Volume II.A

Midwestern Regional Carbon Sequestration Partnership (MRCSP) Phase III (Development Phase)

Mass Balance Accounting for CO_2 Storage with Enhanced Oil Recovery in Northern Michigan

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Notice

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Acronyms and Abbreviations

API	American Petroleum Institute
BBL	Barrel (Oil)
CCUS	Carbon Capture, Utilization, and Sequestration
CO_2	Carbon Dioxide
CPF	Central Processing Facility
CSV	Comma-Separated Value
DEQ	Department of Environmental Quality
DOE	Department of Energy
DTS	Distributed Temperature Sensing
EOR	Enhanced Oil Recovery
ft^3	Cubic Foot
HCPV	Hydrocarbon Pore Volume
HMI	Human-Machine Interface
HP	High Pressure
INJ	Injection
LP	Low Pressure
MCF	Thousand Cubic Feet
MMCFD	Million Cubic Feet per Day
Mscf	Thousand Standard Cubic Feet
MSTB	Thousand Stock Tank Barrels
MT	Metric Ton
NETL	National Energy Technology Laboratory
OBS	Observation
OOIP	Original Oil in Place
PR	Producer
psi	Pounds per Square Inch
SI-P	Shut-in Producer
STB	Stock Tank Barrel
TEG	Triethylene Glycol
WAG	Water-Alternating Gas

1.0 Introduction

Phase III of the Midwest Regional Carbon Sequestration Partnership (MRCSP) is investigating reservoir characterization, modeling, carbon dioxide (CO_2)-enhanced oil recovery (EOR) operations, and monitoring technologies for carbon capture, utilization, and storage (CCUS) at 10 oil-bearing Niagaran pinnacle reefs operated by Core Energy, LLC. Figure 1-1 shows the location of these reefs within Otsego County, Michigan, USA. Like the large reservoirs at Permian Basin in West Texas and New Mexico, these Niagaran reefs are amenable to EOR via a CO_2 miscible flood, allowing additional recovery of "stranded oil" (oil not recovered during primary production) (Haagsma, et al., 2020).

CO_2-EOR operations began at this EOR complex in 1996 with the Dover 33 and Dover 36 reefs. Prior to 2003, the CO_2-EOR operations were under the ownership of another operator. After Core Energy acquired rights to these two reefs in 2003, an additional eight reefs were added to the CO_2-EOR complex. Central to this 10-reef EOR complex is the Chester 10 Facility, which provides the pure CO_2 necessary for EOR.

A total of 10 reefs were in operation as of September 2019 (data shown in this report). Table 1-1 shows the primary production details of the 10 reefs that make up Core Energy's EOR complex. The reefs are assigned to specific MRCSP tasks (Tasks 3, 4 and 5), each with different research objectives. Core Energy owns other reefs in the Michigan region that produce oil via primary production methods; however, these reefs are not discussed in this report.

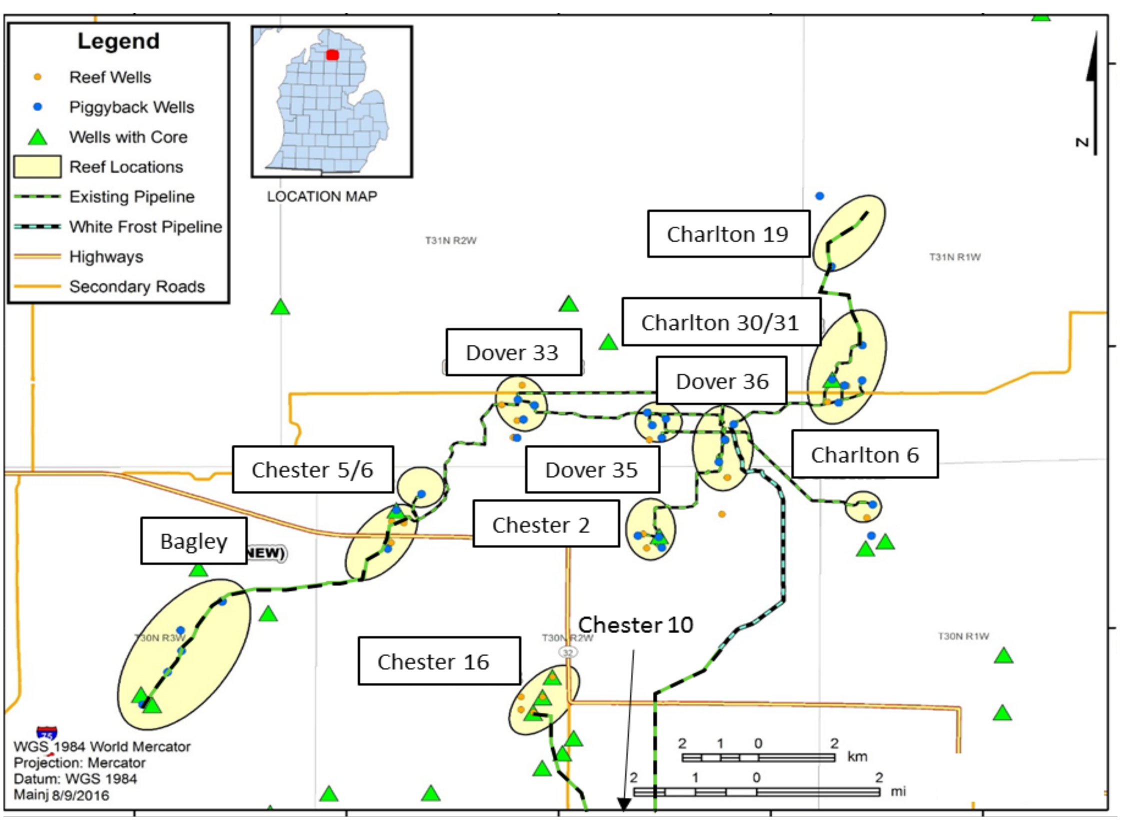


Figure 1-1. Locations of Core Energy's EOR Niagaran pinnacle reefs operated by Core Energy.

Table 1-1. EOR reefs, primary production.

MRCSP Task	Reef	Primary Dates	OOIP (Million BBL)	Primary Production (Million BBL)	Primary Recovery (%)
Task 3	Dover 33	1974 - 1996	3.5	1.3	37%
Task 4	Bagley	1973 - 2015	9.0	2.9	32%
Task 4	Charlton 19	1988 - 2015	2.6	1.1	41%
Task 4	Charlton 30/31	1973 - 1996	6.8	2.6	38%
Task 4	Charlton 6	1982 - 1995	1.7	0.6	37%
Task 4	Chester 2	1971 - 2009	3.2	1.0	32%
Task 4	Chester 5/6	1973 - 1987	2.9	1.2	42%
Task 4	Dover 35	1973 - 2004	2.5	1.0	39%
Task 4	Dover 36	1973 - 1997	3.7	1.2	31%
Task 5	Chester 16	1971 - 1990	6.9	2.4	35%

Most of the reefs underwent primary production activities over a period of 20 to 25 years, beginning in the 1970s. Table 1-1 shows the period during which primary oil production was carried out, estimates of original oil in place (OOIP), primary production of oil, and the recovery factors. These reefs did not undergo secondary methods of production (such as steam or water floods) and were adapted directly to EOR via CO_2 injection. Only the Chester 16 reef had minor quantities of oil produced via water floods. On average, these reefs have approximately 3.5 million barrels of oil (BBL) in place, with a primary recovery factor of 34%. The primary recovery factors of these 10 Niagaran pinnacle reefs are very similar to the 33.7% recovery from 182 large oil reservoirs identified in the Permian Basin in West Texas and New Mexico (ARI 2006).

1.1 Timeline of CO_2-EOR and MRCSP Monitoring Period

As of this report, Core Energy currently operates 10 active EOR reefs in Otsego County in northern Michigan. CO_2 EOR was initiated in each of these reefs at different times, beginning with Dover 33 reef in 1996 (Table 1-2). Chester 16 was the last reef added to the EOR complex in 2017.

Table 1-2. Active CO_2-EOR reefs and date of initial flooding.

Reef	Year CO_2 Flooding Initiated
Dover 33	1996
Dover 36	1997
Dover 35	2004
Charlton 30/31	2005
Charlton 6	2006
Chester 2	2009
Chester 5/6	2011
Charlton 19	2015
Bagley 11-14-23	2015
Chester 16	2017

Battelle's MRCSP Phase III monitoring efforts began on February 3, 2013, with an overarching goal of monitoring at least 1 million metric tons (MT) of net CO_2 stored within Core Energy's EOR complex. For the purposes of this report, most of the mass balance accounting data is shown through September 30, 2019, a period of 5 years, 10 months. MRCSP Phase III monitoring includes three specific tasks:

- Task 3 – Large-scale demonstration of CO_2 storage at Dover 33, a depleted reef.
- Task 4 – Monitoring of CO_2-EOR operations at eight active EOR reefs. These include Dover 35, Dover 36, Charlton 30-31, Charlton 6, Chester 2, and Chester 5/6 reef, which had ongoing EOR operations when the MRCSP monitoring period began. Charlton 19 reef was brought online with a new CO_2 flood in March 2015, and Bagley was added in December 2015. Despite the addition of these two new reefs to the CO_2-EOR complex, for the purposes of reporting, these reefs are part of Task 4 monitoring.
- Task 5 – Construction of two new wells for injection and monitoring of new CO_2 floods at the Chester 16 reef. The Chester #6-16 and Chester #8-16 wells were constructed in 2016, and a flood was initiated in Chester 16 reef in January 2017.

A timeline detailing the CO_2 injection history of all 10 reefs is shown in Figure 1-2, including injection/CO_2 fill-up and injection/secondary recovery. This report describes CO_2-EOR operations and the mass balance calculations of CO_2, and the return product stream consisting of oil, gas, and water between February 2013 and September 2019. During this period, MRCSP has successfully monitored injection of over 1 million MT of new CO_2 in the 10-reef EOR complex. Furthermore, this report will also highlight historical CO_2-EOR operations that indicate that the total associated CO_2 storage in the EOR complex, since injection began in 1996, is currently over 2 million MT (through September 2019).

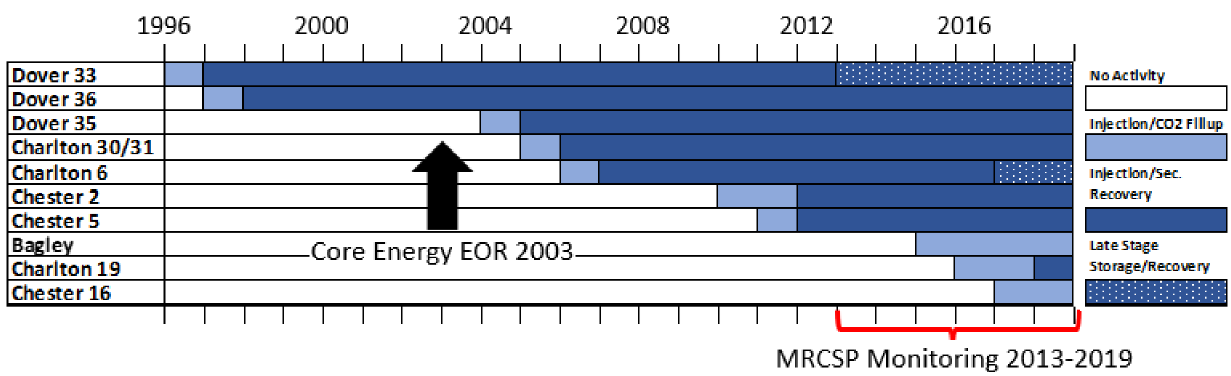


Figure 1-2. Timeline of 10 EOR reefs (1996-2019), focusing on injection fill-up and secondary recovery.

1.2 CO_2-EOR Reef Complex

CO_2 is being injected into the Silurian-age, oil-bearing, carbonate Niagaran pinnacle reefs. The 10 reefs are mostly interconnected by pipelines at a central processing facility (CPF), also known as the Dover 36 Facility. The Chester 16 reef is the sole exception in that it does not connect to recycle gas from the Dover 36 Facility, rather it utilizes pure CO_2 from the Chester 10 Facility. The CO_2-EOR complex encompasses the Chester 10 Facility, which provides the pure CO_2 for EOR purposes; the Dover 36 Facility, where product stream is processed; the EOR reefs; and the pipeline network that connects all the reefs centrally to the Dover 36 Facility. Core Energy plans to build additional processing facilities similar to the Dover 36 Facility; however, at the time of writing this report, all of the product stream is being processed at Dover 36.

Table 1-3 shows the 10 reefs and 36 wells—16 injection wells, 15 oil production wells, and 5 observation/ monitoring wells—in operation at the MRCSP reef complex. It should be noted that the type/status of wells can change over time, depending on operational requirements—an injection well may be converted to a production well, while a production well may be converted to an injection well. Similarly, existing wells that are utilized for observation purposes may be converted to either an injection or production well. This report discusses CO_2 injection at the 16 injection wells, along with details on the processing of product stream (consisting of oil, gas, and water) from the producing oil wells and the recycling of gas separated from the product stream at the Dover 36 Facility. The well type column shows whether the well is considered an injection well or an oil production well, while the well status column indicates whether a well is currently an injector (INJ) well, a producer (PR) well, a shut-in producer (SI-P) well, or a well used for observation (OBS) purposes.

Table 1-3. EOR reefs (10) and wells (36) at the MRCSP reef complex as of September 2019.

Unit	API Permit	DEQ Permit	Well Name	Well Type	Well Status
Dover 33	21-137-29565-00-00	29565	Lawnichak & Myszkier 1-33	Injection	INJ
Dover 33	21-137-00652-00-00	61209	Lawnichak 9-33	Oil	PR
Dover 33	21-137-51603-00-00	51603	Lawnichak & Myszkier 5-33 HD1	Oil	PR
Dover 33	21-137-50985-04-00	55942	Lawnichak & Myszkier 2-33 HD4	Oil	PR
Bagley 11-14-23	21-137-39758-01-00	39866	Wrubel 4-14A	Injection	INJ
Bagley 11-14-23	21-137-30536-00-00	30536	MBM 1-22	Injection	INJ
Bagley 11-14-23	21-137-38240-00-00	38240	Daughters of Friel 2-11	Injection	INJ
Bagley 11-14-23	21-137-37794-00-00	37794	Janik Mackowiac 1-11	Oil	OBS
Bagley 11-14-23	21-137-38286-00-00	38286	Janik Stevens 3-11	Oil	OBS
Bagley 11-14-23	21-137-39748-00-00	39748	Janik Strappazon 3-14	Oil	OBS
Bagley 11-14-23	21-137-38859-02-00	39897	Glasser 1-14B	Oil	OBS
Charlton 19	21-137-42766-00-00	42766	El Mac Hills 2-18	Injection	INJ
Charlton 19	21-137-40911-04-00	57261	El Mac Hills 1-19D	Oil	SI-P
Charlton 19	21-137-41801-01-00	61197	El Mac Hills 1-18A	Oil	PR
Charlton 30/31	21-137-30203-00-00	30203	State Charlton C2-30	Injection	INJ
Charlton 30/31	21-137-59048-00-00	59048	State Charlton & Larsen 3-31	Injection	INJ
Charlton 30/31	21-137-29989-00-00	29989	State Charlton 1-30A	Injection	INJ
Charlton 30/31	21-137-57916-00-00	57916	State Charlton 4-30	Oil	PR
Charlton 30/31	21-137-31287-00-00	31287	State Charlton 2-30	Oil	PR
Charlton 6	21-137-35209-00-00	35209	Zeimet-Higgins & St Charlton 1-6	Injection	INJ
Charlton 6	21-137-59086-00-00	59086	State Charlton & Boeve 2-6	Oil	PR
Chester 2	21-137-29430-00-00	29430	Wolf, Carl 1A	Injection	INJ
Chester 2	21-137-29958-01-00	29958	Wolf, Carl et al. C1-HD1	Oil	PR
Chester 2	21-137-60596-01-00	60596	Cargas 3-2 HD2	Oil	PR
Chester 5/6	21-137-59237-00-00	59237	Borowiak 2-6	Injection	INJ
Chester 5/6	21-137-58926-00-00	58926	Butler 3-5	Injection	SI-I

Unit	API Permit	DEQ Permit	Well Name	Well Type	Well Status
Chester 5/6	21-137-29265-01-00	60833	Piasecki 1-7A	Oil	PR
Dover 35	21-137-29236-00-00	29236	Salling Hanson Trust 1-35	Injection	INJ
Dover 35	21-137-37324-01-00	59238	Pomarzynski et al. 5-35A	Oil	SI-P
Dover 35	21-137-29947-01-00	29995	Salling Hanson Trust 4-35A	Oil	PR
Dover 35	21-137-57787-00-00	57787	Pomarzynski et al. 6-35	Oil	PR
Dover 36	21-137-29348-00-00	29348	Kubacki State 3-35	Injection	INJ
Dover 36	21-137-29235-00-00	29235	Kubacki State 1-36	Injection	INJ
Dover 36	21-137-52719-00-00	52719	Dover State 36 Unit 3-36	Oil	PR
Chester 16 EOR Unit	21-137-61189-00-00	61189	Chester 16 Unit 6-16 Pilot	Injection	INJ
Chester 16 EOR Unit	21-137-61186-00-00	61186	Chester 16 Unit 8-16	Oil/ Injection*	OBS

*Chester 16 Unit 8-16 well was an observation well that was converted to an injection well on September 18, 2019.

The 10 reefs described here are at various stages of the production life cycle. Chester 16 is currently undergoing a new CO_2 injection flood for pressurizing the reefs above the minimum miscibility pressure (~1,190 pounds per square inch [psi]) of CO_2 in oil prior to the commencement of EOR. Eight reefs (Dover 33, Dover 35, Dover 36, Charlton 6, Charlton 19, Charlton 30/31, Chester 2, Chester 5/6) are undergoing active CO_2 EOR injection and production operations. Finally, the Bagley reef had a new CO_2 flood from December 2015 to April 2019 and has been producing oil since April 2019.

1.3 Source of Pure CO_2, Chester 10 Facility

Core Energy currently receives pure CO_2 from a natural gas processing facility (DCP Midstream™ Plant) located in Chester County, approximately 11 miles south of the Dover 36 Facility. Core Energy has rights to capture CO_2 from the DCP Plant that would normally be vented. The natural gas is produced from the Antrim shale and contains approximately 15% by weight CO_2, which is separated by an amine-based sweetening method. Captured CO_2 is delivered at low pressures (7 psi) to Core Energy's compression and dehydration facility at Chester 10. After running through various stages of compression and dehydration, CO_2 is compressed to approximately 1,300 psi (supercritical phase) for transport to the Dover 36 Facility via White Frost pipeline, a 6-inch carbon-steel pipe that delivers pure CO_2 to the Dover 36 Facility for injection to various EOR reefs (Sminchak, et al., 2020).

Core Energy operates three compressor units (East, West, and South units): two Caterpillar Ariel 3608 compressors and one Caterpillar Dresser 3612 compressor. The three units have a total capacity of 30 million cubic feet per day (MMCFD) (about 1,578 MT per day). Core Energy utilizes a triethylene glycol (TEG) dehydration method to remove any moisture from the CO_2 delivered by the DCP Plant. At the Chester 10 Facility, there is land available for future expansion. There is also a salt-water (brine) disposal well located at this unit. Figure 1-3 shows photographs of the Chester 10 compression facility.

Figure 1-3. Photographs of the Chester 10 Facility.

1.3.1 Quantities of Pure CO_2 Available

During the MRCSP monitoring period (February 2013 to September 2019), approximately 1.62 million MT of pure CO_2 was made available by the Chester 10 Facility. Prior to March 2017, when there were two compressors available for CO_2 compression and dehydration, daily production ranged from about 500 to 600 MT/day, resulting in about 15,000 MT per month of CO_2 availability from the Chester 10 Facility. After a new compressor was installed in March 2017, daily production increased to approximately 1,000 MT/day. Since March 2017, on average, 27,000 MT/month of pure CO_2 has been available for injection in EOR reefs.

Table 1-4 shows the yearly availability of pure CO_2 from the Chester 10 Facility over the MRCSP monitoring period. Since 2017, when the new dehydration and compression facilities were constructed at Chester 10 Facility, Core Energy has an operational capacity to capture over 500,000 MT of CO_2 per year. However, there is total capacity of approximately 600,000 MT of pure CO_2 capturable per year from the Antrim shale. It is expected that the natural gas processing plant will continue operations for at least 10 to 20 years, but continued operations will depend on market conditions.

Figure 1-4 shows the monthly averages of quantities of CO_2 made available via the Chester 10 Facility. This report highlights the accounting of the net ~1.6 million MT of (purchased) CO_2 injected in 10 EOR reefs operated by Core Energy. As summarized in subsequent sections, the total quantity of CO_2 injected is ~2.7 million MT, as the produced/recycle gas is added to pure CO_2 available from the Chester 10 Facility, in a closed-loop production cycle at the Dover 36 Facility.

Table 1-4. Quantities of pure CO_2 available.

Prod Year	Pure CO_2 (MMCF)	Pure CO_2 (MT)
2013	3,464	182,321
2014	2,998	157,798
2015	3,139	165,222
2016	3,733	196,448
2017	5,900	310,550
2018	6,166	324,583
2019	5,447	286,673
Total	**30,848**	**1,623,595**

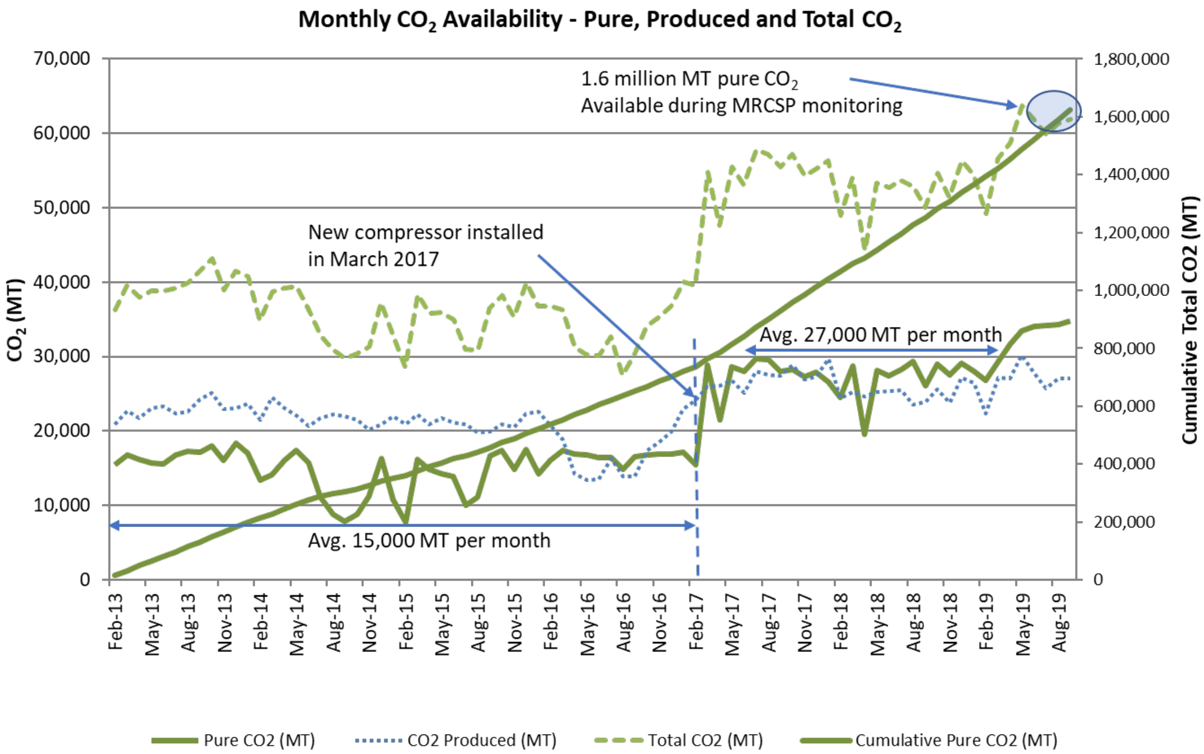


Figure 1-4. Quantity of pure CO_2 from Chester 10 over the MRCSP monitoring period.

1.3.2 Composition of CO_2 from Chester 10 Facility

Core Energy will typically conduct a quarterly composition analysis of CO_2 captured at the Chester 10 Facility. Analysis of past data suggests this CO_2 is approximately 99 mole% pure, with trace amounts of other impurities such as nitrogen and hydrocarbon gases. The most recent sample, taken in August 2019, shows CO_2 that is 99.9 mole% pure. The CO_2 from the Chester 10 Facility is transported via the White Frost pipeline to the Dover 36 Facility, where it can be either injected in its pure form into an EOR reef, or co-mingled with recycle gas and sent back to a reef for reinjection. Figure 1-5 shows the latest composition analysis (2016 – 2019) of pure CO_2 at the Chester 10 Facility.

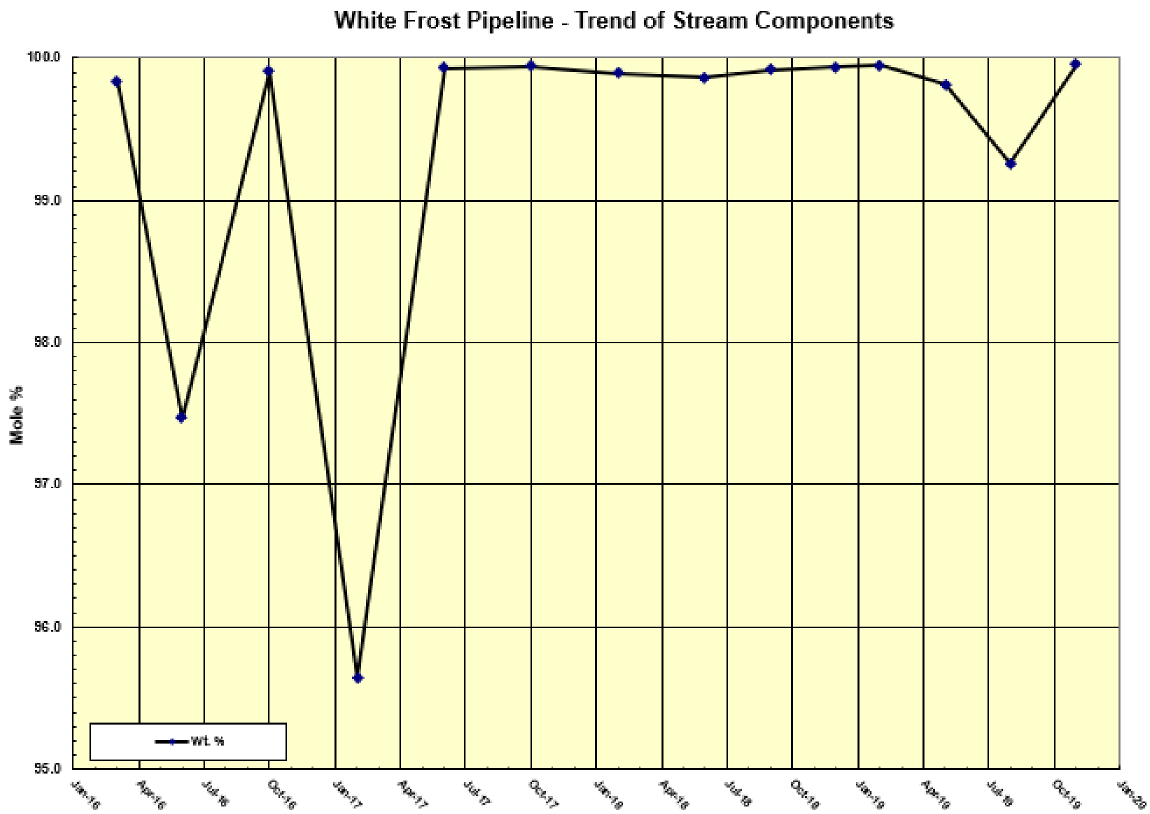


Figure 1-5. White Frost pipeline – trend of stream components (mole% CO_2).

1.4 Central Processing Facility (CPF) – Dover 36 Facility

Table 1-3 lists the active wells, 20 of which are non-injection, oil "producers." These 20 wells are further subdivided by the well status as a current producer (PR), a shut-in producer (SI-P), or an observation (OBS) well. Shut-in producer wells were formerly in production, while observer wells have the potential to be altered to a producer well in the future. Generally, at least one production well is in each reef. For the new reefs, the production wells will be connected to pipelines for produced fluids once they start producing. For the other reefs, all produced fluids from the reefs flow directly to dedicated separators at processing facilities. At Core Energy, the product stream from various production wells is centrally processed at the Dover 36 Facility, which is co-located along with the Dover 36 reef. Core Energy has built a network of pipelines to bring pure CO_2 from the Chester 10 Facility to the Dover 36 Facility and transport the CO_2 injectate to various injection wells located at 10 EOR reefs (Mawalkar, et al., 2020). Additionally, production fluids (mixture of oil, gas, water) are brought back to the Dover 36 Facility via pipelines for processing. Currently, the pipeline network owned and operated by Core Energy is approximately 120 miles long.

1.4.1 Produced Fluid Handling and Processing

Figure 1-6 shows a simplified process flow diagram of the pipeline network at Core Energy's Dover 36 Facility. The network consists of five high-pressure (HP) separators and 12 low-pressure (LP) separators at Dover 36. Product streams from reefs that are producing oil under high pressure (>340 psi) are first sent to an HP separator; product streams from reefs that are producing under low pressure (<340 psi) are sent to one of the LP separators.

