Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR):

Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery

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INTRODUCTION

Much has been written about the need to capture CO_2 from industrial plants, especially coal power plants. The primary driver for this growing attention has been concerns of accelerating accumulation of greenhouse gases in the atmosphere. As this awareness grew, considerable funding and research time has been devoted to 1) developing the technologies for capture and 2) investigating the subsurface reservoirs in which to permanently place the CO_2. Aside from the demand for CO_2 for EOR applications, the fundamental premise of most of the research has been that a governmentally driven imperative(s) would force the application of the technologies and that the CO_2 would be injected into deep saline formations. It is accurate to say that the commercial aspects of the work would be assuaged by what is commonly referred to as a price on carbon, either direct such as a carbon tax, or indirect as in emission trading credits, etc. It is also fair to say that the ongoing storage during CO_2 EOR has been prematurely or, even inaccurately dismissed in some circles as an answer to CO_2 emissions control as it was 1) too small a solution to matter in the end, 2) storing only about half of its injected CO_2, or 3) that it only prolonged a society dependent on carbon-based fuels by adding more oil production to the national and international combustion (emission) profiles already in existence. The problem is that the first two statements can be shown to be inaccurate and the third ignores the reality and magnitude of the role of oil and hydrocarbons in modern society. Nonetheless, the commercial driver for the capture via sales of the "commodity" CO_2 and the ongoing demonstration EOR projects of the technology and application are viewed by some as impediments to the long-term strategies for converting to cleaner energy solutions.

However, CO_2 EOR can accelerate emission reductions and sequestration in two ways. First is by providing value, i.e., the commoditization, of CO_2 via capture and purification which sidesteps, a least to a degree, the NUMBY (<u>n</u>ot <u>u</u>nder <u>m</u>y <u>b</u>ackyard) concerns that many of the planned sequestration projects have faced. The public often views waste injection in a harsh light. Second, the established value of the CO_2 as a commodity in CO_2 EOR contributes to the funding of capture and helps (but does not completely) balance the market solution equation. An ancillary benefit can be to include the qualified injection companies in not only the operations but also to assist with accelerating and pushing for solutions to energy security and safe and secure emission reductions.

One of the purposes of this paper is to reexamine the original baselines of CCS directions in order to reinvigorate and begin to accelerate capture, utilization and storage of CO_2. It is now widely recognized that climate change legislation will not jumpstart sequestration anytime soon, whereas a recognition/endorsement of CO_2 EOR for storage could. With what we now know about concurrent EOR and storage and some new policy initiatives, many believe a worldwide greenhouse gas capture initiative could be occurring at a much faster pace as insurance against an energy, economic, national security, and/or climate crisis.

BACKGROUND AND FUNDAMENTALS OF OIL PRODUCTION AND CO_2 ENHANCED OIL RECOVERY

The oil and gas sector is most often portrayed as an industry dominated by drilling for new oil and

[1] This Report was prepared by L. Stephen Melzer, Melzer Consulting for the National Enhanced Oil Recovery Initiative, Center for Climate and Energy Solutions.

gas fields. And, in fact, most companies could be called exploration companies and make their entire living doing exactly that. However, there is a sub-industry within the larger sector which concentrates on extending the lives of producing fields, i.e., getting more oil from a given discovery (field). Tradition tends to brand these companies as production organizations, in contrast to drilling focused, exploration companies. The production companies require a larger set of engineering skills and are challenged in trying to recover more and more oil (call it advanced recovery) from a "reluctant" reservoir. History shows that the advanced recovery approach is more costly per barrel produced and monetary rewards for success come to these companies slower. In a fast paced world seeking immediate gratification; most companies opt for the exploration path to provide more immediate returns for their shareholders. Although the advanced recovery business plan leads to relatively large oil reserves and long-lived production, fewer companies over time have chosen the route and have opted for an exploration focus.

To provide further background for this paper, it is useful to examine oil and gas production in a framework the industry has come to call the phases of production.

Primary Production Phase

The first producing phase of a reservoir is known as the primary production phase where a new field discovery is found and well penetrations are drilled into the formation. Oil or gas is produced using the pent-up energy of the fluids in the reservoir rock (generally a sandstone or carbonate (limestone, dolomite) formation. As long as you are good at finding new oil or gas and avoiding the "dry holes," the returns come quickly while the reservoir fluid pressures are high. Eventually, however, the energy (usually thought of as reservoir pressure) is depleted and the wells cease to flow their fluids. This requires a stage called "artificial lift" wherein fluids are pushed or lifted to the surface and production can be prolonged. Eventually, the pore pressures are so thoroughly depleted and move so slowly within the formation to the wellbore that the wells produce uneconomic volumes. At this point, as in the case of oil reservoirs, considerable amounts of the oil are left in place, with sometimes as much as 80-90% still "trapped" in the pore spaces of the rock.

Secondary Phase of Production

The field may be abandoned after depleting the fluid pressures or it can be converted to what is called a secondary phase of production wherein a substance (usually water) is injected to repressure the formation. New injection wells are drilled or converted from producing wells and the injected fluid sweeps oil to the remaining producing wells. This secondary phase is often very efficient and can produce an equal or greater volume of oil than was produced in the primary phase of production.

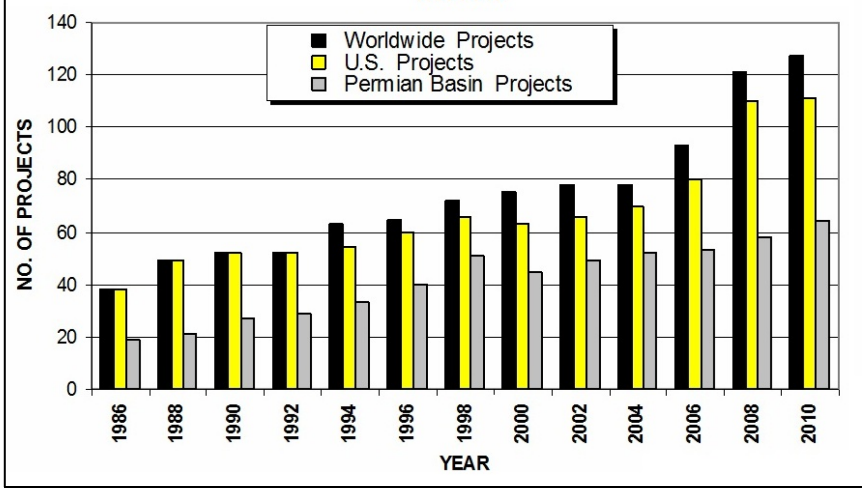
As mentioned, water is the common injectant in the secondary phase of production since water is relatively inexpensive. Normally fresh water is not used during the waterflood and this is especially true today. The water produced from the formation is recycled back into the ground again and again. Ultimately, in most reservoirs, 50-70% of the oil that was present in the field at discovery remains in the reservoir after the waterflood since it was bypassed by the water that does not mix with the oil.

