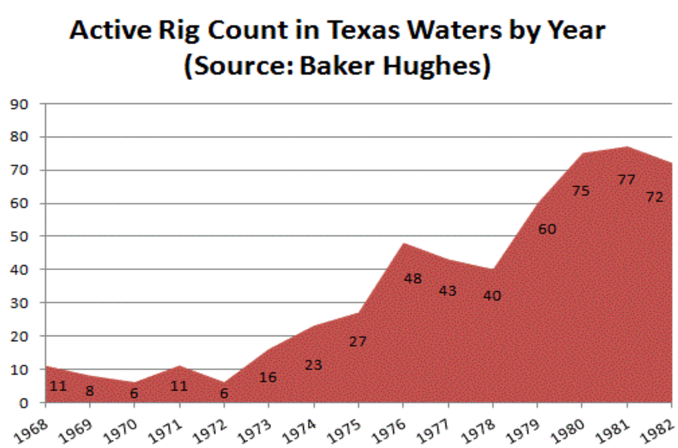

Figure 12: Rotary drilling rig count in Texas Waters by year (Source: Baker Hughes)

In general, the process of offshore oil drilling has not been occurring in Texas as long as onshore. The first offshore well was drilled in Texas in 1938, though oil was not discovered offshore until 1941.[66] Offshore oil exploration and extraction in state waters ramped up significantly in the early to mid 1970's, increasing from six active rotary (drilling) rigs in 1970 to seventy seven active rotary rigs in 1981.[67] (Figure 12)

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[63] Damen et al., *Health, Safety and Environmental Risks of Underground CO_2 Storage – Overview of Mechanisms and Current Knowledge,* 74 Climatic Change 289,298 (2006).
[64] Van Noorden, *Buried Trouble: Protesters saying 'no to CO_2' are just one roadblock facing carbon sequestration*. 463 Nature 871 (2010).
[65] IPCC, *Special Report on Carbon dioxide Capture and Storage*, at 257-258 (2005).
[66] Owen, *Trek of the Oil Finders*, American Association of Petroleum Geologists, Memoir 6, p.800 (1975).
[67] Rig count derived from historical data at BakerHughes, http://investor.shareholder.com/bhi/rig_counts/rigCountArchive.cfm?CategoryID=&SortOrder=FileDate%20Descending&Year=&PageNum=2

In contrast, the first commercial onshore oil exploration and extraction began in Texas in 1866, at Melrose in Nacogdoches County.[68] The proliferation of onshore production in Texas has significantly expanded since that time, with major discoveries and expansions occurring in 1900, 1930 and throughout the rest of the 20th century, including through modern day. Today, Texas has approximately 218,000 active oil and / or gas wells in operation.

As evidenced by data on offshore operations, the proliferation of offshore drilling in Texas waters is considered to be relatively young, with the major expansion occurring in the 1970's, well after the advent of modern record keeping requirements. Accordingly, well drilling operations and platform logs for offshore operations are expected to be of a much higher quality than onshore operations which may have been ongoing for 100 years or longer, surviving numerous transfers of ownership and quality of record keeping. As such, it is expected that any abandoned, plugged, orphaned or operational wells would be able to be easily found during a site survey or characterization for the purposes of CCS site selection.

Current and historical production wells can serve as migratory paths for the escape of injected CO_2 from a target reservoir, meaning the overall better awareness (and reduced number) of active or historic wells in the target confining zone, the lower the possibility that man-made leakage pathways exist. As such, it can be generally surmised that offshore operations are less likely to leak CO_2 in the offshore environment than their onshore counterparts.[69]

In addition to fewer man-made migratory pathways (active or historic wells) giving rise to less opportunities for leakage from the target confining zone, fewer pathways can also equate to a reduced need to monitor for leakage at suspect locations. In the onshore environment, active and abandoned wells are generally thought to be the location with the highest opportunity for leakage from the storage zone, and therefore demand significant monitoring and oversight. However, since offshore sites have a much more limited number of active or abandoned wells through the confining layer, less overall point specific monitoring may be needed, resulting in less costly project oversight.[70]

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[68] Texas State Comptroller of Public Accounts, http://www.window.state.tx.us/specialrpt/energy/nonrenewable/crude.php

[69] Offshore geologic formations are generally intact, with far fewer wells than the onshore environment. See, e.g., Wilson et al., *Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage*, Environmental Science & Technology, Vol. 38, No. 16 at 3479 (2003).

[70] See, e.g., Solomon, Semere, *Carbon Dioxide Storage: Geological Security and Environmental Issues – Case Study on the Sleipner Gas field in Norway*, Bellona Foundation (2007).

E. WIDE ARRAY OF LEAKAGE DETECTION STRATEGIES AND ANALYTICS AVAILABLE

Even though offshore CCS encompasses a different level of complexity for leak detection monitoring and response, the significant variety and extent of tools available to detect CO_2 leakage means that offshore injection operations should not be dismissed for lack of ability to monitor and verify sequestration effectiveness.

Further, although the science of offshore leak detection is developing to this day, there is a suite of accepted analytical and technological techniques to ensure CO_2 sequestration effectiveness. These techniques are discussed in detail in Section VII below, and may include:

- ✓ 3D and 4D seismic monitoring and plume migration mapping;
- ✓ Sea floor surface mapping;
- ✓ Injection condition monitoring;
- ✓ Groundwater (aquifer) testing beyond the extent of the plume;
- ✓ Seawater testing for pH, pCO_2 content, total CO_2 concentration, alkalinity, density and other characteristics;
- ✓ Sediment testing for pH, pCO_2 content, alkalinity, density and other characteristics;
- ✓ Biological testing and monitoring; and
- ✓ Specialized Gas Leakage Systems for widely distributed low level leakage and for point source high level leakage through sonar observations, bubble observations, video capturing, gas sampling and gas flux quantification.

V. ENVIRONMENTAL AND PUBLIC HEALTH RISKS FROM OFFSHORE CCS

In general, risks from the development and operations of CCS project site can be summarized in three potential risk pathway categories as:

- Risks associated with transport of CO_2 streams;
- Risks associated with injection operations; and
- Risks associated with sequestration of CO_2.

For each category of risk, this section evaluates sources of the risk, and then potential causes and impacts. If leakage or other disruption of the natural environment were to occur from a storage site, it could result in one or more of the following impacts:

- Harm to human life;
- Disruption to marine flora and fauna, both in the immediate coastal area and the greater Gulf of Mexico;
- Harm to aquifers suitable for residential and / or agricultural purposes; or
- Increased CO_2 emissions to the atmosphere.

Broadly speaking, the technological risks associated with offshore CCS are well-understood and moderate,[71] and find natural analogues to onshore EOR CO_2 operations.

In Texas, the oil and gas industry at large has decades of experience with oil extraction, CO_2 capture and pipeline infrastructure for use in enhanced oil recovery, and more recent experience globally with onshore and offshore CCS. The first CO_2-flood project in the world began in West Texas in the 1970s, in the Kelly-Snyder field in Scurry County. Since that time, EOR CO_2 has steadily grown in practice to encompass more than 50 projects in Texas today. At the original site in Scurry County, CO_2 injections has purportedly resulted in more than 55 million tons of CO_2 being sequestered[72], though neither logs or MVAR can verify this claim.

Performing CO_2 sequestration in the near-offshore environment presents a close analog to the established practice of onshore CCS, including transportation and pipeline protocols, siting requirements, well construction and injection techniques, and monitoring regimes. In that sense, near-offshore CCS should be seen as presenting no major new technological challenges or need for "experimental" techniques.

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[71] See, e.g., Heinrich et. al., *Environmental Assessment of Geologic Storage of CO_2*, Laboratory for Energy and the Environment, Massachusetts Institute of Technology at 1 (2003); Wilson et. al., *Regulating the Ultimate Sink* at 3476.
[72] Texas State Comptroller of Public Accounts, http://www.window.state.tx.us/specialrpt/energy/nonrenewable/crude.php

A. Risk Pathways - Generally

1. Risks from Transport of CO_2

a. Pipeline Leaks and Breaks

Although ship-bound transportation is potentially an option for CO_2 transmission from point sources to offshore storage sites, CO_2 pipelines are likely to be the more economically feasible technology. There are analogs for these pipelines, both in the practice of enhanced oil recovery and wastewater disposal, which offer some baselines for understanding its safety and environmental risk profile. Overall, CO_2 pipelines are a low-risk transportation technology with a relatively strong safety record.

Roughly 4,000 miles of CO_2 pipelines were in use in the U.S. as of 2010.[73] The U.S. Department of Transportation Pipeline and Hazardous Material Safety Administration (PHMSA) collects statistics on pipeline-related incidents. From 1986-2008 there were 12 incidents of CO_2 pipeline ruptures in 3,500 miles of pipeline, and no human injuries or fatalities reported.[74] It is important to acknowledge that 3,500 miles of pipeline is a relatively small sample size, especially compared to 500,000 miles of natural gas and hazardous liquid pipelines.[75] However, one study ranked CO_2 pipelines as safer than natural gas or hazardous liquid pipelines.[76]

Marine pipelines have similarly low incident rates. Although dragging ship anchors do cause some failures, such events only occur in shallow water (less than 50 m) and at low frequency. Very rarely do ships sink on to pipelines, or do objects fall on to them. Pipelines of 400 mm diameter and larger have been found to be safe from damage caused by fishing gear, but smaller pipelines are generally trenched to protect them.[77]

b. Corrosion Induced Leaks and Breaks

A commonly-discussed source of CO_2 release is a gradual leak due to corrosion of a pipeline or well. The risks of corrosion can be greater or smaller depending on the storage method used, and the environment within which the pipeline is located.

Storing CO_2 in deep saline aquifers is one of the options available to the Texas offshore environment. Similar to oil fields, these formations are prevalent throughout southern Texas and offshore state lands, though they generally are thought to have no other current

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[73] Bliss et. al. *A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide*, IOGCC at 14 (2010).
[74] *Id*. at 23.
[75] Folger & Parformak, *Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues* Congressional Research Service at 5 (2007).
[76] Davison & Gale, *Transmission of CO_2—safety and economic considerations*. Energy Vol. 20., 1319, 1322 (2004).
[77] *IPCC Special Report on Carbon dioxide Capture and Storage* at 188.

commercial value than for storage purposes, though protection as an existing of future gas resources might be a consideration. Since CO_2 can dissolve into the brine and eventually form carbonic minerals, brine formations are commonly accepted as the most secure form of CO_2 trapping. Additionally, since the dissolution of CO_2 into the brine increases its density by about 1%, the CO_2-saturated brine tends to sink to the bottom of the injection formation, rather than buoying upwards.[78] Accordingly, brine injection is thought of as a high quality candidate for CO_2 injection.

However, mixing CO_2 with brine water can potentially create two types of corrosion that may interfere with storage integrity and capacity. CO_2 in contact with water forms carbonic acid (H_2CO_3), a weak acid that can interact with surrounding minerals in various ways. First, the acidification of the pore water reduces the amount of CO_2 that can be dissolved into the formation as a whole. Further, the CO_2-rich water may react with minerals in the reservoir rock or cap rock matrix or with the primary pore fluid. Importantly, the resultant weak acid may also react with borehole cements and steels. Such reactions may cause either mineral dissolution or potential breakdown of the rock (or cement) matrix or mineral precipitation and plugging of the pore system (and thus, reduction in permeability).[79] Accordingly, deep saline aquifer wells and equipment are generally designed to be protected against corrosive forces. UIC well integrity and construction protocol address these issues in detail, which will be explored further in Section VI.

There is a greater risk of corrosion if a captured CO_2 stream is not pure. An unpurified CO_2 waste stream from a power generating plant may contain sulfur dioxide (SO_2), nitrogen oxide (NOx), as well as trace heavy metals including lead, mercury and cadmium.[80] When combined with water in a saline aquifer, SO_2 forms highly corrosive sulfuric acid, which can corrode surrounding materials, including carbonates, potentially creating leakage pathways. [81]Allowing injection of mixed streams underground requires less scrubbing at the plant level and reduces capture costs. However, permitting the disposal of non-CO_2 components alters the risk profile of geological storage as well as the regulatory and legal responses. The United States Geologic Survey report from a pilot study of CO_2 injection into the Frio Formation in Texas raised concerns about this risk. [82]

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[78] J.T. Litynski et al., (2011).
[79] Solomon, S., *Carbon Dioxide Storage: Geological Security and Environmental Issues – Case Study on the Sleipner Gas field in Norway*. Bellona Foundation (2007); Id et al., *CO_2 Leakage Through Existing Wells: Current Technology and Regulations, in Proceedings of the Eight International Conference on Greenhouse Gas Control Technologies* (2006).
[80] U.S. Environmental Protection Agency Website, http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html (2007).
[81] IEA Energy Technology Essentials - CO_2 Capture & Storage, http://www.iea.org/techno/essentials1.pdf (2006).
[82] Kharaka et al., *Gas-Water-Rock Interactions in Saline Aquifers Following CO_2 Injection: Results from Frio Formation, Texas, USA*, American Geophysical Union, Fall Meeting (2005).

2. RISKS FROM INJECTION OF CO_2

a. OVER-INJECTION, FRACTURING AND INDUCED SEISMICITY

As with onshore CCS or EOR CO_2, use of excessive injection pressure, combined with improper site selection or incorrect modeling, could theoretically cause instability or leakage at an offshore storage site through fracturing or induced seismicity.

Instances of induced seismicity have been recorded in the context of waste disposal wells and injection into oil fields. In the 1960s, for example, the U.S. Army Corps of Engineers found that a series of earthquakes near Denver was caused by injection well disposal at the Rocky Mountain Arsenal; one tremor measured 5.5 on the Richter scale.[83] Similar seismic activity has been recorded in both Texas and Arkansas. In general, deep well injection only triggers activity in a seismically unstable area, or when it occurs directly into faulted rock, rather than causing an earthquake in a seismically stable area.[84] Given the stable seismology of offshore state lands in Texas, induced seismicity would be highly unlikely.[85]

Fractures caused by over-injection of the seabed, such as occurred at the Tordis gas field, would similarly be unlikely, as long as operators followed commonly adopted business practices and performed the extensive site characterization required under EPA's Underground Injection Control (UIC) program.[86] The details of this program and its applicability to offshore CCS are discussed in Section VI below. However, it is sufficient to note here that the UIC requirements can (and in most circumstances do) apply to offshore CCS, and will require an operator to perform extensive borehole sampling, mapping, and seismic surveys in order to ensure the selected site comprises a "Confining zone(s) free of transmissive faults or fractures and of sufficient areal extent and integrity to contain the injected carbon dioxide stream and displaced formation fluids and allow injection at proposed maximum pressures and volumes without initiating or propagating fractures in the confining zone(s)."[87]

With proper attention to and enforcement of these and other siting and monitoring protocols already in use for other subsurface injection activities, the risk of fracture or induced seismicity at a Texas coastal offshore storage site is expected to below.

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[83] Osborne, P., *Technical Program Overview: Underground Injection Control Regulations*, U.S. EPA (2001).
[84] Wesson & Nicholson, *Earthquake Hazard Associated with Deep Well Injection*. U.S. Geological Survey. Open-File Report 87-331 (1987).
[85] U.S. Department of Energy, Sminchak, et al., *Issues Related to Seismic Activity Induced by the Injection of CO_2 in Deep Saline Aquifers*. http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p37.pdf
[86] *See* Greenpeace, *Reality Check on Carbon Storage* at 5 (2009).
[87] U.S. CFR § 146.83(a)(2)

3. RISKS FROM SEQUESTRATION OF CO_2

a. LEAKAGE FROM THE CONFINING ZONE TO THE SEAFLOOR SURFACE OR WATER COLUMN

A significant amount of discussion in this document is dedicated to the description of the potential impacts of CO_2 migration away from the target confining zone for CO_2 sequestration. If injected CO_2 does not remain in the target confining geologic structure, it is likely that some injected CO_2 would move laterally and vertically away from the point of injection, opening the door for some of the impacts described below to occur. Moreover, through anticipated plume migration, the zone of influence of a particular project may also elicit undesired impacts if improper attention to time variant plume migration occurs. However, the risk of such impacts occurring can be almost entirely removed by proper site selection, attention to established UIC rules, CO_2 monitoring and modeling, accounting and verification. Additionally, given the enhanced ability of saline aquifer formations to trap injected CO_2, leakage risk may be mitigated by preferential site selection within brine aquifers.