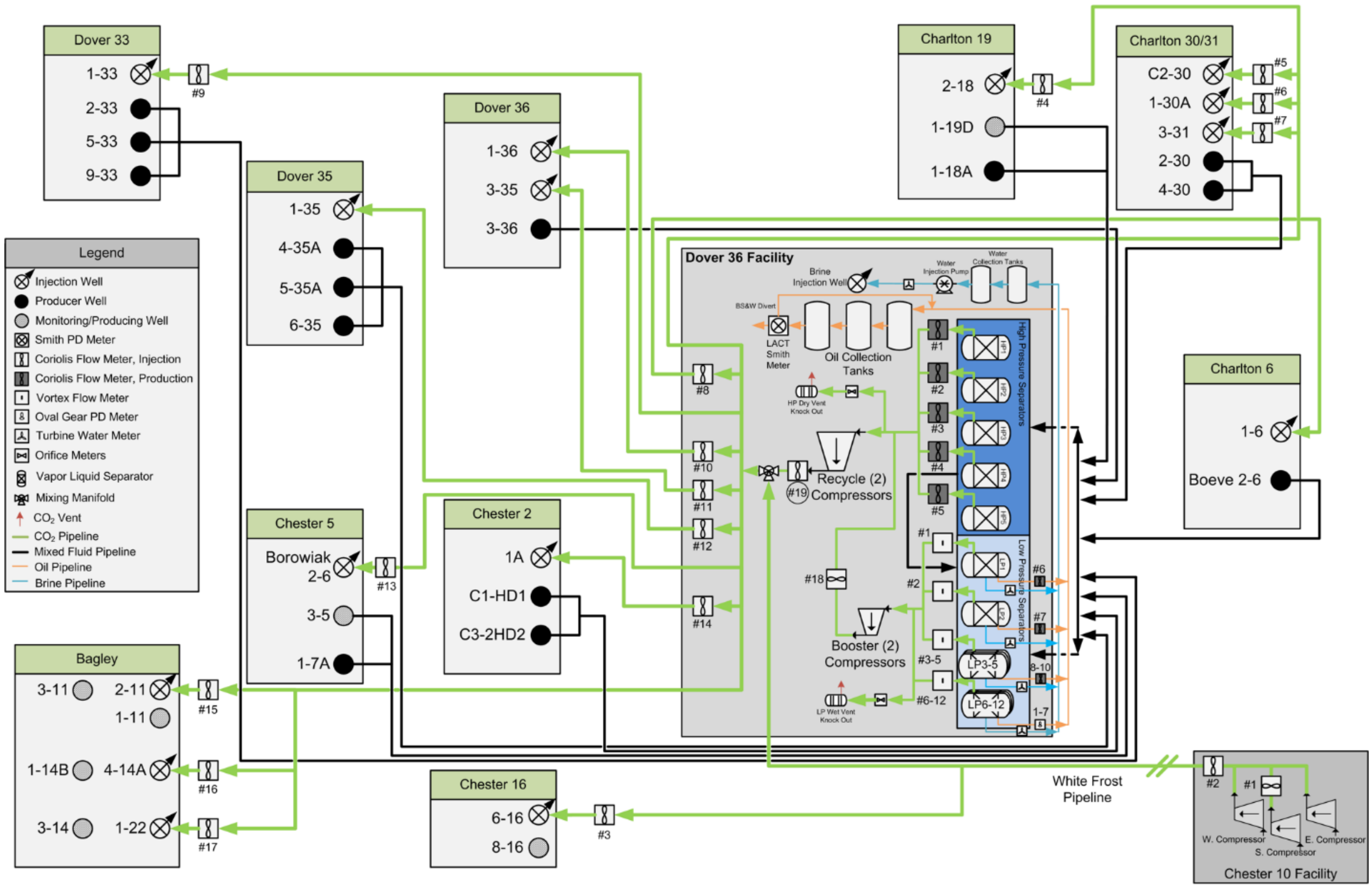


Figure 1-6. Simplified process flow diagram of the Dover 36 Facility pipeline network.

The bulk of the gas in the product stream is captured at the HP separators. The remaining liquid product stream (containing mostly oil and brine) from the HP separator is sent to an LP separator for stripping of any remaining entrained gas. The LP separators also separate the oil from water.

The produced gas, which primarily consists of CO_2 (>95% by weight), is separated from the produced fluid and flows through a Coriolis mass flow meter (meters numbered 1 through 5) at each of the HP separators. It then is sent to the recycle compressor. The bulk of the produced gas is captured in the HP separators (>90% by weight). Meanwhile, the produced gas that is separated at the LP separator flows through a vortex type flow meter. The system of Coriolis mass flow meters (attached to the HP separators) and vortex flow meters (attached to the LP separators) measures the total mass of recycle gas produced from each operational reef. Additionally, one Coriolis mass flow meter (#18) measures the total mass of recycle gas captured at the LP separators, while another meter (#9) measures the total quantity of produced gas from all operational EOR reefs.

The produced gas separated in the HP separator is directly sent to the main recycle compressor, while the gas separated from the LP separator is first sent to a booster compressor before it is compressed at the recycle compressor. The recycle compressor (having multiple stages of dehydration and compression) compresses the gas to approximately 1,400 psi for recycling back to the EOR reefs. A network of pipes and valves at the Dover 36 Facility allows the recycled gas to be co-mingled with pure CO_2 coming from the Chester 10 Facility.

Brine is separated by the LP separators. The collected brine is sent to a brine disposal well located onsite at the Dover 36 Facility. The LP separators record the quantity of water produced from each reef.

Oil is gathered in collection tanks before flowing through a Lease Automatic Custody Transfer meter for offsite sales. A small amount of CO_2 remains entrained in the oil after the CO_2 separation process, which bleeds off as the oil moves through the LP meters into a temporary storage/gathering tank. In 2001, Core Energy hired an external engineering firm to conduct a survey to determine the amount of CO_2 entrained in oil. This study indicated that the concentration of CO_2 entrained in oil is 0.7512% by weight. This translates into roughly 150 tons per year at current operations levels. Because the oil is blended in the gathering tank, Core Energy believes this factor applies uniformly to all oil.

While rare, operational outages periodically occur, which forces produced gas to be vented to the atmosphere. Core Energy has orifice-type flow meters installed at its wet and dry vent locations to measure the mass of recycle gas that is vented. During the more than six years of MRCSP monitoring, a total of 1,202 MT of gas was vented, representing less than 0.06% of the produced volume of gas.

1.4.2 Composition of the Recycle Gas

During primary production of these Niagaran reefs, the bulk of the hydrocarbon gas present in the oil-gas mixture was already produced by the time reefs were converted for secondary methods of recovery with CO_2-EOR. Once the reefs started producing oil with CO_2-EOR, gas that is captured is mostly sent back to the reefs for maintaining operating pressures.

Core Energy routinely collects samples of the recycle gas at the Dover 36 Facility for composition analysis. Figure 1-7 shows that this recycle gas consists primarily of CO_2 (about 95 mole%). Concentration of hydrocarbon gas such as methane, ethane, propane, and other gases is typically less than 5 mole%. As such, the entire recycle gas stream is considered to be almost pure CO_2, equivalent to the pure CO_2 captured at the Chester 10 Facility. The mass balance calculations presented in this report do not distinguish between the two CO_2 streams. Both the pure CO_2 from the Chester 10 Facility and the recycle gas from the Dover 36 Facility are treated equally, as the gas is injected back to the EOR reefs.

The small quantities of hydrocarbon gas present in the recycle gas are neglected, and the recycle gas is treated as if it is pure CO_2 equivalent.

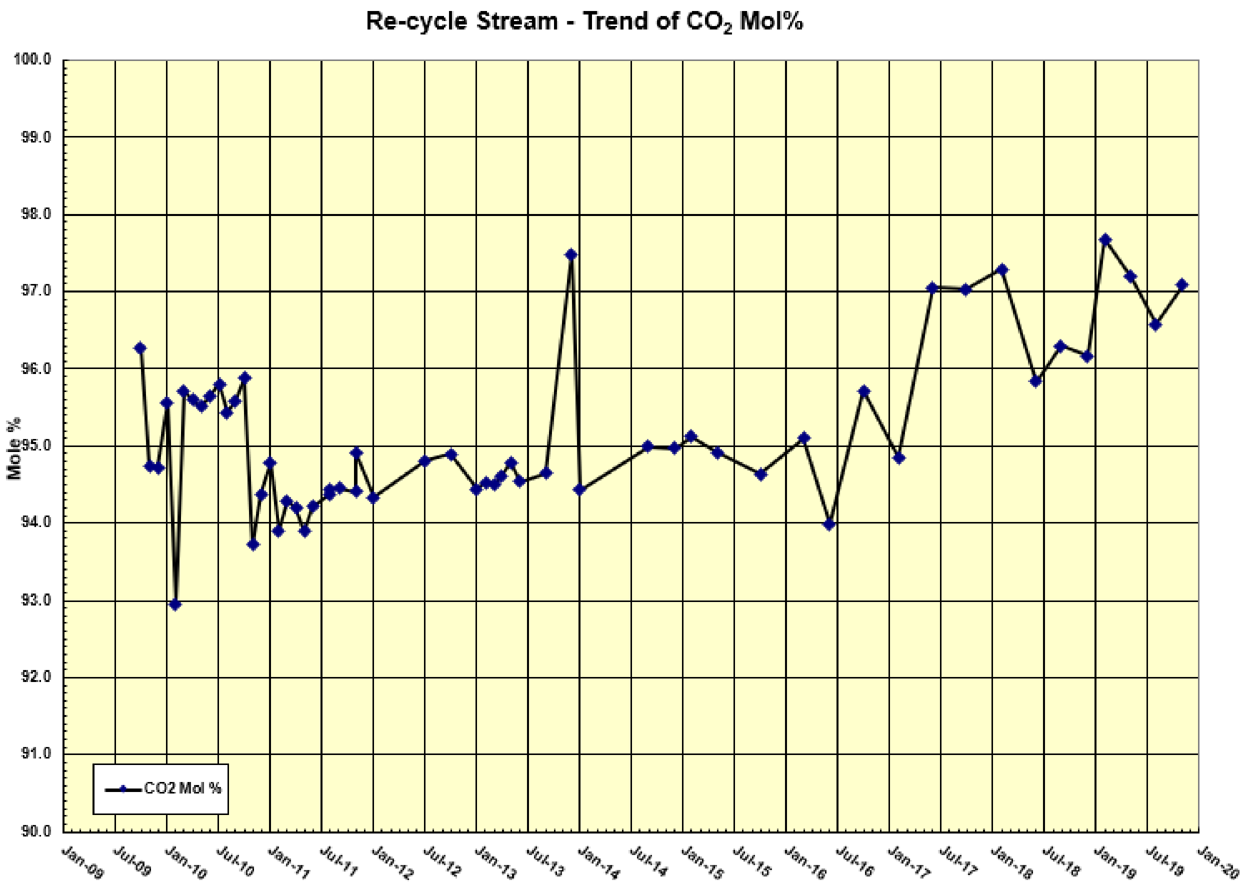


Figure 1-7. Composition analysis of recycle gas stream.

1.5 Data Collection

The system of flow metering at the Dover 36 Facility is centrally tied to a Core Energy human-machine interface (HMI) computer system. Coriolis mass flow meters that are located at the reef-site locations (at injection wellheads) typically have their own data-loggers that collect and store injection data. The HMI system continuously records production and injection data on a per-minute basis for each day of operations. A comma-separated value (CSV) file is generated for each day's operations. Additionally, operators at the Dover 36 Facility record daily totalizer readings from injection and production meters at 9 a.m. every day as production readings for the prior operational day. Operators also make daily site visits to the well sites, where data such as the quantity of CO_2 injected, tubing pressures, casing pressures, and wellhead temperatures are recorded. The data stream from the HMI computer system and the daily production readings recorded by operators provide accurate accounting of 1) all CO_2 acquired from the Chester 10 Facility and injected into EOR reefs, and 2) any recycle gas produced and reinjected at the Dover 36 Facility.

The Coriolis mass flow meters are central to mass balance calculations included in this accounting report. Coriolis flow meters are extremely accurate, with liquid mass flow accuracy of 0.10% and gas mass flow accuracy between 0.35% and 0.5%. These meters measure the bulk of the mass of CO_2 being injected to injection wells and the mass of gas produced at the HP separators where most of the recycle gas is captured. The Coriolis flow meters also provide the density and temperature of CO_2 being injected to various injection wells. These parameters are useful for doing a well-test analysis of CO_2 injection at various reefs. The production metering and computer systems were last updated at the Dover 36 Facility in October 2016, when new Coriolis flow meters were installed at five HP separators and at the aggregate recycle line (from the main recycle compressor). The LP separators have vortex type flow meters that measure CO_2 on a volume basis. The volume of gas is then converted to mass basis by using 19,000 cubic feet (ft^3) per MT of CO_2 as a standard conversion factor.

Parameters reported by various flow meters include:

- Coriolis for gas (injection wells, HP separators, recycle compressor, booster compressor):
    - Assigned well
    - Mass flow rate (MT/day)
    - Gas density (lbs/gal)
    - Gas temperature (deg F)
    - Mass total today (MT)
- Coriolis for oil (LP separators):
    - Assigned well
    - Volume flow rate (BBL/day)
    - Density (lbs/gal)
    - Temperature (deg F)
    - Volume total today (BBL)
- Vortex for gas (LP separators):
    - Assigned well
    - Flow rate (thousand cubic feet [MCF]/day)
    - Gas total today (MCF)
- Orifice meters (dry and wet vents):
    - Assigned well
    - Flow rate (MCF/day)
    - Gas total today (MCF)

2.0 Reef-Level Accounting

This section details the individual accounting of CO_2 injected, CO_2 produced, and the mass of oil and water produced from each of the 10 EOR reefs. Primary production details are not included here; instead, the focus is on EOR operations after the reefs underwent secondary methods of production via CO_2-EOR. Information presented on EOR operations prior to the MRCSP monitoring period (i.e., before February 2013) was submitted to Battelle by Core Energy in the form of Excel files. These files contain data from prior operators as well. Core Energy began its EOR operations in 2003, but reefs such as Dover 33 and Dover 36 were already operating in EOR mode. The reef-level accounting is presented in chronological order of year EOR began, starting with Dover 33 in 1996, and ending with Chester 16 in 2017.

2.1 Dover 33 Reef

Dover 33 is a double reef with a large northern reef and a small southern reef. The reef has a bulk volume of 1,601,575,735 ft^3, a pore volume of 97,288,784 ft^3, 58,567,933 ft^3 of hydrocarbon pore volume (HCPV) oil, and 3,728,000 BBL OOIP. The top of the reef is about 5,300 feet (MD) in the center of the field.

Dover 33 began to produce oil and hydrocarbon gas in 1974. The initial discovery conditions, summarized in Table 2-1, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-1. Initial reservoir properties of Dover 33.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
3,728,000	43.6	2894 psia	108	66.25%	0.00%	33.75%

The primary production period lasted approximately 22 years, between 1974 and 1996 (Figure 2-1). The secondary production period began in May 1996 with CO_2 injection and EOR. The primary production period yielded 1,286,033 BBL of oil, 1,657,593 MCF of gas, and 141,676 BBL of water from January 1974 to May 1996. The Dover 33 reef did not go through other secondary methods of production, such as the water-flood, steam-flood, or water-alternating-with-gas (WAG) floods. Injection of CO_2 became uneconomical around 2006, when large amounts of CO_2 injection were yielding mostly gas and small quantities of oil. At that point, the reef became a late-stage reef, and production and injection were minimal and sporadic until the MRCSP Phase III monitoring period began in February 2013. Subsequently, under Task 3, Battelle began to conduct a large-scale storage test of CO_2 at the Dover 33 reef. The purpose of the storage test was to better understand storage capacity of CO_2 for such late-stage CO_2-EOR reefs and whether CO_2 can be permanently stored. In July 2016, once the storage test was completed, the field was turned over to Core Energy for further secondary EOR operations.

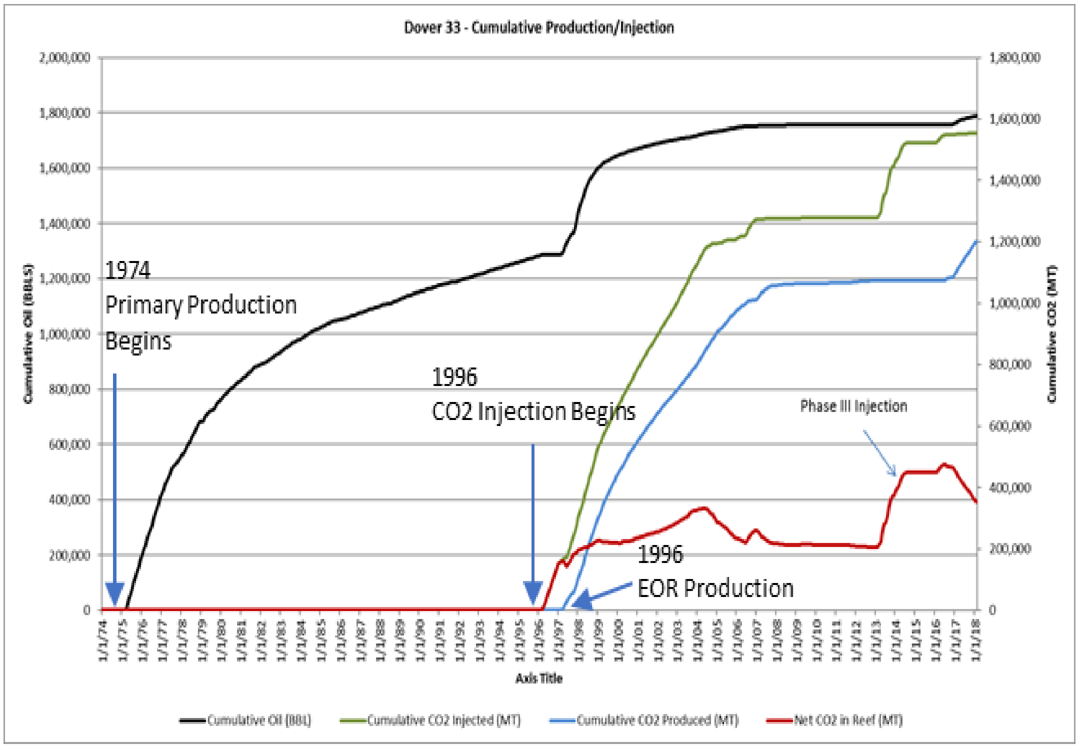


Figure 2-1. Timeline of cumulative production and injection in Dover 33.

2.1.1 Well History

There are four active wells at Dover 33 in the northern reef pod (Table 2-2). Dover 1-33, the primary injection well, was drilled at the center of the reef in April 1974 and drilled vertically to a measured depth of 5,675 feet. Dover 5-33, a deviated production well, was spudded on the southwest side in December 1996 and drilled to a measured depth of 6,436 feet. Dover 2-33, a horizontal producing well, was spudded on the east side in November 2003 and drilled to a measured depth of 7,134 feet. Dover 9-33, a deviated production well, was spudded on the west side in September 2016 and drilled to a measured depth of 6,085 feet.

Table 2-2. Listing of wells at Dover 33 EOR unit.

API Permit	DEQ Permit	Well Name	Shortened Well Name	Well Type	Well Status
21-137-00652-00-00	61209	Lawnichak 9-33	Dover 9-33	Oil	Producing
21-137-50985-04-00	55942	Lawnichak & Myszkier 2-33 HD4	Dover 2-33	Oil	Producing
21-137-51603-00-00	51603	Lawnichak & Myszkier 5-33 HD1	Dover 5-33	Oil	Producing
21-137-29565-00-00	29565	Lawnichak & Myszkier 1-33	Dover 1-33	Injection	Injection

2.1.2 Production Since EOR

Table 2-3 shows the yearly production and injection rates since the start of EOR at Dover 33. Oil production, gas injected, and gas produced rates are highest throughout secondary production, from May 1996 through October 2007. Monthly production rates decreased, and cumulative rates leveled off at that time, when the reef entered its late stage, until February 2013. After February 2013, MRCSP carried out large-scale storage tests until July 2016, when the reef was turned over to Core Energy for routine EOR operations. The Dover 9-33 production well was drilled as a research well for MRCSP and turned over to Core Energy for the purpose of recovering additional oil that remains in the Dover 33 reef.

From the onset of EOR in 1996 through September 2019, the Dover 33 reef has yielded 539,828 BBL of oil, 1,293,876 MT of recycle gas, and 136,494 BBL of water (Table 2-3). During this time, a total of 1,604,775 MT of CO_2 has been injected. From October 2007 to February 2013, production and injection were decreased. The increase in CO_2 injection between February 2013 and July 2016 represents the period of storage operations conducted by MRCSP, during which approximately 271,000 MT of CO_2 was injected. Routine EOR production resumed in August 2016, after MRCSP's research objectives of monitoring bottomhole conditions during storage test were completed. Excess CO_2 produced from this reef was recycled to other reefs within the CO_2-EOR complex, and the net CO_2 in Dover 33 reef has decreased. Gas venting during the entire EOR period has been minimal with only 1,139 MT vented.

Table 2-3. Production at Dover 33 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
1996	932	2,642/139,037	0/0	0/0	76	139,037
1997	137,459	2,648/139,356	1,679/88,388	0/0	5296	190,005
1998	182,356	4,431/233,234	3,731/196,383	0/0	13,403	226,856
1999	55,883	2,742/144,309	2,868/150,938	0/0	7,620	220,226
2000	27,879	2,305/121,324	2,026/106,607	0/0	6540	234,943
2001	20,825	2,117/111,445	1,762/92,725	0/0	3,730	253,664
2002	15,358	2,040/107,348	1,474/77,585	0/0	2,762	283,426
2003	13,120	2,335/122,876	1,530/80,502	0/0	5264	325,800
2004	16,617	1,421/74,795	2,018/106,234	0/0	13,813	294,362
2005	11,989	267/14,027	1,389/73,092	5/283	18,768	235,297
2006	6,512	1,209/63,606	767/40,389	10/509	13,819	258,514
2007	2,566	95/5,006	874/46,007	0/0	17,651	217,514
2008	810	2/118	97/5,092	0/0	1,916	212,540
2009	477	53/2,800	37/1,932	0/0	649	213,408
2010	39	0/0	27/1,431	1/27	257	211,977
2011	641	0/0	53/2,777	1/77	1,341	209,200
2012	775	4/222	84/4,434	4/197	3,701	204,989
2013	45	3,193/168,047	3/167	1/42	79	372,869
2014	0	1,447/76,166	0/0	0/0	0	449,035
2015	0	0/0	0/0	0/0	0	449,035
2016	845	512/26,937	224/11,789	0/0	242	464,181
2017	27,813	85/4,450	1,955/102,912	0/0	10,693	365,719
2018	8,328	6/334	1,054/55,468	0/3	2,427	310,585
2019	8,559	937/49,338	931/49,024	0	6,447	310,899
Total	**539,828**	**30,491/1,604,775**	**24,584/1,293,876**	**22/1,139**	**136,494**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.1.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in February 2013, Dover 33 has yielded 45,590 BBL of oil and 19,888 BBL of water during the secondary production period. A net 105,912 MT of CO_2 have been injected, with 325,272 tons injected and 219,360 MT of gas produced. Table 2-4 shows the production and injection data by well and by year since 2013. All CO_2 injection was conducted at Dover 1-33 injection well. A total of 9,504 MT of CO_2 was also produced from Dover 1-33 over 66 days (33 non-zero days), which was sent directly to the Charlton 19 reef for EOR. Dover 2-33 produced 6,302 BBL of oil, 17,970 MT of gas, and 8,096 BBL of water over the six-year period. Dover 5-33 has produced 18,898 BBL of oil, 78,914 MT of gas, and 4,816 BBL of water during the same time frame. Since 2016, the newly constructed Dover 9-33 well has produced 20,390 BBL of oil, 112,971 MT of gas, and 6,976 BBL of water. Most CO_2 was injected by MRCSP during the storage test period, and most production occurred after the reef was turned over to Core Energy for EOR.

Table 2-4. Production at Dover 33 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (tons)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Lawnichak & Myszkier 1-33	2013	0	168,047	0	0	0	
	2014	0	76,166	0	0	0	
	2015	0	0	0	0	0	
	2016	0	26,937	9,504	0	0	
	2017	0	4,450	0	0	0	
	2018	0	334	0	0	0	
	2019	0	49,338	0	0	0	
Subtotal		**0**	**325,272**	**9,504***	**0**	**0**	
Lawnichak & Myszkier 2-33 HD4	2013	0	0	0	0	0	
	2014	0	0	0	0	0	
	2015	0	0	0	0	0	
	2016	0	0	0	0	0	
	2017	6,290	0	17,857	0	8,073	
	2018	12	0	114	0	23	
	2019	0	0	0	0	0	
Subtotal		**6,302**	**0**	**17,970**	**0**	**8,096**	
Lawnichak & Myszkier 5-33 HD1	2013	45	0	167	42	79	
	2014	0	0	0	0	0	
	2015	0	0	0	0	0	
	2016	447	0	1,024	0	188	
	2017	14,302	0	50,215	0	2,065	
	2018	3,118	0	20,910	3	1,588	
	2019	986	0	6.598	0	896	
Subtotal		**18,898**	**0**	**78,914**	**45**	**4,816**	
Lawnichak 9-33	2016	398	0	1,261	0	54	
	2017	7,221	0	34,839	0	555	
	2018	5,198	0	34,445	0	816	
	2019	7,573	0	42,426	2	5,551	
Subtotal		**20,390**	**0**	**112,971**	**2**	**6,976**	
		45,590	**325,272**	**219,360**	**47**	**19,888**	**105,912**

*The 9,504 MT of CO_2 produced from Dover 1-33 was sent directly to the Charlton 19 reef for EOR.

Figure 2-2 shows the cumulative production and the monthly production rates at Dover 33 since the inception of EOR in May 1996 until September 2019. Since the onset of EOR, 1,604,775 MT of CO_2 have been injected, and 1,293,876 MT of CO_2 have been produced. Therefore, a **net 310,899 MT of CO_2 have been retained** in the reef throughout almost 23 years. Since the MRCSP monitoring period began, 325,272 MT of CO_2 have been injected, and 219,360 MT of CO_2 have been produced. A net 105,912 MT of CO_2 have been injected in the reef during the MRCSP monitoring period.

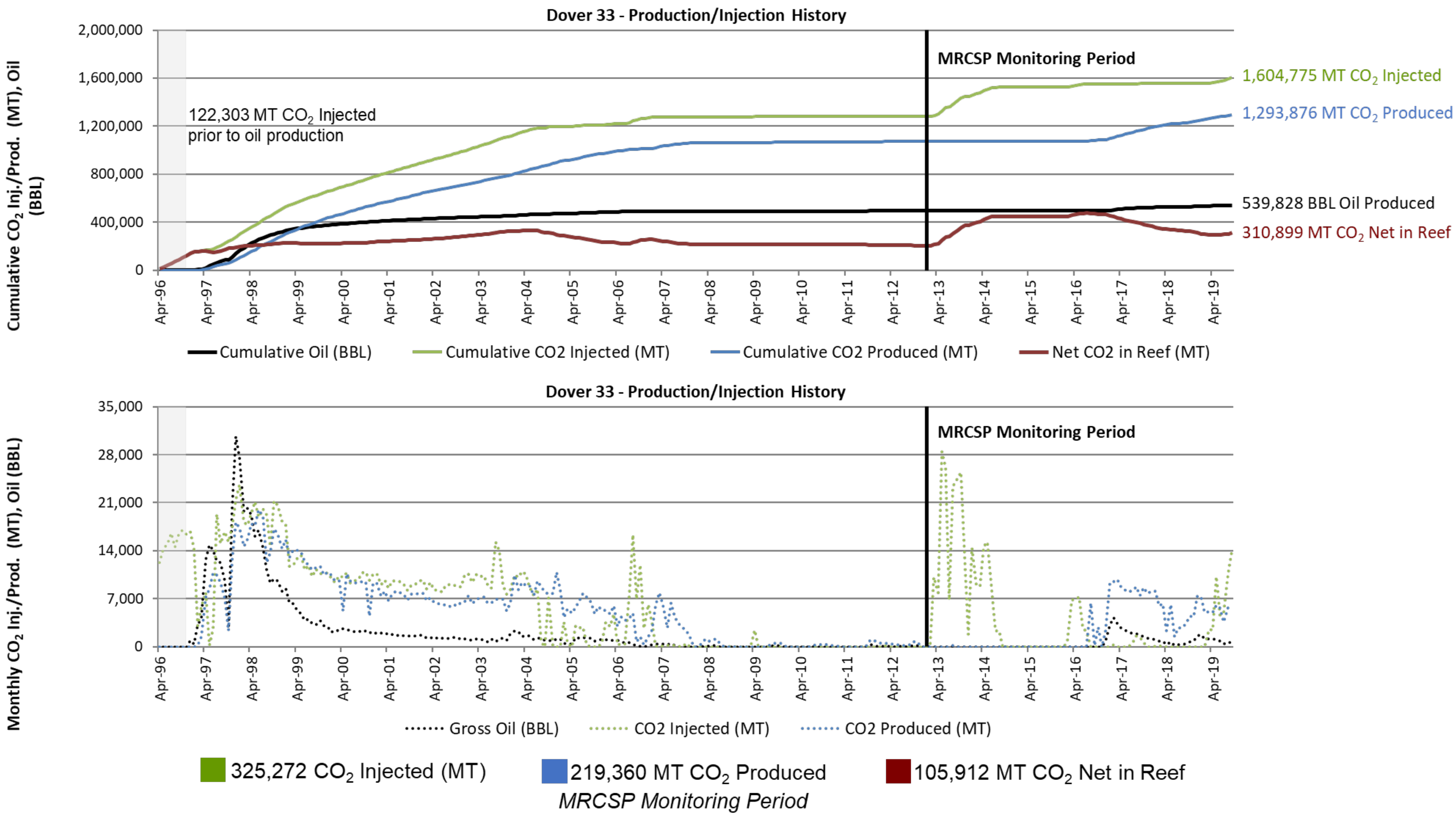


Figure 2-2. Injection rates at Dover 33 since 1996.

2.2 Dover 36 Reef

Dover 36 is an elongated, single-pod reef extending north/south on its long axis. The top of the reef is about 4,200 feet (MD) in depth. Dover 36 began to produce oil in 1973.The initial discovery data, summarized in Table 2-5, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-5. Initial reservoir properties of Dover 36.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
3,728,000	42.8	2,996 psia	108	63.53%	0.00%	36.47%

The primary production period lasted approximately 24 years, between May 1973 and February 1997 (Figure 2-3). Annual field production peaked in 1974, then followed a steady, predictable decline through 1997, when primary production was stopped for CO_2 injection. The primary production period yielded 1,148,891 BBL of oil and 4,579 BBL of water. CO_2 injection began in February 1997, and the production of EOR oil subsequently began in August 1998. CO_2 injection has remained steady and has not yet become uneconomical.

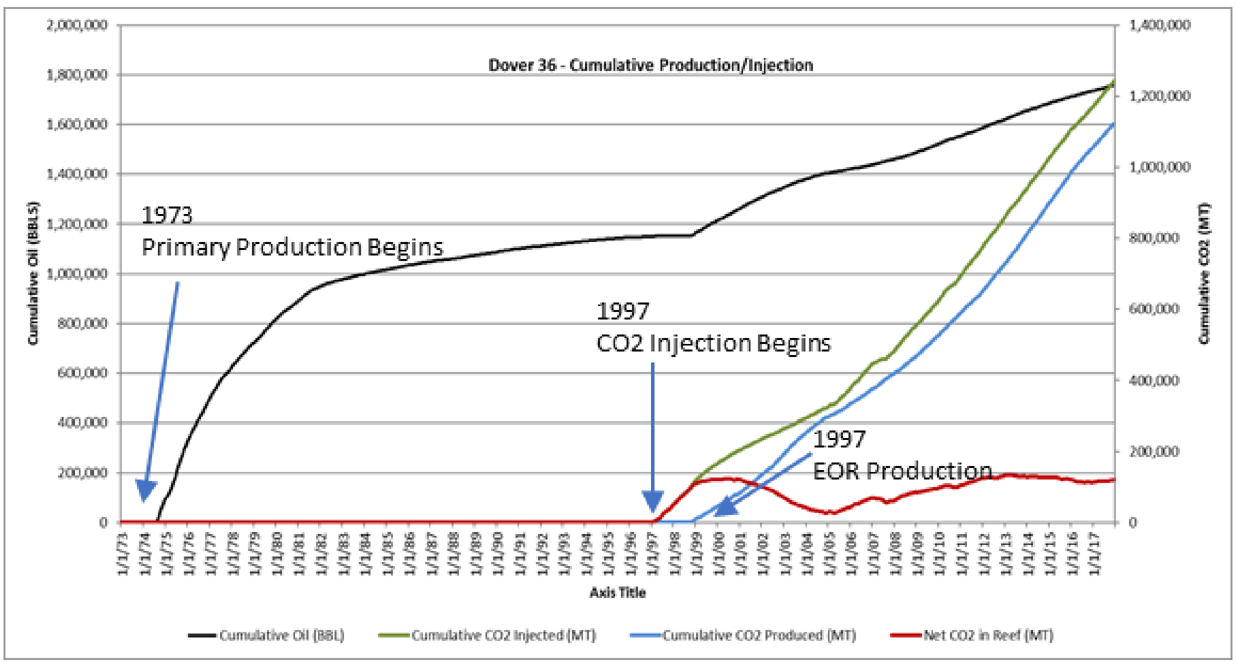


Figure 2-3. Timeline of cumulative production and injection in Dover 36.

