NETL Life Cycle Inventory Data
Process Documentation File

Process Name: Enhanced Oil Recovery Operations

Reference Flow: 1 kg of Crude Oil

Brief Description: This unit process models the injection of CO_2 and water to produce crude and light hydrocarbons via enhanced oil recovery.

Section I: Meta Data

Geographical Coverage: U.S. **Region:** Texas

Year Data Best Represents: 2010

Process Type: Extraction Process (EP)

Process Scope: Gate-to-Gate Process (GG)

Allocation Applied: No

Completeness: Individual Relevant Flows Captured

Flows Aggregated in Data Set:

☑ Process	☑ Energy Use	☐ Energy P&D
	☐ Material P&D	

Relevant Output Flows Included in Data Set:

Releases to Air:	☑ Greenhouse Gases	☐ Criteria Air	☐ Other
Releases to Water:	☐ Inorganic	☐ Organic Emissions	☐ Other
Water Usage:	☐ Water Consumption	☐ Water Demand (throughput)	
Releases to Soil:	☐ Inorganic Releases	☐ Organic Releases	☐ Other

Adjustable Process Parameters:

Brine_inj	*[kg/kg crude produced] Brine injected to the well to facilitate crude recovery*
Brine_prod	*[kg/kg crude produced] Brine produced from the formation with crude oil*

HC_gas_prod	*[kg/kg crude produced] Hydrocarbon gas (C_1-C_5) produced from the formation with crude oil*
Prod_CO2	*[kg/kg crude produced] CO_2 produced from the formation with crude oil*
Seq_CO2	*[kg/kg crude produced] CO_2 permanently stored underground in the formation*
CO2_inj	*[kg/kg crude produced] CO_2 injected to the well to facilitate crude recovery*
EF_CO2	*[kg/(MW-day)] Emission factor for CO_2 released to air from injection compressor and pump*
CO2_inj_pump	*[MWh/kg CO_2 injected] Electricity required for CO_2 compression/pumping*
CO2_leak_form	*[kg/kg CO_2 injected] Amount of sequestered CO_2 that leaks from the formation*
B_Inj_pump	*[kWh/kg brine injected] Power requirements for water injection pump per kg of water injected*
Art_lift_elec	*[kWh/kg crude produced] Power requirement for artificial lifting of crude*

Tracked Input Flows:

Carbon dioxide [Intermediate Product]	*[Technosphere] Captured CO_2 for use in enhanced oil recovery*
Brine [Water]	*[Technosphere] Brine for use in enhanced oil recovery*
Power [Electric Power]	*[Technosphere] Electricity for injection and artificial lift*

Tracked Output Flows:

EOR Crude Oil [Valuable substance]	*Reference flow*
Brine [Water]	*Brine produced from the well along with crude*
Carbon dioxide [intermediate product]	*CO_2 produced from the well along with crude*
EOR Hydrocarbon Gas [Valuable Substance]	*HC gas produced from the well along with crude*
CO_2 sequestered	*CO_2 permanently sequestered*
Carbon dioxide [Inorganic emissions to air]	*Emission to air*

Section II: Process Description

Associated Documentation

This unit process is composed of this document and the data sheet (DS) *DS_Stage3_O_Enhanced_Oil_Recovery_Operations_2012.01.xls*, which provides additional details regarding relevant calculations, data quality, and references.

Goal and Scope

This unit process provides a summary of relevant input and output flows associated with the production of crude oil and sequestration of carbon dioxide (CO_2) via enhanced oil recovery. The inputs to this unit process include CO_2 from a pipeline, brine water produced from other wells in the oil field, and electricity used to power the injection and artificial lift pumps. Outputs include crude oil, light hydrocarbons, CO_2 and brine for recycling back to the reservoir, and CO_2 emissions resulting from injection pump seal leakage and formation leakage of sequestered CO_2. The reference flow of this unit process is: 1 kg of Crude Oil.

Boundary and Description

This unit process provides a summary of relevant input and output flows associated with enhanced oil recovery. The tracked inputs are electricity, CO_2, and brine. The key outputs are crude oil, hydrocarbon gas (C_1-C_5), CO_2 and brine for recycling back to the formation, and sequestered CO_2.