Put simply, due to the physical properties of high pressure CO_2, if it is injected into the subsurface without proper safeguards, leakage from the confining zone to the surface or to lateral geologic structures is possible. In the offshore environment, this would include dissolution into the water column and eventual equilibrium with the atmosphere. As discussed above, leakage of CO_2 into sediments and the water column may result in adverse effects on Gulf benthic organisms, especially those residing in an already low oxygen/high CO_2 environment.

b. GROUNDWATER INTERACTION

A primary concern with onshore geologic storage is the potential of groundwater contamination. In the event of a leak, stored CO_2 or dissolved solids could migrate from a sub-aquifer disposal well, move upward or laterally through leakage pathways and contaminate an underground source of drinking water (USDWs).

Groundwater contamination is less of a concern, though not impossible, with sub-seabed CCS. Although there are no significant aquifer resources in the offshore environment, the Texas coastal environment does include significant freshwater resources in the onshore area near the Gulf coast.[88] Accordingly, groundwater contamination may occur by two main pathways: saltwater intrusion, or injected / displaced fluid interaction.

<u>Saltwater intrusion</u> - Once an aquifer's freshwater is depleted through utilization of the water (not related to the CCS site operations), an up-dip migration of the fresh-salt water interface, or saltwater intrusion, may occur.[89] (Figure 13) This has occurred to some extent along the coastal region, and could be exacerbated by further overdrawing of the Gulf Coast

[88] Texas Water Development Board, *Report 345: Aquifers of Texas,* at 8 (1995).
[89] *Id.* at 14.

aquifer. In this circumstance, salt water begins contaminating the freshwater aquifer. Given the severe drought conditions throughout the state in recent years, this may represent a real concern as aquifers are depleted further.[90] Additionally, salt-water intrusion may be accelerated if the project injection forms a zone of high pressure behind the salt-water interface, providing an extra push for an up-dip occurrence and further contamination of the freshwater aquifer resource.

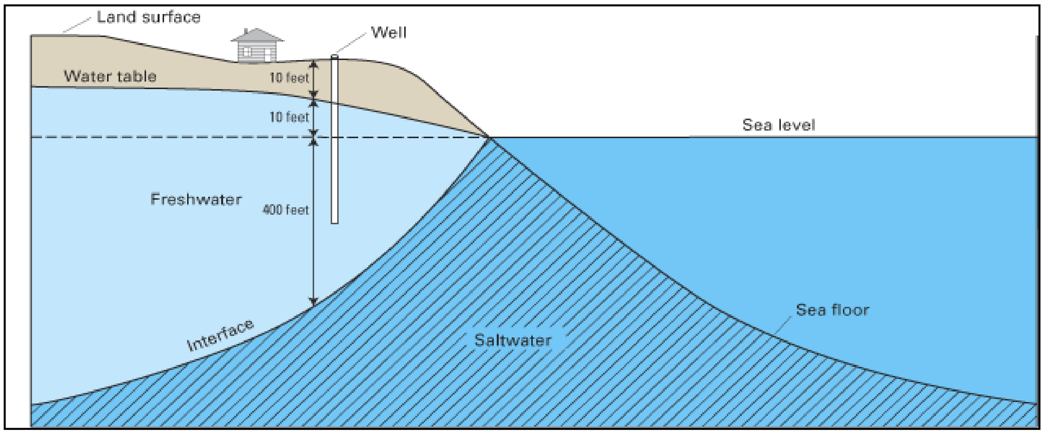

Figure 13: Simplified Diagram, Coastal Zone Freshwater-Saltwater Interface.

<u>Injected fluid or displaced fluid interaction</u> - As CO_2 is injected in the offshore environment, both injected material and displaced fluids (material that used to occupy the area where the injected material is now located) can migrate away from the confining zone. Such a migration could be accelerated by natural underground fluid flows existing prior to the injection, or if CO_2 is dispersed as finger-like migration rather than as a general zone of elevated CO_2.[91] The size and extent of the plume, including finger formations and plume heterogeneity, is dependent on a number of factors associated with the target injection formation characteristics and injection operations.[92,93]

A third pathway, albeit much less likely to occur on a widespread scale, includes leaked CO_2 dissolving rock and material from abandoned petroleum wells, causing toxic compounds such as benzene, phenols, and polyaromatic hydrocarbons to leach and migrate into fresh water sources.[94] Such a series of events would require both interaction with petroleum producing sites and interaction with freshwater resources, presumably in that order and

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[90] Betsy Blaney, *Drought-stricken Texas declared natural disaster area*, Associated Press (Jun. 29, 2011), http://www.star-telegram.com/2011/06/28/3186526/drought-stricken-texas-declared.html.
[91] Solomon, S., at 27-28, 30-31. (2007).
[92] Gasda et al. *Significance Of Dipping Angle On CO_2 Plume Migration In Deep Saline Aquifers*, http://conferences.dtu.dk/fedora/objects/CMWR-XVI:16063/datastreams/PDF/content?contribId=63&sessionId=3&resId=0&materialId=paper&confId=a051
[93] Siln et al., *A Modeling of Buoyant Gas Plume Migration*, http://www.osti.gov/bridge/servlets/purl/948573-wuGEvp/948573.pdf
[94] Kharaka et al., *Changes in the chemistry of shallow groundwater related to the 2008 injection of CO_2 at the ZERT field site, Bozeman, Montana*, Environmental Earth Science at 274 (2010).

prior to discovery of the migration so as to avoid any mitigation – and is therefore rather remote.

Careful management of coastal aquifers, and siting of injection wells at a sufficient distance to avoid groundwater interaction will help minimize, but would not likely eliminate, such risks.

c. CATASTROPHIC RELEASE OF CO_2

There are well-known examples of natural CO_2 venting systems, particularly volcanic formations that can sometimes produce sudden eruptions. When these releases occur in confined topographies in proximity to populated areas, they can be dangerous. Perhaps the best-known CO_2-related incident was the limnic eruption at Lake Nyos in Cameroon in 1986, which released enormous volumes of CO_2, resulting in the death of 1,746 people and thousands of animals.[95] However, limnic eruption is an inappropriate analogy to sub-seabed geologic sequestration, particularly in the Texas offshore coastal environment.

The cause of the release at Lake Nyos was a combination of unusual (though not unique) factors, in particular the lack of natural CO_2 turnover in the lake above an active volcano, which led to the gradual build-up of gas and catastrophic release.[96] In contrast, ocean systems are not subject to the same process. Natural ocean currents provide constant circulation of CO_2, such that even if gas were to escape into the water column, it would be diffused before it could build up to significant pressures. The Texas coastal sites under consideration for CO_2 storage are subject to the kinds of natural flows and currents that would prevent any such catastrophic eruption from occurring, even if leakage were to occur. Accordingly, the Lake Nyos example is relatively inconsequential for the purpose of considering where to site a CCS project in offshore Texas state waters because it does not present a viable risk for the sequestration of CO_2 in the offshore environment.

B. POTENTIAL IMPACTS FROM OFFSHORE CCS IN TEXAS STATE WATERS SPECIFICALLY

1. POTENTIAL IMPACTS ON HUMANS

Given that CO_2 storage will likely take place under the sea bed at a distance of several miles from inhabited areas, the primary vector for direct human impact is through an on-land pipeline leak. In low concentrations, CO_2 is not toxic to humans. However, CO_2 causes significant physiological effects at concentrations over 3% and will produce fatalities above 10%.[97] Given that CO_2 generally disperses in air quickly and effectively at the point of

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[95] Benson, et al., *Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geological Formations*, Earth Sciences Division, E.O. Lawrence Berkeley National Laboratory at 57, http://www.netl.doe.gov/technologies/carbon_seq/refshelf/reg-issues/Lessons%20Learned%20From%20Analogs%20-%20LANL.pdf.
[96] Heinrich, et al. (2003).
[97] Occupational Safety & Health Admin., *Carbon Dioxide*

release, this risk of CO_2 directly impacting humans is minimal. Examples of humans in close proximity to high volumes of naturally released CO_2, such as that emanated from Crystal Geyser, demonstrate the remote possibility of this occurring.

Groundwater interaction is another possible vector for human impact, though the likelihood of such an impact can be mitigated by attention to stringent regulations and precautions in the siting phase. As described above, CO_2 could potentially contaminate an aquifer if it migrates into the Gulf Coast aquifer, or displaces other materials into the aquifer. Texas' current groundwater monitoring regime involves annual monitoring and sampling roughly 2,000 wells across the state's 30 major and minor aquifers for contamination.[98] If significant CO_2 storage operations take place in the offshore region, increased sampling frequency may be desirable for wells in the Gulf Coast aquifer—particularly when aquifer levels are low—in order to quickly detect any intrusion of contaminants. However, given the extensive nature of the existing testing regime for water quality and aquifer protection, it is unlikely that the current groundwater program will miss an impact if it were to occur.

As discussed above, the possibility of a massive CO_2 release from the seabed causing deleterious impacts to humans, similar to what happened when the CO_2-laden cold bottom water of Lake Nyos turned over, is extremely remote. If CO_2 were to be emitted from the subsurface and into the water column, local ocean currents and wave action would likely cause mixing of affected ocean water prior to any damage occurring – though passing emissions to the atmosphere would be likely.

2. Potential Impacts on Aquatic Life (General)

Data illustrating the impacts of offshore CCS on marine life are limited, due to the difficulty of obtaining permission for in-situ experiments,[99] and the absence of any known CO_2 leakage from an existing offshore CCS installation.

However, a variety of studies have sought to simulate the localized impacts of leakage from a sub-seabed CO_2 storage well on various aquatic species.[100] Other studies have assessed the regional impacts of ocean acidification from natural systems and anthropogenic CO_2. These studies provide both 1) examples of acute, localized impacts on stationary animals exposed to elevated CO_2 conditions and 2) an analog to the remote prospect of a massive, widespread leakage of CO_2 sufficient to change the regional pH of the Texas Gulf Coast

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http://www.osha.gov/dts/chemicalsampling/data/CH_225400.html. (2001). As a basis of comparison, the atmospheric concentration of CO_2 in the year 2000 was 0.0368% (368 parts per million).

[98] Texas Water Development Board, *Groundwater Monitoring Section Activities*, http://www.twdb.state.tx.us/GwRD/HEMON/GMSA.asp

[99] Proposed small-scale studies of ocean CO_2 sequestration (i.e. injecting CO_2 directly into the water) were derailed by public opposition in Hawaii and Norway in 2000-01. *IPCC Special Report on Carbon dioxide Capture and Storage* at 285 (2005).

[100] *See, e.g.*, Fabry et al., *Impacts of ocean acidification on marine fauna and ecosystem processes*. ICES Journal of Marine Science, 65: 414–43 (2008); Seibel & Walsh, *Biological Impacts of deep-sea carbon dioxide injection inferred from indices of physiological performance*. 206 *Journal of Experimental Biology* 641-50 (2003).

region in a short time span.[101] A review of these studies provides insight into the potential ecosystem impacts, both moderate and worst-case scenario, of leakage from offshore storage wells.

In general, elevated CO_2 levels and lowered pH can cause two primary impacts on marine fauna: 1) decreased calcification, and 2) disturbance of acid-base regulation, which affects metabolism, reproduction and other levels of activity.[102] Decreased calcification is more of a dispersed, medium- to long-term threat to aquatic life and is already present in many aquatic zones worldwide due to ocean acidification—imposing a particular risk to the survival of tropical coral reefs and calcifying organisms such as mussels, shrimp, and plankton.[103] The addition of additional CO2 into areas already affected by acidification would be expected to exacerbate these adverse impacts.

Disturbance of acid-base regulation, on the other hand, typically requires much higher concentrations of pCO_2, sufficient to produce hypercapnia. This level of exposure is only likely to result from contact with a plume of CO_2 vented from a storage well or natural seep.

3. Potential Impacts on Fauna

As detailed in Part II, the Texas coastal zone includes a variety of aquatic fauna, ranging from phytoplankton, to fish, crabs, cetaceans, and birds. The effect of contact with CO_2 leaked locally into the water column will vary significantly depending on the animal group, age, and level of exposure. (Figure 14)

Arthropods	Description	CO_2 System Parameter	Sensitivity	Reference
Acartia steueri Acartia erythraea	Copepod Copepod	0.2-1%CO_2, ~2000–10 000 ppmv	Decrease in egg hatching success; increase in nauplius mortality rate	Kurihara et al. (2004)
Copepods	Pacific, deep vs. shallow	~860–22 000 ppmv CO_2	Increasing mortality with increasing CO_2 concentration and duration of exposure	Watanabe et al. (2006)
Euphausia pacifica Paraeuchaeta elongata Conchoecia sp.	Krill Mesopelagic copepod Ostracod	pH < 7.6	Mortality increased with increasing exposure time and decreasing pH	Yamada and Ikeda (1999)
Cancer pagurus 1	Crab	1% CO_2, ~10 000 ppmv	Reduced thermal tolerance, aerobic scope	Metzger et al. (2007)

Figure 14: Effect of hypercapnia on various arthropod species, including the edible crab Cancer pagurus.[104]

[101] *See*, *e.g.*, Denman et al., *Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research*." 68 ICES Journal of Marine Science 1019-29 (2011); Seaubien et al., *Potential Hazards of CO_2 Leakage in Storage Systems – Learning From Natural Systems*. Greenhouse Gas Control Technologies, Volume I
[102] Fabry et al. at 414 (2008).
[103] *Id*.
[104] Fabry et al. at 423 (2008).

Significant species for the Texas offshore ecosystem and economy include crab, shrimp, and several variety of finfish (e.g. Red snapper, Amberjack, Yellowfin tuna) and Menhaden, which is caught for use as protein in animal feeds and as a source of Omega-3 oils for human consumption.[105] Below, we perform a detailed evaluation of the potential impacts on four types of aquatic fauna important to Texas (crab, shrimp, fish and stationary bivalves), and which also serve to represent a broad cross section of species types. The evaluation also discusses the impact of cumulative CO_2 loading in the offshore environment and the proliferation of dead zones. This examination is meant to illustrate the types of adverse impacts that may occur if leakage from CO_2 sequestration sites is allowed to occur and provides the basis by which the policy recommendations in Section VII are made.

a. Potential Impacts on Crab

At least four studies have examined the tolerance of various crab species to elevated pCO_2.[106] Perhaps most germane to the present analysis was a study examining the Velvet Swimming crab's (*Necora puber*)[107] resistance to pH levels ranging from 6.05 to 7.96 over a period of 16 days, intended to simulate both short-term, localized CO_2 leakage, and medium- term, chronic exposure through ocean acidification.[108]

Figure 15: *Necora puber*
Source: sealifebase.org

In particular, the Spicer study found that crabs were able to compensate for certain degrees of hypercapnia through an increase in bicarbonate, generally derived from both the environment and through dissolution of their shells. However, compensation was possible only within limited temporal and pH ranges, beyond which the crabs experienced uncompensated acidosis and in some cases mortality.

