Testimony

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PRINCIPLES OF CO_2 FLOODING, NEW TECHNOLOGIES AND NEW TARGETS FOR ENERGY SECURITY AND THE ENVIRONMENT

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BACKGROUND ON THE U.S. AND PERMIAN BASIN OIL INDUSTRY AND THE NEW EXCITEMENT IN THE CO_2 FLOODING SUBINDUSTRY

The oil and gas industry is generally portrayed as dominated by drilling for new oil and 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 concentrating on getting more oil from a given discovery (field). We tend to brand them as production companies where engineering skills are put to test in trying to recover more and more oil from a "reluctant" reservoir. The rewards come to these companies slower and, in a fast paced world seeking immediate gratification; most companies opt for the exploration path to provide more immediate returns for their shareholders.

It is useful background to examine oil and gas production in a framework the industry has come to call the phases of production.

A. Primary Production

The first is the primary 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 sandstone or carbonate (limestone, dolomite) reservoir. 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 expended and the wells cease to flow their fluids. At this point, in the case of oil reservoirs, considerable amounts of the oil are left in place.

B. Secondary Phase of Production

The field may be abandoned after depleting the pressures or it can be converted to what we like to call 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 that 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, more than half of the oil that was present in the field at discovery remains in the reservoir since it was bypassed by the water that does not mix with the oil.

C. Tertiary Phase

If there is a third phase of production, it will require some injectant that reacts with the oil to change its properties and allow it to flow more freely within the reservoir. 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 best of these methods is carbon dioxide (CO_2)

flooding. CO_2 has the property of mixing with the oil to 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. Compared to the other methods of production, this technique is relatively new and was first tested at large scale in the Permian Basin of West Texas and southeastern New Mexico. The first two 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[1] 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 observe 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.

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. Later, however, companies became aware that 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 fields (Figure 2). 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.

The oil price crash of 1986 resulted in a drop of oil prices into single digits in many regions. The economics of flooding for oil was crippled; capital for new projects was nonexistent. But curiously, as demonstrated in Figure 1, the industry survived the crash with fairly minor long term effects and resumed its growth curve until the next price crash in 1998.

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

The 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 (see Figure 1). New CO_2 pipelines are being constructed in the Gulf Coastal region and in the Rockies promising to grow the flooding activity in both 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.

The aggregate production from CO_2 EOR has grown to about 18% of the Permian Basin's 180,000 (see Figure 3) out of the 900,000 barrels of oil per day (bpd) or approximately 5% of the daily U.S. oil production. The oil industry rightfully brags about finding a billion barrel oil field. Such discoveries are very rare and non-existent today in the U.S. It is interesting to note that the billionth 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 tons per year.

[1] 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.

LONG TERM NATURE OF THE INDUSTRY

What may be evident is that the CO_2 flood industry is a long-lived industry. While fluctuation of oil prices have a de-accelerating effect, the steady baseline growth represents a refreshing exception to the otherwise frustrating cyclicity of gas and oil drilling/production. Both of the first two floods (SACROC and Crossett) are still in operation today and are producing nearly one million barrels per year today. 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 power, provide local, state and federal taxes as well as employment and energy production for the area and nation. These barrels will be produced from reservoirs already developed and should represent about 15% of the original oil in place within the reservoirs. Without the advent of CO_2 flooding, the barrels would have been lost, i.e. left in the reservoir upon abandonment of the waterfloods.

PROJECT PLANNING UNDERWAY WITHIN THE PERMIAN BASIN

Many Permian Basin companies are currently planning new CO_2 projects. Denbury Resources has averaged two new startups per year in the Gulf Coast region for the last decade. Wyoming is another area with intense CO_2 activity. My "backlog" of projects in planning is estimated at more than 20.

Much of the impetus for planning 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 oilfields and secondary waterfloods of which many began in the 1950's.