Tertiary Production Phase

If a company desires to produce (access) more of the remaining oil in the reservoir, they can choose to enter a third phase (tertiary phase) of production. This will require the use of some injectant that reacts with the oil to change its properties and allow it to flow more freely within the reservoir. Heat or hot water can do that; chemicals can accomplish that as well. These techniques are commonly lumped into a category called ***enhanced*** oil recovery or EOR. One of the most proven of these methods is carbon dioxide (CO_2) flooding. Almost pure CO_2 (>95% of the overall composition) has the property of mixing with the oil to swell it, make it lighter, detach it from the rock surfaces, and causing the oil to flow more freely within the reservoir so that it can be "swept up" in the flow from injector to producer well. This technique was first tested at large scale in the 1970's in the Permian Basin of West Texas and southeastern New Mexico. The first two large-scale projects consisted of the SACROC flood in Scurry County, TX, implemented in January of 1972, and the North Crossett flood in Crane and Upton Counties, TX initiated in April, 1972. It is interesting to note that installation of these two floods was encouraged by daily production allowable[2] relief offered by the Texas Railroad Commission and special tax treatment of oil income from experimental procedures.

Over the next five to ten years, the petroleum industry was able to conclude that incremental oil could indeed be produced by the injection of CO_2 into the reservoir and the numbers of CO_2 flood projects began to grow. Figure 1 illustrates the growth of new projects and production from 1984 through the present day.

FIGURE 1
ACTIVE WW, U.S., AND PERMIAN BASIN CO2 EOR PROJECT COUNTS
1986-2010



The carbon dioxide for the first projects came from CO_2 separated from produced natural gas processed and sold in the south region of the Permian Basin (Figure 2). Later, however, companies became aware that naturally occurring source fields with relatively pure CO_2 could offer large quantities of CO_2 and three source fields were developed - Sheep Mountain in south central Colorado, Bravo Dome in northeastern New Mexico, and McElmo Dome in southwestern Colorado. Pipelines were constructed in the early 1980's to connect the CO_2 source fields with the Permian Basin oil fields. The new supply of CO_2 led to a growth of projects through the early 80's and expansion to other regions of the U.S.

FIGURE 2
Active U.S. CO_2 Pipeline and Injection Site Infrastructure

[2] During the 1930's through 1972, the Texas Railroad Commission limited statewide oil production by granting production permits to well operators for a certain number of days per month.

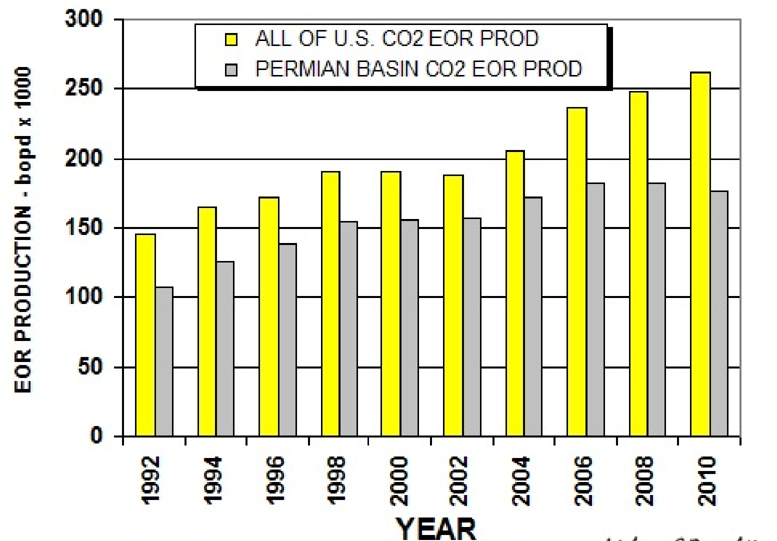
The oil price crash of 1986 resulted in a drop of oil prices into single digits (in units of $/bbl) in many regions. The economics of flooding for oil was crippled; capital for new projects was nonexistent. But, due to the long term nature of the advanced recovery subindustry and as demonstrated in Figure 1, the EOR projects survived the crash with fairly minor long-term effects and the growth curve resumed until the next price crash in 1998.

CURRENT AND PROJECTED CO_2 EOR ACTIVITY IN THE U.S. & PERMIAN BASIN

The most recent decade has once again seen a flourish of new CO_2 floods. Today, 111 floods are underway in the U.S. with 64 of those in the Permian Basin. The numbers have doubled since the economically stressful days of 1998 (as noted in the impact of flood numbers in the year 2000 in Figure 1). New CO_2 pipelines are being constructed in the Gulf Coastal, Mid-continental regions and in the Rockies promising to grow the flooding activity in all three of those regions dramatically. The Permian Basin is effectively sold out of their daily CO_2 volumes and, as a result, growth there has slowed to a crawl and CO_2 prices have climbed to record highs, now approaching half the value of natural gas.

The aggregate production from CO_2 EOR has grown to about 18% of the Permian Basin's total oil production (Figure 3) or 180,000 out of the 1,000,000 barrels of oil per day (bopd). This figure also equates to approximately 5% of the daily U.S. oil production. The oil industry rightfully brags about discovering a new billion barrel oil field. Such new field finds are very rare today in the U.S. It is interesting to note that the billionth U.S. CO_2 EOR barrel was produced in 2005. The CO_2 bought and sold in the U.S. every day now totals 3.1 billion cubic feet or about 65,000,000 tons per year. For a reference point, this equates to the CO_2 capture volumes from 20 Texas Clean Energy Projects (each being 400 MW in size) (Ref 1).

FIGURE 3
U.S. AND PERMIAN BASIN CO_2 EOR PRODUCTION



* Ref: O&GJ Biennial EOR Editions & UTPB Petr Industry Alliance

U.S. Project Planning

To date, the development of carbon dioxide flooding has clearly favored the Permian Basin. In addition to the extensive pipeline infrastructure and the nearby CO_2 source fields, it has a large number of large and mature oil fields which have been shown to be amenable to CO_2 injection. However, things are changing rapidly now with considerable growth in CO_2 EOR occurring in the Gulf Coast, the Rockies, Oklahoma, and in Michigan. EOR companies are currently planning new CO_2 projects in each of those regions.