At the lowest pH level tested, 6.05, mortality occurred widely within the sample populations after 24 hours of exposure, and reached 100% within 4-5 days. Meanwhile, at pH 6.74, the animals took 10 days to show a significant change in haemolymph (the crab's blood-like circulatory fluid) pCO_2. This change was compensated for temporarily by a rise in haemolymph pH, before mortality began occurring around the 14-day mark. At pH level

[105] Mattei, *Fishing for Dollars*. Texas Parks & Wildlife Magazine (2008).
[106] Truchot, JP., *Mechanisms of compensation of blood respiratory acid-base disturbances in the shore crab Carcinus maenas (L)*. 201 J Exp Zool 407-416 (1979); Cameron, JN. *Compensation of hypercapnic acidosis in the aquatic blue crab, Callinectes sapidus: the predominance of external sea water over carapace carbonate as the proton sink*. 114 J Exp Biol 197-206 (1985); Cameron & Iwama, *Compensation of progressive hypercapnia in channel catfish and blue crabs*. 57 J Exp Biol 673-80 (1987); Metzger et al., *Influence of elevated CO_2 concentrations on thermal tolerance of the edible crab, Cancer pagurus.* Journal of Thermal Biology 144-51 (2007); Spicer et al., *Influence of CO_2-related seawater acidification on extracellular acid-base balance in the velvet swimming crab Necora puber*, Marine Biology, 1117-25 (2007).
[107] Large crab native to the coastal area of England, the North Sea and the Mediterranean.
[108] Spicer et al., at 1117.

7.31, compensation also occurred but with no effect on mortality. However, the time scale of the experiments was too short to note potential impacts, even at higher pH levels, of exoskeleton dissolution on predator-prey interaction.[109]

To put these results in perspective, the business-as-usual scenario for ocean acidification predicts global ocean pH will reach 7.5 by 2100,[110] (down from a current open-water average of pH 7.9-8.3).[111]If *Necora puber* is representative of other Gulf crab species, such as the Blue crab (*Callinectes sapidus*) and Florida stone crab (*menippe mercenaria*), these results suggest fairly high resistance of crabs to foreseeable drops in pH due to general ocean acidification. However, since marine organisms can vary dramatically in physiological and ecological characteristics it is not necessarily safe to assume that all crabs will react in a similar fashion to changes in pH and CO_2 levels. Accordingly, additional research may be needed to evaluate the full range of potential impact of crab species due to chronic low level CO_2 exposure resulting in pH modification.

As far as acute exposures in a confined water column, i.e. to pH levels in the pH 6-7 range, results show that *Necora puber* can experience significant die-off within 1-2 days. This suggests that a significant localized leak could have deleterious effects in the injection zone very quickly. However, the impact would lessen significantly as the CO_2 dispersed from the storage site into the greater aquatic zone and the average pH change was diluted.

The second study of crab response to pCO_2 changes focused more on long-term impacts of ocean acidification, and the combined effect of CO_2 concentration and temperature variations on the distribution of crab populations.[112] The study found that under hypercapnic conditions (10,000 ppm of CO_2), the test species, *Cancer pagarus*, was far less able to adjust its metabolic processes under elevated temperatures than in normal CO_2 conditions (normocapnia). This impaired metabolism meant the crab had less energy for feeding, reproduction and survival. In extrapolation, such results indicate that as ocean CO_2 levels increase, this species (and likely other crabs) will be able to inhabit an increasingly limited range, based on what combination of temperature and pCO_2 it can tolerate.

Currently, *Cancer pagarus* inhabits water in the North Sea in a thermal range between 4° and 15° C. Above that temperature, sample specimens in normocapnia were able to maintain metabolic systems up to 18-19°, whereas specimens in hypercapnic conditions (i.e. 1% CO_2, or 10,000 ppm) began experiencing metabolic impairment at 12-13°.[113]

These results suggest another long-term threat to crab from increased CO_2 concentration includes reduced tolerance to sea temperature changes. Higher ambient temperatures may

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[109] *Id.* at 1123.
[110] *Id.*
[111] *Intergovernmental Panel on Climate Change Fourth Assessment Report* at 405 (2007).
[112] R. Metzger et al. (2007).
[113] *Id.* at 149.

interact with higher CO_2 concentrations (lower pH) to reduce the capacity of crabs to respond to additional impacts (such as increased CO_2 levels resulting from CCS leakage).

b. Potential Impacts on Shrimp

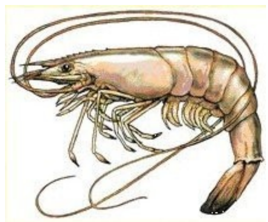

Figure 16: Brown Shrimp
Source: 21food.com

The Brown shrimp (*Farfantepenaeus aztecus*), White shrimp (*Litopenaeus setiferus*), and Pink shrimp (*Farfantepenaeus duorarum*) are the cornerstone of the Texas commercial shrimp fishery, with Texas commercial shrimp landings averaging 74% brown shrimp and pink shrimp, 25% white shrimp, and 1% "other" species.[114] The 1% "other" species consist of seabobs (*Xiphopenaeus kroyeri*), Roughback shrimp (*Trachypenaeus sp*.), Royal Red shrimp (*Hymenopenaeus robustus*), and Rock shrimp (*Sicyonia brevirostris*).[115]

The most extensive study to date on shrimp and CO_2 exposure appears to be conducted through the Institute for East China Sea Research at Nagasaki University in Japan, where several studies have been conducted on the common Indo-West Pacific rocky-shore shrimp (*Palaemon pacificus)*, among other species.[116] Two studies are worth noting; one focused on the impact of two levels of CO_2 exposure on *Palaemon pacificus*,[117] while the other focused specifically on the impact of heightened CO_2 on the development stages of *Palaemon pacificus*.[118]

In the study with two levels of CO_2 exposure, the shrimps were reared in seawater equilibrated with air containing 1,000 ppmv (parts per million by volume, seawater pH 7.89 ± 0.05) of CO_2 for 15 weeks or 1,900 ppmv (pH 7.64 ± 0.09) CO_2 for 30 weeks.[119] Experimental conditions were identical between the two experiments except for the CO_2 concentration. [120]

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[114] Texas Parks and Wildlife. *Executive Summary: Texas Shrimp Fishery. A report to the Governor and the 77th Legislature of Texas*, at 30 (2002).
[115] *Id*.
[116] See, Nagasaki University's Academic Output SITE: NAOSITE is the Nagasaki University's Institutional Repository, Institute for East China Sea Research. http://naosite.lb.nagasaki-u.ac.jp/dspace/handle/10069/20066
[117] Kurihara, et al. *Long-term effects of predicted future seawater CO_2 conditions on the survival and growth of the marine shrimp Palaemon pacificus.* Journal of Experimental Marine Biology and Ecology, 367(1), pp.41-46 (2008).
[118] Kurihara, H. *Effects of CO_2-driven ocean acidification on the early developmental stages of invertebrates*. Marine Ecology Progress Series 373:275-84, http://www.int-res.com/articles/theme/m373p275.pdf. (2008).
[119] Kurihara et al., Ishimatsu et al., *Coastal Marine Animals in High CO_2, Acidified Oceans: Impacts on Early Development, Growth and Reproduction*. Institute for East China Sea Research, Nagasaki University.
[120] Ishimatsu, et al. http://intellagence.eu.com/psi2009/output_directory/cd1/Data/articles/000283.pdf

The results of this study suggest that shrimp could be lethally affected by exposure to seawater equilibrated with the CO_2 concentrations of 1,000 ppmv and 1,900 ppmv, because survival was significantly suppressed in both experimental groups compared to the respective controls. [121] The 1,000 ppmv shrimp group started to die after 18 weeks and had a final survival rate of 55% (9 of 20 individuals died) as compared to 90% (2 of 20 individuals died, 1 died due to handling error) in the control group. The 1,900 ppmv shrimp group started to die in 7 weeks with an exception of one specimen, which had died in 13 days. The final survival rates were 65% (7 of 20 individuals died) for the 1,900 ppmv group and 95% (1 of 20 individuals died) in the control group.

The growth rates of each group were also measured. The growth rate was unaffected in the 1,000 ppmv experiment group, but was significantly reduced in the 1,900 ppmv experiment group compared to the control. Due to the difference in initial size between the 1,000 ppmv (10 mm) and 1,900 ppmv (20 mm) shrimp groups, the authors of the study caution against comparing them.[122] Instead, they direct attention to the important role long-term exposure CO_2 appears to play in the survival rates of *Palaemon pacificus*.

A separate study by the same group of authors focused on the impacts of CO_2 on the development stages of *Palaemon pacificus*. The study found no significant effects on planktonic larval stages where hatched embryos were cultured until settlement stage under 2000 μatm pCO_2 seawater (pH 7.6).[123] However, the CO_2-treated metamorphosing and settling juveniles were significantly smaller than in the control suggesting that settlement state was the most severely affected by pCO_2. [124]

If the Indo-West Pacific rocky-shore shrimp (*Palaemon pacificus)* is a proper indicator for how the brown shrimp, white shrimp, and pink shrimp will be impacted by a potential CO_2 leak from a CCS site in the Gulf of Mexico, it appears that the shrimp population may be able to withstand a short duration of increased CO_2 exposure. Clearly, the longer the duration of exposure and the concentration, the greater the potential harm to the population.

c. Potential Impacts on Fish, Squid and Marine air breathers

Fish and squid are, in general, less likely to be negatively impacted to elevated levels of CO_2 in the water column due to their mobility, though such mobility is likely markedly less in early life stages. However, fish and squid physiology is an important factor in overall impact.

Adult fish appear better adapted to fluctuations in CO_2 levels than squid, likely due to their low metabolic rate, presence of red blood cells to carry oxygen, existence of a venous oxygen reserve, tight epithelia, and efficient acid-base regulations. Tests on shallow-water

[121] *Id.*
[122] *Id.*
[123] Kurihara, H. (2008).
[124] *Id.* at 279, 281.

fish have shown short-term tolerance among adult fish of pCO_2 of 50,000-70,000 ppm. Juveniles are more sensitive to acute CO_2 stress, and are subject to mortality at 13,000-28,000 ppm.[125] In Texas, many fish such as Red drum (*Sciaenops ocellatus)* are spawned in or near gulf-bay passes, and are hatched close to shore. Over time, as fish mature through the larval and juvenile stages, they are generally found in bays and estuaries during early life, extending out into the gulf only at mild distances. For Red drum, studies indicate a maximum distance of 12 mile from the shore for juvenile fish, extending upwards of 70 miles from shore for adults.[126] Accordingly, like Red drum, while some fish may be very mobile in certain life stages (as adults), many species are tied to certain habitat types for completion of other life stages (i.e. larval and juvenile) making them more vulnerable to local impacts. Such impacts may be exacerbated if the species is in a vulnerable life stage (i.e. larval or juvenile) while experiencing elevated CO_2 conditions.

Similar to fish species, squid are also present in the Gulf Coast waters, though squid tend to be more highly sensitive to fluctuations in pH because they do not have red blood cells, which play an important role in regulating blood pH. Acute CO_2 exposure in squid causes acidification of the blood, which blocks oxygen uptake and binding at the gills, and reduces the amount of oxygen carried in the blood. This limits body function and at high concentrations could cause death.[127]

Diving marine air breathers such as turtles, dolphins and whales would also not likely be affected directly by acidification caused by a leak from a CCS operation, because they possess higher pCO_2 values in their body fluids than water breathers and gas exchange is minimized during diving. Such animals could still be affected by impacts of acidification on the ocean food chain.[128]

d. Potential Impacts on Stationary Mollusks

The dangers of localized or regional acidification are different, but even more acute for organisms that are 1) stationary and 2) depend on calcification for the formation of their exoskeletons, such as pteropods[129], oysters, mussels, and coral.[130] The calcification process that forms shells and exoskeletons is impaired as ocean pH decreases, and at certain levels is impaired altogether.

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[125] *Id.*
[126] Davis, *Red Drum, Biology and History*, Southern Regional Aquaculture Center, available at https://srac.tamu.edu/index.cfm/event/getFactSheet/whichfactsheet/59/ (1990).
[127] *IPCC Special Report on Carbon dioxide Capture and Storage* at 303 (2005).
[128] *Id.* at 304.
[129] These small sea snails are particularly critical for many ocean ecosystems, because they represent an important source of food for fish, seals and whales. The calcification process involved in building their shells is highly vulnerable to increases in ocean acidity. National Research Council of the National Academies. *Ocean Acidification: Starting With the Science*. National Academies (2011).
[130] Seibel & Walsh. *Potential Impacts of CO_2 Injection on Deep-Sea Biota*. 294 Science at 391 (2001).

Either sudden or gradual leakage of CO_2 could have significant impacts on these organisms, and potentially broader ecosystem implications. One study, for example, found that a CO_2 induced reduction of water pH to 7.3 (seawater is typically between 7.5 and 8.4) caused a 55% reduction in growth of Mediterranean mussels.[131]

Figure 17: Commercial oyster
Source: Oyster.us

In Texas, the prevalence oysters and mussels in bays and estuaries is well documented, as is the widespread importance of these resources on the local economy. Although CO_2 impacts on Texas specific mollusks has not been studied, analogous studies demonstrate a significant impact may occur if CO_2 leaks into the geographies where these species are present in high numbers – in particular in bays and estuaries – landward of the Texas barrier islands.

e. POTENTIAL IMPACTS THROUGH EXACERBATION AND PROLIFERATION OF CUMULATIVE IMPACTS AND DEAD ZONES

The ocean environment, including the near shore environment, in the Gulf of Mexico is threatened by a combination of conditions related to increasing carbon dioxide and decreasing oxygen concentrations caused by urban and agricultural run-off and pollution.[132] (Figure 18) These "dead zones" represent an area with very low or nearly zero concentration of dissolved oxygen and are typically found at or near the ocean floor. The dead (or anoxic) zone is created through a waste cycling process where phytoplankton produce organic material (waste) at the ocean surface which then sinks to the bottom (benthic zone) where it is broken down by bacteria. Bacteria use oxygen and give off carbon dioxide during this process, causing the anoxic condition. [133]

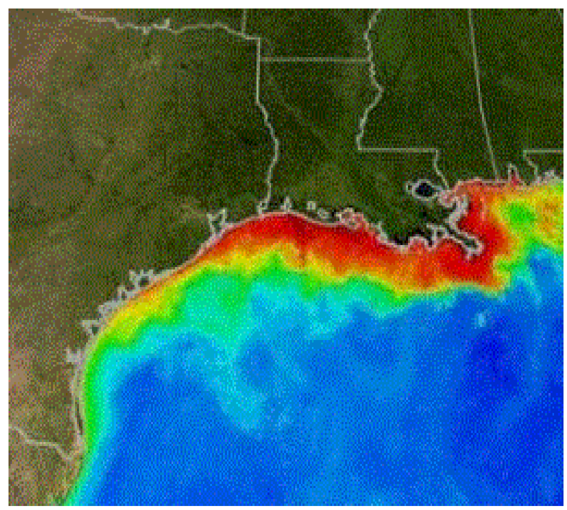

Figure 18: Gulf of Mexico Dead Zone Source: NASA/Goddard Space Flight Center Scientific Visualization Studio

[131] Michaelidis et al., *Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels (Mytilus galloprovincialis)* Marine Ecology Progress Series, 293: 109-18.
[132] ScienceDaily, *Ocean Dead Zones Likely To Expand: Increasing Carbon Dioxide And Decreasing Oxygen Make It Harder For Deep-Sea Animals To Breath (*2009). http://www.sciencedaily.com/releases/2009/04/090417161506.htm
[133] NASA. *Science Focus: Dead Zones*. http://disc.sci.gsfc.nasa.gov/oceancolor/additional/science-focus/ocean-color/dead_zones.shtml (2010).

As identified in the discussion in the sections above, increased CO_2 can be harmful to aquatic life. In the event that anoxic conditions are formed through urban or agricultural pollution and a dead zone is formed in whole or part within Texas state waters, the adding-on of CO_2 from leaking CCS operations could be especially problematic, resulting in a larger impact that if the leakage were to occur in a pristine ecosystem. Accordingly, the cumulative impact of CCS leakage and the proliferation of anoxic conditions through dead zone formation should be considered another potential mechanism of damage to flora or fauna stemming from CCS operations.

