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Author
Jordan, P.D.

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Worker safety in a mature carbon capture and storage industry in the United States based upon analog industry experience

Preston D. Jordan[a,*], Sally M. Benson[b]

[a] Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States
[b] Department of Energy Resources Engineering, Stanford University, Stanford, CA 94305, United States

abstract

Insight into worker safety in a mature carbon capture and storage (CCS) industry in the United States (US) can be gained by analogy to a variety of existing industries. Worker safety in capture facility construction will be below median, as is typical for construction. Worker safety in capture operation will be above median based on the oil refining, fossil fuel electric power generation, and industrial gas processing analogs. Pipeline construction and operation worker injury rates will be below median based on analogy with oil and gas pipeline construction and operation; however construction will have the unfortunately typical high fatality rate. Storage field worker safety will be mixed with below median injury rates but high fatality rates based on the oil and gas production analog. Still, safety in the oil and gas production analog is better than in the heavy and civil engineering construction industry and much better than in some other common industries, such as marine and truck transportation. CCS worker safety will be greater than the analogs due to the lack of flammable fluid handling, extremely high or low temperatures, product transportation by truck, and relatively less drilling effort, more geophysics effort, and more onshore work. Many of these differences also suggest CCS will be safer for the public than the analogs.

1. Introduction

Storage of carbon dioxide (CO_2) in permeable rocks in the subsurface is one option for reducing greenhouse gas emissions in the future. As currently envisioned, CO_2 from large, stationary emission sources, such as power plants and cement factories, would be separated (captured) from the flue gas,purified and compressed to a liquid state. The CO_2 liquid would be transported by pipeline to a suitable storage field where it would be injected into the subsurface for storage in a supercritical state. Likely suitable storage fields are oil and gas reservoirs and permeable rocks filled with brine (saline aquifers) beneath relatively impermeable cap rocks meeting various criteria, such as pressure and temperature. Fig. 1 shows the portions of the coterminous United States (US) underlain by saline aquifers assessed as meeting these criteria as well as the location of all hydrocarbon wells as of 2008.

Taken as a whole, the industry described above is typically termed the carbon capture and storage (CCS) industry (Intergovernmental Panel on Climate Change [IPCC], 2005). The safety of such an industry is an area of active study. For instance Ha-Duong and Loisel (2011) projected hundreds of additional fatalities worldwide resulting from such an industry through 2050. Most of the fatalities were due to mining and rail transportation of additional coal to power capture plants. However it is by no means assured that coal will be the energy source for such plants. For instance the planned post-combustion capture unit on the coal-fired Petra Nova power plant in Texas will be operated on natural gas. In addition, there is considerable uncertainty in projecting how much energy will be needed for capture as the technology develops.

More broadly, numerous studies have identified uncertainties bearing on the environmental and/or public impact of CCS (Wildaya et al., 2011; Koornneef et al., 2012). In general worker safety had not been a particular focus of study, nor what can be learned from existing worker safety data in closely related industries. Such research is motivated by conclusions drawn by the IPCC (2005) indicating that "the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas." It could help bound the uncertainty regarding this key group, and perhaps also provide some perspective on impacts on the public and environment.

This paper pursues such study to develop a perspective on worker safety in a mature CCS industry in the US, using data from current industrial analogs. In particular, this study considers (1) all nonfatal cases of on-the-job injury and/or illness, (2) cases with days away from work due to on-the-job injury and illness, and

* Corresponding author. Tel.: +1 510 486 6774; fax: +1 510 486 5686.
E-mail address: pdjordan@lbl.gov (P.D. Jordan).