2.2.1 Well History

There are three active wells at Dover 36 in the northern part and center of the reef (Table 2-6). Dover 1-36, one of two injection wells, was spudded in April 1973 and drilled vertically to a measured depth of 5,835 feet in the northern area of the reef. Dover 3-35 was spudded in the center of the reef in June 1973 and is currently the second injection well. Dover 3-36, the active producing well, was spudded in July 1998 between the other two active wells. Dover 36 is still considered an active reef with EOR potential for the existing wells.

Table 2-6. Listing of wells at Dover 36 EOR unit.

API Permit	DEQ Permit	Well Name	Shortened Well Name	Well Type	Well Status
21-137-29235-00-00	29235	Kubacki State 1-36	Dover 1-36	Injection	Injection
21-137-29348-00-00	29348	Kubacki State 3-35	Dover 3-35	Injection	Injection
21-137-52719-00-00	52719	Dover 36 Unit 3-36	Dover 3-36	Oil	Producing

2.2.2 Production Since EOR

Table 2-7 shows yearly production and injection rates since the start of EOR in February 1997. The initial CO_2 flood lasted for 21 months, between January 1997 and November 1998, during which approximately 106,000 MT of CO_2 was injected to pressurize the reef. Oil production had started to decrease in 2005 but increased and remained steady for years with increased CO_2 injection. At its peak, about 6,000 BBL of EOR oil per month was being produced during early months of EOR, but overall, the Dover 36 reef continues to produce about 2,000 BBL of oil per month. From the onset of EOR in 1997 through September 2019, the Dover 36 reef has yielded 648,019 BBL of oil, 1,250,840 MT of recycle gas, and 84,069 BBL of water. A total of 1,367,372 MT of CO_2 has been injected. Gas venting has been minimal, with only 290 MT vented.

Table 2-7. Production at Dover 36 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
1997	3,476	875/46,058	0/0	0/0	1,109	46,058
1998	7,364	1,311/68,988	134/7,076	0/0	1,123	107,971
1999	52,608	941/49,548	703/36,977	0/0	600	120,541
2000	47,128	715/37,646	705/37,104	0/0	379	121,084
2001	46,924	592/31,134	947/49,866	0/0	402	102,351
2002	37,806	537/28,262	1,090/57,359	0/0	855	73,254
2003	34,960	593/31,221	1,178/62,010	0/0	1,311	42,465
2004	25,706	575/30,247	884/46,504	0/0	891	26,208
2005	14,910	927/48,778	633/33,294	0/0	417	41,691
2006	17,910	1,339/70,485	819/43,129	0/0	229	69,047
2007	23,346	691/36,374	846/44,522	0/0	306	60,900
2008	26,334	1,401/73,715	932/49,050	2/112	869	85,565
2009	35,245	1,281/67,433	1,112/58,514	3/166	3,456	94,484
2010	32,520	1,317/69,332	1,159/61,000	0/0	4,132	102,816
2011	31,766	1,551/81,656	1,148/60,443	0/0	5,204	124,029
2012	36,389	1,588/83,584	1,446/76,100	0/0	7,512	131,513
2013	35,687	1,535/80,806	1,584/83,360	0/8	6,940	128,959
2014	28,928	1,613/84,912	1,641/86,377	0/0	7,628	127,494
2015	27,319	1,533/80,675	1,648/86,740	0/0	8,041	121,429
2016	23,930	1,229/64,701	1,405/73,956	0/4	7,627	112,173
2017	23,341	1,467/77,205	1,314/69,170	0/0	7,733	120,209
2018	21,838	1,362/71,688	1,418/74,625	0/0	10,340	117,271
2019	12,584	1,006/52,924	1,020/53,664	0	6,965	116,531
Total	**648,019**	**25,980/1,367,372**	**23,766/1,250,842**	**5/290**	**84,069**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.2.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Dover 36 has yielded 170,335 BBL of oil and 54,645 BBL of water during the secondary production period (Table 2-8). The injection rate remained steady at its peak for the first couple years of MRCSP monitoring, but slightly decreased throughout 2015 and on as production rates had been gradually decreasing for more than a year. A net -16,151 MT of CO_2 have been injected, with 504,693 MT injected and 520,844 MT of recycle gas produced. The net injected quantity is negative because during the MRCSP monitoring period, more recycle gas was produced along with oil compared to CO_2 injected quantities. Excess CO_2 produced from this reef is recycled to other reefs within the CO_2-EOR complex, so the net CO_2 remaining within the Dover 36 reef has decreased. All production has occurred at Dover 3-36, which has produced 170,335 BBL of oil, 520,844 MT of gas, and 54,645 BBL of water. During this time, Dover 1-36 has injected 220,320 MT of CO_2, and Dover 3-35 has injected 284,373 MT of CO_2.

Table 2-8. Production at Dover 36 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (MT)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Dover State Unit 3-36	2013	32,425	0	76,311	8	6,311	
	2014	28,928	0	86,377	0	7,628	
	2015	27,319	0	86,740	0	8,041	
	2016	23,900	0	73,956	4	7,627	
	2017	23,341	0	69,170	0	7,733	
	2018	21,838	0	74,625	0	10,340	
	2019	12,584	0	53,664	0	6,965	
Subtotal		**170,335**	**0**	**520,844**	**12**	**54,645**	
Kubacki State 1-36	2013	0	25,637	0	0	0	
	2014	0	32,682	0	0	0	
	2015	0	34,687	0	0	0	
	2016	0	29,407	0	0	0	
	2017	0	36,130	0	0	0	
	2018	0	35,812	0	0	0	
	2019	0	25,965	0	0	0	
Subtotal		**0**	**220,320**	**0**	**0**	**0**	
Kubacki State 3-35	2013	0	46,951	0	0	0	
	2014	0	52,230	0	0	0	
	2015	0	45,988	0	0	0	
	2016	0	35,294	0	0	0	
	2017	0	41,075	0	0	0	
	2018	0	35,876	0	0	0	
	2019	0	26,959	0	0	0	
Subtotal		**0**	**284,373**	**0**	**0**	**0**	
		170,335	**504,693**	**520,844**	**12**	**54,645**	**-16,151**

Figure 2-4 shows the cumulative production and the instantaneous production rates at Dover 36 since the inception of EOR in January 1997 until September 2019. Since the onset of EOR, 1,367,372 MT of CO_2 have been injected, and 1,250,842 MT of CO_2 have been produced. Therefore, a **net 116,531 MT of CO_2 have been retained** in the reef for 22 years. Since the MRCSP monitoring period began, 504,693 MT of CO_2 have been injected, and 520,844 MT of CO_2 have been produced. A net -16,151 MT of CO_2 have been retained in the reef in almost six years due to recycling of excess CO_2 for injection at other reefs within the CO_2-EOR complex.

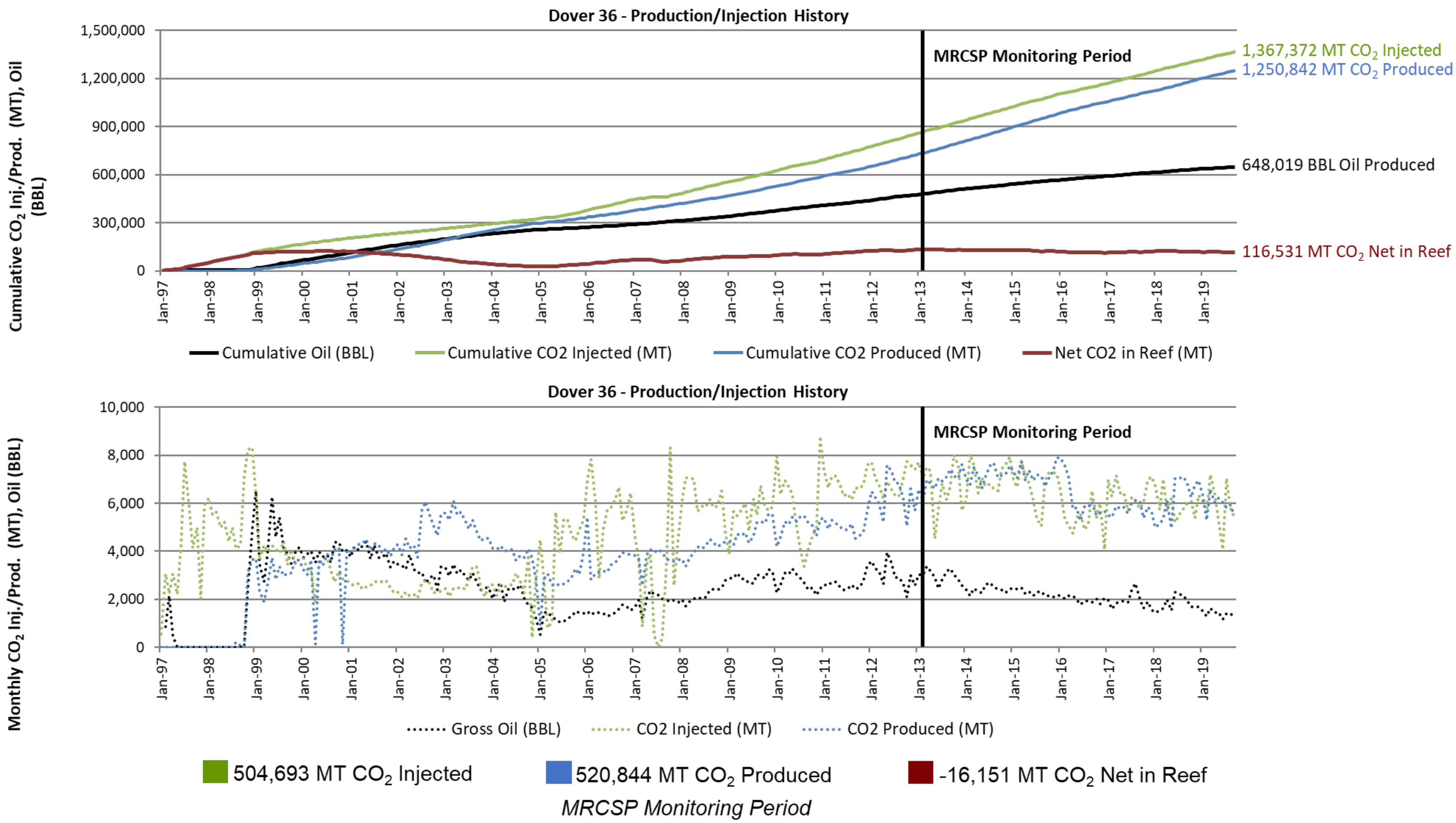


Figure 2-4. Production and injection rates at Dover 36 since EOR inception in 1997.

2.3 Dover 35 Reef

Dover 35 is a round, single-lobe reef in Otsego County. The top of the reef is approximately 5,340 feet (MD) in depth. The initial discovery conditions, summarized in Table 2-9, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-9. Initial reservoir properties of Dover 35.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
2,480,000	41.5	2,946 psia	104	71.88%	0.00%	28.12%

The primary production period lasted approximately 31 years, between June 1973 and April 2004 (Figure 2-5). The primary production period yielded 965,825 BBL of oil and 20,341 BBL of water from June 1973 through April 2004. CO_2 injection and EOR production began in May 2004. Production at Dover 35 was never halted for the initial CO_2 flood, as the reef was put into production mode concurrently. CO_2 injection and production have declined in recent years.

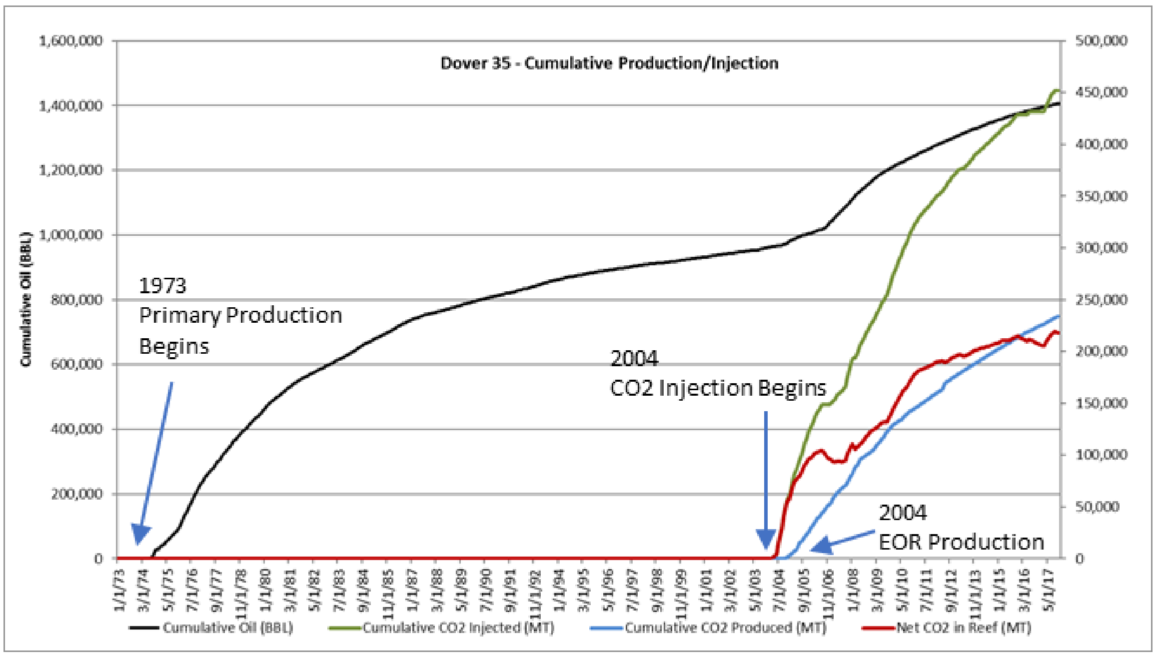


Figure 2-5. Timeline of cumulative production and injection in Dover 35.

2.3.1 Well History

There are four active wells at Dover 35 (Table 2-10). Dover 1-35, the current injection well, was spudded in May 1973 and drilled to 5,780 feet in depth. It was formerly a productive oil well and was spudded in the northeast area of the reef. Dover 5-35, currently a shut-in producer well, was spudded in December 1983 and drilled to 5,864 feet in depth near the center of the reef. Dover 4-35 is an active producing well and was spudded in October 1974 in the northwest area of the reef and drilled to 5,715 feet in depth. Dover 6-35 is the other active producing well just south of Dover 5-35. It was spudded in November 2006 and drilled to a depth of 5,950 feet. Dover 35 is considered an active reef with EOR potential for the existing wells.

Table 2-10. Listing of wells at Dover 35 EOR unit.

API Permit	DEQ Permit	Well Name	Shortened Well Name	Well Type	Well Status
21-137-29236-00-00	29236	Salling Hanson Trust 1-35	Dover 1-35	Injection	Injection
21-137-37324-01-00	59238	Pomarzynski et al. 5-35A	Dover 5-35	Oil	SI-P
21-137-29947-01-00	29995	Salling Hanson Trust 4-35A	Dover 4-35	Oil	Producing
21-137-57787-00-00	57787	Pomarzynski et al. 6-35	Dover 6-35	Oil	Producing

2.3.2 Production Since EOR

Table 2-11 shows yearly production and injection rates since the start of EOR in May 2004 and the secondary production period. The initial CO_2 flood lasted for 29 months, between May 2004 and September 2006, during which about 148,558 MT of CO_2 was injected to pressurize the reef. Injection rates varied but were typically high for the first 29 months. Production rates gradually increased since the start of injection and peaked in 2008 before steeply declining in early 2009. Although there have been some spikes in injection since then, injection and production rates gradually decreased through September 2019. At its peak, about 5,000 BBL of EOR oil per month were being produced, but overall, the Dover 35 reef continues to produce about 1,000 BBL of oil per month. From the onset of EOR through September 2019, the Dover 35 reef yielded 470,798 BBL of oil, 253,069 MT of recycle gas, and 30,120 BBL of water. Additionally, 486,224 MT of CO_2 have been injected and 9,170 MT of gas have been vented.

Table 2-11. Production at Dover 35 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2004	11,804	990/52,080	13/709	0	643	51,372
2005	28,500	1,231/64,801	438/23,027	11/579	3,277	93,145
2006	32,360	602/31,677	514/27,047	11/579	867	97,775
2007	67,411	588/30,927	472/24,829	15/789	739	103,873
2008	62,165	844/44,441	506/26,623	8/421	4,073	121,692
2009	44,508	796/41,896	465/24,448	106/5,579	5,828	139,140
2010	32,522	971/51,099	313/16,458	0/0	1,434	173,781
2011	31,338	529/27,827	267/14,064	2/105	1,311	187,544
2012	29,560	477/25,131	338/17,812	7/368	2,305	194,862
2013	26,126	365/19,199	249/13,097	4/211	1,587	200,964
2014	24,423	369/19,427	238/12,518	2/105	1,179	207,873
2015	21,238	366/19,246	237/12,460	2/105	643	214,658
2016	16,797	74/3,898	200/10,526	2/105	928	208,030
2017	15,806	390/20,506	201/10,567	1/53	2,382	217,970
2018	15,240	385/20,281	205/10,777	1/53	1,829	227,474
2019	11,000	262/13,786	154/8,105	0/12	1,095	233,155
Total	**470,798**	**9,239/486,224**	**4,808/253,069**	**174/9,170**	**30,120**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.3.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Dover 35 has yielded 128,055 BBL of oil and 9,504 BBL of water during the secondary production period (Table 2-12). From the start of MRCSP monitoring through mid-2015, oil production rates were steady at about 2,000 BBL per month but have gradually decreased to approximately 1,000 BBL per month. Injection rates were steady until injection stopped in January 2016, but there have since been sporadic periods of moderately high injection rates. A net 37,560 MT of CO_2 have been injected, with 114,135 MT of CO_2 injected and 76,574 MT of gas produced. Dover 6-35 has produced 82,829 BBL of oil, 40,327 MT of gas, and 2,860 BBL of water. Dover 4-35 has produced 45,221 BBL of oil, 36,180 MT of gas, and 6,644 BBL of water. All injection occurred at Dover 1-35, which has injected 114,135 MT of CO_2.

Table 2-12. Production at Dover 35 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (MT)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Pomarzynski et al. 5-35A	2013	5	0	67	0	0	
	2014	0	0	0	0	0	
	2015	0	0	0	0	0	
	2016	0	0	0	0	0	
	2017	0	0	0	0	0	
	2018	0	0	0	0	0	
	2019	0	0	0	0	0	
Subtotal		**5**	**0**	**67**	**0**	**0**	
Pomarzynski et al. 6-35	2013	15,845	0	6,243	130	376	
	2014	17,503	0	6,698	58	275	
	2015	15,095	0	6,356	60	153	
	2016	10,668	0	5,550	51	235	
	2017	9,656	0	5,786	33	579	
	2018	8,222	0	5,546	21	712	
	2019	5,840	0	4,148	6	530	
Subtotal		**82,829**	**0**	**40,327**	**359**	**2,860**	
Salling Hanson Trust 1-35	2013	0	16,990	0	0	0	
	2014	0	19,427	0	0	0	
	2015	0	19,246	0	0	0	
	2016	0	3,898	0	0	0	
	2017	0	20,506	0	0	0	
	2018	0	20,281	0	0	0	
	2019	0	13,786	0	0	0	
Subtotal		**0**	**114,135**	**0**	**0**	**0**	
Salling Hanson Trust 4-35A	2013	7,701	0	5,311	79	1,072	
	2014	6,920	0	5,821	62	904	
	2015	6,143	0	6,104	61	490	
	2016	6,129	0	4,976	43	693	
	2017	6,150	0	4,781	14	1,803	
	2018	7,018	0	5,230	19	1,117	
	2019	5,160	0	3,957	6	565	
Subtotal		**45,221**	**0**	**36,180**	**283**	**6,644**	
		128,055	**114,135**	**76,574**	**642**	**9,504**	**37,560**

Figure 2-6 shows the cumulative production and the instantaneous production rates at Dover 35 since the inception of EOR in May 2004 until September 2019. Since the onset of EOR, 486,224 MT of CO_2 have been injected, and 253,069 MT of CO_2 have been produced. Therefore, a **net 233,155 MT of CO_2 have been retained** in the reef for 19.5 years. Since the MRCSP monitoring period began, 114,135 MT of CO_2 have been injected, and 76,574 MT of CO_2 have been produced. A net 37,560 MT of CO_2 have been retained in the reef in almost 6 years.

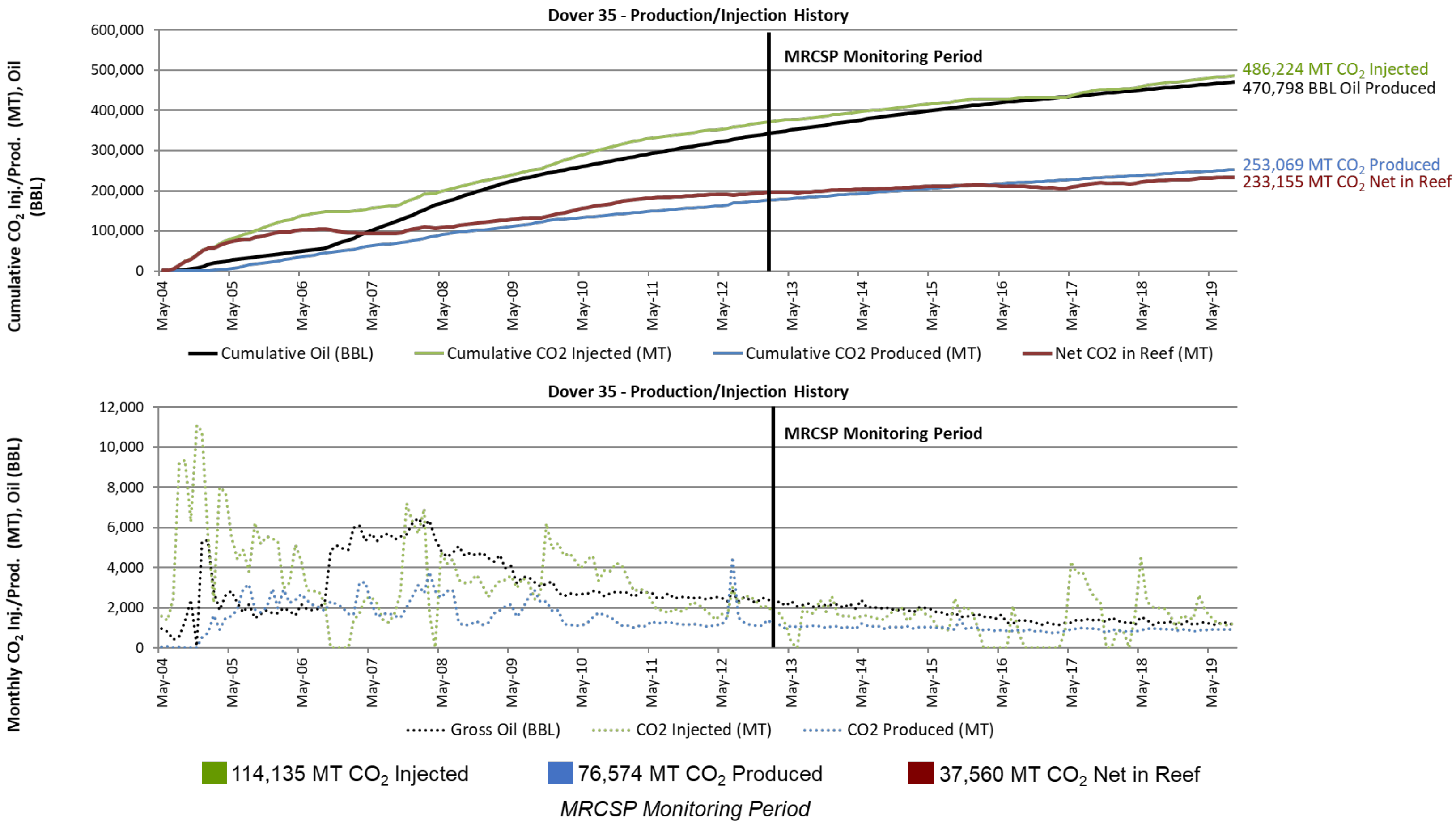


Figure 2-6. Cumulative production and injection rates at Dover 35 since 2004.

2.4 Charlton 30/31 Reef

Charlton 30/31 is an elongated reef extending southwest to northeast. The top of the reef is approximately 5,580 feet (MD) in depth. The Charlton 30-31 began to produce oil in 1974. The initial discovery data, summarized in Table 2-13, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-13. Initial reservoir properties of Charlton 30/31.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
6,800,000	41.9	2,954 psig	103	61.23%	0.00%	38.77%

The primary production period lasted approximately 23 years, from July 1974 until September 1997 (Figure 2-7). Annual field production peaked in 1977, followed by a steady, predictable decline until 1997. The primary production period yielded 2,608,214 BBL of oil between 1974 to 1997. The field was then acquired by Core Energy and additional wells were drilled. No oil was produced from October 1997 until after CO_2 injection began in August 2005. Shortly before injection began in August 2005, 7,318 BBL of water were produced, and production of EOR oil subsequently began in June 2006. CO_2 injection has remained steady and has not yet become uneconomical.

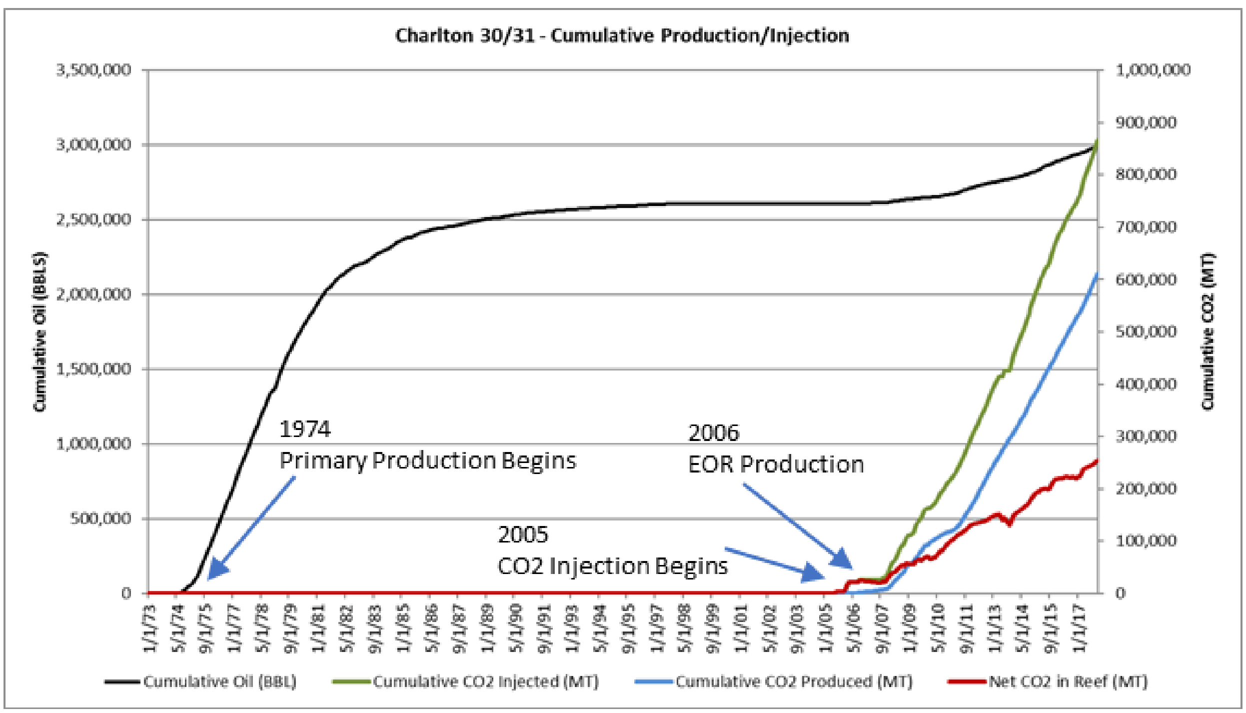


Figure 2-7. Timeline of cumulative production and injection in Charlton 30-31.

2.4.1 Well History

There are five active wells at Charlton 30/31 located throughout the entire elongated reef (Table 2-14). State Charlton C2-30 is one of three injection wells and was formerly a productive oil well. It was spudded in the northwest area of the reef in March 1975 to a total depth of 6,255 feet. State Charlton & Larsen 3-31, a newer injection well, was spudded in the southeast area of the reef in June 2008 to a total depth of 5,800 feet. State Charlton 1-30A is the third injection well, located in the northeast area of the reef, and was spudded in November 1974 to a total depth of 5,650 feet. State Charlton 4-30 is a producing well spudded on the west side of the reef in June 2006 to a depth of 5,800 feet. State Charlton 2-30, the other producing well, was spudded on the east side in November 1976 to a total depth of 5,660 feet. Charlton 30/31 is still considered an active reef with EOR potential for the existing wells.

Table 2-14. Listing of wells at Charlton 30/31 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-30203-00-00	30203	State Charlton C2-30	Injection	Injection
21-137-59048-00-00	59048	State Charlton & Larsen 3-31	Injection	Injection
21-137-29989-00-00	29989	State Charlton 1-30A	Injection	Injection
21-137-57916-00-00	57916	State Charlton 4-30	Oil	Producing
21-137-31287-00-00	31287	State Charlton 2-30	Oil	Producing

2.4.2 Production Since EOR

Table 2-15 shows yearly production and injection rates since the start of injection in August 2005. The initial CO_2 flood lasted 14 months before coming to a stop for a year in October 2006. During this time, only 26,761 MT of CO_2 were injected, and oil production was minimal. Injection resumed in October 2007 but was sporadic until steadily increasing in early 2010. Production rates picked up at this time after years of hovering around 1,500 BBL a month. Injection rates have experienced some variability since MRCSP began monitoring this reef but have remained high on average. Production has followed a similar trend and has only begun to slightly decrease since mid-2017. At its peak, about 6,000 BBL of EOR oil per month were being produced during early 2015, when a cumulative 573,582 MT of CO_2 had been injected. Overall, the Charlton 30/31 reef continues to produce approximately 3,000 BBL of oil per month. From the onset of EOR through September 2019, the Charlton 30/31 reef has yielded 457,775 BBL of oil, 779,213 MT of recycle gas, and 2,085,622 BBL of water. Additionally, 1,056,748 MT of CO_2 have been injected and 2,737 MT of gas have been vented.