Denbury Resources has averaged two new startups per year in the Gulf Coast region for the last decade. Wyoming and Oklahoma are two other areas with intense CO_2 activity. With the advent of new sources of CO_2 and infrastructure build-out, other regions of the U.S. will develop as well. An informal survey by the author of the "backlog" of projects in planning is estimated at more than 20.

Long-Term Nature of the Industry

CO_2 EOR is composed of long-lived projects. While fluctuations of oil prices have an effect of temporarily decreasing the pace of project starts, the steady baseline growth represents a refreshing exception to the otherwise frustrating cyclicity of gas and oil drilling/exploration. To prove the point, both of the first two floods (SACROC and Crossett) are still in operation today and are producing nearly one million barrels per year. After almost 40 years of operation under CO_2 injection, these floods are still purchasing approximately 300 million cubic feet per day (over six million tons per year) of CO_2. The long-term nature of the floods continues to generate enormous economic benefits, providing local, state and federal taxes as well as long-term employment and energy production for the area and nation. These barrels will be produced from reservoirs already developed, most with established surface footprints and should represent another 15% of the original oil in place within the reservoirs. This can occur with CO_2 molecules from captured emissions or from naturally pure underground CO_2 traps. Without the advent of CO_2 flooding, the barrels would have been lost, i.e. left in the reservoir upon abandonment of the waterfloods.

Much of the impetus for the planning of new CO_2 floods results from a broader recognition of the technical success and economic viability of the CO_2 EOR process. The current oil price is a huge factor as well. The last factor relates to the maturity of the North American oilfields and the (secondary) waterfloods of which most are very mature with many beginning over 50 years ago in the 1950's.

Technological advancements are another major reason for the continued growth and development of CO_2 flooding. Three-D seismic, geomodeling and subsurface surveillance techniques have had a measurable impact on delineating heretofore uncharacterized features of many reservoirs. The ability to characterize and model the reservoir and to simulate the effects of CO_2 injection have clearly reduced the risk of a flood (economic) failure and improved the efficiencies in flooding.

SUPPLY AND DEMAND OF CO_2

For the first 25 years of the CO_2 EOR business, the underground natural CO_2 source fields were of ample size to provide the CO_2 needed for EOR. Pipelines had also been built of sufficient throughput capacity to supply the EOR project needs. Today the situation has changed. Depletion of the source fields and/or size limitations of the pipelines are now constricting EOR growth. But costs of new CO_2 supplies are also a factor. With some notable exceptions like natural gas by-product CO_2, the Dakota Gasification Project in North Dakota, and the Coffeyville (petroleum coke) Gasification project in southern Kansas, the new age of anthropogenic supplies of CO_2 has just not advanced to meet the supply shortages. The CO_2 cost gap between industrial CO_2 and the pure, natural CO_2 remains a barrier. Increasing values of CO_2 due to the growing demand and constricted or declining natural sources is helping change the landscape but the gap persists.

As mentioned earlier, the Permian Basin clearly has dominated the CO_2 EOR development picture of the past. The ample pure underground sources and robust infrastructure was a big part of that. Growth continued until running up against the supply barriers. Two other regions, the Gulf Coast and Wyoming, are now “exploding” with new oil development growth today through EOR. As a case in point, the Mississippi growth is a classic example of production growth where CO_2 supply was not a limiting factor. The Jackson Dome natural source field near Jackson, MS has been developed in very rapid fashion to provide the necessary new CO_2 to fuel the expansion of EOR. The State of Wyoming (i.e., ExxonMobil) has a similar story with their LaBarge field and very recent expansion of capture capacity of the Shute Creek plant north of Green River, WY. New announcements of the DKRW coal gasification plant near Medicine Bow, WY and the aforementioned Coffeyville plant in Kansas will further accelerate activity in those regions.

The above case histories of CO_2 EOR development underscore the interrelationship of CO_2 supply and demand. The advances in CO_2 EOR technology suggest that, when ample affordable supplies of CO_2 are available, the demand will grow the fill the void.

THE EFFECTIVENESS OF CO_2 STORAGE IN AN EOR PROJECT

Just as there are certain places where oil, gas and natural CO_2 has been geologically trapped and stored in the subsurface, there will be underground reservoirs where CO_2 captured from power plants and industrial facilities can be safely and securely stored. Oil and the natural gases[3] can be shown to be permanently trapped in many subsurface environments. Such will be the case for CO_2 and, in fact, as a naturally occurring molecule, CO_2 can be shown to be permanently trapped in many geologic situations. However, not every subsurface situation will provide the needed security. Effective storage sites will fall in the former case and lie within the geologic regimes that have certain attributes that assure the CO_2 will stay in the subsurface and not migrate toward the surface due to its buoyancy.

Some excellent work has been accomplished in Canada on this subject and is used as the baseline herein. The criteria for secure storage involve a number of critical site attributes as shown in Reference 2 and Table 1 below.

Table 1 – Basin Scale Criteria for Storage

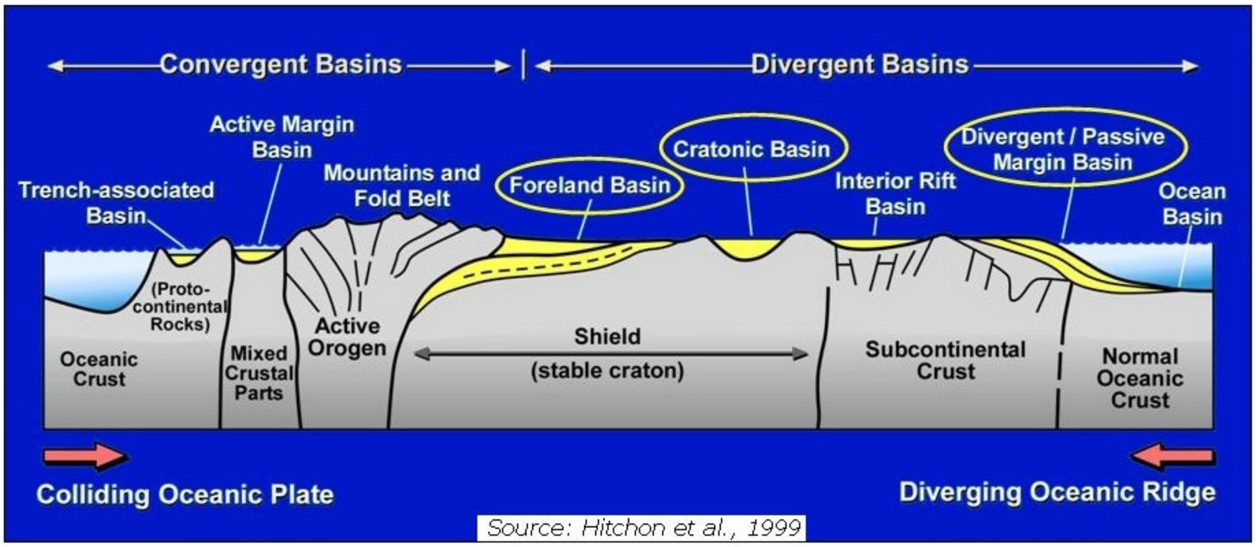
Adequate Depth (>1000 meters)
Strong Confining Seals
Minimally faulted, fractured or folded
Strongly Harmonious Sedimentary Sequences
– adequate volume and permeability for storage
No Significant Diagenesis