Technological advancements are another major reason for the development of CO_2 flooding. Three-D seismic techniques have had a large impact on delineating heretofore unknown features of the reservoir. The ability to characterize and model the reservoir and in simulating the effects of CO_2 injection have clearly reduced the risk of a flood (economic) failure.

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 fields which have been shown to be amenable to CO_2 injection

CO_2 SUPPLY AND DEMAND WITHIN THE PERMIAN BASIN

A. Demand for CO_2

Demand for CO_2 stems from the oilfield opportunities and the ability to reap financial rewards from the oil produced. Many believe that the long term demand for oil has never been greater except in times of imminent war. Additionally, technology has paved the path for moving a field into a new phase of production; such undertakings are considered both viable and desirable. But matching demand with a supply of CO_2 can be expensive and challenging. Historically it was done within an integrated oil company who recognized the oilfield upsides and was willing and able to develop the CO_2 source and connect the two with a pipeline. Today, with the departure of the oil majors, this connection must be accomplished between several corporate entities, each of which knows very little about the business of the others. This is especially true for the industrial sources of CO_2 where we think the large CO_2 supplies for tomorrow must come.

B. New Supplies of CO_2

A new report in preparation by the MIT Energy Institute[2] has examined the economics of CO_2 supplies coming from the fossil fuel power plants and concludes that a "gap" exists between the value of the CO_2 and the costs of capture. Perhaps technology can close that gap but the first few demonstration plants are multi-billion dollar investments and appear to be outside the risk portfolios of companies capable of making those investments.

Alternative sources are smaller but their economics are better. CO_2 value is a function of purity and pressure; some industrial sources can capture CO_2 for the value received. But what is more apparent every day, this all takes time and the cultures of the surface and subsurface industries are so different that barriers constantly impede the progress.

C. Supply/Demand Balance

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 needs. Today the situation has changed. Either depletion of the source fields or limitations of the pipeline are now constricting EOR growth. Cost of capture of industrial CO_2 has not advanced to close the gap between the value of the CO_2 and the cost of capture.

NEW U.S. DEVELOPMENTS OUTSIDE OF THE PERMIAN BASIN

While the Permian Basin clearly dominates the CO_2 EOR development picture today, it is important to note that the Gulf Coast and Wyoming are "exploding" with new growth In fact, 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. Wyoming has a similar story with their LaBarge field and Shute Creek plant.

RESIDUAL OIL ZONES DEVELOPMENTS WITHIN THE PERMIAN BASIN

A new revolution is underway in the CO_2 EOR industry. The oil industry is undergoing a significant shift in the way it calculates resources. New sources of oil are being recovered today using techniques such as CO_2 EOR in intervals known as Residual Oil Zones (ROZs). Furthermore, these intervals appear to be very abundant.

The traditional phases of production, or Ternary view of oil extraction, have often been characterized by three phases. As shown in Figure 4, the bottom of the resource triangle (primary) represents production coming from conventional reservoirs where pent-up energy within the pore fluids is used to produce the oil (or gas). As mentioned earlier, the pressures in these conventional reservoirs eventually are depleted as the fluids are produced and the fluids no longer flow to the producing wells at a commercial rate. Some formations (a subset of the primary produced ones) are amenable to injection of a fluid to re-pressurize and sweep the oil from newly drilled injection wells to the producer wells. This is the second tier shown in Figure 4. Water is usually the chosen fluid

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[2] MIT Energy Institute, July 23, 2010, Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Sequestration, 196 pgs.

for injection since it is relatively cheap and widely available. The oil and gas industry has had a long history developing best practices for optimizing waterflood oil recovery.

A lot of oil will remain in a reservoir even after the waterflooding phase. A common metric for the Permian Basin of West Texas, the largest oil and gas reserve in the US, is that primary processes will get about 15 percent of the original oil in place (OOIP) in the reservoir and secondary processes will get another 20–30 percent. Astonishingly, more than half of the original OOIP is left behind.