Table 2-15. Production at Charlton 30/31 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2005	0	63/3,308	0/0	0/0	28,862	3,308
2006	1,965	446/23,453	60/3,182	52/2,737	154,229	23,578
2007	4,173	122/6,424	106/5,575	22/1,158	84,816	24,428
2008	21,391	1,480/77,891	842/44,296	0/0	161,293	28,023
2009	13,456	992/52,207	756/39,769	0/0	88,338	70,461
2010	19,084	990/52,096	479/25,232	3/158	167,714	97,324
2011	42,893	1,497/78,806	877/46,158	0/0	225,764	129,972
2012	36,229	1,758/92,525	1,437/75,621	0/0	187,608	146,877
2013	29,476	1,288/67,769	1,255/66,053	0/0	184,038	148,592
2014	43,887	2,091/110,061	1,360/71,595	0/0	156,629	187,058
2015	63,796	1,975/103,957	1,387/73,025	0/0	163,046	217,990
2016	52,897	1,484/78,097	1,448/76,199	0/0	160,749	219,888
2017	50,359	2,262/119,052	1,612/84,844	0/0	134,111	254,069
2018	48,154	2,132/112,229	1,880/98,925	77/4,053	122,572	267,401
2019	30,015	1,499/78,872	1,306/68,738	0/0	65,853	277,535
Total	**457,775**	**20,078/1,056,748**	**14,805/779,213**	**52/2,737**	**2,085,622**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.4.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Charlton 30/31 has yielded 315,423 BBL of oil and 969,495 BBL of water for the secondary production period (Table 2-16). Injection rates were fluctuating from month to month at the beginning of MRCSP monitoring but reached a peak in December 2013, with 15,738 MT injected. Since then, injection rates have typically remained between 5,000 and 12,000 MT. Production gradually increased during this period, peaked in July 2015, and have slightly declined since then. A net 128,751 MT of CO_2 have been injected, with 661,631 MT injected and 532,880 MT of gas produced. State Charlton & Larsen 3-31 produced 3,763 BBL of oil in 2013. The well was then converted to an injection well in 2014 and injected 176,443 MT of CO_2. State Charlton 1-30A injected 231,115 MT of CO_2, and State Charlton C2-30 injected 254,073 MT of CO_2. State Charlton 2-30 has produced 135,363 BBL of oil, 247,367 of gas, and 450,402 BBL of water. State Charlton 4-30 has produced 176,297 BBL of oil, 284,925 of gas, and 450,129 BBL of water.

Table 2-16. Production at Charlton 30/31 since MRCSP monitoring.

Well	Production Year	Gross Oil (BBL)	CO_2 Injected (MT)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
State Charlton & Larsen 3-31	2013	3,763	0	588	2	68,964	
	2014	0	15,720	0	0	0	
	2015	0	31,396	0	0	0	
	2016	0	31,324	0	0	0	
	2017	0	37,450	0	0	0	
	2018	0	36,429	0	0	0	
	2019	0	24,124	0	0	0	
Subtotal		**3,763**	**176,443**	**588**	**2**	**68,964**	
State Charlton 1-30A	2013	0	25,139	0	0	0	
	2014	0	41,733	0	0	0	
	2015	0	31,445	0	0	0	
	2016	0	22,651	0	0	0	
	2017	0	44,034	0	0	0	
	2018	0	43,866	0	0	0	
	2019	0	22,247	0	0	0	
Subtotal		**0**	**231,115**	**0**	**0**	**0**	
State Charlton 2-30	2013	11,050	0	28,138	0	48,755	
	2014	15,563	0	32,108	0	65,807	
	2015	28,443	0	38,529	0	72,735	
	2016	21,153	0	29,354	0	91,120	
	2017	22,460	0	38,874	0	67,640	
	2018	22,997	0	47,387	1	64,214	
	2019	13,697	0	32,976	1	40,131	
Subtotal		**135,363**	**0**	**247,367**	**2**	**450,402**	
State Charlton 4-30	2013	11,538	0	30,828	0	48,816	
	2014	28,324	0	39,487	0	90,822	
	2015	35,317	0	34,496	0	90,311	
	2016	31,744	0	46,845	0	69,629	
	2017	27,899	0	45,970	0	66,471	
	2018	25,157	0	51,538	1	58,358	
	2019	16,318	0	35,762	0	25,722	
Subtotal		**176,297**	**0**	**284,925**	**1**	**450,129**	
State Charlton C2-30	2013	0	34,223	0	0	0	
	2014	0	52,608	0	0	0	
	2015	0	41,116	0	0	0	
	2016	0	24,122	0	0	0	
	2017	0	37,568	0	0	0	
	2018	0	31,935	0	0	0	
	2019	0	32,501	0	0	0	
Subtotal		**0**	**254,073**	**0**	**0**	**0**	
		315,423	**661,631**	**532,880**	**6**	**969,495**	**128,751**

Figure 2-8 shows the cumulative production and the instantaneous production rates at Charlton 30/31 since the inception of injection in 2005 until September 2019. Since the onset of EOR, 977,876 MT of CO_2 have been injected, and 710,474 MT of CO_2 have been produced. Therefore, a **net 267,401 MT of CO_2 have been retained** in the reef for 13 years. Since the MRCSP monitoring period began, 661,631 MT of CO_2 have been injected, and 532,880 MT of CO_2 have been produced. A net 128,751 MT of CO_2 have been retained in the reef.

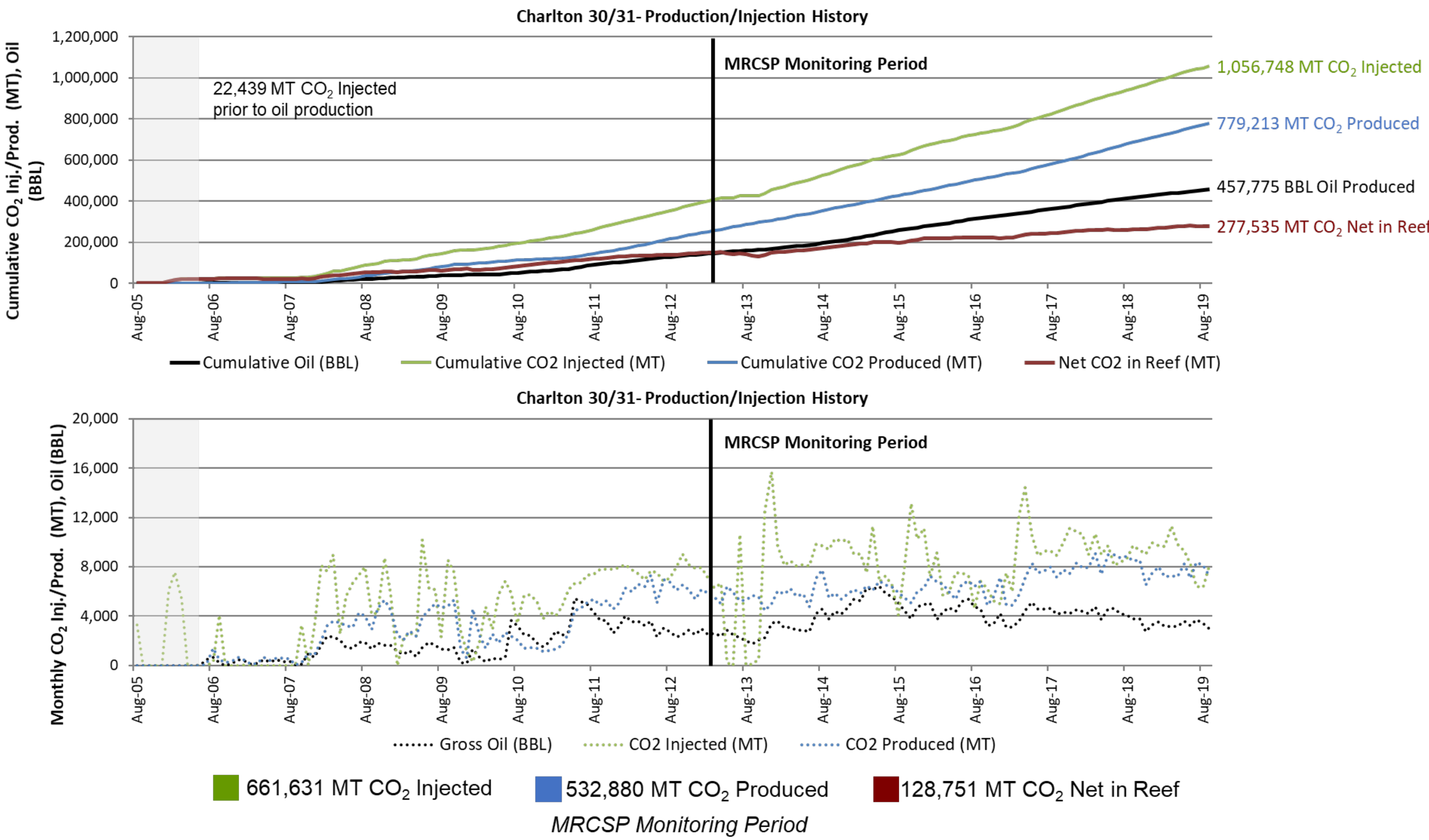


Figure 2-8. Injection rates at Charlton 30/31 since EOR inception in 2005.

2.5 Charlton 6 Reef

Charlton 6 is a relatively small, rounded, single-pod reef. The top of the reef is approximately 5,950 feet (MD) in depth. The initial discovery data, summarized in Table 2-17, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-17. Initial reservoir properties of Charlton 6.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
1,700,000	42.6	3,153 psig	98	78.84%	0.00%	21.16%

The primary production period lasted approximately 24 years, between February 1982 and May 1995, but CO_2 injection did not begin until 2006 (Figure 2-9). Annual field production peaked in 1985 and remained high until 1992, when production followed a steady, predictable decline until stopping in 1995. The primary production period yielded 629,949 BBL of oil and no water production. About 90% of the oil production can be attributed to one well, Zeimet-Higgins & St Charlton 1-6. CO_2 injection began in September 2006, and the production of EOR oil subsequently began in April 2007. CO_2 injection has been minimal in recent years, but Charlton 6 is still considered operational EOR reef. Core Energy also utilizes this reef to inject excess CO_2 available within its EOR complex and produces this CO_2 as needed for injection into other reefs.

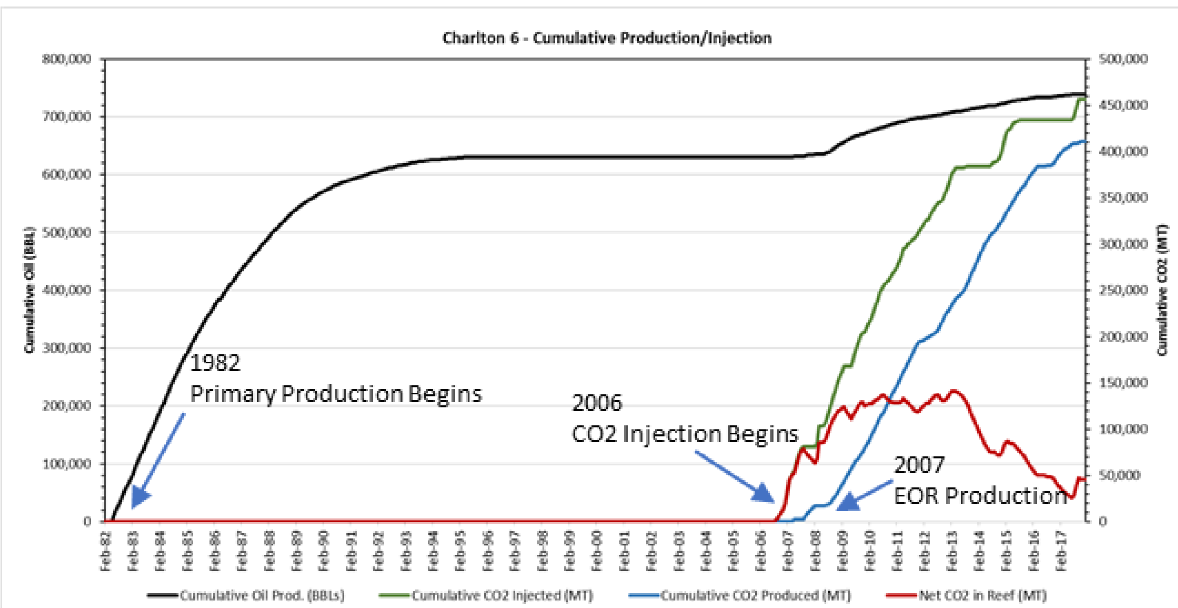


Figure 2-9. Timeline of cumulative production and injection in Charlton 6.

2.5.1 Well History

There are only two active wells at Charlton 6 (Table 2-18). Zeimet-Higgins & St Charlton 1-6, once a productive oil well, is the injection well. It was spudded in the northeast section of the reef in December 1982 and drilled to a total depth of 5,975 feet. The current producing well, State Charlton & Boeve 2-6, was spudded in the western area of the reef in June 2008 and drilled to a total depth of 6,202 feet.

Table 2-18. Listing of wells at Charlton 6 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-35209-00-00	35209	Zeimet-Higgins & St Charlton 1-6	Injection	Injection
21-137-59086-00-00	59086	State Charlton & Boeve 2-6	Oil	Producing

2.5.2 Production Since EOR

Table 2-19 shows yearly production and injection rates since the start of injection in 2006. The initial CO_2 flood lasted for 13 months, from September 2006 through September 2007, during which approximately 81,085 MT of CO_2 was injected to pressurize the reef. Injection rates experienced month-to-month variability when injection resumed in March 2008 until MRCSP monitoring began, but rates tended to decrease. During this time, production peaked in late 2008 and gradually decreased. Injection was uncommon during MRCSP monitoring, and production values continued to decrease. At its peak, about 3,000 BBL of EOR oil per month was being produced during early months of EOR, but overall, the Charlton 6 reef continues to produce less than 100 BBL of oil per month in recent years. From the onset of EOR through September 2019, the Charlton 6 reef has yielded 112,821 BBL of oil, 511,850 MT of recycle gas, and 5,332 BBL of water. Also, 511,850 MT of CO_2 have been injected. Gas venting has been minimal, with only 263 MT vented.

Table 2-19. Production at Charlton 6 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2006	0	233/12,288	0/0	0/0	0	12,288
2007	4,029	1,307/68,797	238/12,517	0/0	351	68,568
2008	15,946	1,322/69,588	382/20,098	5/263	194	118,058
2009	21,257	1,014/53,350	898/47,255	0/0	308	124,153
2010	16,283	1,174/61,766	1,093/57,518	0/0	281	128,402
2011	11,897	930/48,932	1,095/57,625	0/0	212	119,708
2012	7,908	814/42,816	583/30,681	0/0	1,729	131,843
2013	9,248	488/25,682	1,028/54,131	0/0	193	103,395
2014	8,014	467/24,593	924/48,607	0/0	247	79,381
2015	8,743	483/25,412	884/46,525	0/0	1,155	58,268
2016	3,902	0/0	381/20,065	0/0	115	38,203
2017	2,989	429/22,564	308/16,191	0/0	249	44,576
2018	687	129/6,794	82/4,325	0/0	50	47,045
2019	1,918	936/49,268	310/19,339	0/0	248	76,973
Total	**112,821**	**9,726/511,850**	**8,206/434,877**	**5/263**	**5,332**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.5.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Charlton 6 has yielded 32,674 BBL of oil and 2,239 BBL of water for the secondary production period (Table 2-20). Injection occurred at the beginning of MRCSP monitoring but quickly stopped when production languished at less than 1,000 BBL per month. There were a few other short periods of increased injection in March 2014, July 2017, and August 2018, but production rate increases were not economical. A net of 56,304 MT of CO_2 has been produced during the MRCSP monitoring period, with 145,053 MT injected and 201,357 MT of gas produced. Excess CO_2 produced from this reef is recycled to other reefs within the CO_2-EOR complex. Since 2013, State Charlton & Boeve 2-6 has produced 34,592 BBL of oil, 2,239 BBL of water, and 201,357 MT of gas. Zeimet-Higgins & St Charlton 1-6 has injected 145,053 MT of gas.

Table 2-20. Production at Charlton 6 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (tons)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
State Charlton & Boeve 2-6	2013	8,339	0	49,305	0	175	
	2014	8,014	0	48,607	0	247	
	2015	8,743	0	46,525	0	1,155	
	2016	3,902	0	20,065	3	115	
	2017	2,989	0	16,191	0	249	
	2018	687	0	4,325	0	50	
	2019	1,918	0	16,340	0	248	
Subtotal		**34,592**	**0**	**201,357**	**3**	**2,239**	
Zeimet-Higgins & St Charlton 1-6	2013	0	16,422	0	0	0	
	2014	0	24,593	0	0	0	
	2015	0	25,412	0	0	0	
	2016	0	0	0	0	0	
	2017	0	22,564	0	0	0	
	2018	0	6,794	0	0	0	
	2019	0	49,268	0	0	0	
Subtotal		**0**	**145,053**	**0**	**0**	**0**	
		32,674	**145,053**	**201,357**	**3**	**2,239**	**-56,304**

Figure 2-10 shows the cumulative production and the instantaneous production rates at Charlton 6 since the inception of injection in 2006 until September 2019. Since the onset of EOR, 511,850 MT of CO_2 have been injected, and 434,877 MT of CO_2 have been produced. Therefore, a **net 76,973 MT of CO_2 have been retained** in the reef for 12 years. Since the MRCSP monitoring period began, 145,053 MT of CO_2 have been injected and 201,357 MT of CO_2 have been produced. A net of about 56,304 MT of CO_2 have been removed from the reef due to recycling excess CO_2 for injection at other reefs within the CO_2-EOR complex.

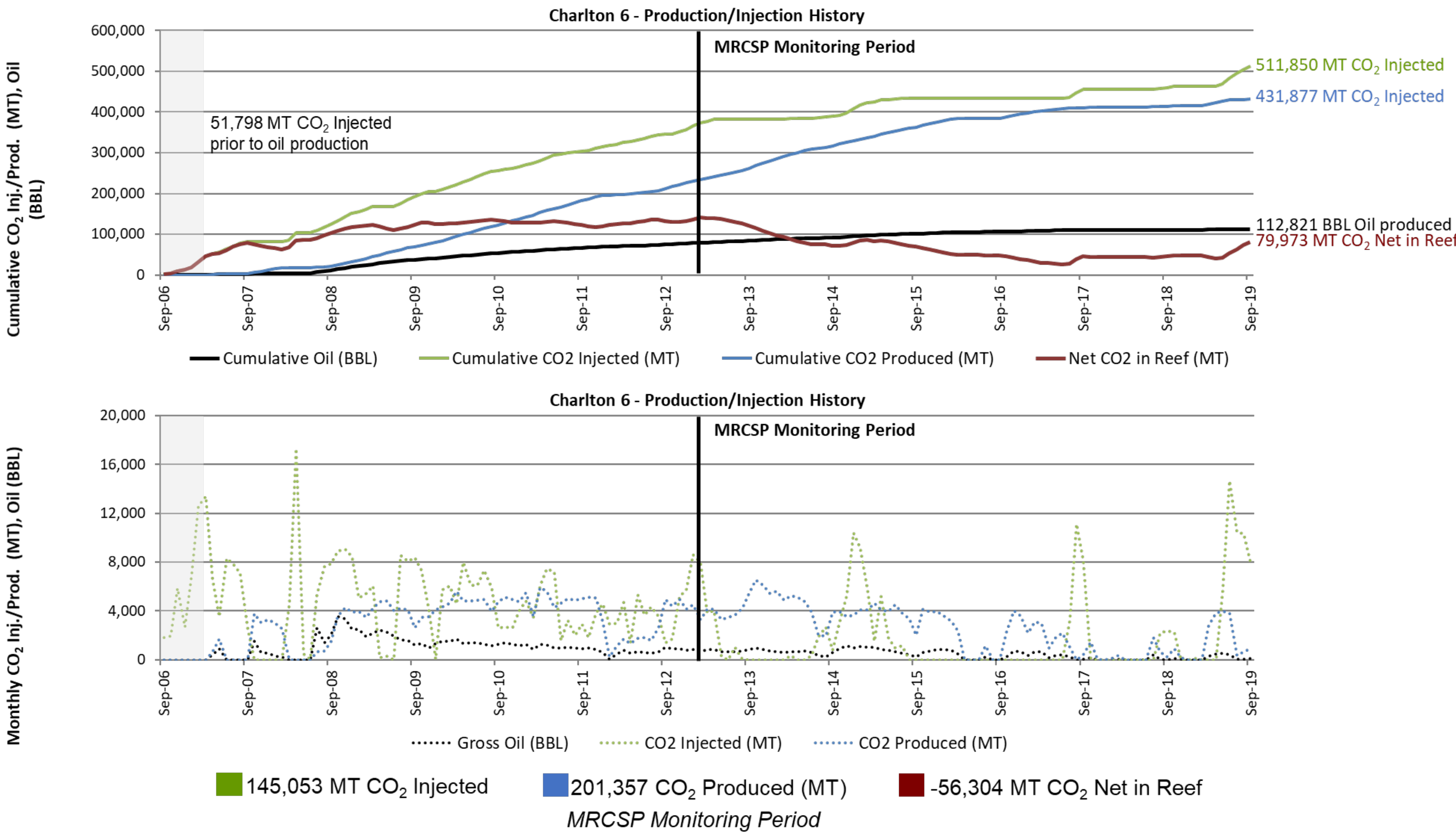


Figure 2-10. Injection rates at Charlton 6 since EOR inception in 1996.

2.6 Chester 2 Reef

Chester 2 is a round, single-pod reef extending north/south. The top of the reef is approximately 5,815 feet (MD) in depth. Chester 2 began to produce oil in 1971. The initial discovery data, summarized in Table 2-21, include OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-21. Initial reservoir properties of Chester 2.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
3,210,000	44	3,000 psig	105	61.97%	0.00%	38.03%

Primary production began in the Chester 2 reef with completion of the first well in October 1971 and ended when CO_2 injection began in 2009 (Figure 2-11). Annual field production peaked in April 1978, followed by a steady, predictable decline until 2009, when primary production was stopped for CO_2 injection. A total of 1,039,304 BBL of oil, 651,545 MCF of gas, and 124,801 BBL of water were produced from this well during primary production. Additional wells were drilled with only one good producer. CO_2 injection commenced in November 2009, with EOR production following in October 2011. Injection has remained steady and has not yet become uneconomical.

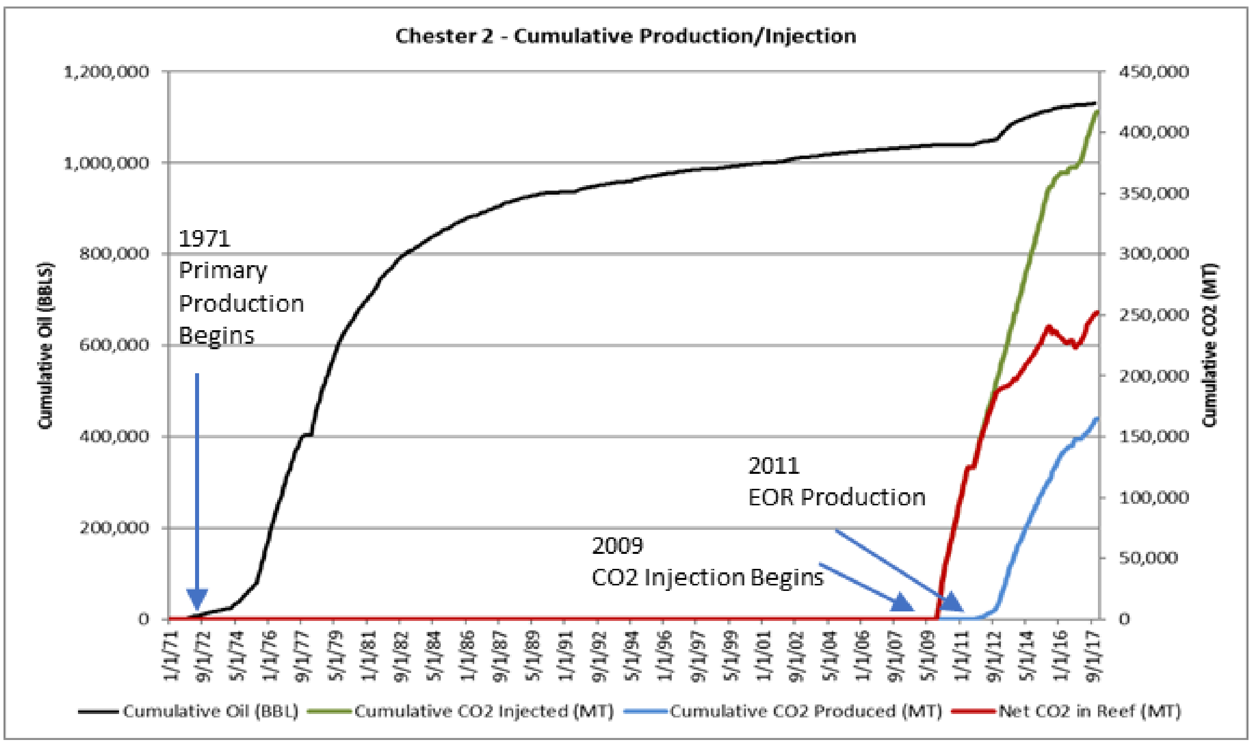


Figure 2-11. Timeline of cumulative production and injection in Chester 2.

2.6.1 Well History

There are three active wells, both in the center of the reef, at Chester 2 (Table 2-22). Wolf, Carl 1A, formerly a production oil well, is the only injector well. It was spudded west of the other two active wells in October 1973 and drilled to a measured depth of 5,973 feet. Wolf, Carl et al. C1-HD1, currently a producing well, was spudded in November 1974 and drilled to a measured depth of 5,806 feet. Cargas 3-2 HD2, the other producing well, was spudded just east of the other two wells in September 2012 and drilled to a measured depth of 6,970 feet. Chester 2 is still considered an active reef with EOR potential for the existing wells.

Table 2-22. Listing of wells at Chester 2 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-29430-00-00	29430	Wolf, Carl 1A	Injection	Injection
21-137-29958-01-00	29958	Wolf, Carl et al. C1-HD1	Oil	Producing
21-137-60596-01-00	60596	Cargas 3-2 HD2	Oil	Producing

2.6.2 Production Since EOR

Table 2-23 shows yearly production and injection rates since the start of EOR and the secondary production period. As of September 2019, approximately 94,090 BBL of oil have been produced from Chester 2 during EOR. A combination of limited reservoir enhancement by dolomitization and pervasive salt plugging in the upper portion of the reef have impeded the EOR project. Development projects, including two lateral wells, have been low producers when compared to the higher quality reservoir of Wolf, Carl 1A.

Instantaneous CO_2 injection rates were highest at the inception of injection operations through July 2011. Over a two-year period, 457,298 MT of CO_2 were injected to get the reservoir to the minimum miscibility pressure for oil mobilization. Injection paused and resumed in October 2011 and remained steady until August 2015. When injection resumed, secondary oil production began, rapidly peaked in December 2012, and gradually declined throughout the MRCSP monitoring period. At its peak, during the early months of EOR, about 3,000 BBL of EOR oil per month was being produced. Overall, however, the Chester 2 reef production has gradually declined to produce less than 200 BBL of oil per month. From the onset of EOR through September 2019, the Chester 2 field has yielded 94,540 BBL of oil, 184,916 MT of gas, and 113,287 BBL of water. Also, 478,969 MT of CO_2 have been injected. Gas venting has been minimal, with only 263 MT vented.

Table 2-23. Production at Chester 2 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2009	0	204/10,737	0/0	0/0	0	10,737
2010	0	1,550/81,582	0/0	0/0	0	92,319
2011	4,059	936/49,256	17/875	0/0	1,656	140,701
2012	12,622	1,101/57,955	216/11,362	5/263	7,325	187,294
2013	36,245	1,130/59,459	911/47,929	0/18	21,179	198,824
2014	16,210	1,151/60,563	682/35,884	0/0	22,131	223,502
2015	12,001	841/44,272	638/33,574	0/0	13,575	234,200
2016	6,267	187/9,846	358/18,818	0/5	12,370	225,229
2017	4,161	831/43,750	313/16,451	0/0	22,331	252,527
2018	2,525	758/39,877	343/18,035	0/0	12,426	274,370
2019	450	412/21,671	38/1,988	0/0	294	294,053
Total	**94,540**	**9,101/478,969**	**3,514/184,916**	**5/263**	**113,287**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.6.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Chester 2 has yielded 74,001 BBL of oil, 168,573 MT of gas, and 102,096 BBL of water for the secondary production period (Table 2-24). The injection rate remained steady at about 5,000 MT per month from the beginning of MRCSP monitoring until rapidly declining in August 2015. Injection increased again in April 2017 through October 2018 but with some sporadic decreases. Chester 2 was most productive at the beginning of the monitoring period and gradually decreased from about 4,000 BBL per month to less than 200 BBL per month. Slight increases in production occurred during increases in injection, but the increases were not sustainable. A net 105,004 MT of CO_2 have been injected with 273,578 MT injected and 168,573 MT of gas produced. All injection occurred at Wolf, Carl 1A, which has injected 273,578 MT of CO_2. Cargas 3-2 HD2 has produced 63,478 BBL of oil, 139,989 MT of gas, and 99,518 BBL of water. Wolf, Carl et al. C1-HD1 has produced 10,523 BBL of oil, 28,585 MT of gas, and 2,578 BBL of water.

Table 2-24. Production at Chester 2 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (MT)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Cargas 3-2 HD2	2013	27,848	0	35,673	0	18,229	
	2014	13,227	0	27,572	0	21,345	
	2015	10,503	0	28,415	0	13,199	
	2016	5,307	0	14,413	5	11,776	
	2017	3,629	0	13,933	0	22,251	
	2018	2,514	0	17,993	0	12,424	
	2019	450	0	1,988	0	294	
Subtotal		**63,478**	**0**	**139,989**	**5**	**99,518**	
Wolf, Carl 1A	2013	0	53,598	0	0	0	
	2014	0	60,563	0	0	0	
	2015	0	44,272	0	0	0	
	2016	0	9,846	0	0	0	
	2017	0	43,750	0	0	0	
	2018	0	39,877	0	0	0	
	2019	0	21,671	0	0	0	
Subtotal		**0**	**273,578**	**0**	**0**	**0**	
Wolf, Carl et al. C1-HD1	2013	4,539	0	8,150	18	740	
	2014	2,983	0	8,312	0	786	
	2015	1,498	0	5,159	0	376	
	2016	960	0	4,404	0	594	
	2017	532	0	2,518	0	80	
	2018	11	0	42	0	2	
	2019	0	0	0	0	0	
Subtotal		**10,523**	**0**	**28,585**	**18**	**2,578**	
		74,001	**273,578**	**168,573**	**23**	**102,096**	**105,004**

Figure 2-12 shows the cumulative production and the monthly production rates at Chester 2 since the injection began in November 2009 until September 2019. Since the onset of EOR, 478,969 MT of CO_2 have been injected, and 184,916 MT of CO_2 have been produced. Therefore, a **net 294,053 MT of CO_2 have been retained** in the reef for nine years. Since the MRCSP monitoring period began, 273,578 MT of CO_2 have been injected, and 168,573 MT of CO_2 have been produced. A net 105,004 MT of CO_2 have been injected in the reef during the MRCSP monitoring period.