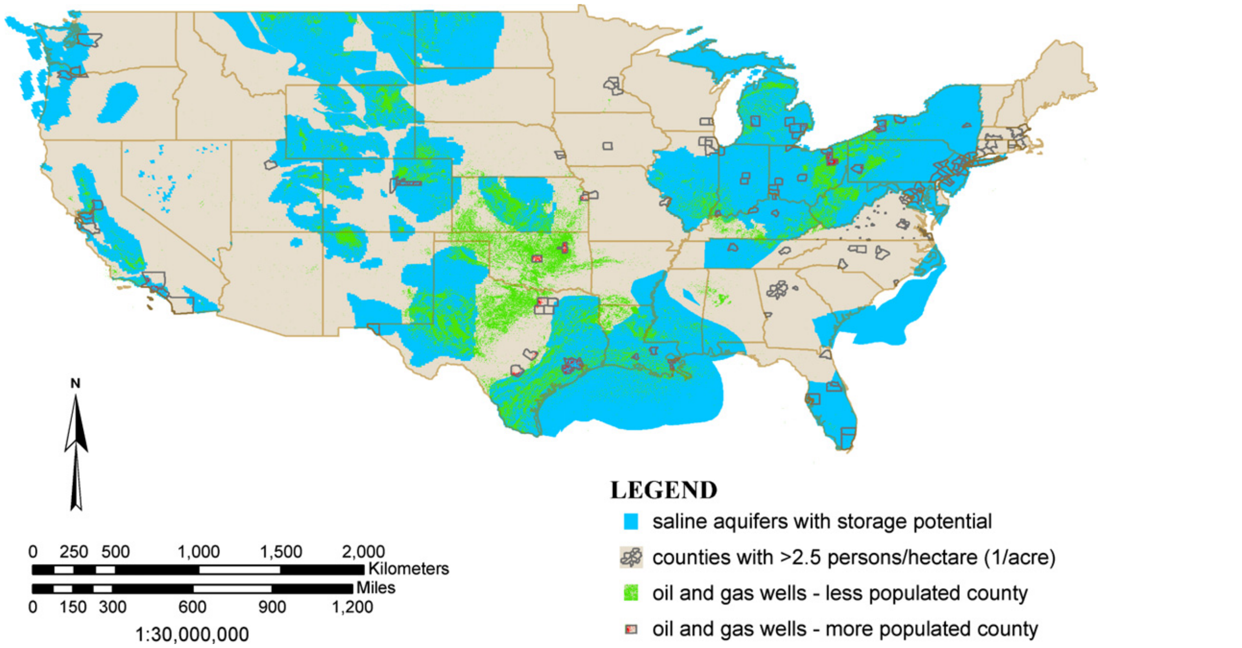

Fig. 1. Saline aquifers with identified storage potential in the coterminous United States (National Energy Technology Laboratory, 2010) along with oil and gas wells (Biewick, 2008) and more populated counties (modified from shape file available through http://www.census.gov/cgi-bin/geo/shapefiles2010/main).

(3) fatalities due to injuries sustained while at work. It goes on to consider differences in processes, materials, the mix of industrial activities, and geography between the analogs and CCS in order to further characterize likely worker safety, and comment on public risk.

2. Industrial analogs for CCS health and safety

Perspective on the size of a CCS industry that can significantly reduce greenhouse gas emissions is afforded by comparing the volume of CO_2 emitted by electric power generation stations in the US to the volume of fluids handled by the analog industries, as shown in Table 1. Even if only a fourth to a third of the CO_2 emissions from power generation are captured, Table 1 suggests that employment in a capture industry would be similar in magnitude to that in the petroleum refining industry, and employment in a storage industry-scaled to store this amount of fluid would be around a fifth that of the oil and gas production industry. Capture and storage of most of the CO_2 emissions from power generation would result in a capture work force similar in size to the fossil fuel power generation industry and a storage work force similar to the oil and gas production industry.

A future CCS industry can be broken into four segments. The carbon capture ("capture") industry will build and operate CO_2 capture facilities. The carbon transportation industry will build and operate pipelines to transport CO_2 from capture facilities to storage fields. The carbon storage ("storage") industry will locate, develop, operate and monitor storage fields. Various manufacturing industries will make the equipment and chemicals needed by the capture, transport and storage industries.

This industrial segmentation is akin to the downstream and upstream segments of the oil and gas industry. A segment of the downstream oil industry refines crude oil into various products through separation, purification and transformation. The upstream oil and gas industry explores for oil and gas fields, develops these fields, and extracts oil and gas from them. Pipeline transportation of oil from the field to the downstream petroleum refining industry is often considered part of the upstream industry, but here is considered a separate industrial segment. Finally there is segment manufacturing goods for the petroleum industry.

The capture facility construction analog is the industry that builds power plants and refineries. There are four potential analogs for the capture operation industry:

- petroleum refining,
- natural gas processing,
- fossil fuel electric power generation, and
- industrial gas manufacturing.

The natural gas processing industry purifies natural gas to transmission pipeline standards, typically by removing excess CO_2 and H_2S from the gas stream as produced. This typically occurs at facilities near to the production field and operated by the upstream industry. As such worker safety data for this activity is subsumed in the data for the entire upstream industry.