Enhanced oil recovery (EOR) involves the injection of CO_2 and brine into a formation to stimulate additional crude production. EOR is considered a tertiary recovery step for crude production which is utilized after primary and water-flood techniques have been exhausted (NETL, 2010). The mechanism by which CO_2 enables additional recovery of crude has to do with the miscibility with crude and the corresponding reduction of viscosity, swelling of crude, and reduction of interfacial tension (NETL, 2010). The injection of CO_2 is often alternated with the injection of brine in what is known as the water alternating gas (WAG) tertiary injection scheme (NETL, 2010). Brine injection prevents the undesired channeling of CO_2 which can result in bypassing the stored oil.

The primary function of EOR is the production of additional crude from a formation; however, EOR also sequesters anthropogenic CO_2 in the process. In this unit process, it is assumed that the CO_2 for EOR originates from a power plant or industrial facility. The brine is assumed to be available at the oil field from other wells. During the life of the well, CO_2 and brine are both injected and produced from the formation. The formation sequesters some fraction of the injected CO_2, but is a net producer of brine. The produced CO_2 is processed along with the other products from the well and recycled back for injection back into the well along with additional makeup CO_2 from a pipeline. In addition to CO_2 and brine, the well also produces crude oil and hydrocarbon gas (C_1-C_5). This combined production stream is processed above ground to separate gas, water, and crude. The resulting gas mixture can be processed by various methods to separate products as desired.

This unit process is based on EOR production in the Permian Basin of West Texas. Based on a survey of wells in the basin, the crude oil produced had a mean API gravity of 36 and was produced from a well with a mean depth of 5,826 feet (NETL, 2010). The hydrocarbon gas produced from the formation contained 72.3 percent (by weight) methane (C_1), 12.2 percent ethane (C_2), 4 percent propane (C_3), 1.3 percent butanes (C_4), and 0.5 percent pentanes (C_5), with the balance of the stream made up by hexanes-plus (C_{6+}), hydrogen sulfide, nitrogen, and helium (NETL, 2010). The NETL study that provides the basis for this unit process evaluated three EOR scenarios: historical, best practices, and high-CO_2. These scenarios are primarily defined by the ratio of the cumulative injected CO_2 to the total hydrocarbon pore volume (HCPV) in the formation. The historical scenario uses and HCPV of 0.4, best practice assumes 1.0, and high-CO_2 assumes 1.5 (NETL, 2010). The cost of CO_2 was the primary driver behind the lower HCPV of the historical scenario relative to the best practice and high CO_2 scenarios. This unit process provides the ability to model each of the three scenarios, each with different injection requirements and production mixes.

The injected CO_2 stream is a combination of makeup CO_2 from a pipeline and recycled CO_2 from the gas processing plant. At pipeline conditions, liquid carbon dioxide forms at a pressure of 1,070 psia. The pipeline pressure is maintained above this critical point to ensure that all CO_2 remains in the liquid state. CO_2 from the gas plant is assumed to be at a pressure of 50 psia. Thus, both streams need to be compressed/pumped to the required injection pressure of 2,200 psia at the wellhead. The calculation of the electricity requirements includes a compression load to increase the pressure of the recycle gas from 50 psia to 1,070 psia and a pumping load to increase the pressure of the entire CO_2 injection stream (recycle plus makeup) to the injection pressure of 2,200 psia.

The power to compress the recycle CO_2 stream from 50 psia to the critical point (1,070 psia) is described by **Equation 1**.

*Power (MW) = 0.0026989*x, where x = CO_2 recycle flow rate (tonnes/day)* **(Equation 2)**

The power to pressurize supercritical CO_2 from its critical point (1,070 psia) to the required injection pressure (2,200 psia) is described by **Equation 2**.

*Power (MW) = 0.0001908*x, where x = CO_2 total flow rate (tonnes/day)* **(Equation 2)**

Both equations are based on performance curves for CO_2 compression and pumping and are a function of CO_2 flow rate (McCollum & Ogden, 2006). This unit process models all CO_2 compression and pumping using electric power.

The operation of CO_2 compressors and pumps results in fugitive emissions of CO_2. The low, mid-range, and high emission factors for CO_2 from compressors are 6,972, 23,240, and 116,200 kg of CO_2 per megawatt-year (MW-yr). These factors are based on natural gas pipeline data that the Intergovernmental Panel on Climate Change (IPCC) collected and adapted to CO_2 pipelines using the relative densities of natural gas and CO_2 (Holloway, Karmijee, Akai, Pipatti, & Rypdal, 2006). On a daily basis, this is equivalent to 19.1, 64.0, and 318 kg CO_2/MW-day. This unit process applies these emission factors to the calculated pump power output to determine the fugitive CO_2 emissions from CO_2 pumps at the injection site.