Certain geological basin types have a preponderance of these characteristics, the best of which are the cratonic, foreland and divergent/passive margin basins (see Figure 4). Examples of the first are the Michigan, Williston and Permian Basins of North America. Examples of the second type are the foreland areas east of the Rocky Mountains. The Gulf Coastal sediments are one example of the divergent/passive margin basins.

[3] Natural gases as defined here include those generated deep within the crust such as methane, CO_2, and nitrogen

Figure 4

Cross Sectional Representation of Various Types of Sedimentary Basins



With selection of good sites in these types of basins and operated in a manner consistent with the widely applied best practices in the oil and gas industry, the public can have confidence that >90-95% of the CO_2 that is delivered to the EOR facility will be contained within the reservoir and its closed-loop, recycle systems and thus kept out of the atmosphere.

MONITORING CO_2 WITHIN THE RESERVOIR: EXISTING PRACTICES

Perhaps because CO_2 EOR has grown at a rapid pace, the scale of current CO_2 injection activity is most often understated. The current injection volumes in just the U.S. alone have recently exceeded 3 billion cubic feet per day or 65 million tons per year. Approximately 3/4^{ths} of this volume comes from nearly pure underground sources with the remainder coming from captured emission streams from dilute underground sources or other industrial sources (refs 3, 4).

Since the average price of this CO_2 has risen to well above $25/ton in some maturing areas, one can imagine that the injecting companies are quite serious about knowing that it is contained and working within their oil reservoirs. In fact, the term reservoir surveillance (aka reservoir management) was coined last century to capture the nature of this monitoring technology. Short courses are taught on the subject, some companies make their business out of servicing the monitoring needs of the industry and specialized tools have been developed to facilitate the surveillance of the injected fluid.

The particular tools most commonly used are shown Table 2 below. Not all of these are employed at every project since the particular attributes of a reservoir need to be considered to select which tools to use. This is also not intended to be an all-inclusive list as many companies have their own proprietary tools and diagnostics to surveil their CO_2 floods but it does represent the types of techniques often utilized.

Table 2: Reservoir Surveillance Tools
Commonly Used in CO_2 EOR

Cement Integrity (Bond) Logs
Injection Logs
Pattern and Material Balance Techniques
Tracer Injection/logging
Step Rate Testing
Fluid Levels and Reservoir Pressure

One of the key practices referred to above as “material or mass balance” deserves special mention. This practice refers to examining reservoir conditions (e.g., temperature, pressures) measured over the injection and production time intervals and balancing the reservoir volumetrics of injection with the equivalent reservoir volumes of fluids produced. The term mass balancing is often avoided owed to the changes in state of many of the compounds involved, in particular, CO_2 and the so-called liquid natural gases (LNGs). If the waterflooding and/or CO_2 flooding history of experience is a true marker, both the lateral and vertical risk profiles of containment will likely be demonstrated during the initial course of injection. And, during the operational phase, the material balance surveillance calculations and measurements will demonstrate decreasing risk profiles and continue to rapidly decrease in the post-closure period as the dynamics of injection/migration cease. Such may not be the case in unproven structural or stratigraphic trapping conditions (e.g., deep saline formations, adsorption traps). Thus, the duration of post-closure monitoring in sites with unproven stratigraphic or structural subsurface trapping, in contrast to proven subsurface trapping conditions, will be necessarily long, i.e., movements of fluids to the surface can be long-term.

MONITORING CO_2 WITHIN THE RESERVOIR: INCREMENTAL REQUIREMENTS FOR CCUS

Figure 5 contrasts the common attributes and needs of CO_2 EOR and carbon capture, utilization and geologic storage (CCUS) with regard to reservoir surveillance/monitoring. As shown, the needs are the same excepting the final item whereupon CO_2 EOR has traditionally not had the post-abandonment worry of injectant permanence. It is fair to say that the EOR industry has not worried about storage permanence with the dual beliefs that 1) the natural containment of the oil/ gas trap is sufficient proof of the permanence and 2) the regulatory policies of well abandonment plugging procedures have withstood the test of time. However, many within the industry have come to expect that incremental operational and/or post-closure monitoring will be required beyond the conventional practices observed today in CO_2 EOR. The complexity and cost of any additional monitoring will play a large role in whether the EOR industry players opt to participate in CCUS. If the new approach involves changing the regulatory agency from the state oil and gas regulatory agencies, charged with balancing all the factors of resource

Figure 5

CO_2 FLOOD SURVEILLANCE vs. CCUS MONITORING, MEASUREMENT AND VERIFICATION (MMV)

NEEDS

	FLOODING	MMV
1)	INJECTION IN ZONE	INJECTION IN ZONE
2)	FLOW PATHS	FLOW PATHS
3)	PRESSURE CONTAINMENT	PRESSURE CONTAINMENT
4)	WELLBORE INTEGRITY	WELLBORE INTEGRITY
5)	SWEEP EFFICIENCY	N/A
6)	N/A	LONG TERM STORAGE

conservation, HSE and resource development, the existing injection companies will likely opt out and moving forward with capture and injection projects will be jeopardized.

Some have referred to the CCUS monitoring requirement as an “overlay of additional monitoring” beyond normal reservoir surveillance practices. Techniques to assure long term security can involve such things as monitoring wells left in place after injection and production ceases. To an oil producing company, this will represent an incremental cost without a commensurate revenue stream. Balancing the cost and requirements of post closure monitoring with site attributes and pre-closure performance will be critical in defining the duration of post closure monitoring required. Many have felt that a new “post closure” industry may evolve to address the longer term environmental concerns.