All analogies by definition have strengths and weaknesses. Table 2 lists some similarities and differences between the identified analog capture operation industries, the upstream industry analog for storage and the prospective CCS industry. The electric power generation industry obviously creates CO_2 as a by product, but its relevance as an analog is because this industry involves the handling of high pressure fluids and the operation of scrubbers to treat flue gas to meet air quality regulations.The industrial gas manufacturing industry is capture industry analog purifies gases from gas mixtures and sells the products. About a fifth of its product by mass is CO_2 separated from high concentration streams, including those from hydrocarbon reformation to produce hydrogen or ammonia or from biological processes such as ethanol production (Universal Industrial Gases, 2008). Most of the remaining four fifths of the mass produced by this industry are equal parts oxygen and nitrogen typically separated from air by cryogenic processes (US Census Bureau, 2005).

The remaining required analog is for transportation. While the US has the world's most developed CO_2 pipeline network, worker

Table 1
A comparison of fluid/gas masses and volumes handled by various CCS analog industries in 2007 (2004 for industrial gases).

Fluid type	Mass (million metric tons)	Volume (million cubic meters)	
		"Standard" conditions[a]	Reference reservoir conditions[b]
Power plant CO_2 emissions	2516[c]	1,270,000[d]	4470[e]
Crude oil withdrawals	345[f]	397[g]	397[h]
Gross gas withdrawals	590[i]	696,000[j]	7000[k]
Water produced with oil and/or gas	3300[l]	3300[m]	3300[h]
Petroleum refinery crude oil inputs	853[f]	879[g]	879[h]
Industrial gases (18% CO_2 by mass)	74[n]	73,700[o]	520[p]

[a] Varies, as shown in footnotes.
[b] 40 °C and 10 MPa (equivalent to temperature and pressure at a depth of 1 km assuming a hydrostatic pressure profile, a surface temperature of 15 °C and a geothermal gradient of 25 °C/km.
[c] US Energy Information Administration (EIA, 2009a).
[d] From mass using a CO_2 density of 1.976 kg/m^3 (occurs at 0 °C and 1.013 bar (Intergovernmental Panel on Climate Change [IPCC], 2005).
[e] From mass using CO_2 density at reference reservoir conditions, which is 563 kg/m^3 (Lawrence Berkeley National Laboratory [LBNL] 2010).
[f] From the oil volume at standard condition (60 °F and 1 atm) using average relative density of 0.87 based on the average produced or refinery input gravity of 30.42 (EIA, 2008).
[g] EIA (2008).
[h] In reservoir volume is typically larger due dissolved gases, but the average of this change (the formation volume factor) is not known. This is typically relatively small in mature fields, and in the context this study, though, and so it is discounted.
[i] From volume at "standard" conditions assuming gas gravities average 0.7. The average density of such gas at the EIA's standard condition (60 °F and 1 atm; EIA, 2009b) is approximately 0.85 kg/m^3.
[j] EIA (2009b). Standard condition is 60 °F and 1 atm.
[k] From volume assuming 0.7-gravity (non associated) gas, the density of which is 100 kg/m^3 at the reference reservoir conditions (Standing and Katz, 1942).
[l] The mass is likely 5–10% higher due to salinity, but the average salinity, temperature and pressure for the produced waters was not reported (Clark and Veil, 2009), so the mass conversion used the density of fresh water.
[m] Clark and Veil (2009).
[n] Most recent available data is for 2004 from US Census Bureau (2005). All gases reported in volume at standard condition (but CO_2. Volumes converted to masses using "standard" condition densities (LBNL, 2010), and then all masses summed.
[o] Most recent available data is for 2004 from US Census Bureau (2005). CO_2 was reported in mass, and so converted to volume using the "standard" condition (70 °F, 1 atm) density of 1.8334 kg/m^3 (LBNL, 2010).
[p] Summation of reference reservoir volumes converted from reported mass for CO_2 and reported volumes for all other gases using densities at the reference reservoir condition (LBNL, 2010).

Table 2
Comparisons between the carbon capture and sequestration industry and the analog industries.