In addition to the fugitive CO_2 emissions from the injection pump, the unit process also assumes some leakage of CO_2 to the atmosphere from the underground storage formation. It is assumed that one percent of the stored CO_2 eventually migrates to the surface over a 100-year monitoring period.

The brine injection pump utilized for the WAG recovery scheme is designed to achieve an outlet pressure of 300 psi for injection into the formation (NETL, 2010). The power requirements for the pump were calculated to be 7.48E-04 kWh/kg brine injected into the formation.

According to NETL (2010), artificial fluid lifting is often required for EOR wells to yield production levels that are economical. Pumps are utilized to lift the reservoir products to the surface in cases where the produced fluid is too deep or viscous to reach the surface based on the reservoir pressure alone (NETL, 2010). The electricity requirements for the artificial lift pump range from 15.8 to 20.0 kWh per barrel of crude produced, depending on the characteristics of the EOR operation (NETL, 2010).

Figure 1 provides an overview of the boundary of this unit process. There are three inputs to this unit process: electricity used for powering the injection and lift pumps, pipeline CO_2, and brine. The fugitive emission of CO_2 is accounted for in this unit process. There are four tracked outputs from the process: EOR crude oil, EOR hydrocarbon gas, brine, and CO_2 to gas processing. There is one waste stream from the process: sequestered CO_2.

Table 1 summarizes emission factors and other parameters that are relevant to this unit process. **Table 2** provides a summary of modeled input and output flows and shows all inputs and outputs on the basis of the reference flow (the production of one kilogram of crude oil). Additional detail regarding input and output flows, including calculation methods, is contained in the associated DS.