For the above reasons, a “one-size-fits-all” requirement for operational monitoring and, especially, post-closure monitoring will not serve to expedite application of CCUS in lower risk reservoirs. Most normal oil and gas structure or stratigraphic closure traps provide storage permanence. Some do not and can be shown to be imperfectly sealed. For example, some oil fields were found by oil seeps to the surface. Another situation suggests careful attention should be given to production history during primary production pressure depletion in lightly consolidated sediments as this may create potential migration paths.

Experienced, competent and impartial regulators are the key to the establishing the permits for CCUS. Knowing the issues of local geology are of paramount importance and the body of knowledge that will serve those decisions has historically rested with the oil and gas regulating agencies in oil and gas producing states. Those are also the regulators that have weighed the resource conservation, HSE and resource development factors mentioned above. These agencies are sometimes perceived to be instruments of the industry and, in some cases, their credibility as storage regulators will be challenged. On the other hand, they are chartered by the states to weigh environmental, HSE, resource development and mineral/storage rights trespass. The states without an oil and gas regulating agency will have to rely, perhaps, on a Federal agency like the Environmental Protection Agency or the US Geological Survey. These national agencies do not have the exposure to state laws governing trespass, unitization and the like and will be at a disadvantage for CCS progress but it can also be said that most of those states are also likely not to have the low-risk sites for CCS since subsurface conditions have not demonstrated trapping capability in significant measure.

CO_2 RETENTION, CO_2 ‘LOSSES’ DURING EOR: THE METRICS AND EXPERIENCE BASE

CO_2 Purchases and Recycle Volumes

For the purposes of this report, it is both important and useful to see actual project examples of the relationships of new (purchased) and recycled CO_2 volumes. A case illustrating the percentage of new (purchased) versus recycle injected volumes on an example project is shown in Figure 6. In this case the de minimus losses (to be discussed later in the section) are assumed to be zero.

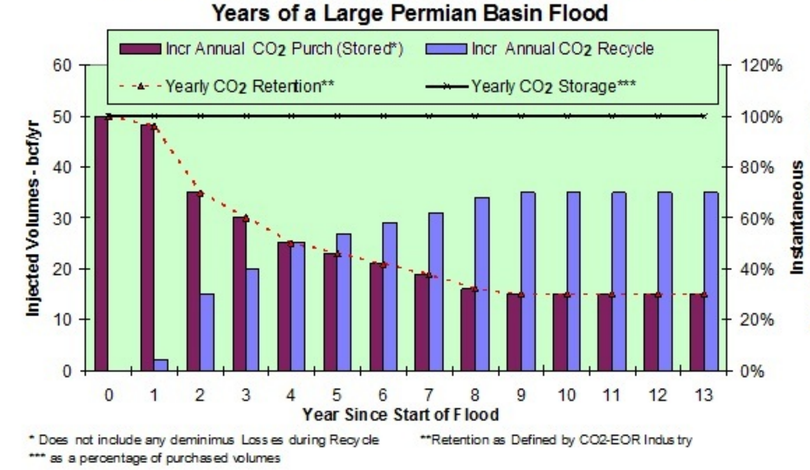


Figure 6
Example CO_2 Purchase Vs. Recycle Volumes During the Early Years of a Large Permian Basin Flood

As mentioned earlier in the report, the EOR project recycled CO_2 is captured, separated from other products (processed), dried, re-compressed and reinjected. As the project matures, the purchased volumes taper off and recycle volumes increase over time. What that means of course is that CO_2 is being stored in the formation all the while (think of this as trapped in solution within the oil in dead-end pores and channels and CO_2 stuck to the rock surfaces).

At this maturing stage of the project, CO_2 contact with oil in the reservoir gets less frequent, less oil is liberated and the oil volumes recede to uneconomic volumes. During this process the oil company will cease buying new CO_2 and allocate the recycled CO_2 to the remaining economic areas within the project. Once all areas drop below economic thresholds, the project needs to be plugged and abandoned. At this point, the CO_2 that has been purchased remains within the formation. Much has been said about CO_2 reuse on new projects. It is fair to say that actual practical attempts at reusing recycled CO_2 in new, nearby projects have either been economically unsuccessful or are requiring continuing CO_2 purchases at the recycling field.

As we transition to the world of CCS and CCUS, giving credit to the CO_2 capturing company for the on-going retention (sequestered) volumes as injection proceeds is of paramount importance. Should the capturing company have to wait until the pure injection or EOR project is complete and plugged out in order to receive the credit, they will likely not undertake the expense of capture in the first place. Thus, in order to have capture projects proceed, real time recognition of capture and storage will be necessary.

CO_2 Retention

CO_2 has been shown to be the most expensive operational cost of an EOR project so it follows that the mass/volume is carefully measured and surveilled both at the surface and within the reservoir. The mechanics of handling the mixture of produced fluids (oil, brine {very salty water}, and CO_2) brought to the surface allows the CO_2 to be separated back out from the oil. All large EOR projects are designed as closed loop systems so the produced CO_2 is then recompressed and combined with newly purchased CO_2 and injected again downhole into the oil reservoir. The oil is transported to a refinery; the produced brine is re-injected into the oil reservoir or other suitable deep subsurface zone. This “Recycling” of the purchased CO_2 prevents it from being released to the atmosphere and provides substantial savings to the oil field operator that would otherwise have had to purchase replacement CO_2 volumes.

A large percentage of the originally injected CO_2 does not come back up with the oil because it gets trapped in the geologic formation, i.e., the CO_2 is trapped in solution within the oil in dead-end pores and channels and is “stuck” to the rock surfaces. The trapping continues as long as the CO_2 is injected.

As a result of this “incidental CO_2 sequestration” what recycled CO_2 is produced must be captured, compressed and continuously augmented with newly purchased CO_2 for EOR operations to continue. Ultimately, and because of the effective ‘closed loop’, the experience of the industry to date is that well over 90-95% of the purchased CO_2 remains securely trapped within the deep geologic formation. The sources of the “de minimus” losses are discussed in the next section.

Confusion has arisen in the past because the terms within CO_2 purchase and sale agreements between the buyers and sellers of the CO_2 are protected by confidentiality agreements. One of the protected terms is the CO_2 purchased volumes. The net effect of this has led to the widespread use of an alternative metric, the non-confidential quantity of total injected volumes (which includes the recycle volumes).