Analog industry	Mass/volume of analog industry fluid stream relative to power plant CO_2 emissions for 2007 (order of magnitude)	CCS industry characteristics				Additional similarities relative to capture and/or storage	Additional differences relative to capture and/or storage
		High fluid pressures	Nonflammable/ nonoxidizing fluids	Fluid component separation	Moderate fluid temperature		
Petroleum refining	Same to −3 (depending on pressure and temperature)	Yes	No	Yes	No, higher		Chemical transformations, wider range of pressure-temperature conditions
Fossil fuel electric power generation	+1 (other flue gases)	Yes	No	Minor (pollutant removal)	No, higher		High voltage/current electricity, bulk material handling
Industrial gas manufacturing	−1 to −2	Yes	No (oxygen)	Yes, including CO_2	No, lower		Some truck transportation of product
Oil and gas production	Same	Yes	No	Yes, including CO_2	Yes	Engineering fluid transfers between the surface and subsurface, locating subsurface volumes meeting specific criteria	Higher well densities, reservoirs contain buoyant fluids initially, some reservoirs initially overpressured

safety data regarding the construction and operation of that network is not readily available. Consequently the natural gas pipeline construction and operation industry, for which there is data, is taken as the analog. There probably is little difference in construction activities relative to worker risk, but operation is another matter. Natural gas is combustible while CO_2 is not, and CO_2 is denser then air while natural gas is not, making CO_2 of more concern for asphyxiation. Natural gas is not as sensitive to pressure and temperature changes at typical operating conditions whereas CO_2 pipelines likely will operate nearer phase boundaries.

Aspects of the analogies upon which this study is based are discussed further in a later section.

3. Worker safety data sources

A number of data sources regarding worker safety in the analog industries were used as the basis of this study. These sources and some of their properties are listed on Table 3 (and are referenced in Appendix A of the supplementary material). These properties are further discussed below. All the sources provide injury rates, lost time due to injury information, and fatality rates or data sufficient to calculate as much.

3.1. Bureau of Labor Statistics

Work-related injuries, illnesses and fatalities are reported annually by the Bureau of Labor Statistics in the US Department of Labor (BLS). Relevant to this study, the BLS reports health and safety statistics by industry class, with whole companies classified by their predominant activity. Starting with 2003, the BLS used the 2002 North American Industry Classification System (NAICS) for this purpose (BLS, 2004). Industry classes involved in the identified analogs were selected for study based on searching the NAICS (http://www.census.gov/eos/www/naics/). This included industry classes judged likely to be significant suppliers to a CCS industry, such as "pump and pumping equipment manufacturing" and "all other basic organic chemical manufacturing" (which currently manufactures capture fluids).

NAICS is substantially different from the Standard Industrial Classification system previously used by the BLS (US Census Bureau, 2000, 2004), so the period for this study starts at 2003. More recently, a 2007 edition of the NAICS was issued and its use by some BLS units relevant to this study commenced in 2009. The end of the period for this study is 2007, providing for a five year period. The sources of BLS data used in this study are listed in the data sources section, which follows the references.

Injuries and illnesses are estimated from data collected by the Survey of Occupational Injuries and Illnesses in the BLS. Worker fatality data is collected and tabulated by the Census of Fatal Occupational Injuries in the BLS. The Survey and Census are carried out in coordination with participating state agencies (BLS, 2011).

Three types of worker injury and illness estimates from the BLS are analyzed in this paper: (1) all nonfatal cases of on-the-job injury and/or illness combined, (2) all non fatal cases of on-the-job injury, and (3) cases with days away from work due to on-the-job injury and/or illness. A case is defined as an injury (or injuries) or illness contracted by a worker from one event. In other words, while a worker may sustain multiple injuries from a single accident, this is counted as one case by the BLS.

In addition to injury and illness data, the BLS collects data on the total hours worked. This allows the BLS to estimate the rate of injuries and illnesses on an hourly basis. The rates are reported in injury or illness cases per 200,000 work hours. Full time equivalent work is 2000 h per year, so this basis is equal to 100 full time equivalent workers (BLS, 2011).

Counts of worker fatalities from the BLS are also considered in this paper. The BLS only collects data on worker fatalities due to injury. The length of time ("latency period") between an occupational exposure that causes an illness, and a fatality resulting from that illness, is quite long for many types of exposure and illness. This introduces large uncertainty into the attribution of these fatalities to a particular occupation and industry. Therefore the BLS does not count work-related illness fatalities due to this uncertainty (BLS, 2011).

3.2. Other data sources

Both employees of the companies owning and operating facilities and employees of contractors to those companies conduct activities in oil and gas production, petroleum refining, and electric power generation. Many of the analog industry classes considered in this study focus on the contractors, such as the "drilling oil and gas wells" and "power and communication line and related structures construction" industry classes. However, it is likely that not all contractors performing work at these facilities regularly are included in these classes.