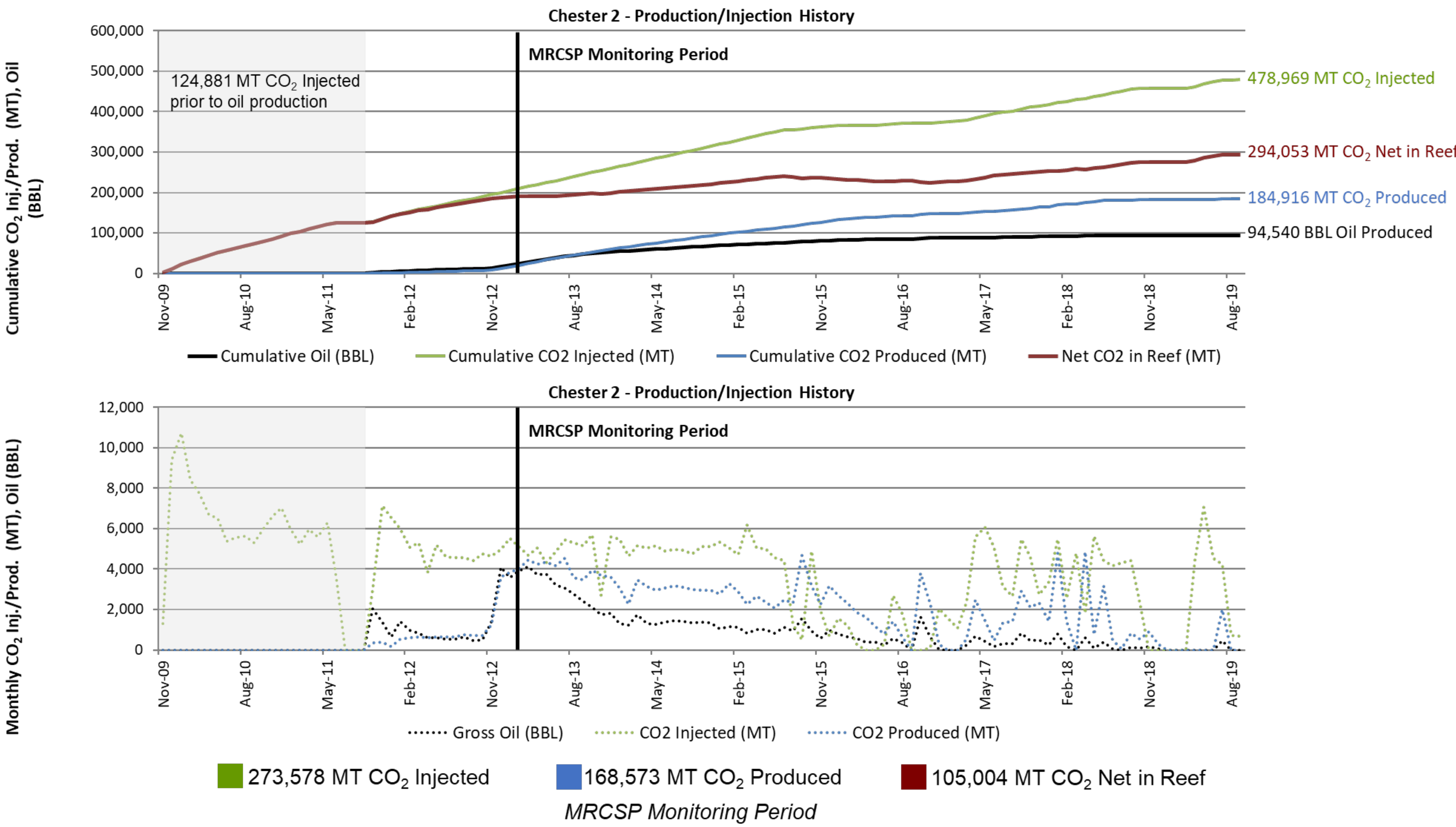


Figure 2-12. Injection rates at Chester 2 since 2009.

2.7 Chester 5/6 Reef

Chester 5/6 is a large, two-pod reef elongated from southwest to northeast. The top of the reef is approximately 5,775 feet (MD) in depth. The reef is divided into one large pod in the southwest and one small pod in the northeast. Chester 6 began producing in January 1973, and Chester 5 began producing in September 1974. The initial discovery data, summarized in Table 2-25, includes OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-25. Initial reservoir properties of Chester 5/6.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
2,890,000	43.6	2,896 psig	103	65.00%	0.00%	35.00%

The primary production period lasted approximately 38 years, from January 1973 through April 2011 (Figure 2-13). The field was inactive for production from September 1987 until June 2010, shortly before injection began. A small amount of production occurred from June 2010 through April 2011, and CO_2 injection began the following month. Annual field production peaked in October 1977, followed by a steady, predictable decline through August 1987 when primary production was stopped. The primary production period yielded 1,229,864 BBL of oil, 1,254,951 MCF of gas, and 55,944 BBL of water. CO_2 injection began in May 2011, and the production of EOR oil subsequently began in January 2012. CO_2 injection has remained steady and has not yet become uneconomical.

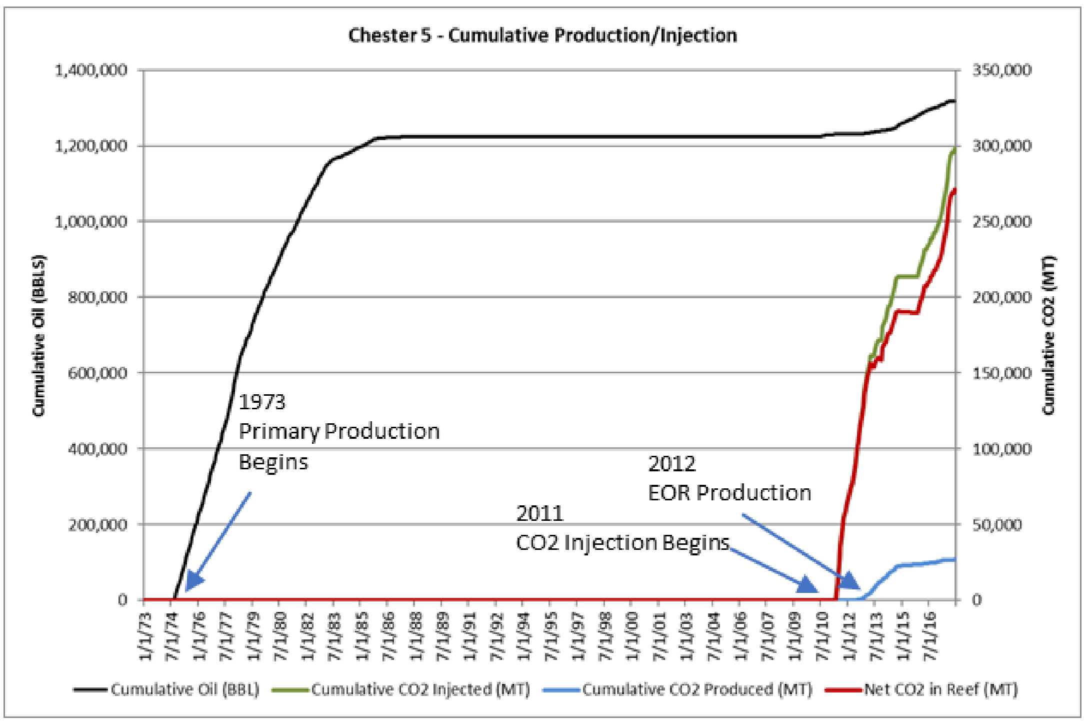


Figure 2-13. Timeline of cumulative production and injection in Chester 5/6.

2.7.1 Well History

There are three active wells at Chester 5/6 across the reef (Table 2-26). Borowiak 2-6, an injection well in the middle part of the reef, was spudded in July 2008 to a total depth of 6,100 feet. Butler 3-5, the other injection well, was spudded in the northeast area of the reef in May 2008 to a total depth of 5,910 feet. The producing well, Piasecki 1-7A, was spudded on the southern portion of the reef in April 1973 to a total depth of 5,760 feet. Chester 5/6 is still considered an active reef with EOR potential for the existing wells.

Table 2-26. Listing of wells at Chester 5/6 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-59237-00-00	59237	Borowiak 2-6	Injection	Injection
21-137-58926-00-00	58926	Butler 3-5	Injection	SI-I
21-137-29265-01-00	60833	Piasecki 1-7A	Oil	Producing

2.7.2 Production Since EOR

Table 2-27 shows yearly production and injection rates since the start of injection in May 2011. The initial CO_2 flood lasted for 24 months, between May 2011 and April 2013. During this time, about 161,228 MT of CO_2 was injected to pressurize the reef. However, the reef started producing as early as January 2012. Injection rates were high during the initial flood and gradually decreased to a brief stop in May 2013. A couple of months later, another CO_2 flood with moderate injection rates occurred from July 2013 through October 2014.

Injection resumed in the MRCSP monitoring period but did not reach pre-monitoring levels. Significant oil production did not begin until mid-2012 and did not significantly increase until after the second CO_2 flood. Production tended to gradually decrease during the monitoring period. At its peak, about 2,000 BBL of EOR oil per month was being produced after the second CO_2 flood, but overall, the Chester 5/6 reef continues to produce about 1,500 BBL of oil per month. From the onset of EOR through September 2019, the Chester 5/6 reef yielded 119,020 BBL of oil, 38,043 MT of gas, and 1,955,779 BBL of water. A total of 370,393 MT of CO_2 was injected. Gas venting was minimal, with only 211 MT vented.

Table 2-27. Production at Chester 5/6 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2011	0	1,177/61,927	0/0	0/0	0	61,927
2012	2,322	1,443/75,922	43/2,288	0/0	96,096	135,561
2013	7,155	812/42,748	215/11,332	3/158	50,136	166,977
2014	17,647	623/32,806	175/9,234	1/53	219,805	190,549
2015	23,290	58/3,045	18/954	0/0	381,410	192,641
2016	21,936	549/28,908	29/1,503	0/0	411,610	220,045
2017	17,772	995/52,361	30/1,598	0/0	308,859	270,808
2018	16,338	588/30,935	86/4,524	0/0	289,693	297,220
2019	12,560	793/41,741	126/6,611	1/54	198,170	332,349
Total	**119,020**	**7,038/370,393**	**722/38,043**	**4/211**	**1,955,779**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

2.7.3 Production Since MRCSP Monitoring

Since MRCSP monitoring began in 2013, Chester 5/6 has yielded 117,743 BBL of oil, 34,821 MT of gas, and 1,852,096 BBL of water for the secondary production period (Table 2-28). Injection resumed in November 2015 and remained steady until quickly reaching a local peak in mid-2017. Since then, injection has hovered around 2,000 MT per month. Production was initially steady at the beginning of MRCSP monitoring but began to decline in September 2016. Since then, production has increased and decreased on a month-to-month basis, depending on injection rates. A net 189,482 MT of CO_2 have been injected, with 224,303 MT injected and 34,821 MT of gas produced. Borowiak 2-6 has produced 10,910 BBL of oil, 19,327 MT of gas, and 89,888 BBL of water, and has injected 156,974 MT of CO_2. Piasecki 1-7A has produced 106,833 BBL of oil, 15,494 MT of gas, and 1,762,208 BBL of water. Butler 3-5 has injected 67,329 MT of gas.

Table 2-28. Production at Chester 5/6 since MRCSP monitoring.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (tons)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Borowiak 2-6	2013	6,300	0	10,397	153	42,549	
	2014	4,610	0	8,930	57	47,339	
	2015	0	3,029	0	0	0	
	2016	0	28,908	0	0	0	
	2017	0	52,361	0	0	0	
	2018	0	30,935	0	0	0	
	2019	0	41,741	0	0	0	
Subtotal		**10,910**	**156,974**	**19,327**	**210**	**89,888**	
Butler 3-5	2013	0	34,507	0	0	0	
	2014	0	32,806	0	0	0	
	2015	0	16	0	0	0	
	2016	0	0	0	0	0	
	2017	0	0	0	0	0	
	2018	0	0	0	0	0	
	2019	0	0	0	0	0	
Subtotal		**0**	**67,329**	**0**	**0**	**0**	
Piasecki 1-7A	2014	14,937	0	304	0	172,466	
	2015	23,290	0	954	24	381,410	
	2016	21,936	0	1,503	13	411,610	
	2017	17,772	0	1,598	3	308,859	
	2018	16,338	0	4,524	8	289,693	
	2019	12,560	0	6,611	54	198,170	
Subtotal		**106,833**	**0**	**15,494**	**102**	**1,762,208**	
		117,743	**224,303**	**34,821**	**312**	**1,852,096**	**189,482**

Figure 2-14 shows the cumulative production and the instantaneous production rates at Chester 5/6 since the start of injection in May 2011 until September 2019. Since the onset of injection, 370,393 MT of CO_2 have been injected, and 38,043 MT of CO_2 have been produced. Therefore, a **net 332,349 MT of CO_2 have been retained** in the reef for seven and a half years. Since the MRCSP monitoring period began, 224,303 MT of CO_2 have been injected, and 34,821 MT of CO_2 have been produced. A net 189,482 MT of CO_2 have been retained in the reef during the MRCSP monitoring period.

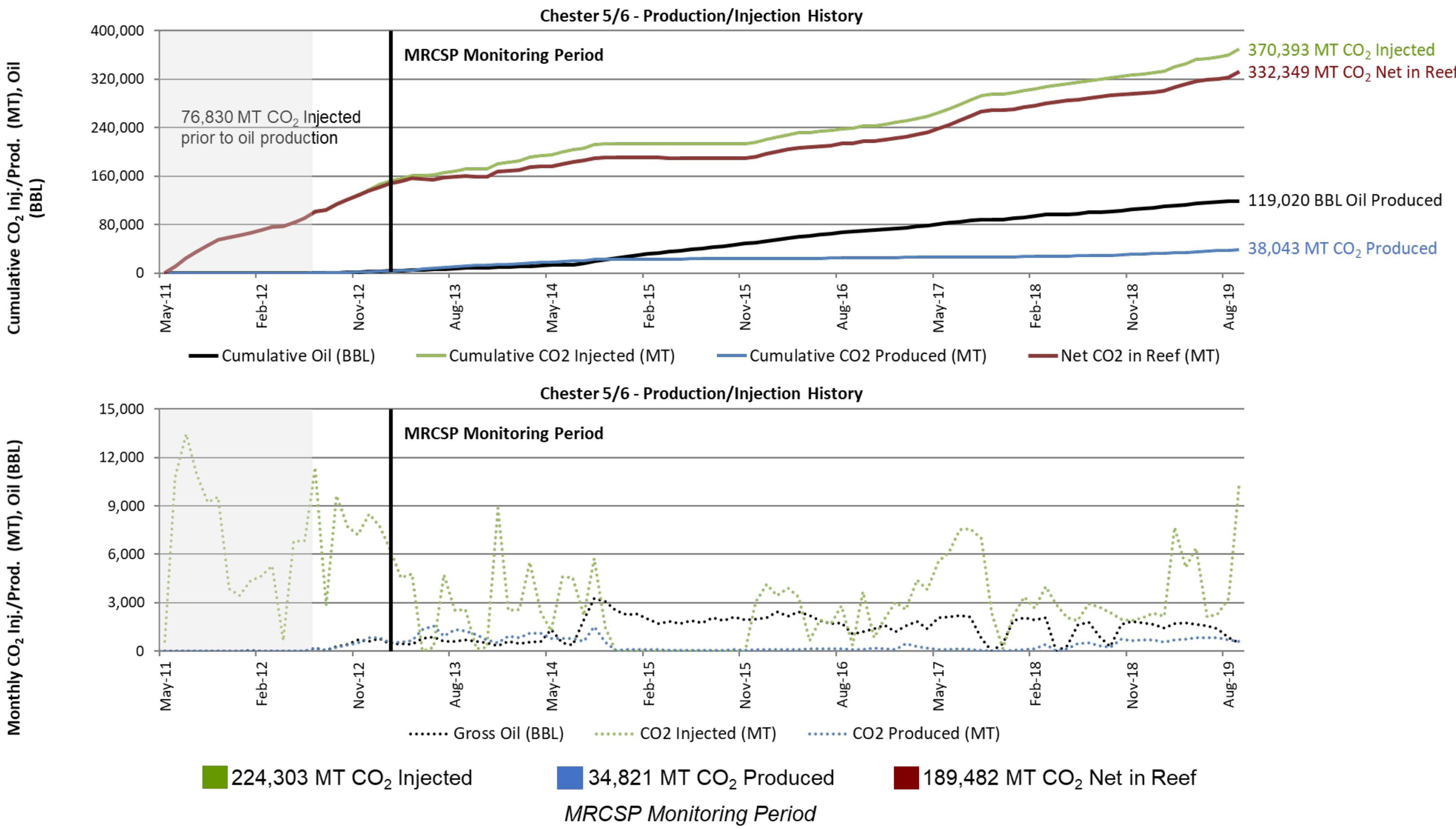


Figure 2-14. Injection rates at Chester 5/6 since 1996.

2.8 Charlton 19 Reef

Charlton 19 is a two-pod reef extending southwest to northeast. The top of the reef core is about 5,300 feet (MD) in depth. Primary production began at Charlton 19 in 1988. The initial discovery data, summarized in Table 2-29, includes OOIP, oil API gravity, discovery pressure and temperature, and fluid saturations. Initial gas saturations were recorded at zero, as gas was produced as it came out of solution during production of oil.

Table 2-29. Initial reservoir properties of Charlton 19.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
2,634,000	42	2,774 psi	103	88.65%	0.00%	11.35%

The primary production period lasted approximately 27 years, from April 1988 through January 2015 (Figure 2-15). Annual field production peaked in 1990, followed by a steady, predictable decline until 2015, when primary production was stopped for CO_2 injection. By the end of primary production, Charlton 19 had produced 1,073,868 BBL of oil, 1,362,221 BBL of water, and 2,304,921 MCF of gas. The southern pod has a significantly smaller volume than the northern pod but accounts for nearly 40% of the production in the Charlton 19 reef. CO_2 injection began in March 2015, and the production of EOR oil subsequently began in June 2017. CO_2 injection has remained steady and has not yet become uneconomical.

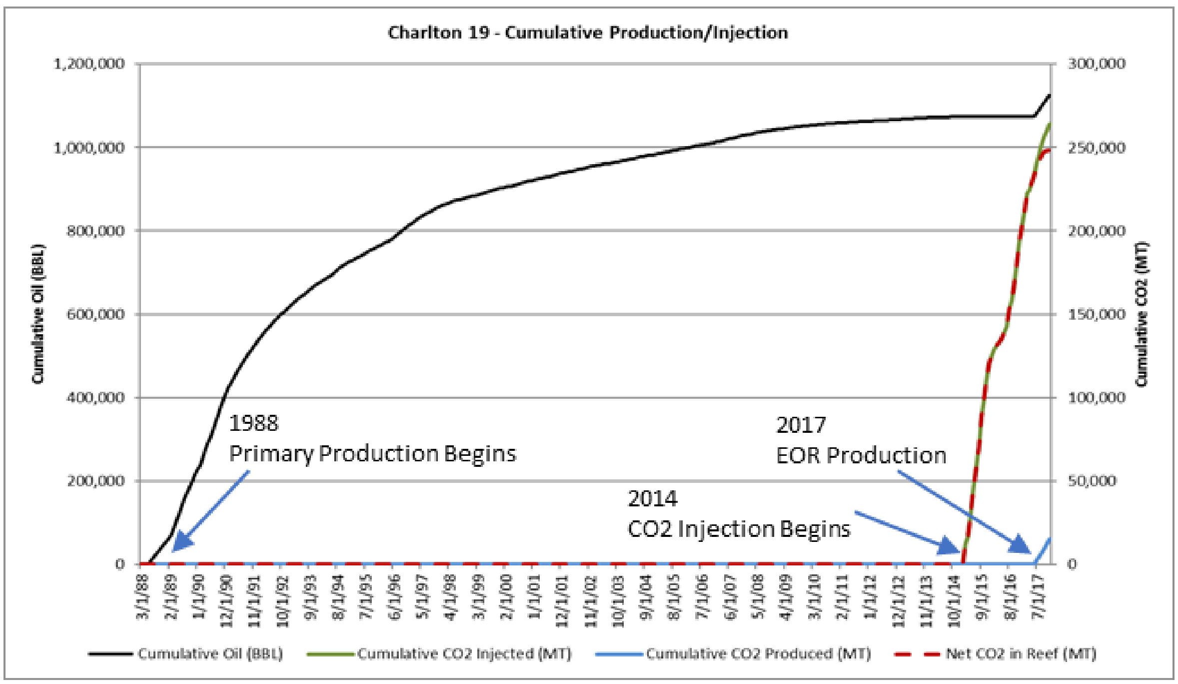


Figure 2-15. Timeline of cumulative production and injection in Charlton 19.

2.8.1 Well History

There are three active wells at Charlton 19 in both pods of the reef (Table 2-30). El Mac Hills 2-18, the current injection well, was spudded in January 1990 and drilled to a measured depth of 5,555 feet. El Mac Hills 1-19D, the SI-P well, was spudded in November 2005 and drilled to a measured depth of 5,495 feet. It is currently the only active well in the southern reef pod. El Mac Hills 1-18A, currently the producing well, was spudded in May 2017 and drilled to a measured depth of 5,546 feet. Charlton 19 is still considered an active reef with EOR potential for the existing wells.

Table 2-30. Listing of wells at Charlton 19 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-42766-00-00	42766	El Mac Hills 2-18	Injection	Injection
21-137-40911-04-00	57261	El Mac Hills 1-19D	Oil	SI-P
21-137-41801-01-00	61197	El Mac Hills 1-18A	Oil	Producing

2.8.2 Production Since EOR

Table 2-31 shows yearly production and injection rates since the start of CO_2 injection in March 2014. The initial flood lasted 27 months, from March 2014 through May 2017. During that time, about 228,983 MT of CO_2 were injected to pressurize the reef.

Injection rates were highest in 2010, the first year of CO_2 injection. A small brief drop of injection rates occurred at the beginning of 2011 but increased until the pressure was high enough for EOR in 2017. Injection decreased in April 2017 but remained steady. Oil production was highest at the beginning of EOR and gradually decreased. At its peak, about 8,000 BBL of EOR oil per month was being produced, but overall, the Charlton 19 reef continues to produce ~6,000 BBL of oil per month. From the onset of EOR through September 2019, the reef has yielded 170,048 BBL of oil, 85,488 MT of recycle gas, and 9,216 BBL of water. A total of 387,042 MT of CO_2 has been injected. No gas has been vented.

Table 2-31. Production at Charlton 19 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2014	131	0/0	0/0	0/0	1,309	0
2015	48	2,283/120,175	0/0	0/0	406	120,175
2016	0	1,389/73,126	0/0	0/0	0	193,301
2017	52,620	1,347/70,874	293/15,441	0/0	3,519	248,734
2018	74,791	1,240/65,250	717/37,749	0/0	3,103	276,235
2019	42,458	1,095/57,617	614/32,298	0/0	879	301,554
Total	**170,048**	**7,354/387,042**	**1,624/85,488**	0/0	**9,216**	-

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

Table 2-32 shows the production and injection by year and by well. The MRCSP monitoring period overlaps with the overall EOR period for the reef. All injection has occurred at El Mac Hills 2-18, where 387,042 MT have been injected. El Mac Hills 1-18A has produced 169,869 BBL of oil, 85,488 MT of gas, and 7,501 BBL of water since 2017. El Mac Hills 1-19D produced 179 BBL of oil and 1,715 BBL of water from 2014 through 2015.

Table 2-32. Total EOR production at Charlton 19.

Well Name	Production Year	Gross Oil (BBL)	CO_2 Injected (tons)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
El Mac Hills 1-18A	2017	52,620	0	15,441	0	3,519	
	2018	74,791	0	37,749	3	3,103	
	2019	42,458	0	32,298	0	879	
Subtotal		**169,869**	**0**	**85,488**	**3**	**7,501**	
El Mac Hills 1-19D	2014	131	0	0	0	1,309	
	2015	48	0	0	0	406	
	2016	0	0	0	0	0	
	2017	0	0	0	0	0	
	2018	0	0	0	0	0	
	2019	0	0	0	0	0	
Subtotal		**179**	**0**	**0**	**0**	**1,715**	
El Mac Hills 2 18	2015	0	120,175	0	0	0	
	2016	0	73,126	0	0	0	
	2017	0	70,874	0	0	0	
	2018	0	65,250	0	0	0	
	2019	0	57,617	0	0	0	
Subtotal		**0**	**387,042**	**0**	**0**	**0**	
		170,048	**387,042**	**85,488**	**3**	**9,216**	**301,554**

Figure 2-16 shows the cumulative production and the monthly production rates at Charlton 19 since the inception of injection in March 2015 until September 2019. During the MRCSP monitoring period, 387,042 MT of CO_2 have been injected, and 85,488 MT of CO_2 have been produced. Therefore, a **net 301,554 MT of CO_2 have been retained** in the reef during the MRCSP monitoring period.

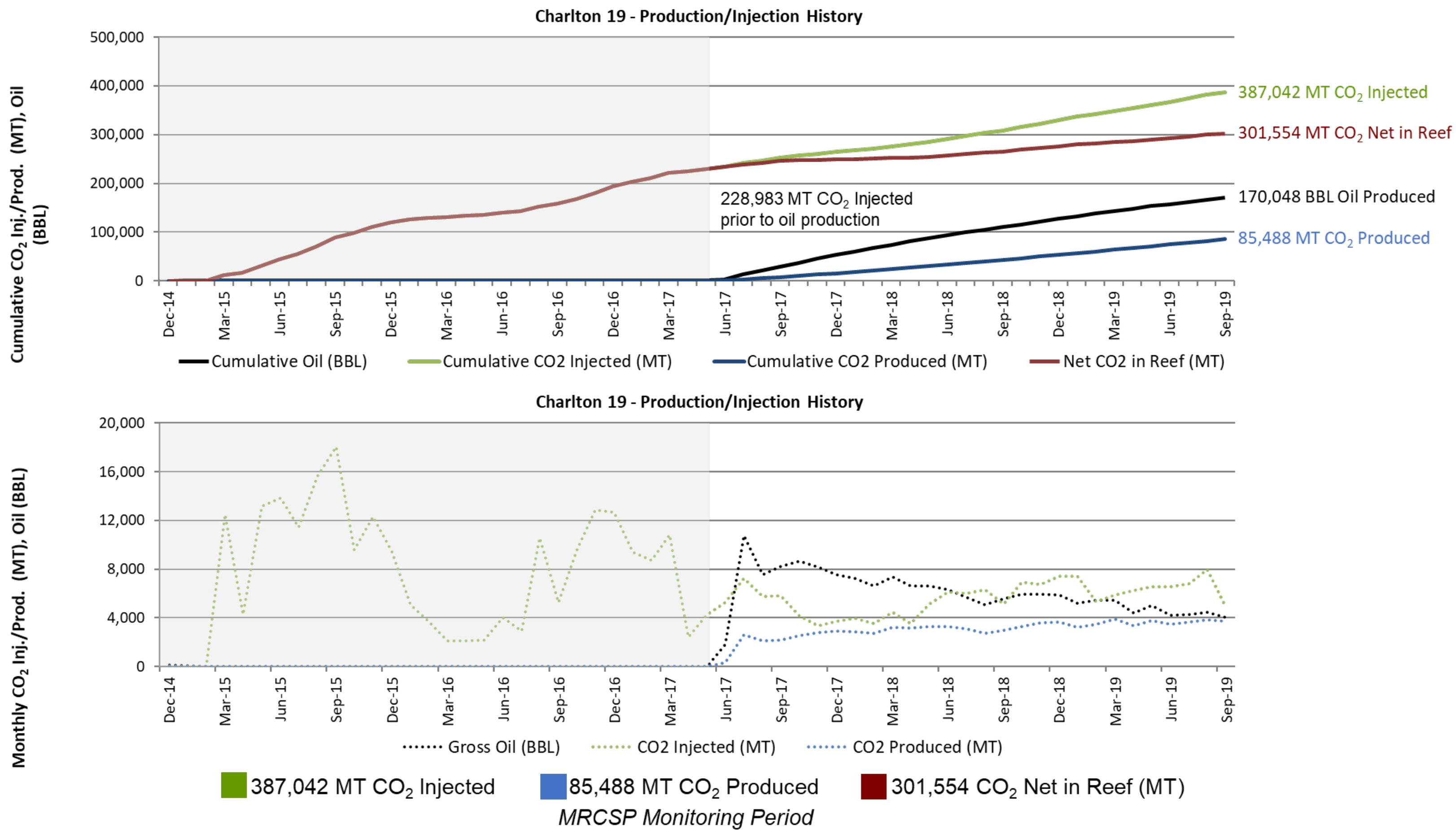


Figure 2-16. Injection rates at Charlton 19 since EOR inception in 2014.

2.9 Bagley Reef

Bagley is a large, hydraulically connected, three-lobe reef in Otsego County, with each lobe unitized as a separate operating unit (referred to as Bagley 11-14-23). The top of the reef tends to be around 5,900 feet (MD) in depth. Bagley began to produce oil in 1973. As shown in Table 2-33, the OOIP was estimated to be over 9 million BBL of oil. The discovery pressure and temperature of the reservoir were 3,096 psia and 104°F. The fluid saturation of the reservoir at inception was 76.72% oil, 0.00% gas, and 23.28% water.

Table 2-33. Initial reservoir properties of Bagley.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
9,046,704	37.4	3096 psig	104	76.72%	0.00%	23.28%

The primary production period lasted approximately 42 years, from October 1973 through October 2015 (Figure 2-17). Production at the Bagley reef commenced with one well; a second well was added in October 1975. Oil production plateaued with increasing water cut beginning in 1979 until reaching approximately 265,000 cumulative BBL in 1984. A significant increase in oil production occurred in 1985 when three additional wells were brought online, eventually leveling off at about 2,919,000 BBL of cumulative oil production before CO_2 gas injection began in December 2015. By September 2019, 485,316 MT of CO_2 had been injected into the reef. Bagley began to produce oil in the northern lobe (Bagley 11) in April 2019.