The formula pertaining to the widely accepted term of retention within the oil and gas industry is shown as follows:

CO_2 Retention (%) = ***(Total CO_2 Injected –*** *CO_2 Produced)* ***/ Total CO_2 Injected****….(1)*

Note that the denominator of the equation is total injected volumes. As discussed, the likely reason for this is the protected nature of purchased volumes but the effect has been that, when people often talk about storage, the retention metric is used. For example, one will commonly hear that 50% of the CO_2 injected is stored. What they should immediately say following that statement is that the 50% number is based on total injected volumes and not based upon the purchased volumes. Since, over the life of a project, the total injected volumes are approximately twice the purchased volumes, the CO_2 retention parameter represents a number which is roughly half of the truly important parameter of the percent of stored volumes as a fraction of the purchased volumes. The formulae for storage should be as follows:

*CO_2 Storage (%) = (****Total CO_2 Injected – CO_2 Produced*** *– CO_2 Losses) / Purchased CO_2 Injected…….(2)*

If the industry and regulators were to adopt the storage metric in (2) above, it would require disclosure of purchased volumes in addition to the bolded quantities shown in the equation. CO_2 losses would be the calculated from the difference between total CO_2 injected and CO_2 produced. Disclosure of purchased volumes can be made a part of CCUS policy in the future.

CO_2 Losses During EOR: Causes and The Experience Base

As was described in the first part of this paper, the experience of CO_2 EOR has matured to a large number of geological conditions over a forty-year period of observation. It needs to be emphasized again that the CO_2 has been purchased and is valuable to the injecting companies. Efficiency of surface operations and recognition of any CO_2 losses from the producing interval are of paramount importance. So what is the experience of the industry on where losses of CO_2 occur during the EOR process?

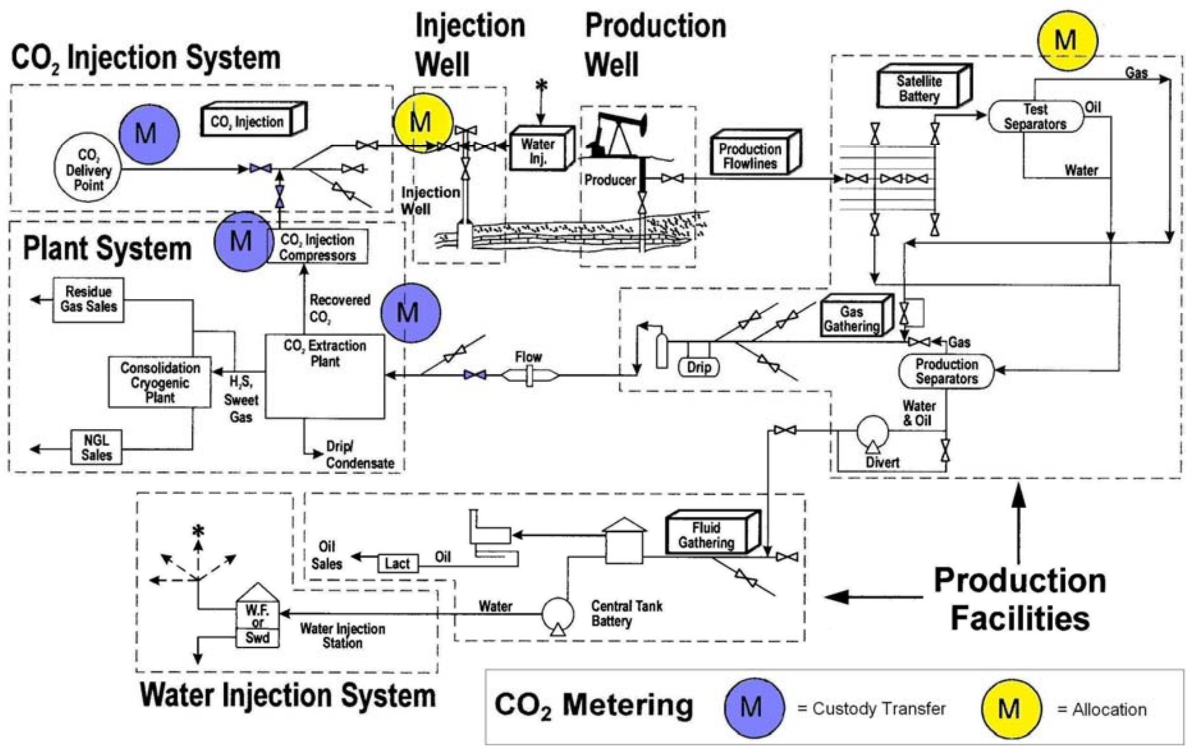
Unlike pure waste disposal, much of the CO_2 is recycled during the EOR process. Thus, during the course of bringing the CO_2 back to the surface, drying, processing and recompressing can add opportunity for small volume losses. Figure 7 provides a schematic process flow for the nominal CO_2 surface process plant.

Some companies have examined the surface plant/recycle process in some detail and characterized the process losses. They have found that the leading contributors to those losses are infrequent power outages, say, due to lightning strikes, equipment repair, or line bleedoff/blowdown. All of these create short-lived periods of time in which the CO_2 and other gaseous substances must be flared. In many of these cases, methane must be added to achieve combustion, creating another expense to the project.

The second area of volume “losses” can occur downhole within the targeted formation. When losses occur, the cause of these is almost always directly attributable to lateral migration within the target zone and inability to assure perfect lateral containment within the flooded area. For example, an adjacent (offsetting) property, producing from the same formation as being flooded, may produce some of the CO_2 that found its way through the containment ring of water injection wells. The flooding area is always kept at pressure creating a tendency for the CO_2 to migrate to the pressure sinks associated with an adjacent non-flooded portion of the field. As those nearby producing wells pump their fluids to the surface, the migrated CO_2 can be carried along resulting in a small amount of CO_2 in the casinghead gas separated at the company’s surface facility. In many cases, however, the flooding company will have worked out an arrangement with the non-flooding company to purchase their casinghead gas stream containing CO_2 and have it brought back to the flood processing facility area.

Figure 7

CO_2 EOR PROCESS FLOW



Adapted from SPE MONOGRAPH Practical Aspects of CO_2 Flooding, Figure 5.1

Vertical migration (downward or upward) can occur in unusual circumstances. This can be the result of improperly plugged wells by the previous operator. It can also occur in those situations mentioned earlier wherein lightly consolidated formations were drained of their fluid pressures, formation consolidation ensued, and relative displacements occurred between the cement sheath and formation. In most cases, the injectant, CO_2 or water, has found it way into a deeper or shallower low pressure zone just below or above the target interval. The good news is that when the material balance indicates pressures within the formation are not behaving as expected, the offending well will be identified with logging tools, the well squeezed and problem quickly resolved.