The next phase of resource recovery (tertiary) goes after the oil left in place and this is where the aforementioned EOR techniques are used. It is a more expensive process than waterflooding so fewer reservoirs make it to this stage and oil production here has been important but relatively small when compared to both primary and waterflood applications.

EOR typically aims for the oil bypassed during waterflooding. When CO_2 contacts the oil, it enters into solution with the oil. This alters the density and viscosity of the oil, expanding it, and changes the oil's surface tension with the rock. EOR using CO_2 is so effective at loosening and displacing oil that the process often leaves less than 10 percent of the OOIP behind. The engineering challenge to EOR using CO_2 revolves around the ability to contact large portions of the oil reservoir. To gauge success, engineers use a metric called "volumetric sweep efficiency." In the Permian Basin, where the techniques have been polished, CO_2 has been used in EOR processes to obtain an additional 15–20 percent of the OOIP.

A. ROZ Targets

Residual Oil Zones that are not man-made, but created by natural waterfloods in reservoirs, are being looked at as possible commercial targets for oil production today. Natural causes, such as ancient tectonic activity, can cause oil to move around in basins and water can encroach into a former trap. Industry is now looking at how much oil is left behind in naturally swept reservoirs and finding that these natural waterfloods can leave behind levels of residual oil similar to those left behind by manmade waterfloods. These ROZ targets can be very large and open a whole new resource for development.

Today, nine CO_2 EOR projects have targeted ROZs in the Permian Basin. Most notable among these are three projects being developed by Hess Corporation. The first two were Hess pilot projects designed to deepen wells into the ROZ to evaluate the technical and commercial feasibility of a 250-foot thick ROZ. The ROZ resource at the field is given nearly one billion barrels of oil in place and the results from the two pilots have led to a phased and full field project designed to recover 200+ million barrels of oil. Stage 1 of the full field deployment is two years old and budget approvals are being put in place to expand into Stage 2. Time will tell what the total recovery figures will be, but the current 29 patterns (injection wells) are already responsible for over 5,000 barrels of oil per day with rapidly upward trending production. The oil being produced in these wells could not have been produced except by EOR techniques since the target oil is the residual oil left behind when a natural waterflood swept out the originally entrapped oil sometime in the geological past.

B. Quaternary View

The new ("quaternary") view of oil production (Figures 4 and 5) are the new ways to visualize the ROZ opportunity. It can be called the fourth phase of oil resource production as in the Hess project or, alternatively, can offer production possibilities in swept reservoirs where primary or secondary production could not be obtained. How much oil is there to recover via EOR that would not otherwise be part of the recoverable reserves of a Nation? On-going Permian Basin studies suggest that these quaternary phase producible resources are enormous—perhaps as large a future production figure as the cumulative production of oil from this basin to date (30 billion barrels). A proposal to more closely examine the sizes of this resource in the Permian Basin and extend the methodology to two other U.S. Basins is awaiting approvals at DOE.

SUMMARY

The technological innovations sweeping the world are also evident in the oil and gas industry. One of these developments is carbon dioxide flooding where oil that would be abandoned in existing fields is being produced. CO_2 EOR was shown to grow during times of $20 per barrel oil and is clearly demonstrating all the symptoms of rapid growth and expansion. Formerly led by the Permian Basin, new CO_2 floods are becoming commonplace. In the U.S. and Permian Basin today, the percentage of production attributable to CO_2 injection is 5% and 18% of total production, respectively. The numbers are capable of growing rapidly.

CO_2 EOR utilizes an injectant that is considered by many to be an air emissions issue. When pressured and purified, it becomes a valuable commodity that can produce oil and, when its work is done, effectively all of it can remain stored in the subsurface. CO_2 EOR becomes both a mechanism for oil production and an environmental tool for emission reductions.

Historically, CO_2 EOR has been cast in a framework where it is insignificant in terms of the emission streams that are to be captured. However, the truth is that it can provide an enormous "demand pull" for the needed CO_2 supplies. Additionally, the emergence of residual oil zones as viable EOR targets changes the dialogue. And, maybe best of all, it pushes the public discussion from waste disposal (sequestration) to resource extraction and energy security.