VI. EXISTING LEGAL AND REGULATORY LANDSCAPE FOR OFFSHORE CCS AND INSTALLATION OF ASSOCIATED INFRASTRUCTURE

As currently being documented by the Interstate Oil and Gas Compact Commission (IOGCC) and formerly by a number of legal and regulatory scholars, geologic CO_2 storage in offshore lands is likely subject to a variety of existing state and federal jurisdictions and corresponding laws governing transport, injection, storage, monitoring, and long-term liability of CO_2. (Note: This document does not address regulations concerning closure and plugging of wells nor property rights associated with captured CO_2). The applicability of these legal and regulatory systems and changes depends on whether the CCS project is located within a state boundary (i.e. within the 10.3 mile line from the Texas coast), or whether they are in the open ocean.

The vast majority of the techniques and technologies involved in offshore CCS are identical to those used in onshore CCS, and are thus subject to established regulations. Therefore, the legal and regulatory framework for offshore CCS is hardly a blank slate. However, given the relative novelty of offshore CCS in the U.S., the exact overlay of agencies and jurisdictions is not completely established, and further regulations and amendments to existing regulations are likely to emerge.

This section identifies laws relevant to environmental regulation that will be components of the offshore CCS framework and how they will likely apply. For the purpose of this paper, only the legal and regulatory aspects that apply to Texas state waters are examined.

A. PIPELINES

1. JURISDICTIONS

The jurisdictions of note include the General Land Office (right of way on public land) and the Railroad Commission Pipeline Safety Division (HLPSA monitoring and enforcement).

Pipelines are the most economical, and thus most likely, mode of transporting high volumes of CO_2 to an offshore injection and sequestration site. The U.S. oil and gas industry currently operates more than 4,000 miles of CO_2 pipelines nationwide for CCS and enhanced oil recovery.[134] The Department of Transportation's Pipeline Hazardous Material Safety Agency (PHMSA)[135] oversees these operations and sets regulations under the

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[134] Carbon Sequestration Leadership Forum, siting: Interstate Oil and Gas Compact Commission, *A Policy, Legal and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of CO_2* (2010).

[135] One of 10 agencies within the DOT, PHMSA was created in 2004 under the Norman Y. Mineta Research and Special Programs Improvement Act (P.L. 108-426) of 2004, which was signed into law by President Bush on November 20, 2004.

Hazardous Liquid Pipeline Safety Act of 1979 (HLPSA).[136] In many states, including Texas, PHMSA delegates monitoring and enforcement authority to state agencies.

In Texas, the Pipeline Safety Division of the Texas Railroad Commission (RRC) has authority over "the intrastate pipeline transportation of hazardous liquids or carbon dioxide and all intrastate pipeline facilities as provided in 49 U.S.C. §§60101, *et seq.;* and Texas Natural Resources Code, §117.011 and §117.012."[137] Pipelines crossing federal waters are subject to a different set of jurisdictions, including Bureau of Ocean Management, Regulation and Enforcement (BOEMRE), the Federal Energy Regulatory Commission (FERC), and potentially the U.S. Coast Guard, but the present analysis focuses on state waters only, making those jurisdictions inapplicable.

While some commentators have proposed amending federal regulations to facilitate the construction of CO_2 pipelines, for example by issuing federal permits exempt from state eminent domain restrictions, this document will not comment on the potential merits of such proposals.[138] Rather, the analysis below seeks to characterize the existing law and its implications for offshore CCS in Texas.

2. Regulatory authority

In Texas, the Department of Transportation's Pipeline Hazardous Material Safety Agency (PHMSA) delegates primary HLPSA responsibility for safety of intrastate CO_2 pipelines to the Pipeline Safety Division of the RRC. Under this delegated authority, RRC adopts minimum federal standards and makes an annual certification to the Office of Pipeline Safety at PHMSA.[139] The regulation also includes reporting requirements, integrity assessment and management plans, notification requirements, and periodic inspections.[140] In addition, the Texas Administrative Code includes a subchapter that outlines provisions applicable to hazardous liquids and CO_2 pipelines only. This section includes reporting requirements, corrosion control measures, and public education measures.[141]

3. Right of way over public lands

The General Land Office (GLO) has authority to grant right of way and easements on public lands "for any purpose, under any terms, and for any term that the commissioner deems to be in the best interest of the state."[142] This includes easements for pipelines running over onshore and offshore state lands. However, the GLO is generally required to avoid

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[136] 49 U.S.C. 60102(i)
[137] 16 Tex. Admin. Code §8.1(C).
[138] Sean McCoy, ed. *Policy Brief: Regulating Carbon Dioxide Pipelines for the Purpose of Transporting Carbon Dioxide to Geologic Sequestration Sites* Carnegie Mellon University at 2. (2009).
[139] Nordhaus and Pitlick, *Carbon Dioxide Pipeline Regulation,* 86 Energy Law Journal Vol. 30:85 (2008).
[140] 16 Tex. Admin. Code § 8.1-8.315
[141] *Id.*
[142] 31 Tex. Admin. Code § 13.12

impacting areas designated part of the Coastal Barrier Resources System (CBRS).[143] This includes islands located immediately on the coastline such as Galveston Island and Matagorda Island, among others.[144] Requests for pipeline easements running through these areas would presumably be disfavored by the GLO.

4. SITING & EMINENT DOMAIN

In Texas, pipeline operators can choose to become private carriers or common carriers, as defined by the Texas Natural Resources Code.[145] A common carrier, (a carrier that "owns, operates, or manages, wholly or partially, pipelines for the transportation of carbon dioxide or hydrogen in whatever form to or for the public for hire") has the statutory right of eminent domain, which allows them to "enter on and condemn the land, rights-of-way, easements, and property of any person or corporation necessary for the construction, maintenance, or operation of the common carrier pipeline." Property owners subject to eminent domain are entitled to just and adequate compensation for the public use of their land. The standard easement granted is fifty feet wide.[146]

Unlike federal pipeline permitting, Texas does not require CO_2 pipeline operators to obtain a certificate of need and public convenience before the power of eminent domain is granted, which expedites the permitting process.[147] Siting is not performed by the state, but by the pipeline operator, which has the authority to decide the route a pipeline takes.[148] The Safety Division of the RRC oversees pipeline construction and grants permits for operations of intrastate hazardous liquids pipelines.

As mentioned above, the GLO has primary authority for granting pipeline access over public lands, and would take into consideration environmental resources potentially impacted by pipeline passage. Indeed, the GLO must act consistently with the goals of the Coastal Management Plan.[149] In addition to avoiding siting a pipeline in proximity to a CBRS-designated area, GLO would likely avoid granting right of way through any other significant environmental asset onshore or along the coast.

5. SAFETY AND REPORTING STANDARDS

As mentioned, the Pipeline Safety Division of the RRC adopts minimum safety and reporting standards from HLPA. This involves annual reporting by operators to RRC, immediate reporting of any accidents, following of basic best practices around pipeline corrosion, as well as public notice requirements for pipelines sited within 1,000 feet of a school.

[143] 31 Tex. Admin. Code § 13. 19
[144] See John H. Chafee Official Coastal Barrier Resources System online database for full list of CBRS areas: http://projects.dewberry.com/FWS/CBRS%20Maps/Forms/AllItems1.aspx
[145] 3 Tex. Nat. Res. Code Ann. § 111.002
[146] 3 Tex. Nat. Res. Code Ann. § 111.0194
[147] Nordhaus at 97
[148] *Id.*
[149] 31 Tex. Admin. Code § 16.2

B. Drilling, Injection & Storage

1. Jurisdiction

The jurisdictions of note regarding drilling, injection, and storage include the U.S. EPA, Texas RRC Injection & Storage Division, TCEQ and Texas GLO.

The primary regulatory framework for CO_2 injection and storage in the U.S. is the UIC program within the federal Safe Drinking Water Act (SDWA). While the federal UIC program is administered and supervised by U.S. EPA, states can apply for primacy of UIC responsibility within their state, as is the case in Texas. Responsibility for UIC in Texas is shared between the RRC and the TCEQ.[150]

Until December 2010, the federal UIC program included five classes of wells, each with different safety and materials requirements, including Class II, which concerns CO_2 injection for enhanced oil recovery or non-permanent storage.[151] On December 30, 2010, U.S. EPA adopted final rules (first issued in July 2008) creating a new Class VI well type governing injection and geologic storage of anthropogenic CO_2.[152] The rule thereafter came effective on September 7, 2011.[153] As it has for Classes I-V, Texas plans to apply for primacy for Class VI wells from EPA, and has 270 days to do so after issuance of the final rules. [154] Until that time, U.S. EPA retains primary authority over the Class VI well system.

Classes	Use	Inventory
Class II	Inject brines and other fluids associated with oil and gas production, and hydrocarbons for storage.	151,000 wells
Class VI	Inject Carbon Dioxide (CO_2) for long term storage, also known as Geologic Sequestration of CO_2	6-10 commercial wells expected to come online by 2016.

Figure 19: UIC well classes governing CO_2 injection and storage.[155]

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150 University of Texas, *Injection and Geologic Storage Regulation of Anthropogenic Carbon Dioxide: A Preliminary Joint Report by The Texas Gen. Land Office, RRC, TCEQ, In Consultation with The Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin.* http://www.rrc.state.tx.us/forms/reports/notices/SB1387-FinalReport.pdf (2010)

151 U.S. EPA UIC website, available at http://water.epa.gov/type/groundwater/uic/wells.cfm

152 Id.

153 56982 Federal Register / Vol. 76, No. 179 / Thursday, September 15, 2011, available at http://www.gpo.gov/fdsys/pkg/FR-2011-09-15/pdf/2011-23662.pdf

154 Email communication from Doug Johnson, Manager of Injection-Storage Permits and Support, Technical Permitting Section, Oil and Gas Division, Railroad Commission (Aug. 8, 2011).

155 U.S. EPA UIC website: http://water.epa.gov/type/groundwater/uic/wells.cfm)

Prior to EPA issuing the final Class VI rules, Texas had developed its own rules governing storage of anthropogenic CO_2 pursuant to SB 1387 (2009), which directed the General Land Office, in consultation with several other state agencies,[156] to develop geologic sequestration rules consistent with future EPA regulations.[157] In late 2010, RRC adopted rules governing geologic sequestration, largely modeled on the UIC Class VI regulations. However, significant differences exist between state and federal rules that may need to be reconciled prior to RRC obtaining primacy.

With regard to the differences between the 2010 Texas rules and the Class VI UIC rules, one major difference exists in the area of "Minimum criteria for siting." In the Class VI regulations, chosen geologic systems must comprise "a confining zone free of transmissive faults or fractures" to protect underground sources of drinking water.[158] The RRC rules, meanwhile, only require that an applicant for a storage permit identify "the location, orientation, and properties of known or suspected transmissive faults or fractures that may transect the confining zone within the area of review and [determine] that such faults or fractures would not compromise containment."[159] Additionally, the minimum siting criteria under Class VI also require, "[a]n injection zone(s) of sufficient areal extent, thickness, porosity, and permeability to receive the total anticipated volume of the carbon dioxide stream."[160] In comparison, the RRC rules contain no such requirement, meaning that an applicant need not prove that a selected site has sufficient capacity to contain the volume of CO_2 proposed to be injected.

In order to obtain primacy, the Texas RRC must show that the state programs meet EPA's minimum federal requirements for UIC programs, including construction, operating, monitoring and testing, reporting, and closure requirements for well owners or operators.[161]

2. CLASS II VS. CLASS VI

Assuming the standards set by EPA are included in the final Texas regulations, the Class VI regulations will likely apply to geologic sequestration of CO_2 in brine aquifers, and set a significantly higher bar than Class II in terms of siting, wellbore, and monitoring requirements. Examples of elements required by Class VI but not Class II include, but are not limited to, the following: [162]

- The target site must include an injection zone with sufficient properties to receive the total anticipated volume of CO_2.

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[156] RRC, TCEQ and the Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin.
[157] S.B. 1387 Sec. 27.048(a)
[158] 40 CFR § 146.83(a)(2)
[159] 16 Tex. Admin. Code 5.203(c)(2)(C)
[160] 40 CFR §146.83(a)(1)
[161] 40 CFR § 145
[162] 40 CFR Part 146, Subpart H.

- The confining zone must have sufficient integrity to allow injection at maximum proposed pressure without initiating or propagating fractures.
- Operator must use all available data and modeling to predict the extent of the CO_2 plume over the lifetime of the project.

3. Site selection and wellbore requirements

Class VI regulations include extensive specifications for site selection and wellbore construction. Without listing all of these elements, it is worth noting some key safeguards against environmental risk included in the regulations:

- **Identifying potential leakage pathways:** An operator must identify all penetrations, including abandoned wells, that may penetrate the confining zone, and provide a description of each well's type, construction, date drilled, location, depth, record of plugging and/or completion, and determine which abandoned wells have been plugged in a manner to prevent the movement of CO_2 and fluids into USDW, including using CO_2 compatible materials. If a well has not been properly plugged, the operator must take corrective action to ensure the well does not permit the leakage of CO_2 from the confining zone.[163] In the offshore environment, there should be fewer abandoned wells than onshore, but this measure is still vitally important in order to close off potential leakage pathways from the confining zone.

- **Stringent corrosion-resistance materials requirements:** All materials used for casing, cementing, tubing and packer must be compatible with fluids that they may come in contact, and meet or exceed standards for those materials by API, ASTM, or others. This includes ensuring the materials can resist corrosion from CO_2 and formation fluids, as well as all internal and external pressure predicted at the site.[164] This requirement is critical, as carbonic acid and other corrosive fluids may come into contact with well materials at various times in the project’s lifetime and could create leakage pathways if sufficiently corrosion-resistant materials are not used.

- **Mechanical Integrity Testing:** Prior to injection, the well operator must conduct a series of tests designed to demonstrate the internal and external mechanical integrity of injection wells, which may include:

    i. A pressure test with liquid or gas;
    ii. A tracer survey such as oxygen activation logging;
    iii. A temperature or noise log;
    iv. A casing inspection log; or
    v. Any alternative methods that provide equivalent or better information and that are required by and/or approved of by the Director.[165]

[163] 49 CFR § 146.84
[164] 49 CFR § 146.86
[165] 49 CFR § 146.87(a)(4)

Extensive mechanical integrity testing prior to injection is crucial to ensuring suitability of a site, and can identify problems preemptively rather than waiting for a blowout or fracturing of casing once storage operations are underway.

4. TEXAS COMMISSION ON ENVIRONMENTAL QUALITY INVOLVEMENT

Although the Texas RRC would likely have authority over permitting of geologic sequestration projects in the offshore zone, the TCEQ has jurisdiction over injection of carbon dioxide into a zone "below the base of usable quality water…and that is not productive of oil, gas, or geothermal resources."[166] While the offshore area is not believed to contain usable water, if EPA or the Texas Water Board were to find otherwise, TCEQ would have jurisdiction under this provision of the Texas Water Code.

Additionally, RRC may not issue a permit for geologic sequestration projects until the applicant has submitted a letter from the TCEQ stating that the storage project will not "injure any freshwater strata in that area" and that "the formation or stratum to be used for the geologic storage facility is not freshwater sand."[167] Thus, even where storage is not done beneath an underground source of drinking water, TCEQ must provide certification that no underground sources of drinking water will be affected (using a methodology outlined in the Texas Water Code).[168] This shared responsibility between RRC and TCEQ ensures that RRC permitting complies with groundwater protection under the SDWA.

C. MONITORING, TESTING, ACCOUNTING AND REPORTING

1. JURISDICTION

In general, the jurisdictions of note include the U.S. EPA; RRC Injection & Storage Division (primacy pending). A discussion of the interplay between these jurisdictions and the primacy application process is included above.