In summary, the sources of losses to the CO_2 EOR system can lay in either the surface processing realm or in the process of lateral migration to pressure sinks in adjoining (offsetting) producing properties. These conditions will vary between properties and areas; the degree of loss is usually quite insignificant (de minimus). Obviously the larger the injection (flooded area) property, the less likely it will be to lose any of the CO_2 offsite. And the more reliable and efficient the power supply and equipment at the recycle plant, the smaller the plant-related volumetric losses will be.

HOW TO MOVE FORWARD? THE URGENCY AND AREAS FOR CAUTION

The international state of affairs in greenhouse gas emissions reductions (ER) appears, at least for the moment, locked into a world of accelerating emissions. The two-decades-long worldwide effort within Kyoto to set a path for reductions does seem to have helped increase the pace of energy conversion efforts in Europe and the Americas. But, the reality of the numbers is that those are completely offset by both the energy needs of rapidly advancing standards of living in countries such as India and China and the recognition that the clean energy options are economically challenged in comparison to the hydrocarbon based fuels. Perhaps it is just the scale of the challenge but the rate of ER progress seems to have never been anything more than “crawl.”

One of the bright spots for recapturing momentum and renewing the ER emphasis is the growing recognition that there are very large uses of the emission waste gas, CO_2. Absent a carbon emissions constraint, emphasizing “utilization” of CO_2 seems appropriate. The economic challenges are still present as the CO_2 must be captured, purified and put to work but the cost challenges are less and workable options exist. Perhaps most evident is the cost gap differential between capture disposal costs and value of the CO_2. It can be noted in fact that this is already being accomplished by the CO_2 enhanced oil recovery marketplace for certain high purity off-take CO_2 streams.

Three important factors are responsible for the growing recognition of the value of CO_2 EOR in moving forward on the policy front. First is that the commodity value of oil to assist with fueling local and national economies has never been higher. Second, the worries over imports of oil have never been higher. Third is the growing recognition of the very large sinks wherein CO_2 can be utilized to produce incremental oil and accrue incidental storage. This latter awareness has just become mainstream thinking in many circles.

Several barriers exist as well. Most of the companies with the emission streams are, with some notable exceptions, ignorant of the marketable value of their CO_2 “by-product” and the subsurface opportunities. Merging the differing cultures of the power generation world with the entrepreneurial subsurface companies is no small task. Additionally, accomplishing this cultural merger has to be done while the oil and gas community has discovered new and exciting unconventional drilling opportunities that provide faster returns than the capital-intensive engineering projects of CO_2 EOR. But, In spite of the barriers, the expansion of CCUS is “teed up” and ready to gather speed. In this new world oil price environment, CO_2 EOR will indeed be growing but only at a pace dictated by the availability of affordable pure CO_2.

So how can one accelerate the growth of CCUS and EOR? Probably the most efficient and rapid way is to familiarize the emitting companies with the market that exists for the captured CO_2 ***and to incentivize its capture***. There is an alternative approach; i.e., incentivizing EOR so that the injection companies can afford to pay more for the CO_2. However, in this world of high priced energy, it is a hard sell to a public already being directly impacted (at the gas pump) and indirectly squeezed (at the grocery store) by increasing energy costs. That alternative course of action will be met with cries of corporate welfare given to an industry already burdened with image problems.

Beyond incentivizing the CO_2 capture, the storage rules need to specifically concentrate on regulating concurrent EOR and storage. In the right subsurface conditions, water and CO_2 has been stored permanently in formations not only for the history of waterflooding and CO_2 flooding but in naturally trapping situations. So to layer onerous post-closure requirements on the class of good subsurface sites will only delay action at best and defer storage progress altogether.

The good news on this front is that the regulatory movement is already occurring. Much education and progress has occurred but, unfortunately, the rules have been concentrating on the class of unproven storage sites and ones with only scarce geologic data and characterization (deep saline formations). As a result, many believe a set of national rules has been published which addresses environmental security in higher risk, unproven trapping sites. Concentrating on nature's proven trapping situations is being accomplished at the state level. There is still some "devil in the details" but the state-based reference frameworks are in place. A review of the existing and developing regulatory storage fundamentals is in order before proceeding to what could be termed the facilitating actions and details.

Storage Frameworks

The widely discussed and emerging regulatory pathways to storage of CO_2 are effectively two: *A)* Injection into deep saline formations without concurrent production of formation fluids and *B)* CO_2 enhanced oil recovery. In the first case (dubbed *Case A* herein), the waste stream of captured emissions will be injected and pressurize the formation beyond the original pressures and, generally, into formations wherein trapping of gases or other hydrocarbons has not been demonstrated by natural processes. In the U.S., this class of injection has taken on the name of Class VI injection (see UIC or the Underground Injection Control Program) and has been led by the EPA. Rules for reporting (Subpart RR[4] {Ref 5}) and monitoring (Subpart UU[5]{Ref 6}) have been published, commented upon, and posted. Interestingly, no projects appear to be moving down that pathway at present in spite of large sums of Federal funds to overcome the economic barriers such projects face. Many suggest that the long-term monitoring and liability concerns related to the fate of CO_2 in unproven traps are the two major reasons for industry pushback here. It is probably very fair to say that the experienced injection industry sees this pathway as a non-starter.

The second approach to supervising storage builds on the existing regulatory structure in place within most of the states with oil and gas production. In those situations, the public has familiarity with injection projects, has a qualified state regulatory agency in place and decades of experience from which regulations have evolved. With an overlay of monitoring that is tunable to the site characteristics and commensurate with the perceived risks of long-term storage along with the revenues associated with the commoditization of CO_2 for EOR and resulting revenue stream, the impasse can be sidestepped. What must be preserved is participation of the qualified injection companies. An opt-in to storage while performing EOR using anthropogenic CO_2 is the single highest objective.

This second approach (called *Case B* herein) is currently viewed in the context of CO_2 EOR with incidental storage. As was shown in an earlier section, 90-95% or more of the purchased CO_2 is stored so certification of that storage is paramount to the regulatory process. To explain, it is imperative that the capturing company be given storage certification as his project proceeds. The notion that an EOR project, with its incidental on-going storage, has to wait until the end of EOR to receive credit[6] for the storage is unacceptable to the capturing company.