For instance, an explosion at a BP refinery in 2005 killed 15 workers (Olsen, 2005). However, the BLS did not report any fatalities for the petroleum refining industry that year (BLS, 2006). It is possible these fatalities are included in some of the other analog classes. However to provide higher assurance that the current analysis studies the analog industries inclusive of both employees and contractors, some data sources in addition to the BLS were utilized, including the International Association of Oil and Gas Producers (OGP), National Petrochemical and Refiners Association (NPRA; now the American Fuel and Petrochemical Manufacturers), and Electric Power Research Institute (EPRI).

The OGP is an association of most of the largest oil and gas producers and upstream service companies. The OGP members produce about half of the oil and a third of the gas in the world (OGP, 2012). The supplementary material includes a table of members that provided annual safety data regarding injuries for their employees and their contractors' employees. The OGP performs data quality assurance on the data and then analyzes and publishes it. Consequently these reports provide a perspective on the safety of an industry sector without regard to the confounding effect of company versus contractor inherent in the BLS data. The OGP reports utilized in this study are listed in Appendix A.

Another advantage of the OGP worker safety reports is the breakdown of safety measures by functional sector and geographic location. The OGP reports safety measures for the four functional sectors exploration, drilling, production and other/construction. The last sector was termed "other" prior to 2006 and "construction" after 2005. The "construction" and "other" sector are not exactly equivalent, but appear to have sufficient overlap such that they are treated as a single data series in this study. The OGP also reports safety measures for work onshore versus offshore, which is not available in the BLS data.

The OGP reports all safety measures by all breakdown categories for the world. Only some overall and double breakdown safety measures are reported for large multi-country areas. For instance total recordable and lost-time injury rates for exploration contractors in North America are reported, but not the fatality rate (an OGP incident appears equivalent to a BLS case except the former includes fatalities and the latter does not). Only the overall lost time incident rate is reported by country.

The NPRA produces annual reports similar to those by the OGP. The NPRA annual reports are based on submissions from virtually all US oil refiners and cover refinery employees and contractors. The NRPA safety measures are akin to those from the

Table 3
Properties of data sources. "NA" means "not applicable." Other acronyms defined in text.

	Data source (CCS segment covered by analog)			
	BLS (all)	NPRA (capture)	EPRI (capture)	OGP (storage)
Company	Yes	Yes	Yes	Yes
Contractor	Upstream yes; downstream no	Yes	No	Yes
Onshore	No	NA	NA	Yes
Offshore	No	NA	NA	Yes

BLS. Lastly, the EPRI produces a similar report for the power generation industry, although this report does not cover contractors (EPRI, 2008). Still, it provides injury cause data relevant to considering the power generation industry as an analog. The NPRA and EPRI data sources used in this study are listed in the data sources section.

4. Analog industry health and safety data analysis methodology

4.1. Bureau of Labor Statistics measures

Table 4 presents the average worker health and safety rates during the study period and the percentile of those rates in the order of the four industry segments discussed. The average worker health and safety rates for each analog industry class were calculated using the number of hours worked annually in each class as a weight. The hours worked in each industry class is not reported by the BLS, but it can be estimated from the BLS reported total number of cases divided by the case rate. The average number of hours worked annually in the analog classes is shown in Table 4. A table with the calculated hours for each year as well as tables with the reported rates for each year is included in Appendix B (available in the supplementary material).

The percentile for each average rate is provided in Table 4. Analysis of the total rate set indicated the rate ranges, and to a lesser extent medians, vary with industry class size as measured by total work hours. So the percentiles were calculated against the set of 100 next larger and 100 next smaller classes by hours worked. This comparison set was selected because it was sufficiently small to represent the distribution within the immediate neighborhood of classes, but sufficiently large that the rate of change of the percentile with respect to varying the size of the comparison set was small. Considering percentiles also deals to some extent with any bias due to under reporting, presuming it is relatively consistent across industries.

As mentioned, BLS injury and illness results are based on surveys. As such they are subject to uncertainty due to sampling. The BLS reports the relative standard error for the annual injury and illness rate estimates. These were combined as the square root of the sum of their squares divided by the number of years with reported rates. This approach assumed the sample size in an industry class was consistent from year to year. The BLS uses a stratified sampling approach for the injury and illness survey, so this assumption is reasonable given the relative consistency in employment hours in each industry class during the study period.

The resulting relative standard errors for the study period were applied to provide the 95% confidence interval injury and illness rates shown on Table 4. The percentile range was subsequently calculated. This did not account for uncertainty in the 200 rates against which the percentiles were calculated on the presumption that uncertainties in this population canceled out.