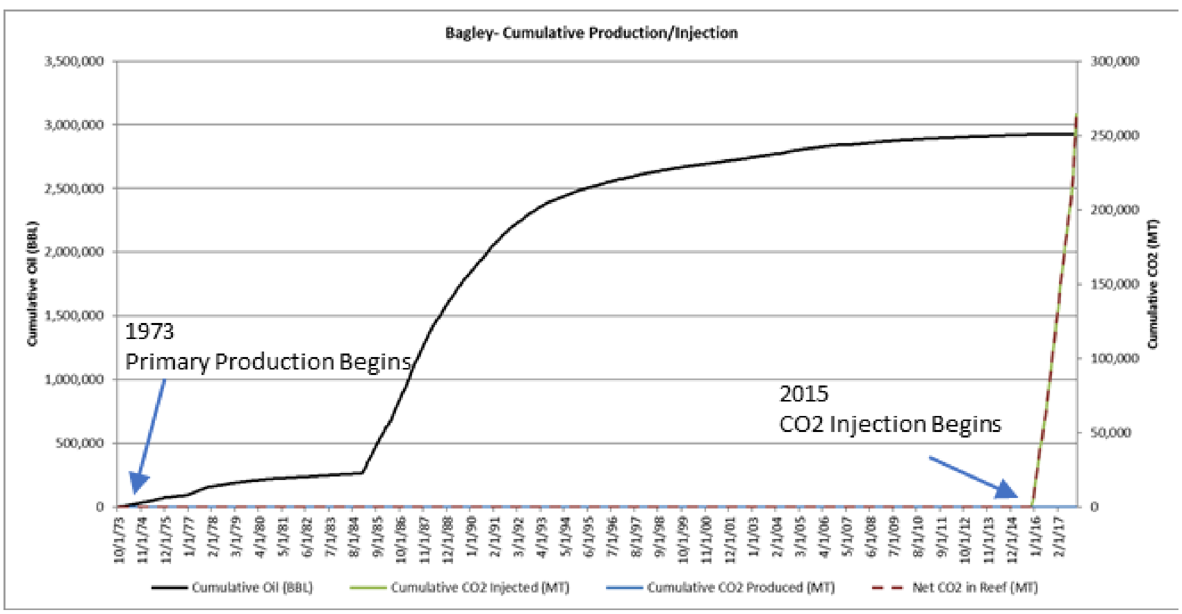


Figure 2-17. Cumulative production in the Bagley reef from 1973 through 2018.

2.9.1 Well History

There are seven active wells between the northern, middle, and southern lobes at Bagley (Table 2-34). Daughters of Friel 2-11, currently an injection well in the northern lobe, was spudded in September 1984 and drilled to a measured depth of 6,250 feet. Wrubel 4-14A, the second active injection well in the middle lobe, was spudded in March 1986 and drilled to a measured depth of 6,200 feet. MBM 1-22, the third injection well in the southern lobe, was spudded in September 1975 and drilled to a measured depth of 6,013 feet. Each lobe has one injection well.

Janik Mackowiac 1-11, currently an observation well, was spudded in June 1984 and drilled to a measured depth of 6,326 feet. Janik Stevens 3-11 was spudded in October 1984 and drilled to a measured depth of 6,045 feet. Janik Strappazon 3-14 was spudded in January 1986 and drilled to a measured depth of 6,000 feet. Glasser 1-14B was spudded in March 1986 and drilled to a measured depth of 6,130 feet.

Table 2-34. Listing of wells at Bagley EOR unit.

API Permit	DEQ Permit	Well Name	Lobe	Well Type	Well Status
21-137-38240-00-00	38240	Daughters of Friel 2-11	Northern	Injection	Injection
21-137-37794-00-00	37794	Janik Mackowiac 1-11	Northern	Oil	Observation
21-137-38286-00-00	38286	Janik Stevens 3-11	Northern	Oil	Observation
21-137-39758-01-00	39866	Wrubel 4-14A	Middle	Injection	Injection
21-137-38859-02-00	39897	Glasser 1-14B	Middle	Oil	Observation
21-137-30536-00-00	30536	MBM 1-22	Southern	Injection	Injection
21-137-39748-00-00	39748	Janik Strappazon 3-14	Southern	Oil	Observation

2.9.2 Production Since EOR

Table 2-35 shows yearly injection rates since the flood was initiated in December 2015. Initially the CO_2 flood only targeted the northern lobe with injection in the Daughters of Friel 2-11 injection well. Injection rates steadily increased from December 2015 until a sharp increase in October 2017, when the middle (Wrubel 4-14A) and southern lobes (MBM 1-22) were added to the Bagley reef, injecting over 16,000 MT of CO_2 monthly. From the onset of injection through September 2019, 622,463 MT of CO_2 was injected in the Bagley reef.

Table 2-35. Production at Bagley since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2015	0	89/4,698	0/0	0/0	0	4,698
2016	0	2,085/109,763	0/0	0/0	0	114,461
2017	0	2,858/150,418	0/0	0/0	0	264,879
2018	0	4,188/220,437	0/0	0/0	0	485,316
2019	7,947	2,606/137,147	707/37,199	3/153	3,730	584,264
Total	**7,947**	**11,737/622,463**	**0/0**	**3/153**	**3,730**	**-**

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2

Table 2-36 shows the injection rates by lobe and by year at Bagley. Like Charlton 19, Bagley's EOR period overlaps with the MRCSP monitoring period. The northern lobe injection well has injected 295,859 MT of CO_2 since 2015. The middle lobe injection well has injected 164,388 MT of CO_2 since 2017. The southern lobe injection well has injected 162,216 MT of CO_2 since 2017. Oil production only recently started in April 2019 at the Bagley reef; to date, 7,947 BBL of oil have been produced from the three lobes combined.

Table 2-36. Yearly injection rates at Bagley since onset of EOR.

Lobe	Production Year	Gross Oil (BBL)	CO_2 Injected (tons)	CO_2 Produced (MT)	Gas Vented (MT)	Produced Water (BBL)	Net CO_2 Injected (MT)
Middle	2017	0	25,547	0	0	0	
	2018	0	91,944	0	0	0	
	2019	4,815	46,897	20,280	71	2,118	
Subtotal		**4,815**	**164,388**	**20,280**	**71**	**2,118**	
Northern	2015	0	4,698	0	0	0	
	2016	0	109,763	0	0	0	
	2017	0	105,990	0	0	0	
	2018	0	34,512	0	0	0	
	2019	50	40,896	9,636	49	53	
Subtotal		**50**	**295,859**	**9,636**	**49**	**53**	
Southern	2017	0	18,881	0	0	0	
	2018	0	93,981	0	0	0	
	2019	3,082	49,354	7,284	34	1,559	
Subtotal		**3,082**	**162,216**	**7,284**	**34**	**1,559**	
		7,947	**622,463**	**37,199**	**153**	**3,730**	**585,264**

Figure 2-18 shows the cumulative injection and the monthly rates at Bagley since the start of injection in December 2015 until September 2019. Since then, 622,463 MT of CO_2 have been injected, and 37,199 MT of CO_2 have been produced. Therefore, a **net 585,264 MT of CO_2 have been retained** in the reef.

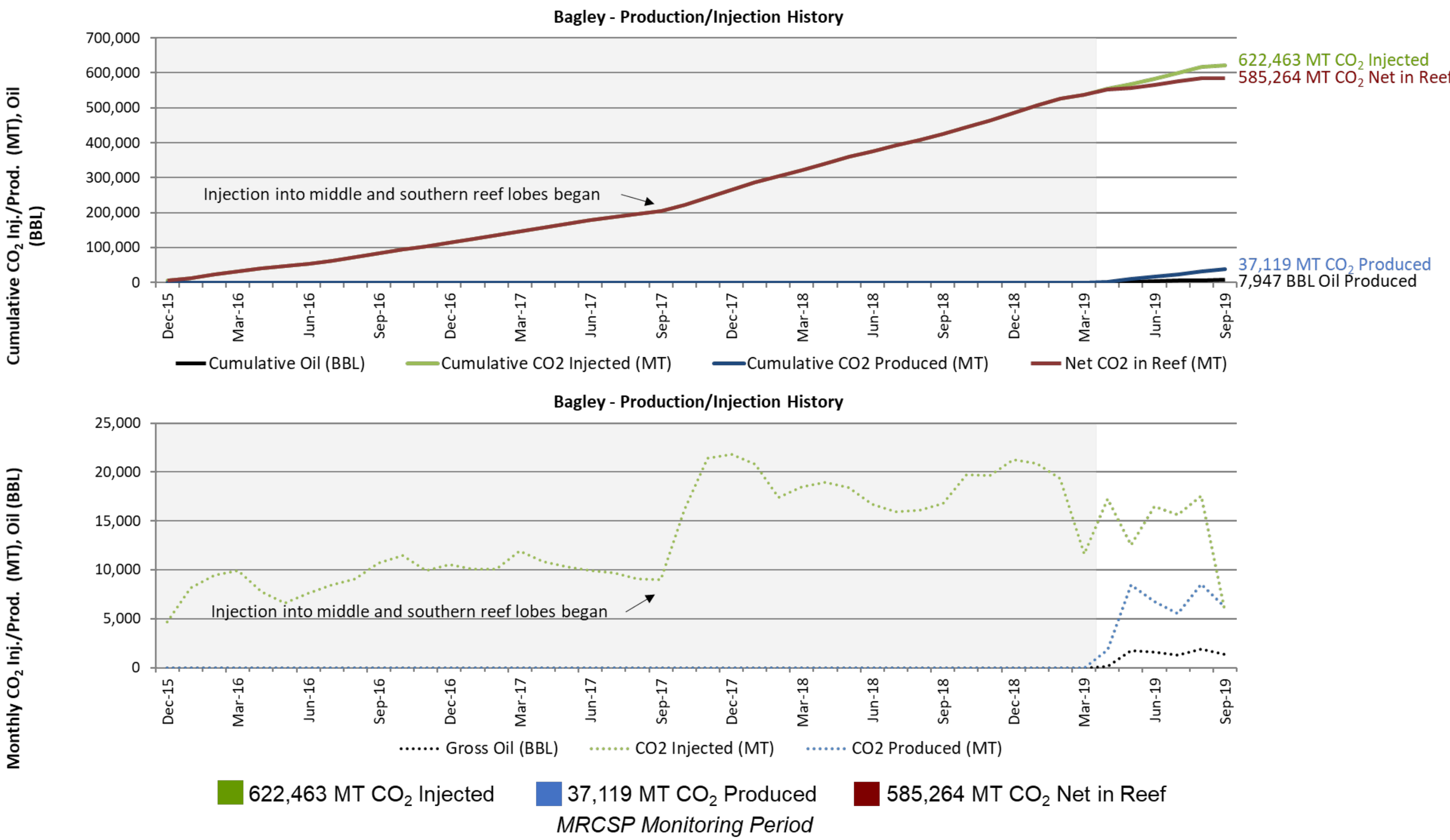


Figure 2-18. Injection/production rates at Bagley reef.

2.10 Chester 16 Reef

Chester 16 is a two-pod reef. The top of the northeast reef pod is about 4,300 feet (MD) in depth, and the top of the southwest pod is about 4,440 feet (MD) in depth. The discovery reservoir conditions prior to the start of production, described in Table 2-37, included OOIP, API gravity, discovery pressure and temperature, and oil/gas/water saturations. It should be noted that the initial gas saturations were 0%; however, gas was produced from the wells as it came out of solution during production of oil.

Table 2-37. Initial reservoir properties of Chester 16.

OOIP (BBL)	API Gravity	Discovery		Saturation		
		Pressure	Temperature (F)	Oil	Gas	Water
6,855,000	43	3,148 psig	110	90%	0%	10%

All wells in the Chester 16 reef were drilled and completed in the early 1970s. The Chester 16 reef produced 3,001,429 MCF of gas and 2,370,247 BBLs of oil during primary production from January 1971 to July 1990. The largest producers were in the center of the reef, and the poorest producers were located on the flanks. CO_2 injection did not begin until January 2017. Figure 2-19 shows the cumulative production for the entire Chester 16 reef with a relative timeline of events. Primary oil production began in 1971 and was further enhanced through water flooding that began in 1983 and ended in 1990. CO_2 injection operations began within this reef in 2017 during the MRCSP monitoring period.

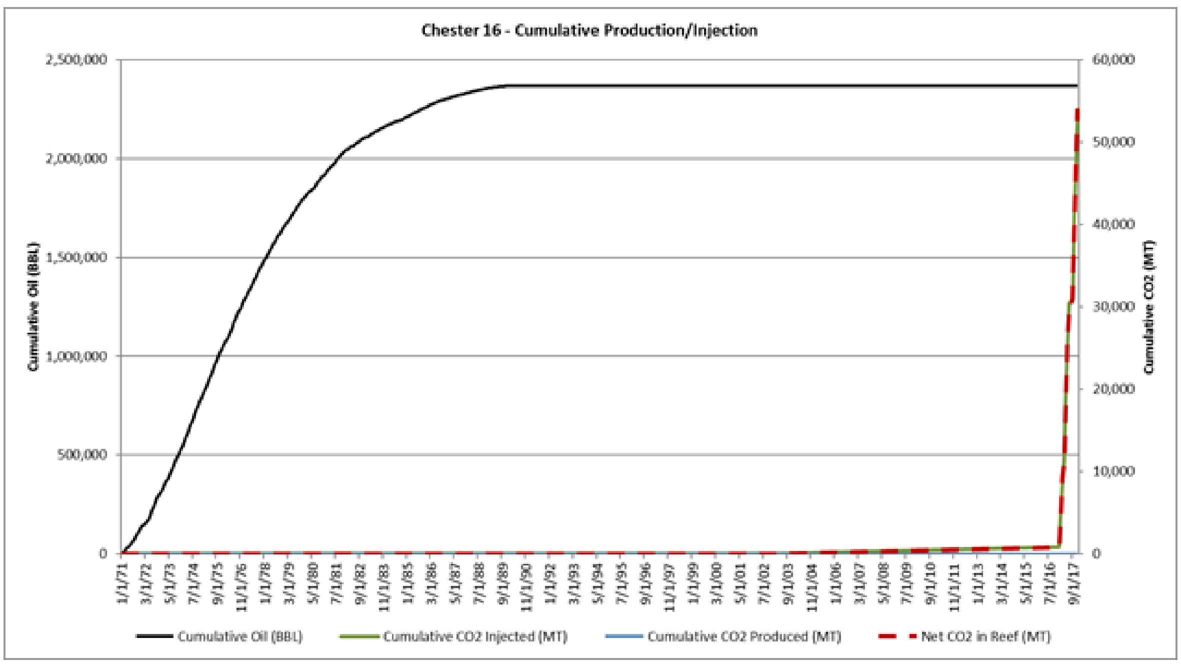


Figure 2-19. Cumulative production in the Chester 16 reef from 1971 through 2017.

2.10.1 Well History

There are currently two active wells (five inactive wells at Chester 16 have been plugged and abandoned) (Table 2-38). Both the Chester #6-16 injection well and the Chester #8-16 observation well were drilled in 2016 during the MRCSP monitoring period. Both wells are instrumented with a distributed temperature sensing (DTS) fiber-optic cable to monitor temperature conditions in the reservoir. The Chester #8-16 well was perforated in August 2019 for injection, but prior to that date, this well was used for monitoring reservoir conditions with behind-casing temperature and pressure sensors.

Table 2-38. Listing of wells at Chester 16 EOR unit.

API Permit	DEQ Permit	Well Name	Well Type	Well Status
21-137-61189-00-00	61189	Chester 16 Unit 6-16 Pilot	Injection	Injection
21-137-61186-00-00	61186	Chester 16 Unit 8-16	Oil	Observation

2.10.2 Production Since EOR

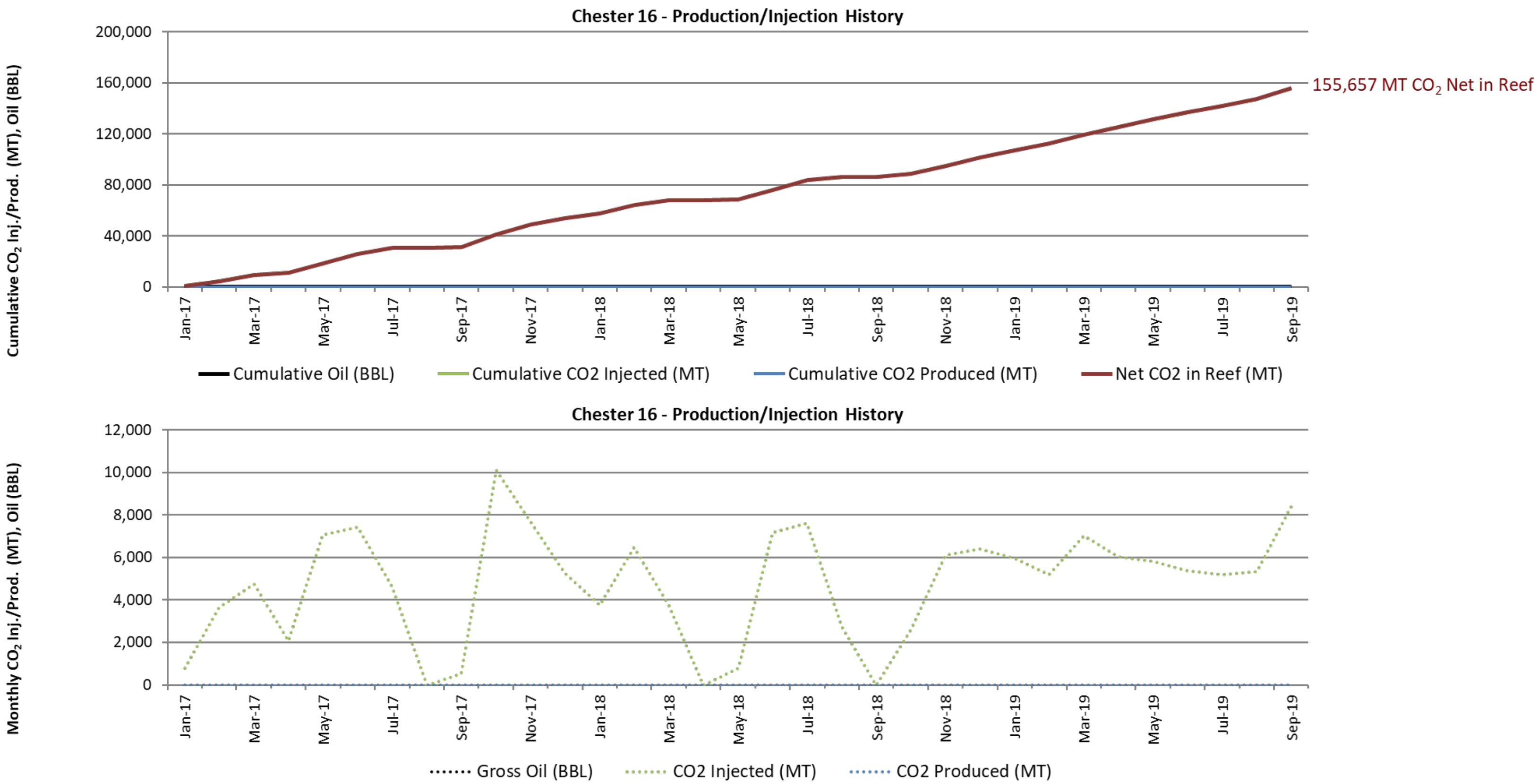
Table 2-39 shows yearly injection rates since the flood was initiated in January 2017. The injection well can be configured to inject CO_2 to the A1 Carbonate or Brown Niagaran formation. These injection details are discussed further in the “Task 5 Chester 16 Reef, Distributed Temperature Sensing (DTS)” report. From the onset of injection through September 2019, 155,657 MT of CO_2 were injected in the Chester 16 reef.

Table 2-39. Production at Chester 16 since onset of EOR.

Production Year	Gross Oil (BBL)	CO_2 Injected (MMCF/MT*)	CO_2 Produced (MMCF/MT*)	Gas Vented (MMCF/MT*)	Produced Water (BBL)	Net in Reef CO_2 (MT*)
2017	0	1,026/54,003	0	0	0	54,003
2018	0	900/47,363	0	0	0	101,366
2019	0	1,032/54,291	0	0	0	155,657
Total	**0**	**2,957/155,657**	**0**	**0**	**0**	

*Core Energy applies a conversion of 19,000 ft^3 per MT of CO_2.

Figure 2-20 shows the cumulative injection and the monthly rates at Chester 16. Since this reef has not yet produced oil or gas, a **net 155,657 MT of CO_2 have been retained** in the reef in the two-year period.



155,657 MT CO_2 Injected | 0 MT CO_2 Produced | 155,657 MT CO_2 Net in Reef

MRCSP Monitoring Period

Figure 2-20. Injection rates at Chester 16 since 2017.

3.0 Aggregate MRCSP Accounting

3.1 Aggregate Accounting of Production Data Since EOR Began

Analysis of detailed production and injection records of individual reefs indicates that since 1996, over 6 million MT of CO_2 have been injected into the 10 reefs that comprise the EOR complex. In the same period, about 4 million MT of CO_2 have been produced from the EOR complex, resulting in the net storage of about 2.2 million MT of CO_2 in the 10 active reefs. Figure 3-1, Figure 3-2, and Figure 3-3 show the CO_2 injection, CO_2 production, and oil production by year for all 10 reefs within the MRCSP reef complex. The figures detail the variability of the reef complex operation over time, including when new reefs are brought within the complex, and indicate the overall level of activity in each reef per year from 1996 through 2019.

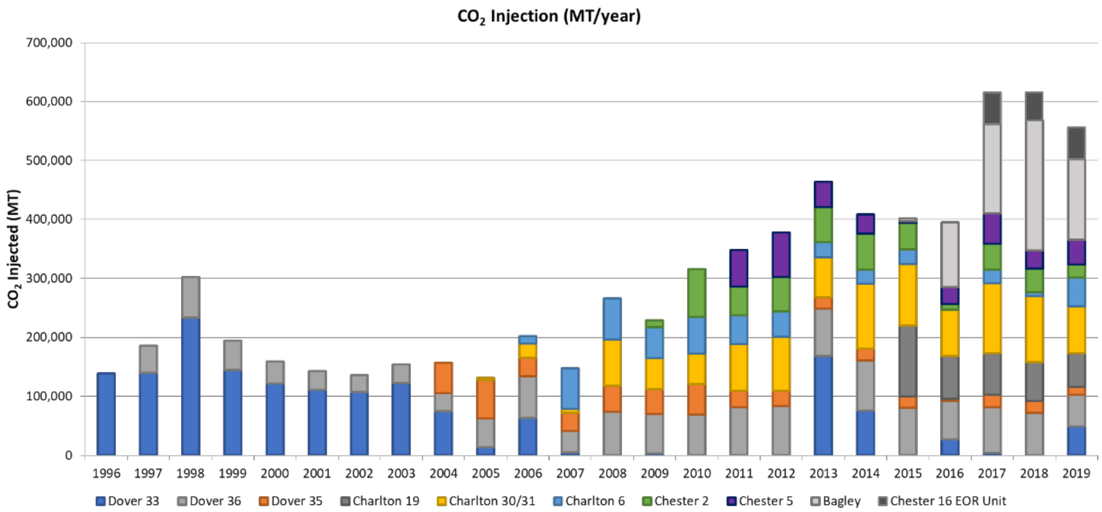


Figure 3-1. Yearly CO_2 injection over the life of the secondary recovery period within the MRCSP reef complex.

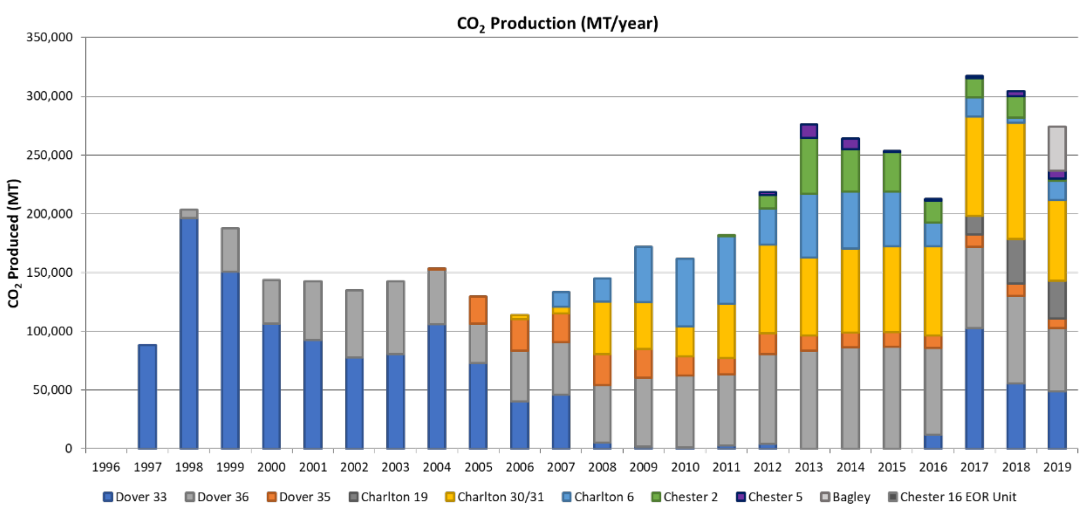


Figure 3-2. Yearly CO_2 production by reef over the life of enhanced recovery operations within the MRCSP reef complex.

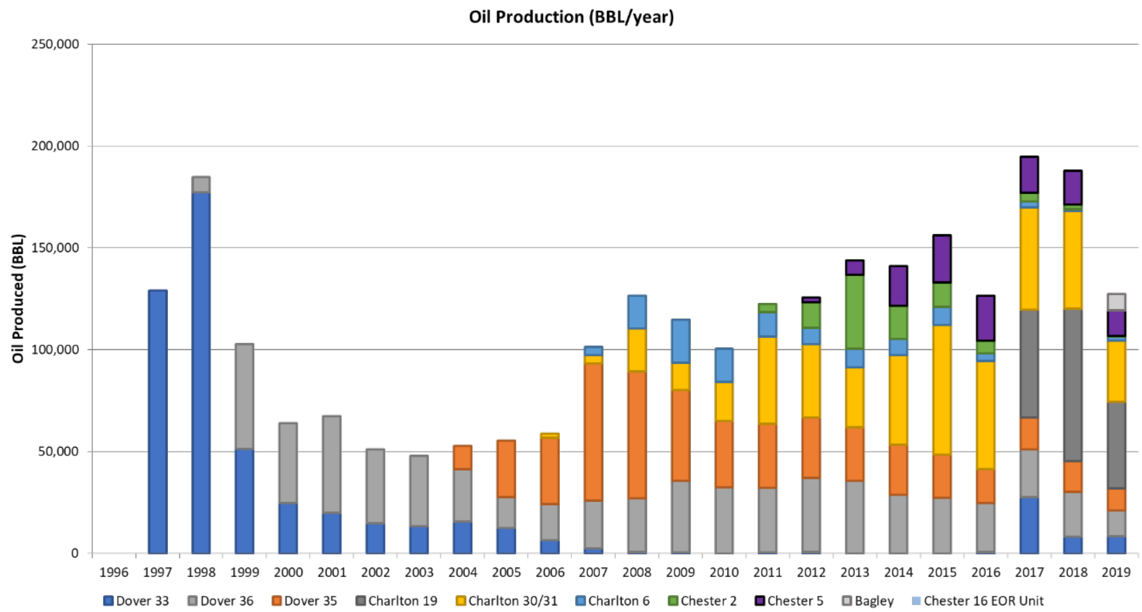


Figure 3-3. Yearly oil production by well over the life of secondary recovery within the MRCSP reef complex.

Figure 3-4 combines all relevant injection and production values over the life of enhanced recovery within the MRCSP reef complex. The orange line details the key metric in these operations, namely the net CO_2 that remains stored within the individual reefs at the end of every calendar year. Through the life of enhanced production operations with the 10 reefs, approximately 2.7 million MT of CO_2 remain stored within the reef complex as of September 30, 2019.

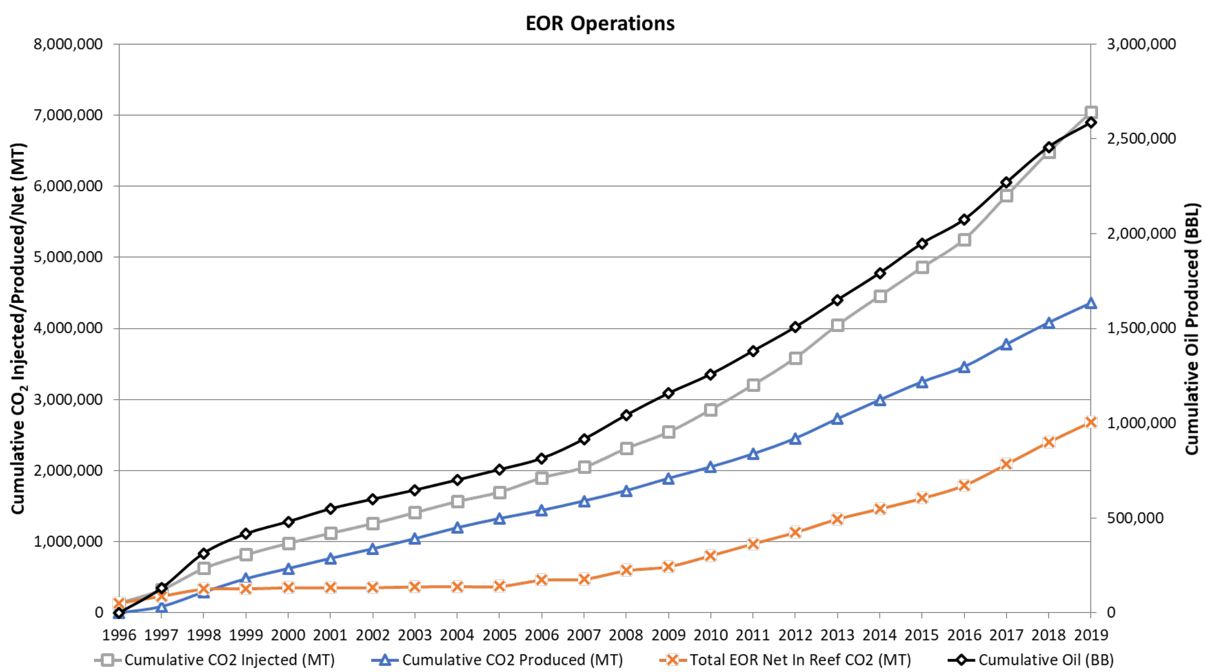
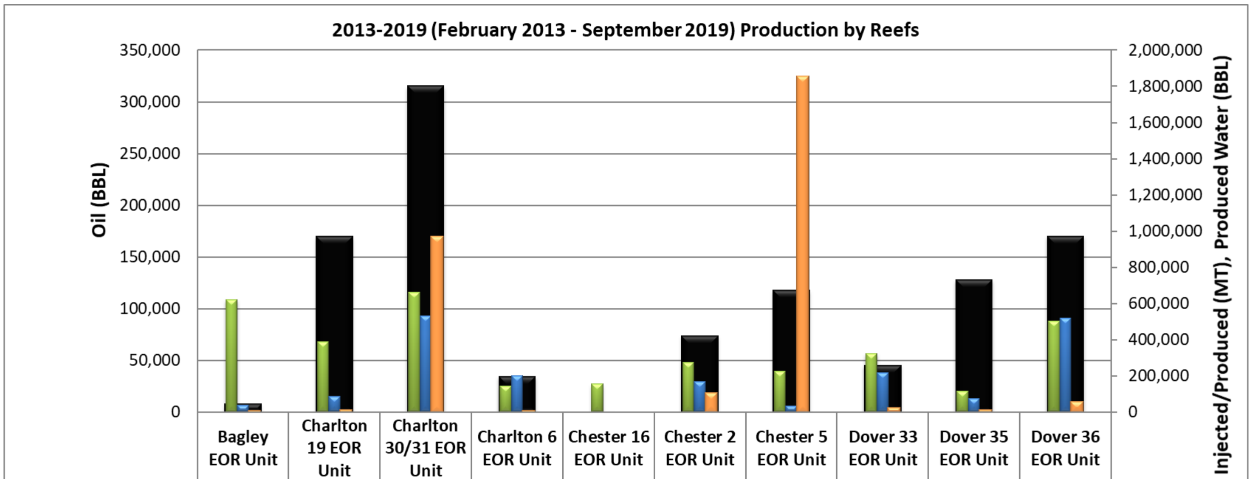


Figure 3-4. Yearly EOR production over the life of secondary recovery within the MRCSP reef complex.