FIGURE 1: **Number of CO_2 EOR Projects (Worldwide, U.S. and Permian Basin)**

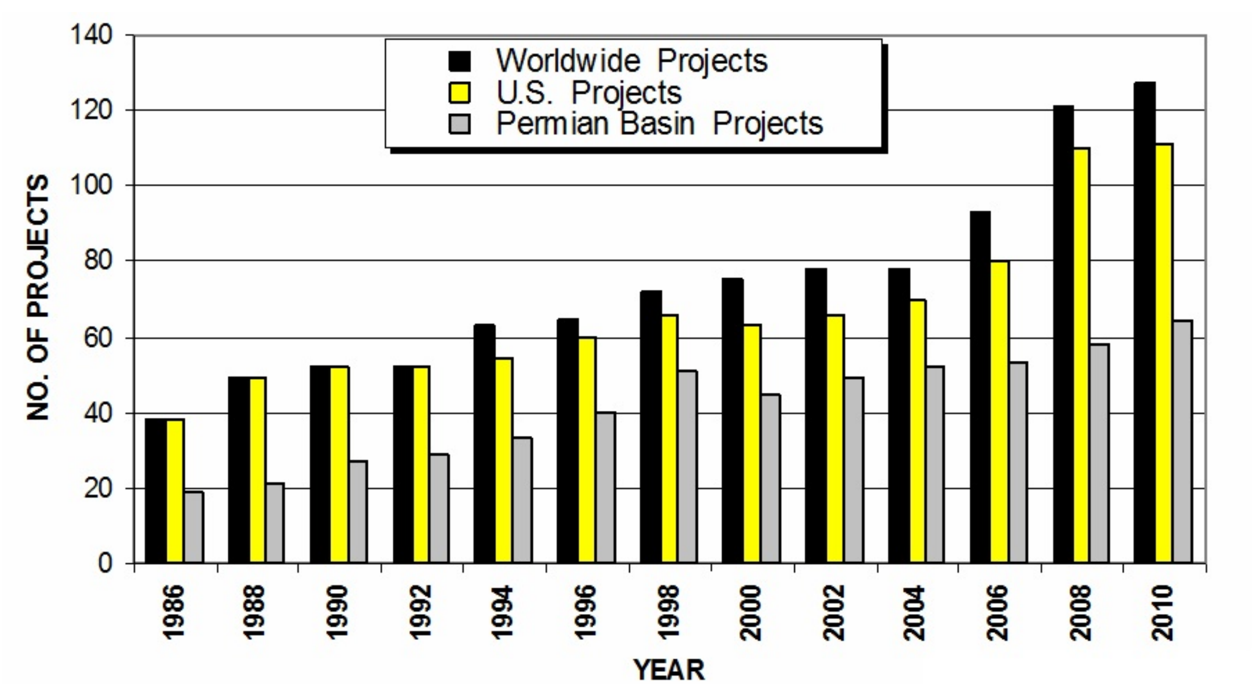

FIGURE 2: **U.S. CO_2 EOR Projects, Supply Sources and Pipelines**