2. MONITORING & TESTING

Unique among UIC classes, Class VI requires that applicants submit, along with their permit application, a "testing and monitoring plan" that includes a variety of measures. Key measures include:

a) Regular chemical and physical analysis of the carbon dioxide stream;
b) Installation and use, except during well workovers, of continuous recording devices to monitor injection pressure, rate, and volume; the pressure on the

[166] Tex. Water Code § 27.022
[167] Tex. Water Code § 27.046
[168] *Id.*

annulus between the tubing and the long string casing; and the annulus fluid volume added;

c) Quarterly corrosion monitoring of the well materials for loss of mass, thickness, cracking, pitting, and other signs of corrosion;
d) Periodic monitoring of the ground water quality and geochemical changes above the confining zone(s) that may be a result of carbon dioxide movement through the confining zone(s) or additional identified zones; and
e) Testing and monitoring to track the extent of the carbon dioxide plume and the presence or absence of elevated pressure. [169]

A robust testing and monitoring program is critical to ensuring that a storage site is effective at containing the injectate, and that the plume is behaving as predicted. The current RRC rules effectively require the same minimum elements outlined above.[170] In addition to including these minimum elements, under the UIC regulations—but not current RRC rules—every five years an operator must review its program and submit a revised testing and monitoring program to the program administrator, or explain why no changes to its program are necessary.[171]

Overlapping with the UIC regulations in this area is another EPA-issued regulation, on mandatory reporting of greenhouse gases (GHGs) at CO_2 injection and storage sites.[172] The purpose of the mandatory reporting rule is to establish a reliable recording regime,[173] as well as to monitor efficacy of carbon capture and storage projects. Whereas the UIC program operates under the authority of the Safe Drinking Water Act, the GHG regulations operate under authority of the Clean Air Act.

The 40 CFR part 98 subpart RR rule, pertaining to CO_2 storage, includes its own monitoring, reporting and verification (MRV) requirements for CO_2 storage projects (the accounting component of the rule is discussed separately below). While a UIC Class VI permit may satisfy some parts of the subpart RR rule's MRV requirement, the applicant must include additional information outlining how monitoring will achieve detection and quantification of CO_2 in the event surface leakage occurs.[174]

The Subpart RR MRV plan requirements include five main components: [175]

[169] 49 CFR § 146.90
[170] 16 Tex. Admin. Code § 5.203(j)
[171] 49 CFR § 146.90(j)
[172] Mandatory Reporting of Greenhouse Gases: Injection and Geologic Sequestration of Carbon Dioxide; Final Rule, 40 CFR Parts 72, 78, and 98
[173] For example, if a storage site is injecting 1 $MMTCO_2E$ per year, but leaking 20% of that volume due to improper storage methods, the operator should not be credited for the full amount injected.
[174] 75 Fed. Reg. 230 at 75063
[175] 40 CFR § 98.448(a)(1)-(5)

1. Delineation of the maximum monitoring area (MMA) and the active monitoring area (AMA);
2. Identification and evaluation of the potential surface leakage pathways and an assessment of the likelihood, magnitude, and timing, of surface leakage of CO_2 through these pathways in the MMA;
3. A strategy for detecting and quantifying any surface leakage of CO_2 in the event leakage occurs;
4. An approach for establishing the expected baselines for monitoring CO_2 surface leakage; and
5. A summary of considerations made to calculate site-specific variables for the mass balance equation.

Again, some overlap exists between these components and the elements of the "testing and monitoring" plan required by UIC Class VI. While both are concerned with detecting leakages from the storage site, the Subpart RR MRV requirements focus more on quantifying the leakages through baseline and post-leak measurements for accounting purposes.

Research and Development: Of note, subpart RR exempts research and development (R&D) projects from reporting if they meet the eligibility requirements. If so, they report instead under Subpart UU, which requires reporting mass of CO_2 received, and does not require reporting CO_2 injected or leaked.[176] Exempt projects include those that "investigate or will investigate practices, monitoring techniques, or injection verification, or if it is engaged in other applied research that focuses on enabling safe and effective long-term containment of a CO_2 stream in subsurface geologic formations, including research and injection tests conducted as a precursor to a larger more permanent long-term storage operation."[177] A pilot offshore CCS project such as that developed within this project may qualify for this exemption to the extent that is characterized as evaluating the potential for more extensive storage in the offshore environment.

3. Accounting

Central to the U.S. EPA Subpart RR GHG reporting rule is a methodology for measuring net sequestration of GHGs at the storage site. The rule calculates this net amount using a "mass balance" equation, which subtracts leakage measured from various points in the well and injection site (e.g. between the flow meter and the injection wellhead; between the production wellhead and the flow meter, etc.) from the total volume of CO_2 injected into the well or a group of wells to reach a final total:

$$CO_2 = CO_{2I} - CO_{2P} - CO_{2E} - CO_{2FI} - CO_{2FP} \quad \text{(Equation RR-11)}$$

[176] 40 CFR § 98.472
[177] 40 CFR § 98.440(d)

Where:

CO_2 = Total annual CO_2 mass sequestered in subsurface geologic formations (metric tons) at the facility in the reporting year. CO_2I = Total annual CO_2 mass injected (metric tons) in the well or group of wells covered by this source category in the reporting year.

CO_{2P} = Total annual CO_2 mass produced (metric tons) in the reporting year.

CO_{2E} = Total annual CO_2 mass emitted (metric tons) by surface leakage in the reporting year.

CO_{2FI} = Total annual CO_2 mass emitted (metric tons) as equipment leakage or vented emissions from equipment located on the surface between the flow meter used to measure injection quantity and the injection wellhead, for which a calculation procedure is provided in subpart W of this part.

CO_{2FP} = Total annual CO_2 mass emitted (metric tons) as equipment leakage or vented emissions from equipment located on the surface between the production wellhead and the flow meter used to measure production quantity, for which a calculation procedure is provided in subpart W of this part.

This final amount indicates how much sequestration a project should be credited for in a given year.

D. LONG-TERM LIABILITY AND FINANCIAL RESPONSIBILITY

1. JURISDICTION

The agency with primary responsibility for long term liability from a project site located in the Texas coastal region will be the Texas RRC as it implements the U.S. EPA Class VI UIC regulation.

2. EXISTING REGULATORY LANDSCAPE

In addition to placing requirements on site operation and development, the UIC Class VI regulations also address the question of long-term responsibility for monitoring and maintenance of a storage site after closure has occurred.

The UIC Class VI regulation requires that an owner or operator must conduct monitoring as specified in the Director-approved Post-Injection Site Care (PISC) and site closure plan following the end of injection, until the owner or operator can demonstrate to the Director that the geologic sequestration project no longer poses a danger to underground sources of drinking water.[178] Once an owner or operator has met all regulatory requirements under part 146 for Class VI wells and the Director has approved site closure pursuant to requirements at § 146.93, the owner or operator will generally no longer be subject to enforcement under section 1423 of SDWA for noncompliance with UIC regulatory requirements. However, an owner or operator may be held liable for regulatory

[178] http://www.federalregister.gov/articles/2010/12/10/2010-29954/federal-requirements-under-the-underground-injection-control-uic-program-for-carbon-dioxide-co2#p-601

noncompliance under certain circumstances even after site closure for violating § 144.12 of the UIC rule, such as where the owner or operator provided erroneous data to support approval of site closure.

Additionally, an owner or operator may always be subject to administration jurisdiction if the Administrator deems necessary to protect the health of persons under section 1431 of the SDWA after site closure – for example if there is fluid migration that causes or threatens imminent and substantial endangerment to an underground sources of drinking water. For example, the Administrator may issue a SDWA section 1431 order if a well presents an imminent and substantial endangerment to the health of persons, and the State and local authorities have not acted to protect the health of such persons. The order may include commencing a civil action for appropriate relief. If the owner or operator fails to comply with the order, they 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, depending on the fact scenario, remain liable under tort and other remedies, or under other Statutes including, but not limited to, Clean Air Act, 42 U.S.C. §§ 7401–7671; CERCLA, 42 U.S.C. § 9601–9675; and RCRA, 42 U.S.C. 6901–6992.

E. Wildlife & Coastal Zone Management and protection

1. Jurisdiction

The agencies of record for jurisdiction are the Texas Coastal Coordination Council (CCC) in concert with the Texas RRC, TCEQ; Texas Parks and Wildlife Department (TPWD); National Marine Fisheries Service (NMFS).

2. Existing regulatory landscape

Development activity in the Texas coastal zone is subject to laws protecting the coastal environment. This includes the federal Coastal Zone Management Act of 1972 (CZMA),[179] which authorizes states to create their own Coastal Management Plans (CMPs), making them eligible for federal grants for coastal improvement and restoration projects.

The Texas CCC, part of the Texas GLO, manages Texas' CMP,[180] administering federal grants and ensuring various agency actions affecting the Texas coastal zone are consistent with the goals and policies of the CMP.[181] This includes RRC permitting within the coastal zone.[182]

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[179] 16 U.S.C. § 1451
[180] Tex Nat. Res. Code § 33.203(22)
[181] Texas General Land Office website http://www.glo.texas.gov/what-we-do/caring-for-the-coast/grants-funding/cmp/index.html
[182] 31 Tex. Admin. Code § 505.11(a)(3)

Under RRC rules, the RRC is required to determine if a proposed permitted activity will have a "direct and significant impact" on any coastal natural resource area (CNRA).[183] If the RRC determines that a proposed activity in the coastal zone will not have a direct and significant impact on any CNRA, then the RRC must issue a specific written determination.

In addition to the CZMA, development in the Texas coast zone may also implicate the Federal Endangered Species Act and Magnuson-Stevens Fishery Conservation and Management Act for the purpose of protecting wildlife and critical habitat.

The 1996 amendments (known as the "Sustainable Fisheries Act") to the Magnuson-Stevens Fishery Conservation and Management Act of 1976 require federal and state agencies to consult with the National Marine Fisheries Service (NMFS) and local Fisheries Management Council (FMC)[184] before approving any activity that may adversely affect the habitat of a fishery resource in the development area, including essential fish habitat.[185] Essential fish habitat can include coastal areas, oceans, and rivers used by anadromous fish (i.e. living in the ocean but migrating upstream in freshwater rivers for breeding). If it is determined that the activity would adversely affect essential fish habitat, the FMC and NMFS will recommend measures to the agency for conserving the habitat. Although the Act does not require the federal or state agencies to carry out the measures, if a federal agency elects not to follow the recommendation, it will be required to explain in writing their reasons for not following the recommendations.[186]

F. PUBLIC REVIEW AND COMMENT

A myriad of regulations and administrative requirements establish a wide array of public review and comment procedures for development projects located in the Texas coastal zone and state waters.

Safe Drinking Water Act Rules: Under RRC rules, Texas has adopted the central public notice and comment provisions of the SDWA, requiring an applicant to provide notice to both the general public and to specific individuals when a permit application is filed with the RRC.[187] First, a copy must be made available to the public with the County Clerk at the courthouse of each county where the storage facility is to be located, or at another equivalent public office. The applicant also must provide an electronic copy of the complete application for access on the Railroad Commission website.

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[183] 16 Tex. Admin. Code § 3.8(j) A coastal natural resource area is a coastal barrier, coastal historic area, coastal preserve, coastal shore area, coastal wetland, critical dune area, critical erosion area, gulf beach, hard substrate reef, oyster reef, submerged land, special hazard area, submerged aquatic vegetation, tidal sand or mud flat, water in the open Gulf of Mexico, or water under tidal influence, as these terms are defined in -§33.203 of the Texas Natural Resources Code.
[184] The FMC for Texas is the Gulf of Mexico Fishery Management Council; http://www.gulfcouncil.org/
[185] 16 U.S.C. § 1855(b)(3) (2009). "Essential fish habitat" refers to the waters and substrate necessary to fish protected under the Magnuson-Stevens Act "for spawning, breeding, feeding or growth to maturity."
[186] 16 U.S.C. § 1854(b)(4)(B)
[187] 16 Tex. Admin. Code § 5.204

Additionally, under the RRC rules, general notice must be made through a local newspaper of general circulation, and specific notice given to adjoining or overlying owners and leaseholders of land and mineral rights, as well as: the clerk of the county or counties where the proposed storage facility is located; the city clerk or other appropriate city official where the proposed storage facility is located within city limits; and any other class of persons that the director determines should receive notice of the application.[188]

If RRC receives a protest from one of the specific individuals who were notified of the application, the commission cannot administratively approve the application. It must then schedule a hearing, notifying all affected persons, local governments, and other persons who express, in writing, an interest in the application.[189] Administrative hearings are open to the public and allow opponents to the application to present evidence, but hearings do not otherwise include time for public comment. If no protest to the application is received, RRC may administratively approve the application.[190]

School Land Board Rules: When an application for geologic sequestration concerns use of state land, the School Land Board's (SLB) public review process would apply.[191] The SLB usually meets twice a month and publishes notice of any meeting and action under consideration in the Texas Register. Time is allotted at the end of every meeting for public comment, giving the opportunity for any public member to provide input on any matter where SLB approval is sought, including whether a tract of land is permitted for geologic storage. Following SLB's determination of which tracts are suitable, the public or staff may nominate any or all of the tracts for inclusion in an upcoming lease sale. Notice of the lease sale will be published, giving the public an opportunity comment on the proposed lease at any SLB meeting up to and including the day bids are opened.[192] The public may at any time during the life of the lease request to be placed on the SLB agenda to discuss on-going operations and to request SLB action on their concerns.

National Environmental Policy Act Rules: The SDWA UIC permits are ostensibly exempt from performing an Environmental Impact Statement (EIS) under section 101(2)(C) and an alternatives analysis under section 101(2)(E) of NEPA under a functional equivalence analysis. See *Western Nebraska Resources Council* v. *U.S. EPA,* 943 F.2d 867, 871–72 (8th Cir. 1991) and EPA Associate General Counsel Opinion (August 20, 1979).[193] However, this determination could potentially change if federal funding is involved in an offshore CCS project. This document will not speculate as to the applicability of NEPA requirements, which is a highly fact-specific determination. However, the question of environmental review is discussed in more detail in Section VII.

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[188] 16 Tex. Admin. Code § 5.204(b)(1)-(2)
[189] 16 Tex. Admin. Code § 5.204(c)(1)
[190] 16 Tex. Admin. Code § 5.204(c)(2)
[191] University of Texas (2010).
[192] *Id.* at 52.
[193] 75 Fed. Reg. 237 at 77236

VII. POLICY RECOMMENDATIONS FOR ENVIRONMENTAL RISK REDUCTION DURING SITE SELECTION

A. GENERAL RECOMMENDATIONS FOR PROJECT SITE SELECTION

The research and analysis outlined in Sections II-VI has examined the potential risks inherent in offshore CCS in the Texas coastal region, and the existing laws that regulate those potential risks. Based on this review, we conclude, as others have concluded about geologic storage generally, that an offshore CCS project in Texas can be done safely and responsibly if existing laws, best operational and management practices, and newly adopted UIC class VI regulations are applied and complied in a precautionary manner. However, we also emphasize the large risks posed by failure of governmental oversight, as has been documented at other large infrastructure projects, must also be closely watched and managed.

Currently, there are only a few CCS projects thus far in the offshore environment, and only a handful of operational commercial scale CCS projects in the onshore environment (not including enhanced oil recovery without CCS). Accordingly, offshore development of CCS and the associated mechanisms for leak detection must still be considered an emerging area of technological development - regardless of the ability to analogize experience in the onshore environment. Therefore, to manage risk and protect the environmental health of the Texas offshore environment, at the heart of this set of recommendations for siting policy is:

> **Recommendation 1:** Any project for offshore CCS should be sited, designed and operated to avoid direct and significant impacts on human health or coastal natural resources (as defined by the Texas Natural Resources Code). To ensure adverse and / or unexpected environmental impacts are avoided, any offshore CCS project in Texas state waters must utilize the full range of precautions and safeguards available in all phases of the project timeline – including, but not limited to, site characterization, site selection, development, operation, monitoring, and closure. CCS site selection must evaluate whether the full range of precautions and safeguards are available at the target site.

Although offshore CCS is a relatively new area of development, as discussed above, the strong experience and applicability of existing injection and storage techniques used in the onshore environment, coupled with a long history of characterizing risks and vulnerabilities of the aquatic environment, can be generally thought of as meaning that offshore CCS presents few unknown risks generally. However, knowing whether a risk exists is not the same as saying no risk exists. On the contrary, empirical evidence shows, and discussed above, that CCS development in the Texas water does carry risks, albeit manageable. Such risks include both acute and chronic risks to flora and fauna stemming from CO_2 release, migration or other related activity; as well as cumulative risks related to the reduced resilience of the Gulf from existing human activities (i.e. large scale hydrological and sediment modifications, existing networks of underwater pipelines and drilling platforms, inputs of nutrients, large-scale anoxic events, etc,).