3.2 Accounting of Production Data over MRCSP Monitoring Period

Once MRCSP monitoring began in February 2013, aggregate accounting for all reefs started counting toward the goal of 1 million MT stored. While 1 million MT net stored within the MRCSP reefs remained the primary goal, individual accounting of all injection and production throughout the life of the monitoring period allows for a more in-depth understanding of the nature of reef production behavior over time. Figure 3-5 shows the variability of the production performance of the individual reefs over the life of the MRCSP monitoring period.



	Bagley EOR Unit	Charlton 19 EOR Unit	Charlton 30/31 EOR Unit	Charlton 6 EOR Unit	Chester 16 EOR Unit	Chester 2 EOR Unit	Chester 5 EOR Unit	Dover 33 EOR Unit	Dover 35 EOR Unit	Dover 36 EOR Unit
Gross Oil (BBL)	7,947	170,043	315,401	34,592	0	74,001	117,731	45,590	128,050	170,321
CO2 Injected (MT)	622,463	387,042	661,631	145,053	155,657	273,578	224,303	325,272	114,135	504,693
CO2 Produced (MT)	37,199	85,488	532,880	201,357	0	168,573	34,821	219,360	76,574	520,844
Prod Water (BBL)	3,730	9,215	969,482	2,239	0	102,096	1,852,092	19,888	9,504	54,645

Figure 3-5. Overall reef production during the MRCSP monitoring period (February 2013 through September 2019).

As mentioned in Section 1.0, the MRCSP program was divided into tasks that represented differentiated conditions and inquiry with the MRCSP reef complex. Task 3 focused on the Dover 33 reef. Task 4 expanded this approach to include eight reefs, some of which had been operational prior to MRCSP involvement and some that were incorporated into the reef complex during the MRCSP program. Task 5 focused on the Chester 16 reef. Table 3-1 details the yearly injection and production accounting by task over the MRCSP monitoring period. The primary net injection (amount of CO_2 that remains stored) occurred with the eight Task 4 reefs, with over 1.2 million MT of CO_2 stored, while Tasks 3 and 5 both have a net in-reef total of over 100,000 MT of CO_2.

Table 3-1. Task-level accounting of CO_2 during MRCSP monitoring period.

Task	Production Year	CO_2 Injected (MT)	CO_2 Produced (MT)	Net Injection (MT)	Gas Vented (MT)	Oil Produced (BBL)	Water Produced (BBL)
Task 3	2013	168,047	167		42	45	79
	2014	76,166	0		0	0	0
	2015	0	0		0	0	0
	2016	26,937	11,789		0	845	242
	2017	4,450	102,912		0	27,813	10,693
	2018	334	55,468		3	8,328	2,427
	2019	49,338	49,024		2	8,559	6,447
	Subtotal:	**325,272**	**219,360**	**105,912**	**47**	**45,590**	**19,888**
Task 4	2013	253,467	251,010		391	129,353	235,987
	2014	332,362	264,215		177	141,140	408,928
	2015	401,480	253,278		145	156,399	568,276
	2016	368,338	201,068		119	125,699	593,399
	2017	556,731	214,262		50	167,048	479,184
	2018	567,491	248,960		52	179,573	440,013
	2019	453,026	224,944		220	118,932	277,935
	Subtotal:	**2,857,169**	**1,657,737**	**1,275,158**	**1,155**	**1,018,144**	**3,003,022**
Task 5	2017	54,003	0		0	0	0
	2018	47,363	0		0	0	0
	2019	54,291	0		0	0	0
	Subtotal:	**156,657**	**0**	**156,657**	**0**	**0**	**0**
	Total:	**3,413,824**	**1,877,097**	**1,536,727**	**1,202**	**1,063,734**	**3,022,910**

Figure 3-6 shows the distribution of the **net amount of CO_2 stored (approximately 2.7 million MT)** in the 10-reef EOR complex since EOR began in 1996, and **over 1.5 million net MT of CO_2 stored** in last 6+ years of the **MRCSP monitoring period**. The main objective of MRCSP monitoring net 1 million MT CO_2 stored target was achieved in March 2018. The color-coded bars in Figure 3-6 show the amount of CO_2 stored in each individual reef.

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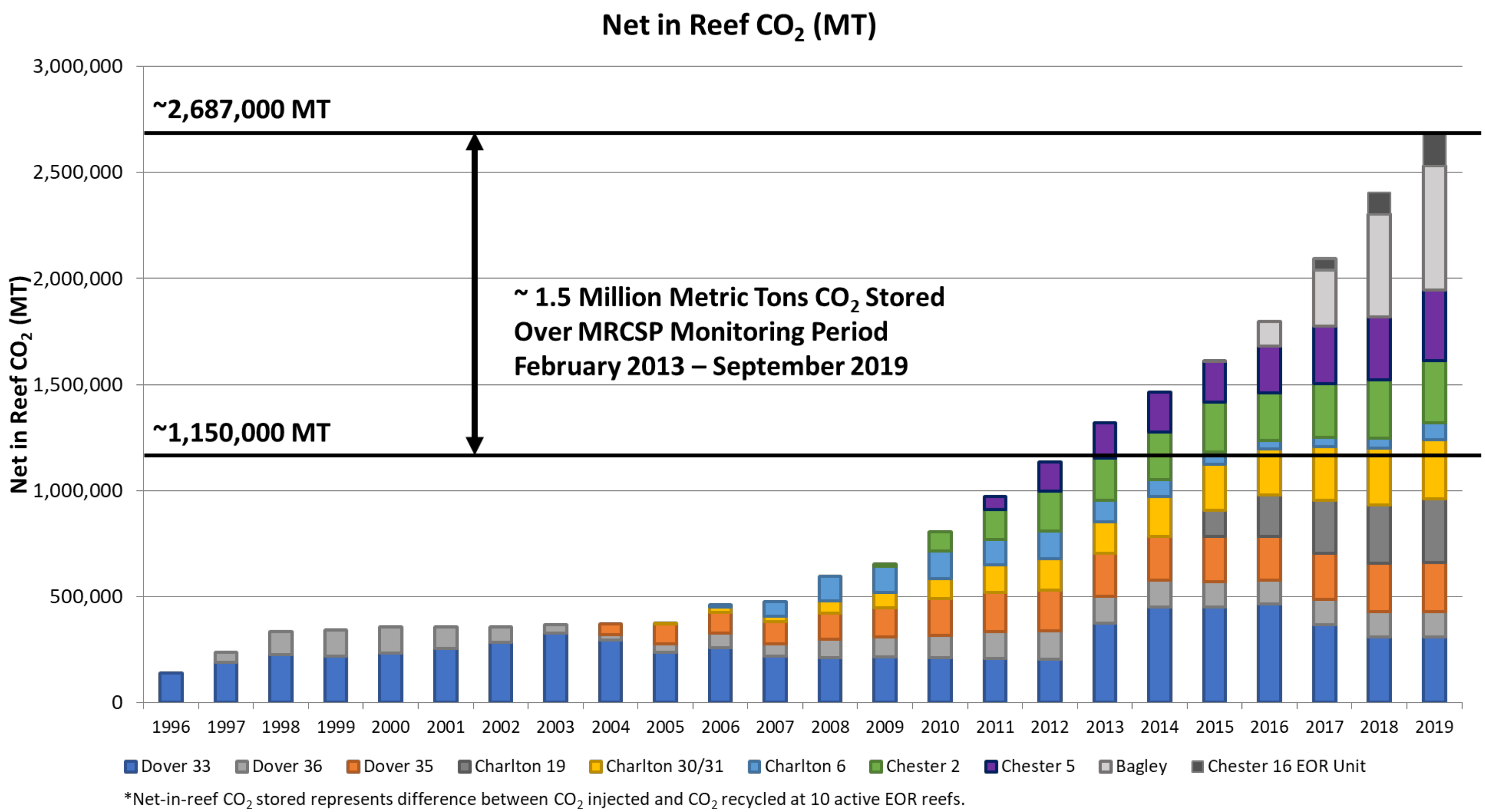


Figure 3-6. Net in-reef CO_2 over the life of secondary recovery within the MRCSP reef complex.

A reef-level summary of the injection and production accounting during the MRCSP monitoring period is presented in Table 3-2. All 10 reefs within the MRCSP reef complex have had at least 100,000 MT of CO_2 injected into them between 2013 and 2019, the life of the monitoring period. In the case of the Charlton 6 and Dover 36 reefs, the net CO_2 injected (stored) within the reef at the end of the monitoring period (September 2019) is negative, indicating that the CO_2 produced from these reefs over the monitoring period exceeds the amount of CO_2 injected. The CO_2 produced from these reefs was used for injection in other reef operations at that time.

Table 3-2. Reef-level accounting for all 10 reefs over MRCSP monitoring period.

Task	Reef	CO_2 Injected (MT)	CO_2 Produced (MT)	Net CO_2 Injected (MT)	Produced Oil (BBL)	Produced Water (BBL)
Task 3	Dover 33	325,272	219,360	105,912	45,590	19,888
Task 4	Bagley	622,463	37,199	585,264	7,947	3,730
Task 4	Charlton 19	387,042	85,488	301,554	170,048	9,216
Task 4	Charlton 30/31	661,631	532,880	128,751	315,423	969,495
Task 4	Charlton 6	145,053	201,357	-56,304	34,592	2,239
Task 4	Chester 2	273,578	168,573	105,004	74,001	102,096
Task 4	Chester 5/6	224,303	34,821	189,482	117,743	1,852,096
Task 4	Dover 35	114,135	76,574	37,560	128,055	9,504
Task 4	Dover 36	504,639	520,844	-16,151	170,335	54,645
Task 5	Chester 16	155,657	0	155,657	0	0
	Total:	**3,413,824**	**1,877,097**	**1,536,727**	**1,063,734**	**3,022,910**

3.3 Reporting Monthly Accounting of CO_2 to DOE

The accounting data discussed in this report were routinely made available to project manager(s) at the National Energy Technology Laboratory, U.S. Department of Energy (DOE) on a monthly basis. This accounting occurred between February 2013 and September 2019, the MRCSP monitoring period for Task 3, 4 and 5 reefs. This report shows monthly accounting of CO_2 injected and produced by reef and cumulative totals since February 3, 2013. Also, the report shows total amount of CO_2 made available by the Chester 10 reef over the MRCSP monitoring period. Finally, new CO_2 floods for Charlton 19, Bagley, and Chester 16 reefs were tracked separately.

4.0 Advanced EOR Metrics

Effective monitoring of reservoir performance is a vital part of any reservoir management strategy designed to ensure that the CO_2 flood is performing as planned and is as efficient as possible in terms of producing the most amount of incremental oil to compensate for the inevitable permanent storage of CO_2 that occurs. With candidate sites for CO_2-EOR also serving as CO_2 storage sites, it is also necessary to be able to quantify and benchmark the performance of the CO_2 flood—in terms of both oil recovery and CO_2 retention—individually and against other reservoirs in the region. These objectives are typically achieved by observing the behavior of a select set of metrics as the flood progresses. While studies outlining various options for evaluating the performance of the reservoir are available, many such metrics are not applicable to depleted oilfields that are commonly encumbered with limited data availability, or are not particularly geared for carbon capture, utilization, and storage (CCUS) purposes.

This section focuses on establishing the desired objectives for the performance metrics and describing the set of metrics that meet these objectives. These metrics are categorized into four distinct categories and implemented in a dashboard. The manner in which the performance metrics collectively provide complementary and non-redundant information is outlined. The input requirements for generating graphs of each metric are discussed and demonstrate the value of this choice of metrics for their speed and portability. Next, the practicality of these metrics in assessing the performance of CO_2-EOR floods and CO_2 storage is demonstrated, using data from ongoing CO_2-EOR operations in the reservoirs of the MRCSP large-scale test region. Two dashboards are presented: one for diagnosing the performance of individual reservoirs, and the second for comparing the performance of various reservoirs.

The utility of the selected set of metrics is demonstrated with data obtained from CO_2-EOR activities in depleted oilfields of the MRCSP region. First, a nine-panel dashboard is populated using the metrics discussed for the Dover 33 reservoir. The dashboard will be shown to be useful in quantifying CO_2 storage capacity, highlighting reservoir performance parameters (CO_2 breakthrough, oil recovery, voidage-related pressure changes during EOR, etc.), and identifying CO_2 flood maturity. Second, a four-panel dashboard is displayed as a comparative tool across all reservoirs in the region in order to highlight best- and worst-performing reservoirs and establish representative ranges for reservoir performance. Both dashboards will be useful when comparing performance against averages published in literature. Finally, the work is summarized and the value-added proposition of the dashboard-based workflow for the study of the CO_2-EOR activities in the MRSCP large-scale test region is demonstrated. Suggestions of additional metrics are suggested if a more expansive dashboard is desired.

4.1 Objectives

The requirement for a comprehensive and graphical summary of operational data acquired for each reservoir during CO_2-EOR can be met by selecting a set of performance metrics that condense the vital statistics of each reservoir's response, and reduce uncertainty in CO_2 storage capacity estimates for the depleted oil field. Collectively, these metrics should serve the following purposes:

- Quantify expectations for the CO_2 flood's long-term incremental oil recovery performance
- Estimate CO_2 storage capacity created as a result of EOR activity
- Establish a set of performance benchmarks in order to assess CO_2-EOR performance
- Flag reservoir performance parameters such as CO_2 breakthrough and CO_2 injection efficiencies for reservoir management feedback purposes
- Qualitatively assess the economic feasibility of future projects
- Facilitate comparison of the MRCSP regional efforts with other basins and partnerships

4.2 Performance Measures

Several authors have discussed metrics and their utility in managing reservoir performance and monitoring CO_2 storage efficiency in detail. Masoner et al. (1996) present a comprehensive set of graphs, to be used as diagnostic tools for monitoring CO_2 flood performance both from a reservoir engineering perspective (injection-production ratio, %CO_2 uncontacted reservoir fluid remaining, etc.) and an economic perspective (cumulative cash flow, operating expense per barrel of oil, etc.). These graphs are based on actual recorded data from more than 260 floods in northwest Colorado. Jarrell et al. (2002) describe a number of graphs as tools suitable for managing oil recovery and CO_2 use. They discuss a plot of gross CO_2 utilization factor against cumulative volumes of CO_2 injected—useful to detect inefficiencies in injection whenever the ratio begins to rise—and a plot of the oil cut against cumulative injected volumes, where a prolonged or abnormal decrease suggests serious reservoir performance impairment that should be investigated. Finally, based on a survey of data from more than 30 reservoirs, Azzolina et al. (2015) discuss essential parameters to compute when monitoring the CO_2 storage performance of the reservoir, such as CO_2 retention, incremental oil recovery factor, and net utilization factor, and establishing median values and ranges expected for these metrics. While such studies have presented an abundance of metrics and demonstrated their value in providing insight into reservoir performance, literature condensing these studies into a more streamlined set of metrics to holistically assess the CO_2 flood is limited.

While an exhaustive list of performance metrics can be easily obtained by a review of the literature on the topic, it is important to bear in mind that reservoirs that are candidates for EOR are frequently legacy fields (i.e., highly depleted fields that have been in production via primary and even secondary recovery over several decades). A complete description of historical production and pressure data for such fields may not always be readily available. Data such as bottom-hole and/or reservoir pressure information dating several decades ago may not be accessible or may simply not be traceable because the assets may have undergone multiple changes in ownership. Often, due to budgetary constraints, operators may even opt to avoid incurring the costs associated with acquiring certain types of data (fluid pressure-volume-temperature [PVT] properties, well-test data)—not an uncommon problem to encounter when working with mature basins in general. This limits the choices of metrics available for creating a universal dashboard that can readily be calculated when studying reservoirs from other basins.

4.2.1 Categorization of Performance Measures

Metrics were selected to provide a better understanding of various aspects of reservoir behavior and to monitor the performance of an EOR flood. Considering the overarching objectives of the MRCSP program and the availability of data, a set of nine metrics were selected. These metrics broadly fall into four categories: 1) flow rate and cumulative production data; 2) EOR performance trends; 3) operational performance trends, and 4) storage performance trends. The final list of metrics is introduced below. The first category consists of essential information that enables the analyst to summarize the injection-production history at a glance. All the performance metrics of the other three categories have been normalized to represent a percentage of original HCPV to facilitate comparison.

- Summary of production data
  - Historical flow rates
  - Cumulative production data

- EOR performance trends
  - Incremental oil recovery efficiency
  - CO_2 storage efficiency
  - Net CO_2 utilization factor
- Operational performance trends
  - Voidage replacement ratio
  - Producing CO_2-oil ratio
- Storage performance trends
  - Incremental oil recovery factor vs CO_2 storage
  - CO_2 storage capacity vs voidage

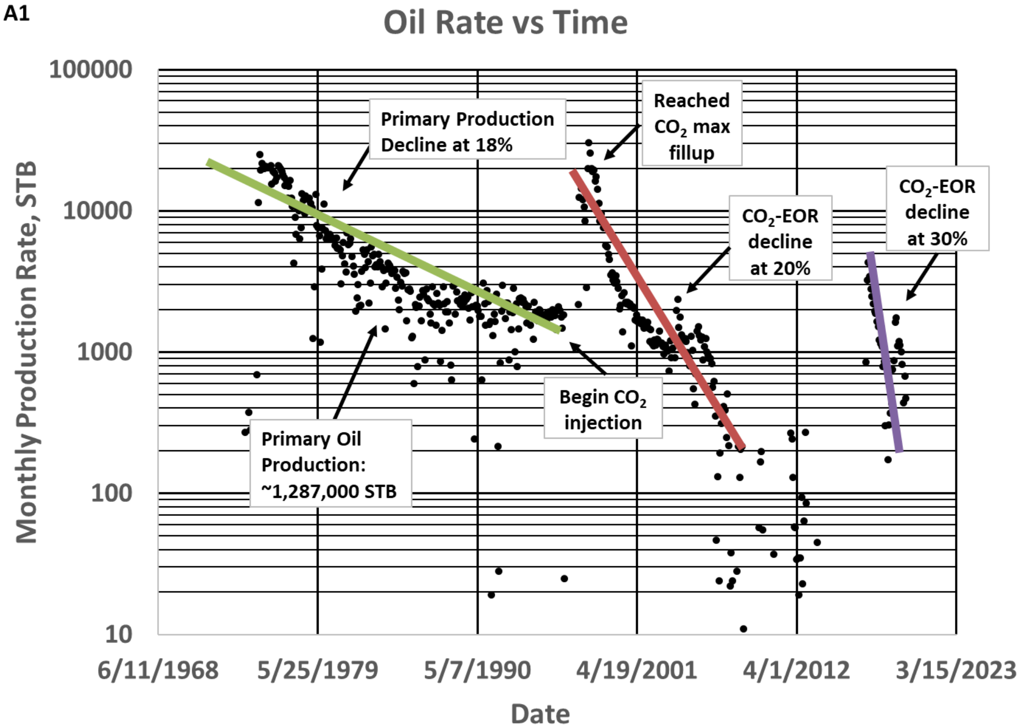
Because the tertiary production history of each reef varies widely, all metrics have been computed from the beginning of fill-up to the end of the first EOR period except for the oil-rate history plot. The fill-up period refers to a period of CO_2-injection only (without production), typically done to repressurize a reservoir before the start of EOR operations. EOR occurs in the period when CO_2 injection and production of reservoir fluids both occur simultaneously.

Category A: Flow Rates and Cumulative Production Data.

This group of two plots is intended to be a short summary of the reservoir's history. Plot A1 (Figure 4-1, top panel) is a semi-log plot of the monthly oil-rate vs time as they decline from discovery to the end of the first EOR period. Intended for reference purposes only, this plot identifies key-dates and broad decline-rates. The decline rates described are straight-line declines for quick, back-of-the-envelope references to the reservoir behavior, and not necessarily a reference to physical processes occurring in the reservoir.

Plot A2 (Figure 4-1, bottom panel) shows cumulative volumes of oil produced and the cumulative volumes of CO_2 injected and produced from the onset of fill-up to the end of the EOR period. The CO_2 volumes injected and produced, however, are normalized to the available HCPV in the reservoir. This helps identify any critical points during injection that change the oil-producing behavior of the reservoir. Both plots serve as a simple summary of incoming production data with limited manipulation.

A1



A2

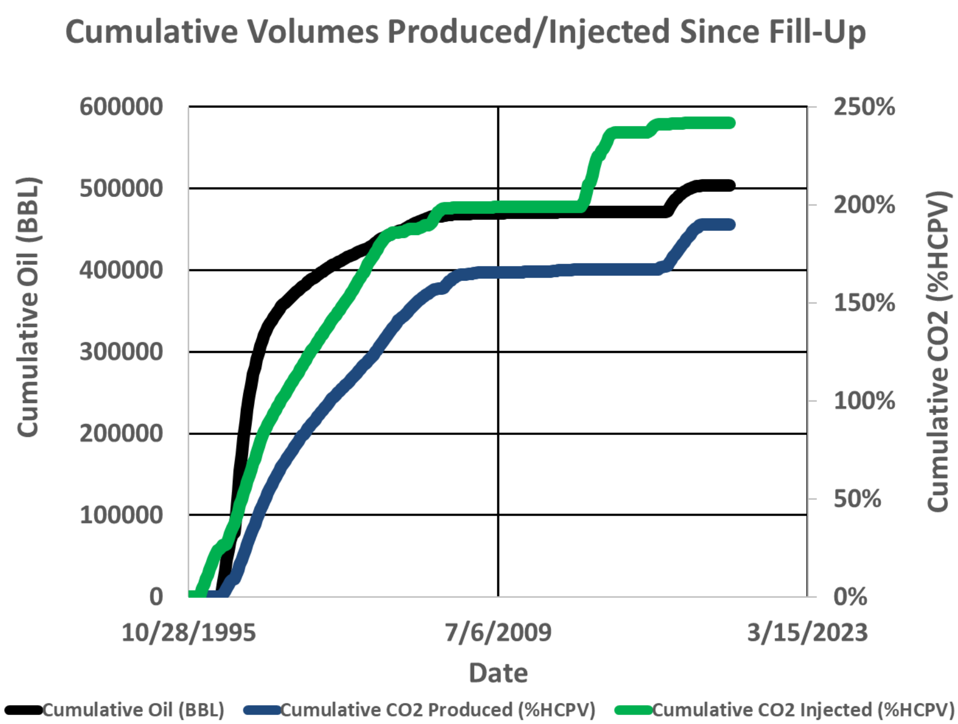


Figure 4-1. Schematic of plots summarizing the injection-production data in category A, numbered A1 (top) and A2 (bottom).

Category B: EOR Performance Trends

Figure 4-2 presents a schematic of the metrics that relate to EOR performance. Plot B1 (Figure 4-2, top panel) shows the incremental oil recovery after the fill-up period. This plot charts the amount of oil produced as a result of EOR normalized to an estimate of the total available oil in the reservoir, as a function of quantity of CO_2 injected into the reservoir. The inflection points may be identified for investigation. This incremental recovery factor is useful when compared against the primary decline or against other fields.

Plot B2 (Figure 4-2, middle panel) displays the net CO_2 utilization factor vs %HCPV of CO_2 injected. The net utilization factor represents the difference between the total quantity of CO_2 injected and produced—or the total volume CO_2 stored (lost) in the reservoir for each barrel of oil produced—measured at standard conditions. Typically, an asymptote is reached ~8 to 10 Mscf (thousand standard cubic feet) CO_2/STB, with a lower asymptote suggesting a more efficient EOR operation. The data are plotted as a function of injected volume of CO_2 to determine the point of diminishing returns and can be used to determine a break-even point for a given price of oil and CO_2.

Plot B3 (Figure 4-2, bottom panel) shows the CO_2 storage efficiency ratio. It represents the quantity of CO_2 injection required to store each unit of CO_2 and is presented as a function of HCPVs of CO_2 injected. From an EOR perspective, a higher value is desirable as it suggests better performance of the reservoir, since CO_2 not stored is produced and can be recycled. However, too low or too high a value may suggest a state of residual oil-saturation, maximum CO_2-oil contact, or CO_2 breakthrough between injectors and producers.

Category C: Operational Performance Trends

Figure 4-3 presents a schematic of the metrics that relate to operational performance. Plot C1 (Figure 4-3, top panel) provides information on the voidage replacement ratio vs time. The ratio is defined as the reservoir barrels of fluid (CO_2) injected into the reservoir to the reservoir barrels of fluid (oil + CO_2) produced. Since dynamic pressure-data may not always be available, these numbers are calculated at discovery pressure. A ratio higher than 1 typically results in average pressure increase (e.g., fill-up periods), and a ratio lower than 1 results in a decline (e.g., production). From a reservoir management perspective, large fluctuations in this graph are undesirable. A gentle slope, with voidage managed around 1, suggests ideal conditions with EOR being carried out at constant pressure.

Plot C2 (Figure 4-3, bottom panel) shows the change in the producing CO_2-oil ratio as a function of time. Typically, this graph is expected to slope gently upward as the mixing zone between the injected CO_2 and oil advances toward the producers. A sharp increase in the slope, or large fluctuations, may suggest breakthrough or viscous fingering of CO_2. Higher numbers also suggest poor performance or attainment of CO_2 flood maturity.

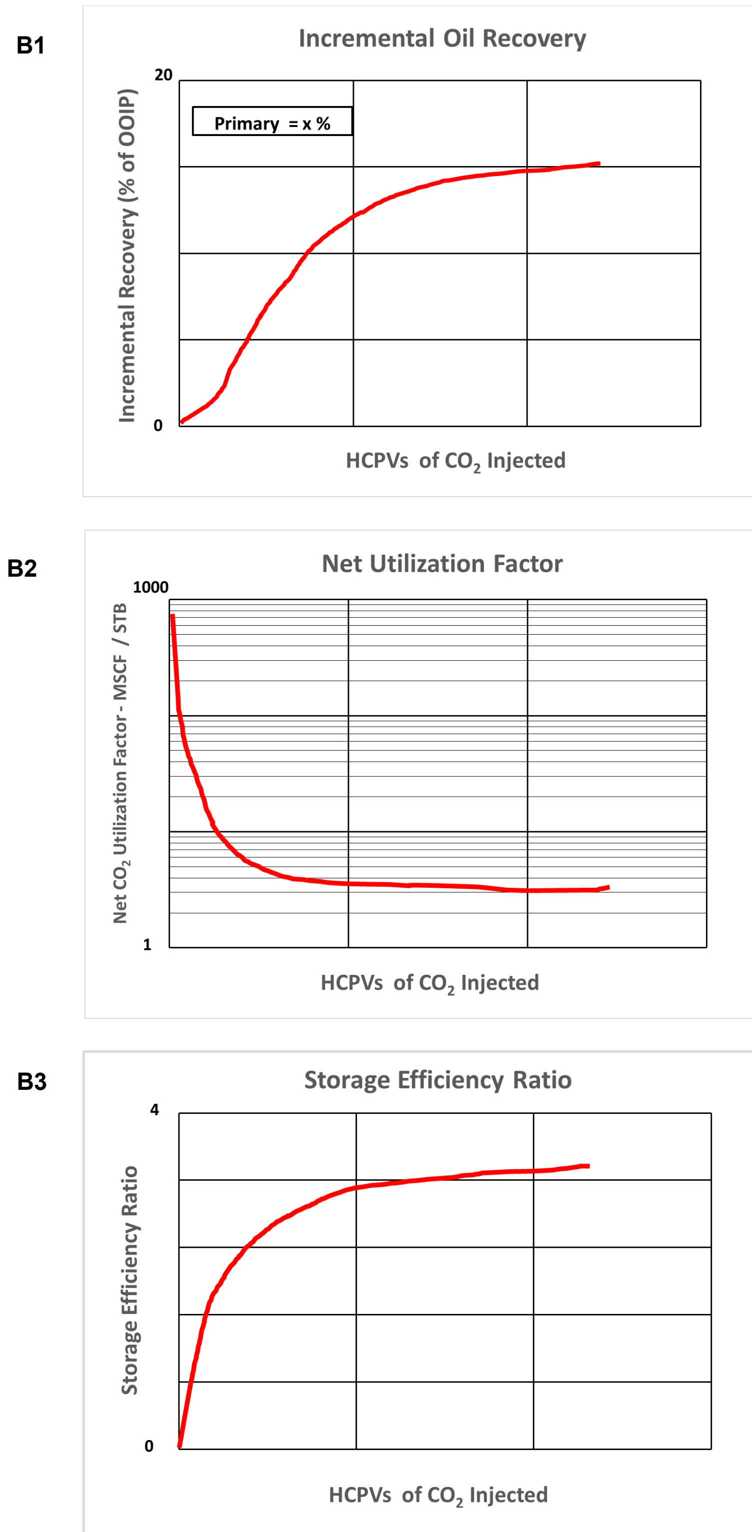
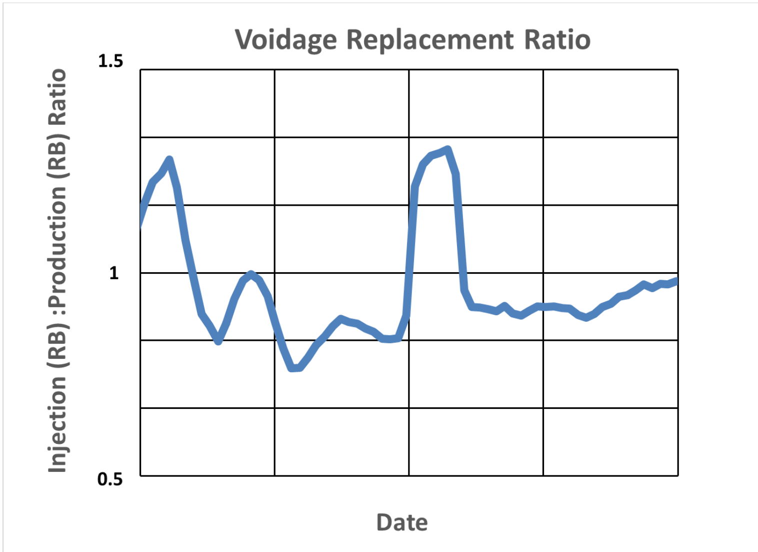


Figure 4-2. Schematic of performance metrics in category B, numbered B1 to B3 from top to bottom.