Figure 1: Unit Process Scope and Boundary

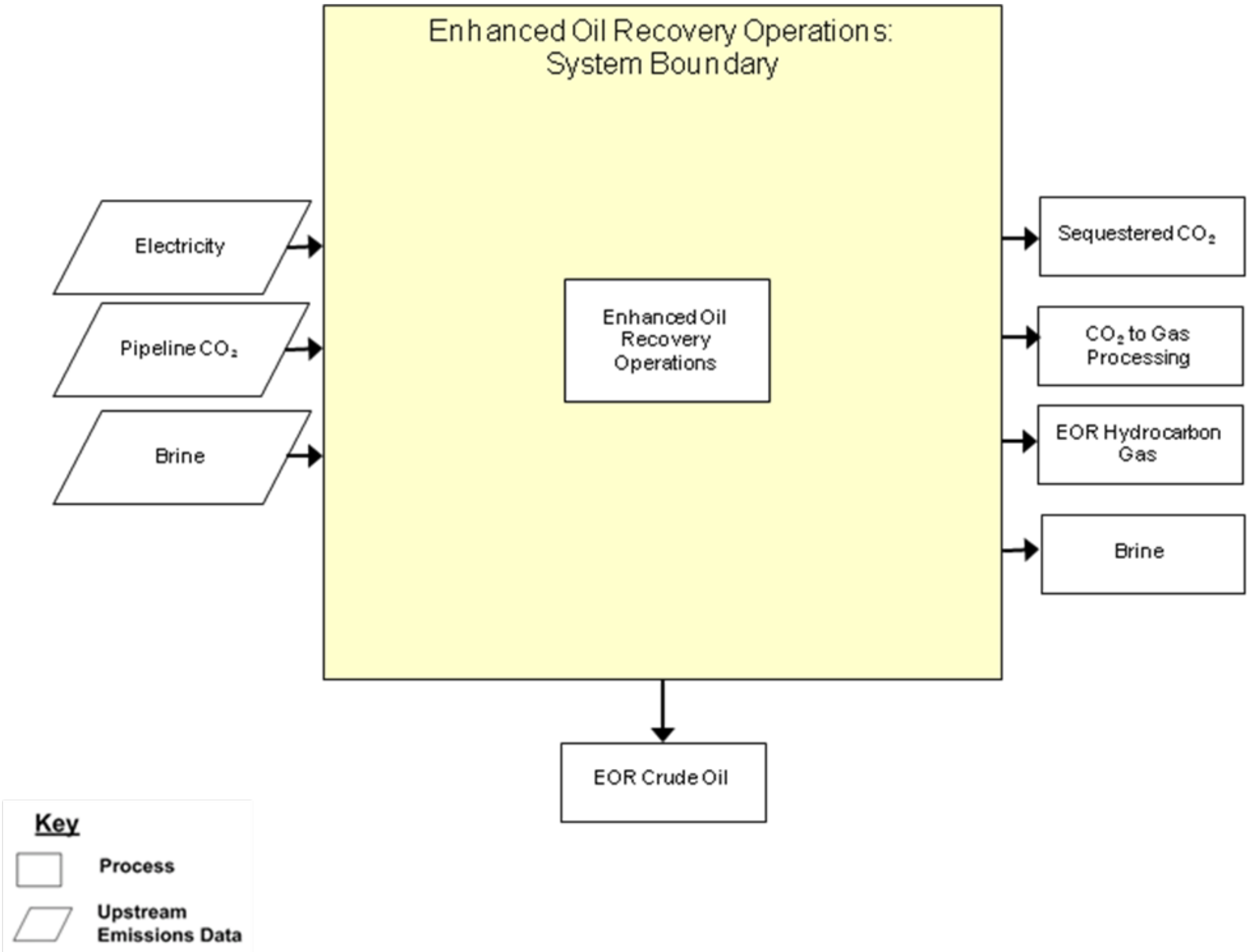

Table 1: Enhanced Oil Recovery Parameters – Best Practice Scenario (1.5 HCPV)

Parameter	Value	Units	Reference
Brine injection	1.21E+01	kg/kg crude	NETL, 2010
Brine production	1.30E+01	kg/kg crude	NETL, 2010
CO_2 injection	5.90E+00	kg/kg crude	NETL, 2010
CO_2 production	4.17E+00	kg/kg crude	NETL, 2010
Hydrocarbon gas production	1.43E-01	kg/kg crude	NETL, 2010
CO_2 recycle flow to injection	1.85E+01	tonne/day	NETL, 2010
CO_2 makeup flow to injection	7.70E+00	tonne/day	NETL, 2010
Total CO_2 flow to injection	2.62E+01	tonne/day	NETL, 2010
Artificial lift electricity	1.18E-01	kWh/kg crude	NETL, 2010
Brine pump electricity	7.87E-04	kWh/kg brine	NETL, 2010
Injection Pump CO_2 Emissions	64	kg/(MW-day)	Holloway et al., 2006
CO_2 Leakage from Aquifer	1.00	percent (over 100 year monitoring basis)	NETL Engineering Assumption

Table 2: Unit Process Input and Output Flows – Best Practice Scenario (1.5 HCPV)

Flow Name	Value	Units (Per Reference Flow)
Inputs		
Carbon dioxide [Intermediate Product]	1.76E+00	kg
Brine [Water]	1.21E+01	kg
Power [Electric Power]	4.24E-01	kWh
Outputs		
EOR Crude Oil [Valuable substance]	1	kg
Brine [Water]	1.30E+01	kg
Carbon dioxide [intermediate product]	4.17E+00	kg
EOR Hydrocarbon Gas [Valuable Substance]	1.43E-01	kg
CO2 sequestered	1.74E+00	kg
Carbon dioxide [Inorganic emissions to air]	1.82E-02	kg

* **Bold face** clarifies that the value shown *does not* include upstream environmental flows.

Embedded Unit Processes

None.

References

Holloway, S., Karmijee, A., Akai, M., Pipatti, R., & Rypdal, K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy, Chapter 5: Carbon Dioxide Transport, Injection, and Geological Storage*. Intergovernmental Panel on Climate Change Retrieved September 10, 2012, from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_5_Ch5_CCS.pdf

McCollum, D. L., & Ogden, J. M. (2006). *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity*. (UCD—ITS—RR—06-14). Davis, California: Institute of Transportation Studies University of California Davis Retrieved September 10, 2012, from http://pubs.its.ucdavis.edu/publication_detail.php?id=1047

NETL. (2010). *An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO2-Enhanced Oil Recovery in the Permian Basin*. (DOE/NETL-2010/1433). Pittsburgh, PA: National Energy Technology Laboratory Retrieved October 18, 2012, from http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=333

Section III: Document Control Information

Date Created: October 19, 2012

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Revision History:

Original/no revisions

How to Cite This Document: This document should be cited as:

NETL (2012). NETL Life Cycle Inventory Data – Unit Process: Enhanced Oil Recovery Operations. U.S. Department of Energy, National Energy Technology Laboratory. Last Updated: October 2012 (version 01). www.netl.doe.gov/energy-analyses (http://www.netl.doe.gov/energy-analyses)

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