To fully mitigate the full slate of known risks, a coherent technical framework for project site selection specifically tailored to take into account the range of conditions in the offshore environment is necessary. Additionally, since an offshore CCS project in Texas state waters will likely be the first of its kind in the United States, and possibly the world (taking into account site differences between the Texas environment and that of the currently operating projects), strict adherence to best management practices and use of conservative (precautionary) assumptions throughout the project site selection, development and operations phase is critically important. Such practices must also be paired with exceptionally robust institutions of high integrity capable of handling an innovative project like this.

Recommendation 2: The siting of an initial project or projects to develop CCS in the offshore environment of the Texas coastal region must take a precautionary approach to prevent impacts on environmental attributes of concern. A similar approach should be taken during the development and operation phase of the project. A precautionary approach should be used for offshore CCS deployment until such time as commercial scale deployment of CCS is achieved or a regulatory framework specific to managing offshore projects is adopted into law.

In the context of offshore CCS project development for the BEG project, use of the precautionary principle should be thought of as an obligation to avoid causing harm in the project site selection phase as a foundational canon. In practice, use of the principle would mean avoiding or mitigating conditions that are potentially harmful to the offshore environment (i.e. avoid choosing sites that have not been fully evaluated, or mitigating any leak as opposed to only leaks of a certain size, etc.) even if there is not absolute scientific proof that the particular action would actually cause harm. The principle is at its strongest if the potential harm is irreversible. Historically, the precautionary principle has been used to require manufacturers to supply enough information to conclude that new and existing chemicals are safe and don't endanger public health or the environment.

What follows are suggestions and recommendations for key policies and practices that should be considered throughout the entire project timeline for an offshore CCS project in Texas state waters. Many of these recommendations are built upon an application of the precautionary principle in practice. Although the express purpose of this overall research agenda is to assist the process of site selection ongoing at BEG, this research may also be helpful as an exploratory document resulting in specific recommendations for further discussion in other parts of the project development process. Accordingly, this set of recommendations will, at times, extend beyond the scope of being purely associated with site selection and speak to the offshore CCS endeavor in general. The intent of this document in that regard, and the analysis involved, is for consideration in the context of further discussions related to developing offshore resources for CCS.

These recommendations are meant to complement compliance with existing regulations, in order to mitigate or reduce the potential for public health or environmental impacts from offshore CCS. The recommendations are organized, at a high level, based on their applicability in the overall project development timeline, as identified below, and divided into four general phases: 1) site characterization and selection, 2) permitting / planning, 3) development / operation and 4) closure. This classification is made for the purposes of organization of this document and do not necessarily reflect how industrial operators or site developers engage in planning.

Since the task of this research project is to assist the selection of a sequestration site, the bulk of recommendations included herein refer to that phase (Phase 1) of the project development timeline. Additionally, to the extent that choices made during the site selection process affect the suitability of mechanisms to reduce potential environmental impact during other phases, that issue is noted and discussed. Phases 2 and 3 are discussed in less detail, and Phase 4 is evaluated least.

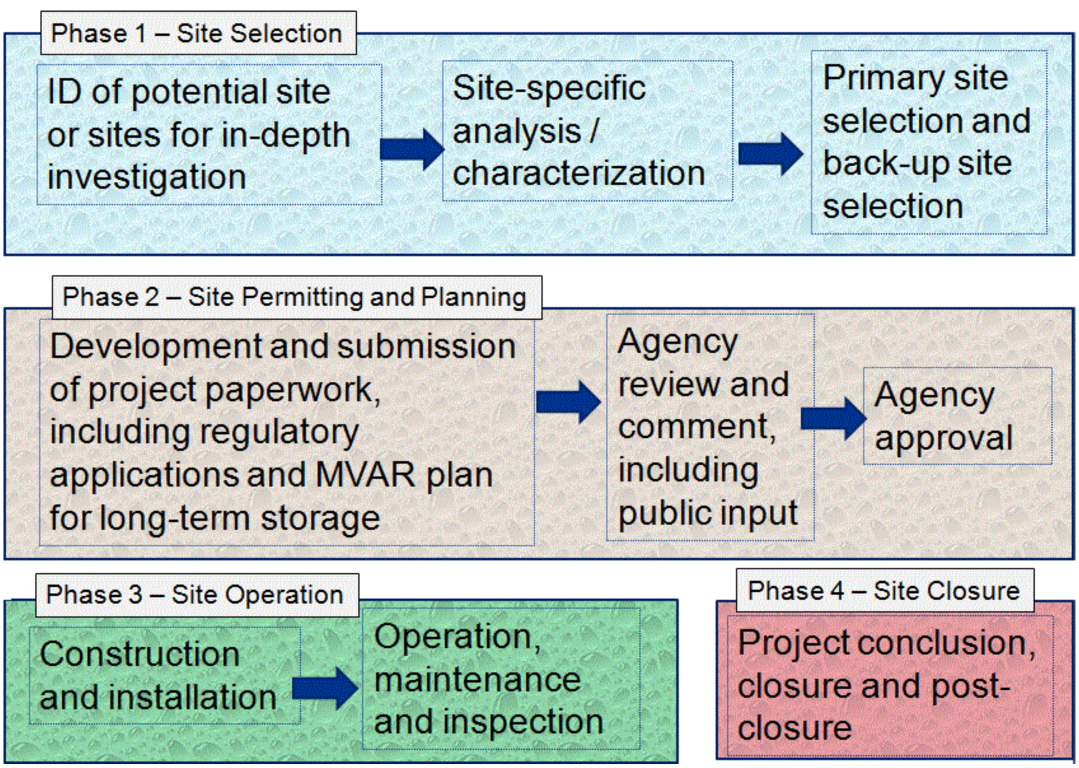
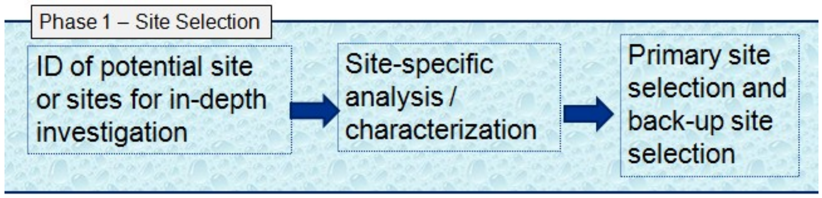


Figure 20: Simplified Project Development Timeline

B. PHASE I – SITE SELECTION



1. IDENTIFICATION OF PROSPECTIVE SITES

At the outset, examination of potential storage sites for offshore CCS development will require an in-depth evaluation of a range of factors, including, but not limited to, suitability for containing injected material over geologic time periods, potential for adverse environmental impact from development and operation, costs and project economics. As the site assessment phase is performed, evaluating coarse indicators to assess site suitability may be helpful for narrowing down the universe of available project sites to a few select sites worthy of additional, more in-depth evaluation.

As a starting point, an initial evaluation of potential project sites in Texas waters should look to the following factors as coarse indicators of site suitability. Some, but possibly not all, of these factors will be relevant for evaluation of projects further offshore, though that is beyond the main focus of the research assignment. Final selection of the project site is discussed after this discussion.

a. COARSE INDICATORS OF SUITABLE SEQUESTRATION SITES

<u>Source-sink match</u> - A site's proximity to point sources of CO_2 generation provides shorter piping runs, which can reduce environmental impact and the risk of being struck by ships. Shorter distances also provide greater ease of maintenance and inspection. Accordingly, sites with a strong source-sink match should be evaluated closely for suitability. This should nonetheless be balanced with the need to ensure a buffer zone between the storage site and resources of concern such as onshore aquifers or sensitive habitat.

<u>Isolation from human activities</u> - Facilities should be sited to avoid shipping lanes, which pose the risk of pipeline damage, and interference with economically valuable activities in the coastal area such as commercial and recreational fishing, water sports, boat cruises and others. This minimizes the economic impact of offshore CCS on the coastal zone. Siting facilities away from human activity will also significantly reduce the risk that a leak, if it were to occur, would cause harm to humans. Accordingly, sites with less proximity to human operations should be considered preferential.

Proximity to existing infrastructure and pipelines - Piggybacking on existing infrastructure can produce lower ecosystem impacts compared to new construction.[194] Further, coordinating pipeline corridors with existing equipment can also help.[195] Accordingly, sites with close proximity to developed infrastructures and pipeline corridors should be considered preferential.

Depth of water column - In general, shallower-depth seafloor installations are easier to develop and maintain than greater depth, though increasing experience and technological capabilities have significantly closed the gap. However, since there is little experience implementing the comprehensive monitoring framework systems necessary to ensure CO_2 sequestration offshore, it is highly likely that the shallower systems will be much less costly to monitor and maintain for CO_2 sequestration at the outset. Additionally, due to the decreased ocean pressures associated with decreased water column, a larger availability of monitoring tools may be available to project operators in shallower installations. Furthermore, if leakage were to occur, shallower sites are more likely to be impacted by wind and wave action which would therefore lead to greater dispersion of leaked CO_2 into the ocean water, leading to potentially less overall impact on aquatic species of concern before the leak could be remedied. Accordingly, for the BEG research project, sites where the sea floor is located at a shallow depth should be considered preferential.

Presence of preferential geologic features in the injection zone - As a threshold matter, sites with unfit geologic structures for sequestration cannot be used for CCS, and should not be considered. However, certain geologic features can serve a coarse indicators that one project site might be preferable to another. Such indicators and preferential features include high storage volume potential, deeper confining zone, large confining layer thickness, absence of transmissive faults or fractures near the zone of influence, small numbers of active or abandoned wells in the confining area, lack of freshwater aquifers near the lateral border of the CO_2 plume's zone of influence, high distance from resources defined by the Texas Coastal Management Plan as critical areas,[196] and lack of obstacles to using the full range of MVR provisions for leakage detection and site analysis.

2. In depth site specific analysis and characterization

Regardless of the use of coarse indicators to narrow down potential project sites, rigorous application of site analysis and characterization must be performed prior to ultimate site selection, and completed in concert with opportunities for public participation.

Recommendation 3: Prior to site selection, a proposed site must undergo a site specific evaluation of its potential for geologic sequestration to cause significant environmental impacts, including an evaluation of whether the full range of monitoring and mitigation techniques will be available to minimize impacts both at the point of injection and throughout the area of review / full zone of impact. Such a review should include a full characterization of potentially significant direct and indirect impacts prior to initiating development.

Site analysis will need to encompass, but should not be limited to:

- Geologic, hydrogeologic, and geomechanical site assessment - A thorough evaluation of a site's geologic suitability for permanent sequestration is critical. As discussed in Section VI above, the UIC Class VI regulations governing geologic sequestration (GS) require a comprehensive set of tests and surveys, which should serve as a model for any GS site characterization, including in the offshore environment.

- Ecosystem assessment - Documentation of the potentially affected flora, fauna, and water resources in the area of review (AoR), based on the full range of site activities, including the cumulative impacts of those activities with respect to existing conditions to provide an assessment of how a proposed project may add to or synergize impacts.

- Upfront assessment of monitoring options - Whether natural or man-made surface or subsurface features would prevent or enable the use of the full range of project monitoring and mitigation options known or available to project site operators. The full slate of monitoring options that must be considered for offshore CCS projects is included in the discussion of Phase 2 (Recommendation 9) below.

For an initial project in Texas state waters, a comprehensive environmental impact assessment must occur, taking into account the full range of site features which may affect the impact of the project on the offshore environment. This includes performing a review of both direct and indirect impacts, and evaluating the likelihood of those impacts occurring based on the project design. If a significant environmental impact is likely to occur at a project site, based on the project design and as determined by the site specific evaluation, then the project must be redesigned or another site selected to prevent those direct and significant impacts from occurring. Any mitigation techniques used to prevent impacts must be performed on-site to prevent those impacts from occurring rather than ameliorating impacts after they occur.

Although we believe that offshore CCS can be done safely and responsibly, it is critical that agencies take into account the environmental assets in the full geographic extent of the area of review, including flora and fauna, and perform an alternatives analysis to identify the least-impactful option for a project. This is important not only to minimize environmental harm, but also to provide the public with a complete set of facts regarding offshore CCS projects, and a robust process through which to make their concerns and suggestions heard. This level of accountability will build public confidence in offshore CCS and encourage stronger safety measures.

This recommendation pertains to the project or projects to be developed pursuant to the BEG Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect project. Environmental impact assessments as thorough as that presented here may or may not be required under Federal or State regulations for individual projects outside this study - and should be applied according to the law. Applicability in this project is derived from the application of the precautionary principle as described above.

3. Primary Site selection

a. Development of the sequestration site with most suitable geology and retention integrity

A bedrock principle associated with CO_2 sequestration is that operations should not occur if the target geology is not sufficient to sequester the injected material for the desired time period. In some cases though, such as in choosing between one or more sequestration sites, the issue may be more a matter of degree than a clear marker of non-suitability. One site may be considered better than another even though both might be able to sequester the requisite volume of material. Accordingly, in these situations, a site with the best characteristics should be chosen.

Recommendation 4: If the project must choose between two or more similar or equally situated sites for ensuring long term sequestration of injected CO_2, the CCS project site should be located in the geologic formation which has the least amount of potentially transmissive pathways (pathways capable of allowing leakage of CO_2 from the confining reservoir) through the caprock formation.

b. Application of US EPA Class VI siting rules

At the national level, the current mechanism for ground water protection from permanent CO_2 sequestration is the recently enacted US EPA UIC Class VI regulation, described in detail above in Section VI. In particular, Class VI requires that:

- Chosen geologic systems must comprise "a confining zone free of transmissive faults or fractures" to protect underground sources of drinking water;[197]
- The injection zone(s) be of sufficient areal extent, thickness, porosity, and permeability to receive the total anticipated volume of the carbon dioxide stream;[198]

[197] 40 CFR §146.83(a)(2)
[198] 40 CFR §146.83(a)(1)

- An operator must identify all penetrations, including abandoned wells, that may penetrate the confining zone, and provide a description of each well's type, construction, date drilled, location, depth, record of plugging and/or completion, and determine which abandoned wells have been plugged in a manner to prevent the movement of CO_2 and fluids into USDW, including using CO_2 compatible materials. If a well has not been properly plugged, the operator must take corrective action to ensure the well does not permit the leakage of CO_2 from the confining zone;[199]

- The confining zone must have sufficient integrity to allow injection at maximum proposed pressure without initiating or propagating fractures; and[200]

- Operator must use all available data and modeling to predict the extent of the CO_2 plume over the lifetime of the project.[201]

Although freshwater resources are not likely to come into contact with the injected material at the project site selected by BEG, Class VI rules are strong enough so as to ensure a basic general atmospheric protection and to ensure injected CO_2 remains trapped in the geologic feature into which it was injected.

> **Recommendation 5**: Regardless of regulatory applicability, strict application of the site characterization and control requirements of U.S. EPA UIC Class VI well regulations should be performed to ensure permanent retention of injected material is achieved. Future offshore GSC projects should be sited and operated where the best geology and site characterization exists, and with strict application of U.S. EPA UIC Class VI requirements as required by law or as necessary to ensure permanent retention of injected material.

[199] 49 CFR § 146.84
[200] *Id.*
[201] *Id.*

c. CONSIDERATION OF BRINE AQUIFER INJECTION

One of the benefits of the UT Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect Project is that by facilitating the siting and development of a commercial scale CCS project in Texas waters, it can help set the stage for other carbon sequestration in the subsurface. As identified by U.S. DOE, the sites with the largest sequestration potential in the gulf, and elsewhere, are brine formations. Accordingly, although it is not a recommendation made in this paper since our focus (as covered in Recommendation 4) is to ensure the development of the best available site, we recommend the site selection process, at a minimum, place focus on the suitability of brine formations as suitable sequestration sites.