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[4] This rule requires reporting of greenhouse gases (GHGs) from facilities that inject carbon dioxide underground for geologic sequestration. Geologic sequestration (GS) is the long-term containment of carbon dioxide in subsurface geologic formations.

[5] This rule requires reporting of greenhouse gases (GHGs) from facilities that inject carbon dioxide underground for the purposes of enhanced oil and gas recovery or any other purpose other than geologic sequestration. Facilities that report under subpart RR for a well or group of wells are not required to report under subpart UU for that well or group of wells.

[6] Credit is defined herein to its broadest of meanings and does not have to entail monetary value. It can be as simple as obtaining the certification by the empowered regulator that storage is occurring.

Incidental storage during BAU EOR occurs today. What is sought is an "opt-in" by the injection companies when using anthropogenic CO_2. This opt-in feature of *Case B* with its CO_2 EOR under the Class II UIC umbrella is more legally complex than first meets the eye. Current regulators at both the national and state levels have, to date, overlooked this complexity. Figure 8 attempts to characterize the various storage options.

A normal *Case B* project can be done with just mineral rights and many believe will not require control of storage rights. This concept of incidental storage without storage rights should hold up in court unless the EOR operator receives value for storage. For example, in a waterflood, incidental water storage occurs and the U.S. has almost a century of legal precedent for this.

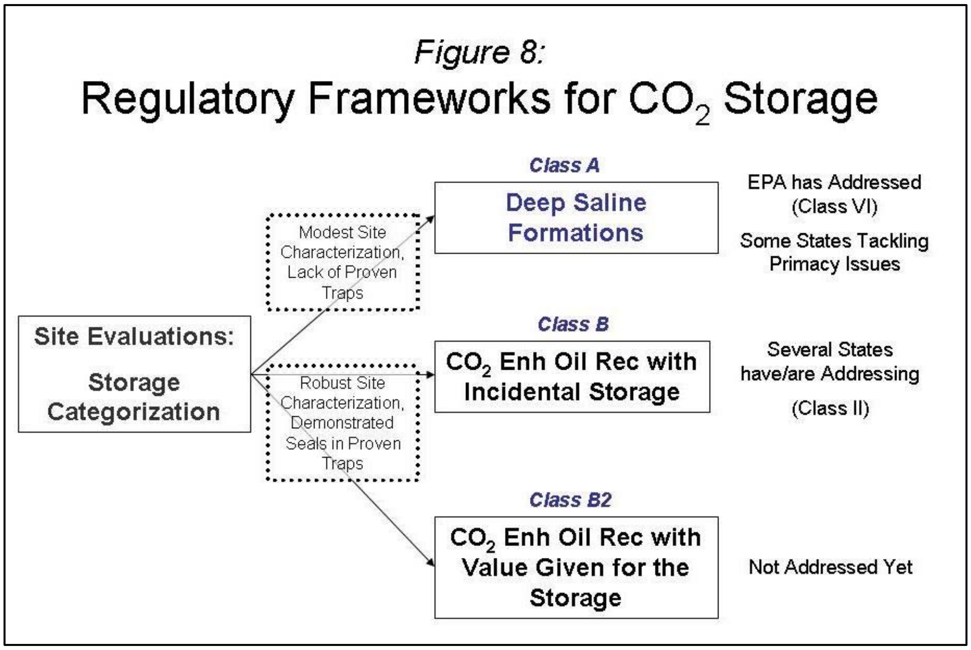

Figure 8:
Regulatory Frameworks for CO_2 Storage

Case A (deep saline) is effectively a waste injection project without the requirement of control of mineral rights. It cannot have production of minerals lest the injector acquire control (e.g., lease) of the produced minerals and compensate the mineral owner.

There is another case of importance here that has been effectively overlooked to date by all parties (regulators/oil companies/academics/NGOs). This case (called B_2 herein) would occur if the EOR operator opts to receive value for storage. In this case, both storage and mineral rights need to be controlled and payments made to each of mineral and storage rights owners. We could call this storage with oil production and contrast it to *Case B* which would be production with incidental storage. One might argue this 'dual rights' case can be avoided and most injection companies might choose to do exactly that with the approach of *Case B* while receiving a non-monetary certification of storage from the state or national regulatory bodies.

Now, to be very clear, *Case* B_2 does not automatically involve injection pressures beyond normal EOR reservoir pressures (i.e., the Class IIB exercise that the multi-stakeholder group addressed (Ref 7). It could involve higher pressures, of course, but does not require it. But it is a separate approach from *Case B* because of the need for storage rights. It is more akin to Class II than to Class VI since it would be accomplished in oil reservoirs. Facilitating opt-in by the injection companies to either or both *Case B* and *Case* B_2 should be of highest priority to move ER forward.

Recommended Actions

Providing the technical dialogue and basis for and facilitation of ER through the use of CO_2 EOR has been the subject of this report. The important steps for accomplishing those objectives are two:

1) Incentivizing capture through cleverly devised tax credits or other mechanisms to close

the gap between capture costs and the value of CO_2 for EOR and

2) Providing a regulatory structure which encourages injection companies to opt-in to storage while using anthropogenic CO_2 for EOR.

Several incentives beyond the loan guarantees and grants currently being employed by the U.S. Department of Energy are already being discussed. Tax credits are clearly one favored approach with a history of success in the past.

The underground storage sites of first priority and of lowest risk are those that have demonstrated oil and gas (geological) trapping capability. It will be noted by some that not all oil reservoirs are perfect seals for gases but it is likely very safe to say that in the U.S. greater than 99% are without surface seeps or migration of deep-sourced hydrocarbons into the underground sources of drinking water (USDWs) or to the surface. With the security of storage in oil and gas reservoirs in mind, the existing regulatory structures in place within the States under Class II UIC rules need to be preserved. This will be familiar ground to the qualified injection companies and will encourage an opt-in to storage. A storage permitting "front-end" can eliminate the occasional and naturally leaky traps for storage. A fit-for-purpose, site variable and tunable monitoring overlay to those rules is appropriate to fill the reporting void of demonstrating the permanence of storage. Most companies perform those tasks already but are not yet uniformly required to report results to the regulator.

The storage of CO_2 during EOR can occur both with and without the need for acquisition of storage rights. A third option (beyond Deep Saline Formations and BAU CO_2 EOR with incidental storage) called *Case B_2* herein needs to be addressed wherein rules for reporting of storage revenues and tax treatment are called out and defined within the states.

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