C1



C2

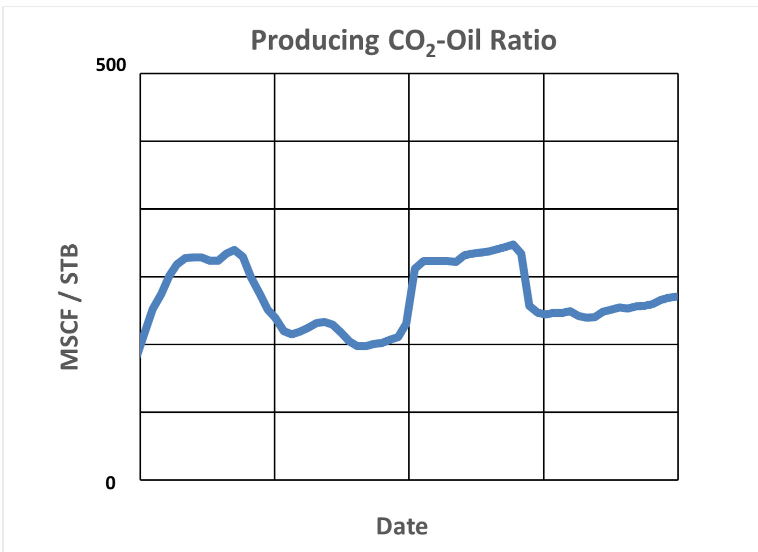


Figure 4-3. Schematic of performance metrics in category C, numbered C1 (top) and C2 (bottom).

Category D: Storage Performance Trends

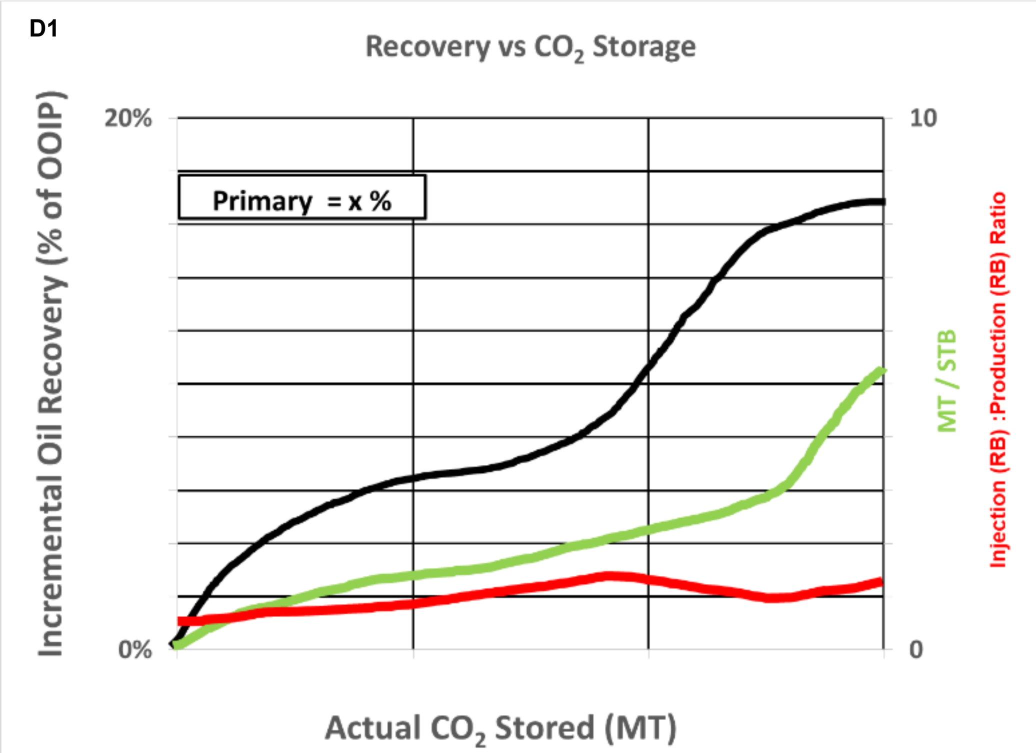
Figure 4-4 presents a schematic of the metrics that relate to CO_2 storage performance. Plot D1 (Figure 4-4, top panel) tracks the incremental oil recovery factor (%) as a function of the net CO_2 stored in the reservoir based on field data. A change in slope may suggest several possibilities, such as maximum contact between oil-CO_2 reached, the end of the pressure-diffusion mechanism, change in type of sweep (horizontal / vertical), and breakthrough of CO_2 from injector to producer. This metric may additionally reveal causes of underperformance (or expectation-exceeding performance) when viewed in tandem with voidage ratios and/or producing CO_2-oil ratios. For instance, if the rate of recovery with respect to storage begins to increase with no accompanying changes in either of the other two charts, it suggests that the driving production mechanism may have shifted from the mixing zone laterally sweeping the oil toward the producers to a more gravity-dominated expanding CO_2 gas-cap pushing the oil down.

Plot D2 (Figure 4-4, bottom panel) provides information on the maximum storage capacity as a function of cumulative oil produced from the reservoir. The red line represents net CO_2 stored in the reservoir based on field data, while the purple line estimates the maximum volume of CO_2 that can take up the pore space vacated by the produced oil, if the reservoir were to be repressurized up to discovery pressure. Due to the highly compressible nature of CO_2, this estimate is necessarily a function of average pressure at which it is stored. As a result, any increase (or decrease) in the rate of net storage observed in the field—the slope of red line becomes steeper (or gentler) than the purple line—suggests that the average pressure of the reservoir is rising (or falling). Analyzing this plot alongside oil rate (black line) may reveal if the CO_2 flood has reached maturity (e.g., rising pressure alongside oil rates significantly below peak or plateau rates.) The distance between the purple and red line allows the analyst to visually assess potential for additional storage in the reservoir.

4.2.2 Computation of Performance Measures and Input Requirements

Generating these graphs requires the following data:

- Field-level historical oil and gas produced volumes; before CO_2-injection operations
- Field-level current oil, gas, and CO_2 injection/production volumes, at least on a monthly basis; from the onset of CO_2-injection operations
- Original oil in place (OOIP), STB
- Original reservoir pressure, or discovery pressure, P_r – psi
- The following fluid properties calculated at this discovery pressure:
    - CO_2 formation volume factor, B_{g,CO_2} – rcf/scf
    - Gas formation volume factor, B_g – rcf/scf
    - Oil formation volume factor, B_o – RB/STB
    - Solution gas-oil ratio, R_s – Mscf/STB
    - CO_2-oil solution gas-oil ratio, R_{s, CO_2} – Mscf/STB



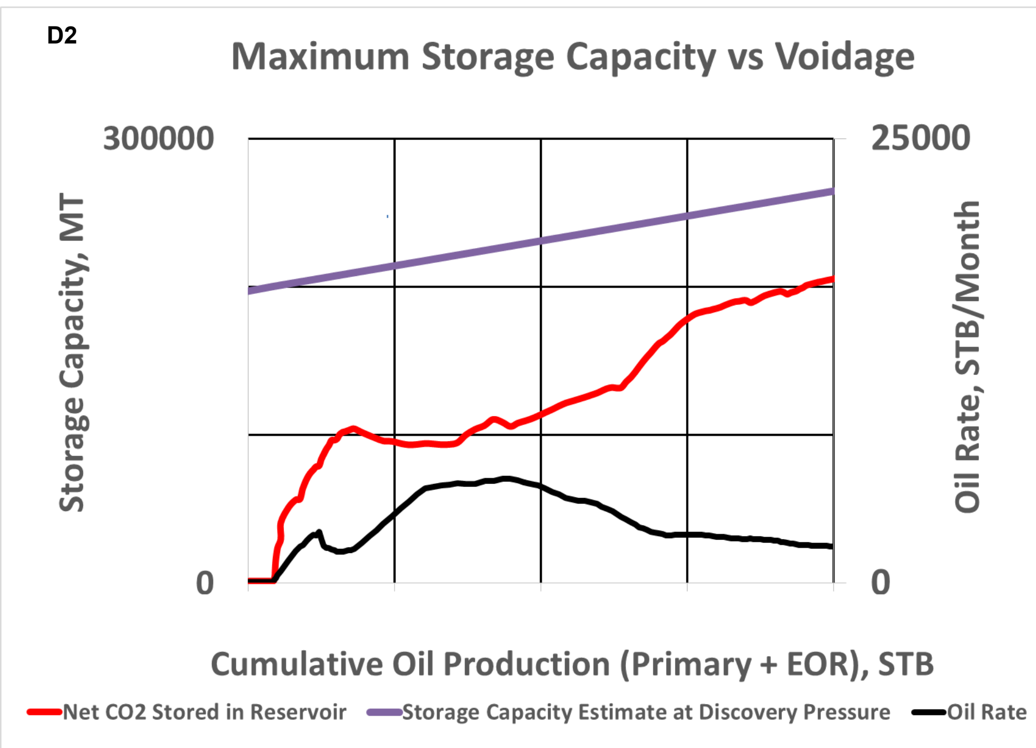


Figure 4-4. Schematic of performance metrics in category D, numbered D1 (top) and D2 (bottom).

While OOIP estimates from material-balance calculations are preferred, a volumetric estimate using the areal extent, formation thickness, porosity, and initial oil saturation may be used as a substitute where the data are unavailable. This is essential for calculating the HCPV of the reservoir used to normalize all metrics. If laboratory measurements of PVT properties are unavailable, industry-standard fluid correlations may be used instead, for both oil and CO_2. (McCain Jr 1991). These correlations typically require the following inputs:

- Bubble-point pressure, P_b – psi
- Initial producing gas-oil ratio, GOR – scf/STB
- Oil API gravity
- Specific gas gravity
- Reservoir temperature, T_r – F

The definitions of key terms and metrics are described in the equations below. Note that where applicable, these terms will be calculated at the discovery pressure of the reservoir. It is also pointed out that while most metrics are in oilfield units, CO_2 storage capacity is computed in metric tons (MT) to be consistent with units referenced by CCUS literature.

$$\text{HCPV (RB)} = \text{OOIP} * B_o$$

Equation 4-1

$$\text{HCPV's of } CO_2 \text{ Injected or Produced (\%)} = \frac{Q_{Co2} * B_{g,CO_2}}{\text{HCPV}}$$

Equation 4-2

$$\text{Incremental Oil Production (STB)} = Q_o - Q_{o,pri}$$

Equation 4-3

$$\text{Incremental Oil Recovery Factor (\%)} = \frac{Q_{o,EOR}}{\text{OOIP}}$$

Equation 4-4

$$\text{Net } CO_2 \text{ Utilization Factor } \left(\frac{\text{Mscf}}{\text{STB}}\right) = \frac{(Q_{CO_2,Inj} - Q_{CO_2,Prod})}{Q_{o,EOR}}$$

Equation 4-5

$$CO_2 \text{ Storage Efficiency Ratio } \left(\frac{\text{Mscf}}{\text{Mscf}}\right) = \frac{Q_{CO_2,Inj}}{(Q_{CO_2,Inj} - Q_{CO_2,Prod})}$$

Equation 4-6

$$\text{Voidage Replacement Ratio } \left(\frac{\text{RB}}{\text{RB}}\right) = \frac{\frac{(Q_{CO_2,Inj} * B_{g,CO_2})}{5.615}}{\frac{Q_{CO_2,Prod} * B_{g,CO_2} + Q_{g,EOR} * B_g}{5.615} + Q_{o,EOR} * B_o}$$

Equation 4-7

$$\text{Producing } CO_2 - \text{Oil Ratio } \left(\frac{\text{Mscf}}{\text{STB}}\right) = \frac{Q_{CO_2,Prod}}{Q_{o,EOR}}$$

Equation 4-8

$$\text{Actual CO}_2\text{ Stored (MT)} = \frac{(\mathrm{Q}_{\mathrm{Co_2,Inj}} - \mathrm{Q}_{\mathrm{CO_2,Prod}})}{19}$$

Equation 4-9

The maximum storage capacity of the reservoir is an upper-bound estimate that sums: 1) the total free-gas volume of CO_2 that can take the place of the produced reservoir fluids, and 2) the total volume of CO_2 that can dissolve into the remaining oil (assuming 100% contact) at some pressure. This quantity refers to the total theoretical volume that the reservoir can hold, if at every point during the EOR period the reservoir was repressurized to a given pressure by injecting CO_2. For the sake of standardization, this pressure has been fixed at discovery pressure, P_r.

$$\text{Maximum Storage Capacity (MT)} = \left\{\frac{\mathrm{HCPV} - [(\mathrm{OOIP} - \mathrm{Q_o}) * \mathrm{B_o}] - [(\mathrm{Q_o} * \mathrm{R_s} - \mathrm{Q_g}) * \mathrm{B_g}]}{\mathrm{B_{g,CO_2}} * 19}\right\} + \left\{\left[\frac{(\mathrm{OOIP} - \mathrm{Q_o}) * \mathrm{R_{s,CO_2}}}{19}\right]\right\}$$

Equation 4-10

Since the lack of availability of fluid properties may be a recurring problem, a separate tool to calculate fluid properties as inputs for the main spreadsheet performing the calculations for the dashboard (Barclay and Mishra 2014) is recommended.

4.3 Generation of Performance Metric Dashboards for MRCSP Reefs

The utility of the performance metrics discussed above is demonstrated using data from reservoirs in Michigan currently undergoing CO_2-EOR, as part of the phased development programs administered by the MRCSP.

4.3.1 Individual Reef Analysis - Dover 33

Dover 33 and other reefs of the MRCSP region have been subjected to extensive primary and secondary recovery. Around 1.2 million MT of CO_2 have been cumulatively injected into this reservoir during the EOR period. Data suggest that Dover 33 is a relatively smaller reservoir compared to other reefs in the region and is relatively isolated from the reefs on either flank. It has been estimated to carry around 4,000 MSTB of OOIP.

Figure 4-5 shows the dashboard of plots generated for Dover 33. Plots A1 and A2 belong to category A; Plots B1, B2, and B3 to category B; Plots C1 and C2 to category C; and Plots D1 and D2 to category D. Plot A1 summarizes the sequence of activities performed on this reservoir, from primary depletion to a brief fill-up period to bring the reservoir pressure up to minimum miscibility pressure, before EOR commenced. The current oil production rates with CO_2-EOR are approaching the levels at which the reservoir was shut-in initially after primary production. Plot A2 shows that with around 80% by HCPV of CO_2 injected, the rate of oil recovery was significantly curtailed.

Plot B1 suggests that beyond 80% by HCPV of CO_2 injection, the reservoir's incremental oil recovery began approaching a plateau and the reservoir entered the late stages of EOR. Even after producing 31% and around 12% of OOIP from primary production and CO_2-EOR, respectively, most of the OOIP (more than 55%) remains unrecovered from the reservoir. This warrants a feasibility study with a modified CO_2 flood design to investigate whether the estimated ultimate recovery of the reservoir may be extended further. Plots B2 and B3 confirm that the CO_2 flood has reached maturity, with the net utilization factor (Plot B2) and the CO_2 storage efficiency ratio (Plot B3) stabilizing at 5 Mscf/STB and 3.5 Mscf/STB, respectively. Compared to the benchmark values of 9 and 2 Mscf/STB (Azzolina et al., 2015), it appears that the CO_2 flooding in Dover 33 has been relatively more efficient.

Plot C1 shows that the voidage ratio has been maintained around unity during CO_2 injection, suggesting that the flood was carried out at a constant pressure. Plot C2 shows consistently increasing producing CO_2-oil ratios until reaching a threshold, which suggest an advancing mixing zone until the effects of fingering and breakthrough are eventually felt at the producing wells around 5 years of injection later.

Beyond showing that optimal incremental oil recovery is accompanied by a period of low CO_2-oil ratio, Plot D1 also illustrates that upon breakthrough of CO_2, the reservoir has transitioned into CO_2 storage. Because the injection does not result in any material improvement in oil recovery, this plot in fact suggests that CO_2 injection should cease as soon as possible to either examine the flood design or consider abandoning the reservoir altogether. Finally, Plot D2 confirms that the CO_2-EOR has reached the point of diminishing returns with CO_2 storage no longer incidental with oil production (straight line parallel to purple line). The reservoir has instead begun to repressurize as it transitions into a CO_2 storage unit with limited oil production. Dover 33 can hold a maximum of approximately 370,000 MT of CO_2, assuming injection is performed until the reservoir pressure returns to the original discovery pressure.

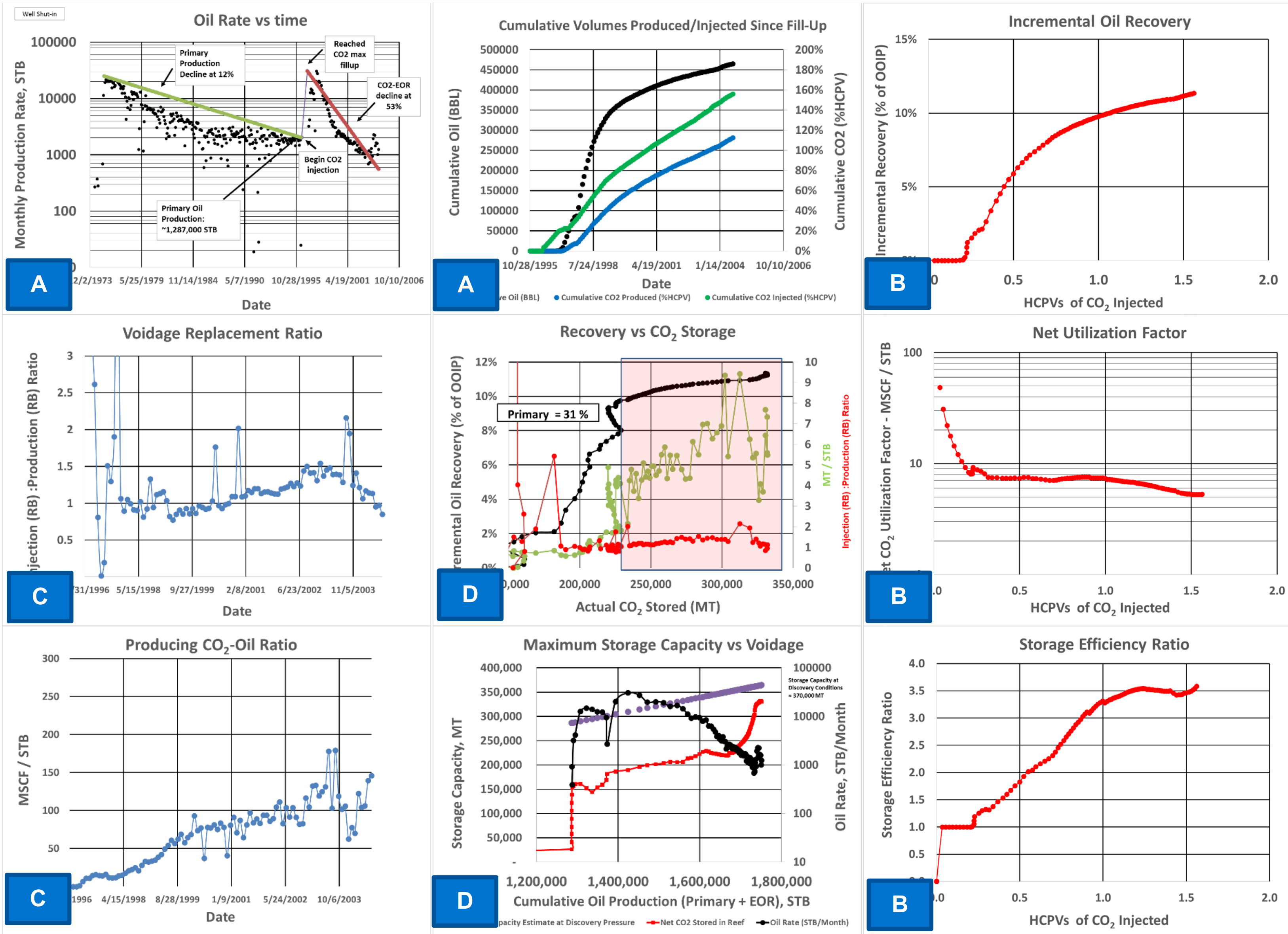


Figure 4-5. Dashboard generated for Dover 33. The dashboard suggests that this reef is in the late-EOR phase where continued CO_2 injection may not yield significantly more oil recovery, and that this late EOR period has been accompanied by a rapid increase in reservoir pressure.

4.3.2 Inter-Reef Comparison

Figure 4-6 shows an annotated dashboard put together with four of the seven performance metrics discussed earlier, used to place each reef's CO_2-EOR performance in context. Dover 33, Dover 35, and Charlton 6 collectively capture the bandwidth of reservoir responses observed in the MRCSP large-scale test region. These metrics (clockwise from top left) are CO_2 stored, CO_2 storage efficiency factor, incremental oil recovery, and net utilization factor. This particular choice is useful not only to identify top and worst performers, but also to benchmark the MRCSP test region's performance as a whole to averages published in literature (Azzolina et al. 2015).

Dover 35 and Charlton 6 are both among the smallest reservoirs in the area. Both have considerable primary and secondary recovery history, with Dover 35 in production since 1973 from nine wells and Charlton 6 since 1982 from three wells. Dover 35 underwent primary production from 1973 to 1994 to yield 965 MSTB of oil. Subsequently, the reservoir was deemed uneconomic and was abandoned from 1994 to 2004. Since 2004, however, Dover 35 has been undergoing EOR with two wells converted into CO_2-injectors. To date, an additional 342 MSTB have been recovered, for around 420,000 MT of cumulative CO_2 injection. Charlton 6 underwent primary production from 1982 to 2006 to yield 630 MSTB of oil, and has been undergoing EOR from 2006 to present, with only one injection well. CO_2-EOR in Charlton 6 has recovered an additional 105 MSTB of oil, for a cumulative injection of around 430,000 MT of CO_2. Of the two reefs, Dover 35 is bigger with around 2,500 MSTB of OOIP as compared to 1,700 MSTB for Charlton 6.

Plot B3, illustrating CO_2 storage vs HCPVs of CO_2 injected, enables a comparison of the absolute quantities of CO_2 stored in each reef. With a far larger volume of CO_2 injected (and consequently volume of oil recovered from the reservoir that vacates pore-space for CO_2 to be stored), Dover 33 has both stored the most CO_2 (solid line) and created the greatest maximum capacity for CO_2 storage in the future (solid point above line). However, given that the actual quantity of CO_2 stored in the reservoir is typically a function of various dynamic and geologic factors that may vary between reservoirs, it is more meaningful to analyze the gap between the point and the line. This gap represents the additional quantity of CO_2 that can be stored in each reservoir (if the reservoir were to be repressurized to discovery pressure with CO_2 injection). With 1 HCPV of CO_2 injected, however, we observe that Dover 35 has stored just as much quantity of CO_2 as Dover 33, despite having a lower overall reservoir size.

A comparison of the storage efficiencies across the reservoirs shows that every unit of CO_2 storage requires between 2 to 3.5 times more injection. This is similar to the range observed by Azzolina et al. (2015). With the results of the previous plot and with the storage efficiency factor being directly proportional to the quantity of CO_2 recycled rather than stored, Dover 35 is determined to be the best-performing reef in terms of storage performance.

The bottom right plot of Figure 4-6 shows that for around 1 HCPV of CO_2 injected, Dover 35 has produced the highest percentage of its OOIP, and also does not display signs of having reached a plateau. Charlton 6 appears to be approaching its plateau and is also the poorest-performing reef based on this metric, suggesting that its flood design may merit revisiting. Incremental oil recovery in the MRCSP large-scale test region possibly ranges between 5% and 20%, which is very similar to the results of Azzolina's study.

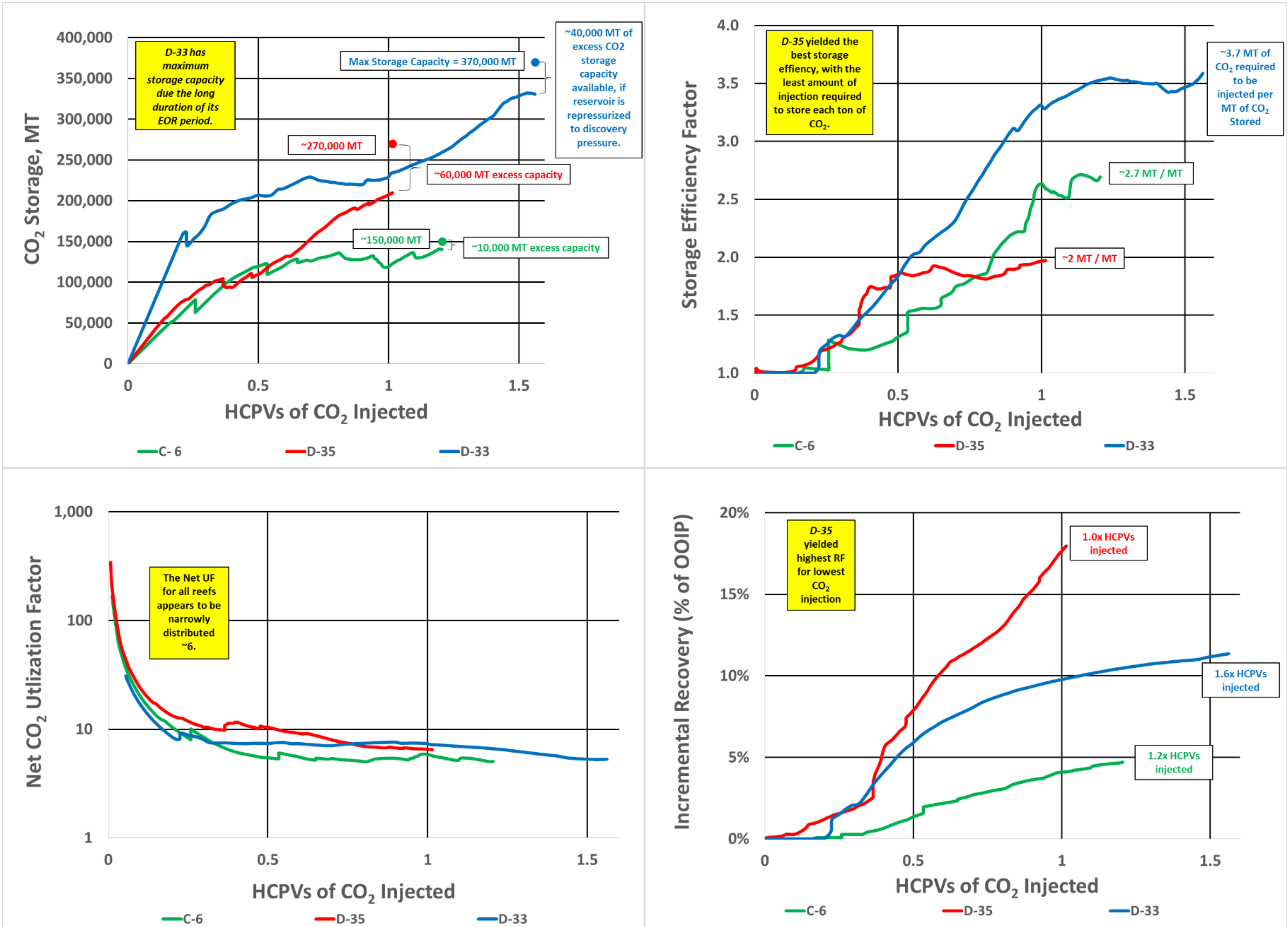


Figure 4-6. The three reefs that span the bandwidth of the performance measures described in this paper. CO_2-EOR in the MRCSP region appears to store ~6 Mscf of CO_2 for every incremental barrel of oil produced. Other parameters, however, vary widely. Dover 35 is the best-performing reef, possessing strong characteristics in both storage and oil recovery.

Finally, the net utilization factor shows the highest degree of consistency in describing the reefs. Around 6 Mscf of CO_2 is stored per barrel of oil produced in the MRCSP large-scale test region, which is less than the median value of 9 Mscf/STB obtained from the Azzolina et al. (2015) study. This finding implies that the MRCSP region's oil recovery is relatively better managed than the average. It is important to point out that this style of presentation also highlights Dover 35 as the best-performing reef overall, in terms of both oil recovery and CO_2 storage.

4.3.3 Potential for Improvements

The metrics and graphs discussed in this work have been designed to place minimal demands on data; therefore, they can be broadly applied to any mature basin undergoing CO_2-EOR. However, where additional data are available, the following additional metrics or improved graphs are worthy of consideration:

- Computing all the metrics above via a simulation model and displaying it alongside the field-data as "expected" response. This may especially be useful to establish what may be considered "optimal" for oil recovery and producing CO_2-EOR response, to identify production issues.
- Developing a graph of the oil and CO_2 cut (in-situ fraction of phase production) if bottom-hole pressure data are available. This is especially useful if a pattern-flood is in place.
- Calculating HCPVs of CO_2 injected/produced, and voidage replacement ratios at bottom-hole or reservoir pressure rather than discovery pressure.
- Plotting field cash-flows per day if economic data on CO_2 costs and oil prices are readily available.

5.0 Conclusions

The primary objective of the MRCSP program is to store at least 1 million MT of CO_2. This storage objective also implies that the CO_2 is stored safely, securely, and permanently. In order to qualify the success of the storage from the perspective of long-term sustainability, the accurate accounting of all fluids that enter and exit the storage zone are of critical importance. The MRCSP program partnered with Core Energy, LLC, an existing oil and gas company, and developed storage fields that have been producing oil and gas—in some instances, for decades. The ability to properly account for all present fluid migration in and out of reservoirs depends on the accuracy of the instrumentation measuring flow, but it also requires an accurate history of prior production and injection that can create a total accounting picture through the life of these storage reservoirs.

The MRCSP program involved three tasks. Task 3 involved performing long-term storage tests at a depleted Dover 33 reef. Task 4 involved monitoring EOR operations and accounting for CO_2 injection/production and net CO_2 stored at eight active EOR reefs. Two of these reefs (Bagley and Charlton 19) also involved new CO_2 floods that overlapped with the MRCSP monitoring period. Finally, in Task 5, MRCSP monitored Core Energy's acquisition of a new Chester 16 EOR reef that involved construction of new injection and observation wells and new CO_2 flood to pressurize the reef.

Two practical dashboards incorporating relevant performance metrics have been developed to assess and benchmark the efficiency of CO_2-EOR operations, as well as the concurrent retention of CO_2 in the reservoirs, for the MRCSP large-scale test region. A preliminary understanding of CO_2 flood maturity, underperformance, and CO_2 storage capacity was identified by collectively analyzing the metrics presented in the nine-panel dashboard. The four-panel dashboard presented was helpful in comparing each reservoir's performance against the other in order to highlight the best- and worst-performing reservoir and to compare the performance of CO_2-EOR activity in the region as a whole to averages established in literature. Among the conclusions reached based on this analysis were:

- Dover 33's CO_2 flood has reached maturity, and the reservoir has transitioned into a CO_2 storage unit instead.
- Dover 33 can hold up to 370,000 MT of CO_2 at discovery pressure.
- Based on the net utilization factor, the MRCSP region's CO_2-EOR activities have been relatively well managed.
- Dover 35 is the best-performing reef in terms of both CO_2 storage performance and incremental oil recovery.

The MRCSP program, starting in February 2013, began monitoring CO_2 injection within storage reservoirs and accounting for the CO_2 using instrumentation at wellbores and within the main production facility. Through the life of the project, the number of flow meters was increased throughout the network of gas pipelines, and the accuracy of the accounting increased through the acquisition of more precise instrumentation. As of the writing of this report, MRCSP has successfully demonstrated the safe and secure injection of over 1 million tons of CO_2 within the storage reservoirs, and through the detailed and accurate accounting over this period, the monitoring of the injection/production operation has maintained a confident assessment of the total CO_2 that remains stored permanently within the storage zones.

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It can be done