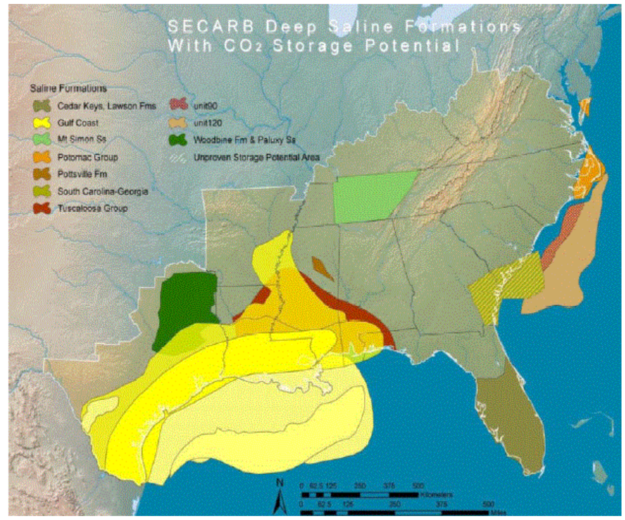


Figure 21: SECARB Brine Formation Map. Source U.S. DOE

d. DEVELOPMENT AWAY FROM ASSETS OF CONCERN

Although there are benefits to locating storage sites closer to sources of CO_2, or to shoreline resources (i.e. shorter piping runs, more convenient monitoring and inspection, etc.) the risk to human health, onshore aquifers and critical ecological assets on the coastline is reduced by locating CO_2 storage sites further from resources of concern yet still within the 10.3-mile state water boundary. Furthermore, requiring that no groundwater aquifers or coastal natural resource areas be located within and above the area of review (full zone of impact, including zones of elevated pressure or displaced fluid migration), the project site selection takes into account uncertainty that exists associated with predicting plume migration extent.

> **Recommendation 6**: All offshore CO_2 sequestration projects associated with the UT project should, to the extent feasible, be located at the maximum feasible distance from the shoreline and existing aquifers, but in no case closer than a distance where the zone of influence / area of review will overlap with resources of concern. This recommendation should also be followed for all projects, not just those associated with the BEG project, until further commercialization of offshore CCS occurs. Distance from the shore, aquifers or areas of concern should be built into the determination of site suitability, though must not undermine the paramount need to have a site that represents the best geology for long-term sequestration.

As mentioned, although a good deal of information is documented relating to the lateral migration associated with existing CO_2 injection projects, there continues to be some uncertainty related to the full extent of migration possible from a CO_2 injection site. In Texas, modeling indicates that injected CO_2 plume migration in the Frio sandstone formation may reach 320 km^2 for a commercial sized 30-year injection project entailing emissions from an 800 MW power plant.[202] This aspect of storage is being evaluated as part of a current research project conducted by the UT BEG.

Accordingly, and in part based on the uncertainty that still exists related to plume migration, the application of the precautionary principle in project siting should result in site selection that places injection as far away from resources of concern as possible within the state waters. In particular, locating storage sites farther from shore reduces risks of contaminating the Gulf Coast aquifer (or other aquifers), sensitive coastal habitat or human population through saltwater intrusion, CO_2 migration, or displaced fluids. Although aquifer protection may be inherently built into the siting program by other recommendations, or by up-front requirements to place sequestration offshore, away from bays and estuaries, the added protection of maximizing distance from resources of concern, for a first mover project, is advisable.

In most cases, application of this recommendation will mean the project should be located as close as possible to the 10.3 mile state waters boundary as possible, and seaward of any barrier islands. Of course, the ultimate choice of a primary injection site will necessarily be based on a number of factors - with the first and foremost factor undoubtedly being whether the site contains geologic conditions suitable for retaining the CO_2 in the subsurface over geologically and climatologically relevant timescales (greater than 1,000 years). However, as this document is focused on avoiding environmental impact, Recommendation 6 (above) should also be implemented during site selection as a rule.

e. UTILIZATION OF EXISTING INFRASTRUCTURE

As described above and shown in the figures below, (Figures 22 and 23) the offshore area within Texas state waters has already undergone significant development for oil and gas extraction. According to well logs, this work began in earnest in the mid 1970's and has continued through modern day, though most oil exploration and production has shifted to deeper water, and deeper geologic formations located further offshore.

As a result of the historic oil and gas development in Texas waters, significant existing infrastructure, (i.e. wells, pipelines and rigs) remain. Well density manuscripts for the offshore environment show that the upper coast is more developed than the lower or middle coast, though maps indicate numerous areas up and down the Texas coastal region in close proximity (within 1 - 10 miles) of a wide array of existing equipment capable of being co-located with equipment necessary to perform CCS. To the extent that existing

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[202] Gresham et al*., Implications of Compensating Property Owners for Geologic Sequestration of CO_2*
Environ. Sci. Technol, 44, 2897–2903 (2010).

infrastructure is suitable and usable for reuse or co-location with new equipment, it should actually be reused or co-located be as a general rule of thumb. Similar treatment should be given to existing and developed rights-of-way that have already undergone environmental review.

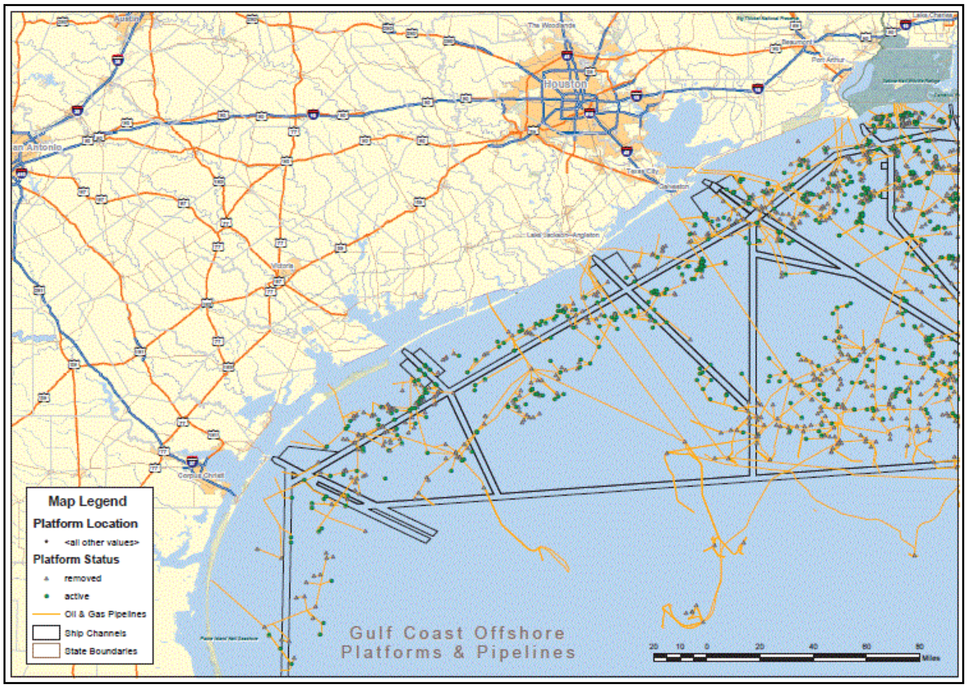


Figure 22: Existing Oil Infrastructure near Galveston, Texas (2009)

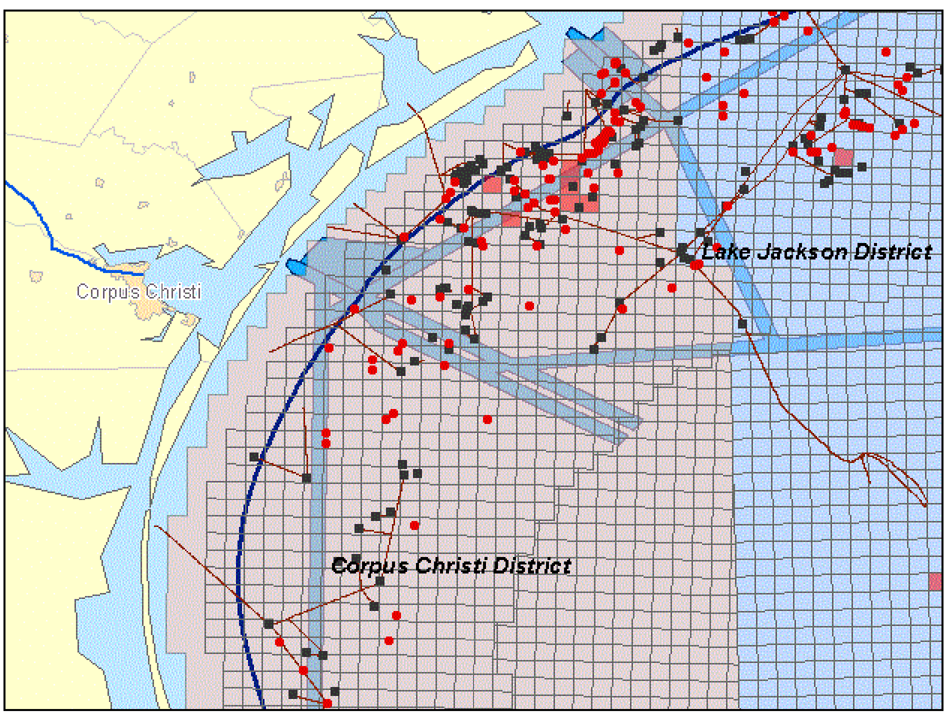


Figure 23: Existing Oil Infrastructure near Corpus Christi, Texas (2006)

> **Recommendation 7**: All offshore CO_2 sequestration project sites should be evaluated for whether their proximity to existing infrastructure and right-of-ways would allow for re-use or co-location of new equipment so as to reduce the potential environmental footprint of any new project.

4. Review of Multiple project sites and selection of a back-up

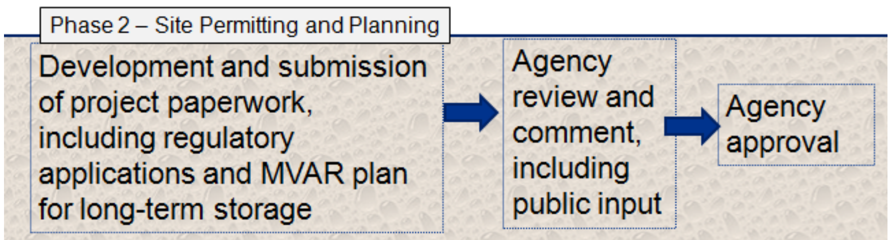
The process of choosing a site for CO_2 sequestration in the Texas offshore environment is complex and time consuming, requiring the evaluation of geological appropriateness in combination with several other factors as described and recommended above. The ultimate decision on which proposed site or sites should be pursued for further in-depth analysis leading to site selection should therefore be subject to review and inquiry by qualified experts prior to becoming final.

In addition to the review of multiple project sites, prior to selecting any one site the proximity of that site to another suitable geologic reservoir capable of acting as a back-up or contingency site should also be performed. Assuming suitable geologic conditions exist and suitable site specific monitoring mechanisms are available, sites that are located in close proximity to a back-up should be preferred to those that are not. A back-up or contingency site would be useful to act as a type of fail-safe option to quickly mitigate the CO_2 emissions stream in the event that unexpected conditions arise which cannot be mitigated at the primary site. Prior to utilizing a back-up site however, a full site assessment must be performed and a site-specific MVAR plan developed.

> **Recommendation 8**: The overall BEG project should thoroughly evaluate several potential candidate sites for project development, allowing for critical evaluation of multiple locations and geologic characteristics by qualified experts prior to making a final determination. Assuming suitable conditions exist for sequestration, projects that are located in close proximity to another suitable site capable of acting as a back-up site for contingency purposes should be preferred.

C. PHASE 2 – SITE PERMITTING AND PLANNING

As noted above, the key aims of the research project end at site identification and characterization. Accordingly, Phases 2, 3 and 4 discussed below are somewhat beyond the study scope. However, due to the importance of performing offshore CCS in a manner that mitigates the risk to the human population and the offshore environment, this paper goes into some detail and makes two initial recommendations related to the phases after site selection.



1. DEVELOPING A MONITORING, VERIFICATION, ACCOUNTING AND REPORTING PLAN

In Recommendation 3 (above), this paper states that an up-front site characterization for project site selection must evaluate the set of monitoring options available at a proposed project site prior to making the determination of its suitability. In this evaluation is the inquisition of whether natural or man-made features (surface or subsurface) would prevent or enable the use of the full range of project monitoring and mitigation options known or available to project site operators. In this section, the suite of monitoring tools is discussed.

To determine whether the full range of monitoring mechanisms are available at a project site, an evaluation of the extent of monitoring that should be pursued must first be performed. At the heart of any site specific monitoring, verification, accounting and reporting (MVAR) plan is making sure project operators are aware of the conditions and location of injected CO_2 when it is in the subsurface. The MVAR plan must be comprehensive enough to detect widespread low level releases as well as high concentration single point leaks, and include contingency procedures (mitigation procedures) to be implemented in the event that a problem or leak is discovered. Such a plan is also necessarily coupled with a detailed site characterization and site operation procedure that informs operators of what practices they must follow to operate the overall injection project without leakage or accident.

Although many of the conditions and practices associated with site monitoring on-shore may be the same as that in the offshore environment, certain important aspects are different and require special attention. In particular, downhole inspections cannot be performed in the offshore environment as they can on land, nor can surface leak detection using portable, hand-held instrumentation. Additionally, if a leakage from a confining zone on land occurred, wind or other conditions may disperse the leaking CO_2. However, in the ocean, a leak presents the risk of localized ocean acidification that has the potential to lead to changes in biologic systems.

> **Recommendation 9**: An up-front site characterization for project site selection must evaluate the set of monitoring and mitigation options available at a proposed project site prior to making the determination of its suitability. All offshore CO_2 sequestration projects must utilize an MVAR plan that is able to detect migration or leakage of CO_2 from the target confining zone early on in the formation of a non-conforming condition. In addition to monitoring injection conditions as required under federal law, the MVAR plan must also include a regime of water, biological and sediment monitoring and testing, and must be operationalized both onshore and offshore prior to the start of operations. Further, a specialized gas leakage detection regime must be overlain onto the MVAR as a whole.

As described in the prior sections, coastal water resources and biological systems, both onshore and offshore, could be impacted if CO_2 leakage from storage sites occurs. Therefore, it is crucial that monitoring and testing be performed frequently enough to quickly detect any such leaks or CO_2 migration away from the target confining zone. At present, the Texas Water Development Board monitors roughly 2,000 wells on an annual basis for water quality and contamination. [203] While this may seem like a large amount of monitoring at first glance, this frequency is insufficient, by itself, to exist as an adequate total monitoring regime for coastal monitoring in areas that could be impacted by leaks from nearby CCS project sites.

An adequate MVAR plan to detect CO_2 migration and leaks will need to include a baseline evaluation of the project site prior to the start of the project, be rigorous and frequent enough to provide deep early detection of non-conformance conditions, and include periodic observations and testing of groundwater, seawater, sediment and biological resources.