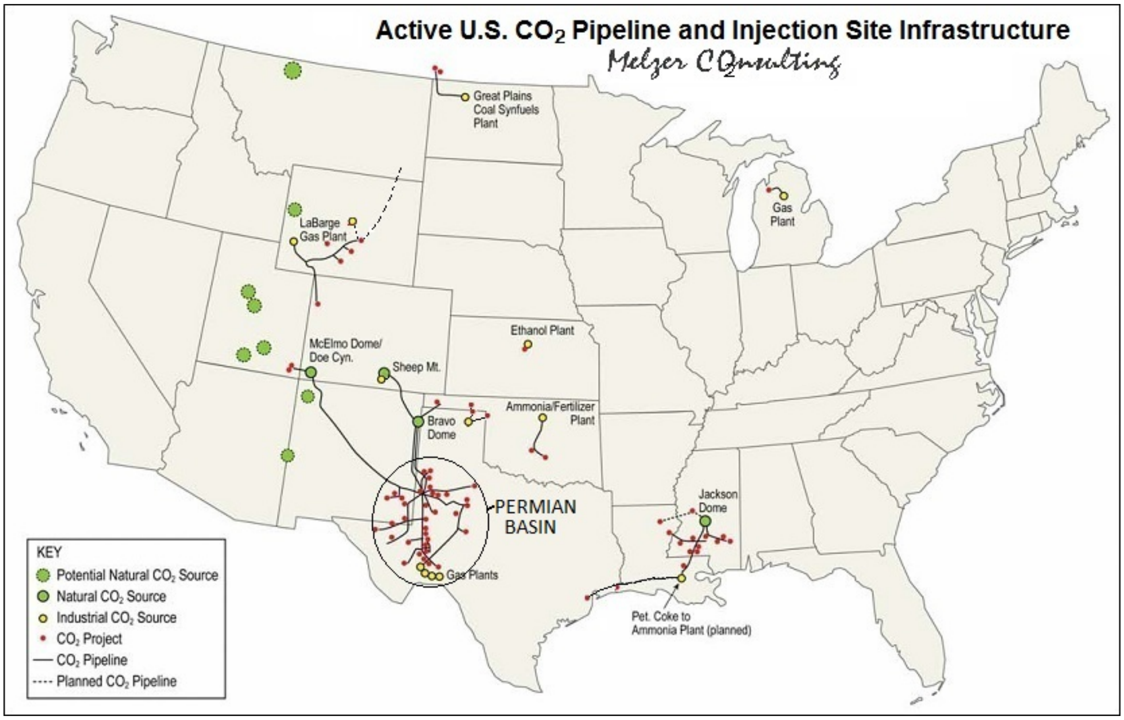

FIGURE 3: **CO_2 EOR Production (U.S. and Permian Basin, 1992-2010)**

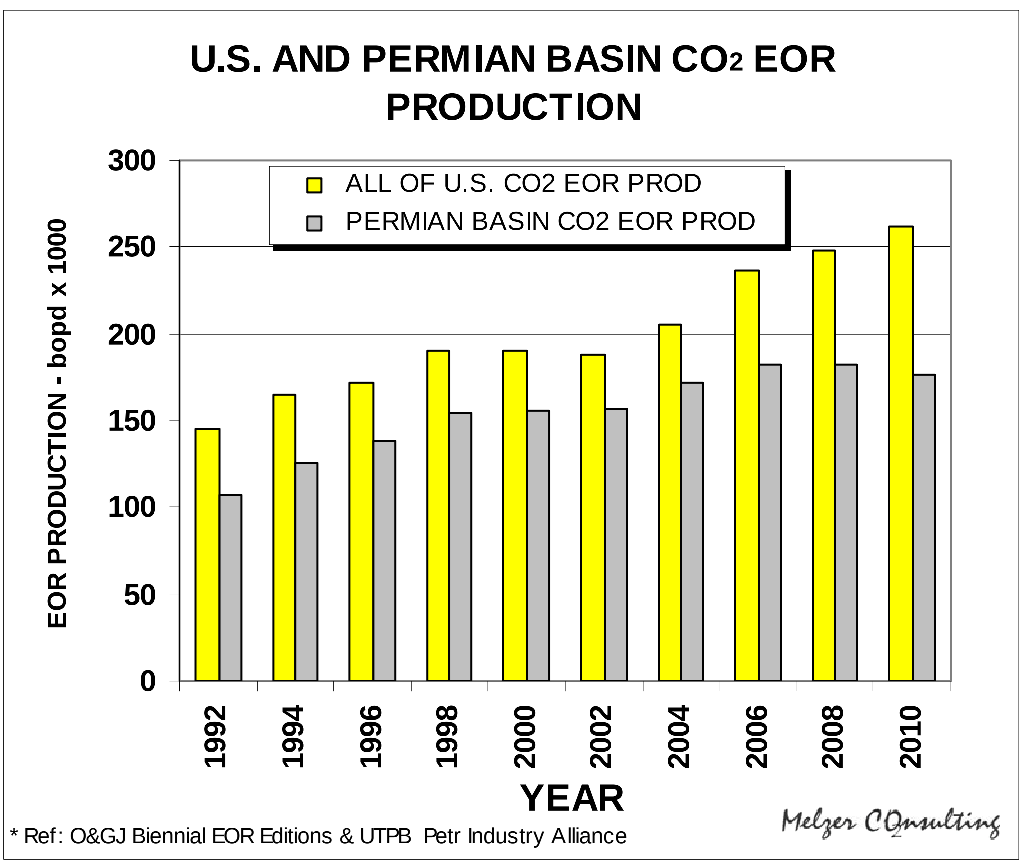

FIGURE 4: Example of a Quaternary (Fourth) Peak in Oil Production in a Large San Andes Field in West Texas

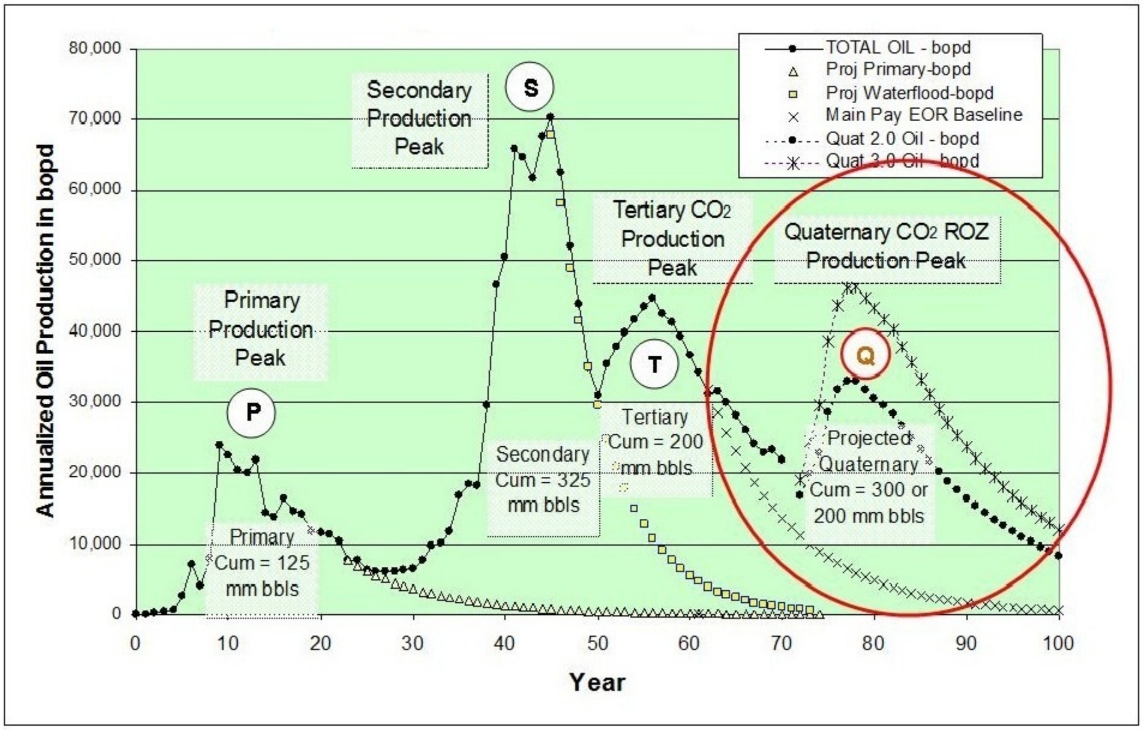

FIGURE 5: New Approach for Oil Resource Development with Carbon Capture and Storage