- ✓ 3D and 4D seismic monitoring and plume migration mapping

Prior to injection, in the site assessment phase, predictive plume migration mapping will create a picture to determine the likely extent or lateral and vertical plume migration based on subsurface geology and injection conditions. By conducting real-time seismic plume mapping, both as snapshots and for comparisons over time, project operators can determine whether actual plume migration conditions are taking place as predicted. Non-conformance with plume simulation models is helpful to identify the presence of leakage

[203] Texas Water Development Board, Groundwater Monitoring Section Activities, http://www.twdb.state.tx.us/GWRD/HEMON/GMSA.asp (2011).

pathways or characteristics that may impact long-term storage conditions. This type of modeling, while complex and time consuming, is a foundational cornerstone of any MVAR plan and has proven helpful in evaluating the storage effectiveness of other offshore CCS projects.[204]

- ✓ Injection condition monitoring

As required under UIC Class VI regulations, a project operator must perform significant monitoring of injection conditions throughout the period of injection to ensure that subsurface conditions are as predicted and to also prevent deleterious impacts associated with over-injection or compromised infrastructure (well casing) integrity.[205] Specifically, among other requirements, UIC rules require injectate monitoring, corrosion monitoring of the well's tubular, mechanical, and cement components and pressure fall-off testing.[206] UIC rules also require ground water quality monitoring, CO_2 plume and pressure front tracking, and, at the Director's discretion, surface air and soil gas monitoring.[207] Taken together, this monitoring regime is a step towards making sure injectate is safely confined in the target formation, costs are minimize costs, injection pressure changes follow predictions, and area of review modeling is accurate. However, for CCS in the offshore environment, conformance with Class VI requirements is not enough.

- ✓ Groundwater testing

Due to the importance of the Gulf Coast aquifer as a critical resource for Texas, the project must ensure that it can detect the presence of migrating CO_2 from an injection site that may come into contact with groundwater aquifer located on land. Accordingly, the project developer should develop a monitoring system for monthly or quarterly testing of a limited number of underground observation and sampling wells both proximity to the CO_2 storage site or sites, at the leading edge of any nearby aquifers, and at specified intervals in between, taking into account groundwater flow and migration trends. Detecting migration, if it were to occur, prior to it reaching the aquifer should be the primary focus.

- ✓ Seawater testing[208]

Due to the importance and sensitivity of the offshore environment to leakage and exposure to CO_2, the project must ensure that it can detect the presence of elevated CO_2 in ocean water associated with the project operations. Testing at randomized and targeted locations and comparing values against baseline conditions measured prior to project initiation will be necessary.

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[204] R. Arts et al, *Ten years' experience of monitoring CO2 injection in the Utsira Sand at Sleipner, offshore Norway,* first break volume 26 (2008)
[205] 75 Fed. Reg. 237 at 77230
[206] *Id.*
[207] *Id.*
[208] Hamanaka, *CCS Monitoring Under the Marine Pollution Prevention Law*, Presentation for the 5th Meeting of the IEA-GHG Monitoring Network (2009).

Accordingly, the project operator should develop and apply a seawater monitoring system for regular testing that includes, but need not be limited to, the following conditions:

- Seawater pH;
- Seawater pCO_2 content;[209]
- Seawater total CO_2 concentration;
- Seawater alkalinity;
- Seawater density; and
- Other characteristics of seawater that could indicate the presence of a CO_2 leak or other adverse impact from CO_2 storage sites.

Figure 24, Seawater testing for elevated CO_2 Source: ECO2

✓ Sediment testing

Due to the importance and sensitivity of the offshore environment to leakage and exposure of CO_2, the project must ensure that it can detect the presence of elevated CO_2 in seafloor sediments, as a proxy for detecting leaks into the water column. Testing at both randomized and targeted locations under the sea floor, though close to the seafloor surface, and comparing values against baseline conditions present prior to initiation of the project will be necessary. Accordingly, the project operator should develop and apply a sediment testing monitoring system for regular testing of sediment physical and chemical characteristics that includes, but need not be limited to, the following conditions:

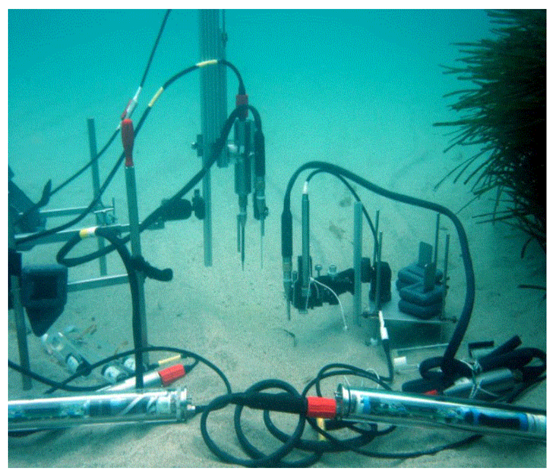

Figure 25: Sampling Equipment in Mediterranean, Source: ECO2 (2011)

- pH;[210]
- Alkalinity;
- pCO_2 content; and
- Any other measures that could indicate the presence of a CO_2 leak or other adverse impact from CO_2 storage sites.

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[209] Annunziatellis, *Development of an innovative marine monitoring system for CO2 leaks: system design and testing*, Energy Procedia 1 2333–2340 (2009).
[210] European Commission, *Safety of deep carbon storage needs careful site selection*, Science for Environmental Policy, January 2011, http://ec.europa.eu/environment/integration/research/newsalert/pdf/226na3.pdf

✓ Biological testing[211]

Periodic evaluation of the health of sensitive biological systems (flora and fauna) must occur in the area of review to detect the presence of changes to environmental quality stemming from undetected leakage of CO_2. Evaluation of biological system impacts must include, but not be limited to the following:

- Condition of marine organism (observation for changes);
- Population density in water column of phytoplankton;
- Presence of dead fauna in area of review;
- Health of nearby critical areas;
- Health of benthic organisms located on seabed in area of review;
- Health of high-sensitivity organisms in area of review (esp. calcareous organisms);
- Condition of commercially-fished organisms in proximity to AOR (e.g. shrimp, tuna, etc); and
- Any other measures that could indicate the presence of a CO_2 leak or other adverse impact from CO_2 storage sites.

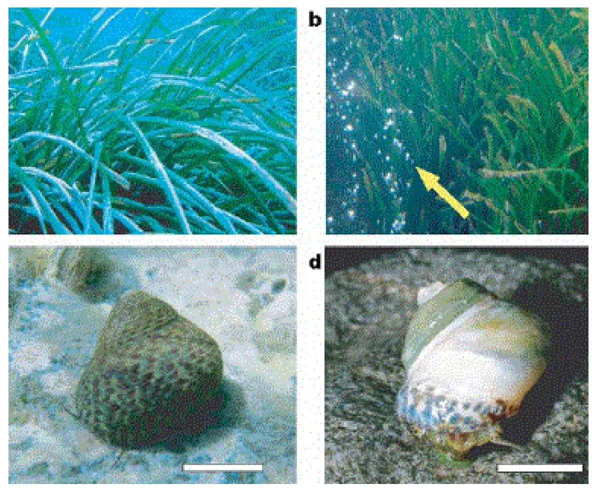


Figure 26, Biological testing for elevated CO_2
Source: ECO_2

✓ Specialized Gas Leakage System

Probably one of the most important and publically visible aspects of an MVAR program for offshore CCS is detection of leakage of CO_2 using specialized gas leakage detection equipment. Such systems are not generally used in the onshore environment since they are either only relevant to the aquatic environment or are so new as to have not been widely considered. Rather, most of the information associated with offshore leak detection from specialized equipment discussed below is based on research and development in the scientific community – and is therefore still an emerging field.

Whatever system is used to detect CO_2 leakage from the target confining reservoir, it must be able to perform two functions – 1) detect widely distributed low level leakage throughout the area of review and 2) detect point source high level leakage within the full area of review, and with targeted focus at points most likely to result in leakage. At the heart of these two functions may exist different types of equipment and leak detection practices. Examples of equipment and practices associated with both functions are

[211] Reitz, *Sub-seabed CO2 storage: Impact on Marine Ecosystems*, ECO2 (2011); Siting: Hall-Spencer et al., (2008).

identified above and below. (Figures 27 and 28) However, due to the cost and accuracy associated with utilizing these leakage detection systems, it will likely be up to the discretion of the project operator to establish the proper leakage detection regime using specialized equipment. If certain types of equipment are not used, the project developer should identify the reason why, and should be able to demonstrate that the MVAR as designed will achieve the same level of accuracy in leak detection as the specialized practice not chosen.

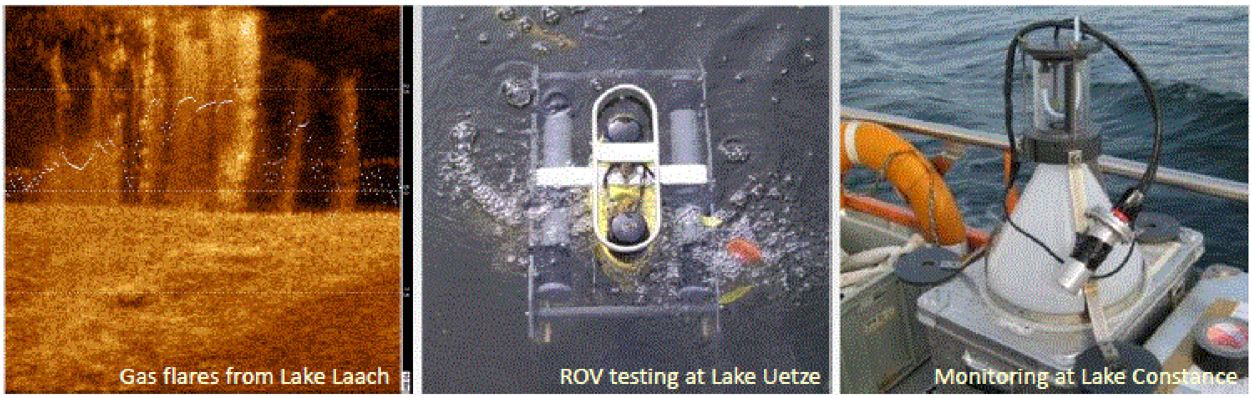


Figure 27: Offshore leakage detection methodologies being developed at research sites
Source: Moehller (2011)

Evaluation of sea floor surface leaks from an offshore CCS project should include, but not be limited to the following:

- Sonar observations, including, but not limited to, sidescan sonar, multibeam echosounder, sediment echosounders, and hydroacoustical monitoring able to cover large surface areas;[212]
- Visible bubble observations using submersibles, boats and / or divers;
- Video capturing (in the event that an anomaly or bubbling is detected);
- Gas sampling (in the event that an anomaly of bubbling is detected);
- Gas flux quantification (in the event that an anomaly or bubbling is detected).

[212] Moeller, *Integrated Monitoring Research at Natural CO2 Vents: Lake Laach (Germany)*, Presentation for the 6th CO_2Geo Net Open Forum, Venice, May 9-11, 2011, http://www.co2geonet.com/UserFiles/file/Open%20Forum%202011/PDF-presentations/2-03_Moeller.pdf

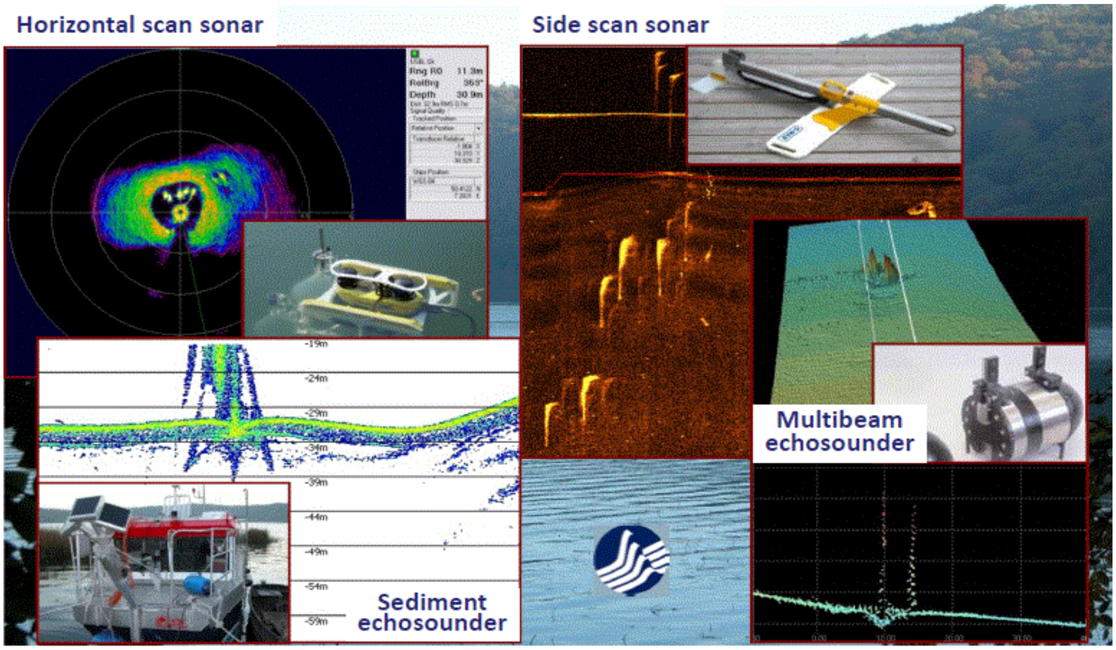


Figure 28: Offshore leakage detection methodologies using sonar Source: Moehller (2011)

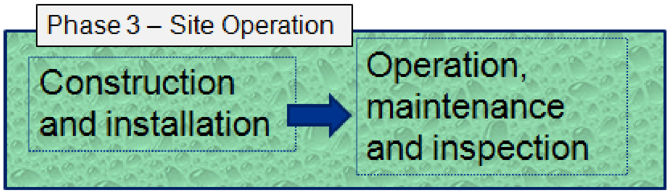
2. RELEASE MITIGATION AND PLANNING

Recommendation 10: *All offshore CO_2 sequestration projects should, prior to the start of any injection, finalized and publish a contingency and remediation plan.*

In the event that a developed CCS site does not operate as designed, or that CO_2 is discovered to be leaking from the target confining zone, the operator must respond quickly to prevent damage to the Texas coastal environment. Accordingly, prior to any injection, the project operator will need to have a contingency plan for mitigation of problems that may be observed. Such a plan is as important (for the assurance of CO_2 sequestration) as a site specific MVAR plan. Mitigation plans should include a provision to immediately cease injection if leakage from the target confining zone is observed.

At the core of any mitigation plan must be methods to determine the extent of the plumes non-conformance with expected behavioral models and expectations, including identifying size of any transmissive pathways and leaks, the cause of the leak, and the method to stop the leak. For the purpose of this document, we reference the full range of leak detection methodologies discussed above as critical components of any mitigation plans because the size, extent and characteristics of a leak will be a determining factor for understanding the likely impact on the offshore environment. Of course, a project developer must develop a mitigation plan that incorporates all three aspects, and potentially others as needed.

D. Phase 3 – Site Operation



Perhaps the most effective way to prevent unwanted environmental impacts from an offshore CCS project is to create a comprehensive development plan that takes into account all of the protections and best business practices available, and observe the site with rigorous governmental oversight.

Included in a site development and operations plan should, at a minimum, be all the necessary parameters associated with site construction, installation, operation, maintenance and inspection. For example, development plans should identify and require conformance with best practice standards regarding well design, materials selection, installation, operation, and maintenance in the offshore environment. Additionally, development plans should include injection pressure and flow rate guidance.

By following established guidelines built from the site specific development plan and the site specific MVAR plan, including guidelines associated with contingency planning, project operators and developers will have a course of action predetermined to minimize undesired impacts and prevent project delays.

With reference to governmental oversight, as a threshold manner full cooperation with governmental officials prior to, and during, the development and operation of a project site will be necessary. Additionally, institutional capacity and integrity for rigorous governmental oversight should be thoroughly evaluated on a periodic basis, including the nature of the relationships between oversight bodies and project personnel. Finally, critical reviews of institutional performance should inform whether correction action is needed and to ensure regulators remain informed yet unbiased.

E. Phase 4 - Site closure and post-closure

The purpose of this document was to examine the environmental risks and regulatory considerations associated with offshore CCS in Texas coastal waters. In this report, methods and opportunities to minimize the potential environmental impact of CCS associated with leakage of CO_2 and infrastructure installation was discussed. Site closure and post-closure are critical aspects of an environmental protection regime, but are likely to be well into the future and based on project dynamics observed during the development and operations phase. Accordingly, site closure and post-closure are outside the bounds of this project at this time and are not discussed further.

Phase 4 – Site Closure

Project conclusion, closure and post-closure