The fatality rates shown in Table 4 are not those reported by the BLS, because those are per number of employees. The average number of hours worked by an employee per year varies significantly from one industry class to another, though. Among the analog industry classes the average employee work time during the study period ranges from a high of 2400 h per years in support activities for oil and gas operations to 2000 h per year in pipeline transportation of natural gas. These figures were calculated for each year in the study period by dividing the annual estimated total work hours in the class by the reported number of employees, and then averaging by weighting the result for each year by the total number of work hours for that year. So comparing the BLS reported rates from one class to another does not account for differences in exposure time.

Outside of the analog classes there is even more variation. For instance full-service restaurant employees worked 1300 h per year on average. Consequently the reported rates of fatalities per number of employees do not properly account for exposure time, which is why the BLS switched to reporting rates of fatalities per employment hours in 2008 (BLS, 2011). For this study, fatality rates were calculated by dividing the absolute number of fatalities reported by the total work hours estimated for that class for each year in the study period.

For roughly half the industry classes in Table 4, the BLS did not report the total number of fatalities in at least one of the study years for which the number of hours worked could be estimated. This appears to be due to a surmised minimum reporting limit of three fatalities (Olsen, 2005). BLS (2011) does not confirm this, nor would BLS personnel. Rather BLS personnel explained that a number of reporting rules are used for fatality data by agreement with the data sources to protect their confidentiality, and BLS does not publish these rules because this could jeopardize source confidentiality (Steve Pegula, personal communication, 24 January 2012).

In the cases of unreported fatality totals, fatality rates were calculated by assuming each of the possible absolute total fatality values of 0, 1 and 2 for the missing data based on the surmised minimum reporting limit. This resulted in the three rates shown in Table 4 for those classes with a missing fatality total. These three provide some perspective on the range and distribution of possible fatality rates in an industry class.

Table 4 also shows the fatality rate percentiles. Calculating these percentiles from a set of classes with only reported fatalities would significantly skew the results. In particular it would reduce the analog class percentiles because the comparison set would be biased to classes with higher numbers of fatalities, and so higher fatality rates. To somewhat compensate for this, a more representative rate set was constructed across all classes by randomly assigning 0, 1 or 2 fatalities to classes with unreported fatalities. This assumes a uniform probability density function for these values, which is almost certainly not accurate as the distribution of reported values suggests smaller values are more likely than larger values. However as most of the assigned values resulted in rates less than those in the analog classes, little error in the calculated analog class fatality rate percentiles would result.

4.2. International Association of Oil and Gas Producers Measures

The OGP safety measures of (1) worker injury incident rate, (2) rate of worker injury incidences causing lost time and (3) worker

Table 4
Average United States Bureau of Labor Statistics' worker safety rates for the 2003–2007 study period and rate percentiles based on inter industry class comparison. Averages based on weighting by number of hours worked each year. "FTE" stands for full time equivalent workers. 95% confidence intervals shown in parentheses for injury and illness rates and rate percentiles (see text for assumptions).

CCS industry segment	Industry class name	NAICS code	Average hours worked per year	Injury and illness cases		Injury cases		Lost time injury and illness cases		Fatalities due to injury	
				/100 FTE	Percentile	/100 FTE	Percentile	/100 FTE	Percentile	/100,000 FTE	Percentile
Capture	Power and communication line and related structures construction	23713	2.7E+08	5.3 (4.7–5.9)	54 (46–67)	5.1	53	2.0	75	21	95
	Fossil fuel electric power generation	221112	2.6E+08	3.7 (3.5–3.9)	36 (35–39)	3.3	35	1.2	38	3.4	58
	Petroleum refineries	32411	1.5E+08	1.5 (1.2–1.8)	10 (7–13)	1.3	10	0.4	6	2.3–3.1–3.9	48–61–65
	Industrial gas manufacturing	32512	4.6E+07	1.5 (1.1–1.9)	7 (5–9)	1.5	7	0.6	11	0.0–4.4–8.7	0–45–75
Transpor-tation	Oil and gas pipeline and related structures construction	23712	1.9E+08	2.5 (2.1–3.0)	17 (15–20)	2.5	15	1.0	30	17.5	92
	Pipeline transportation of natural gas	4862	5.1E+07	2.4 (2.0–2.9)	12 (7–16)	2.1	11	0.7	18	0.0–3.5–7.0	0–34–62
Storage	Drilling oil and gas wells	213111	1.5E+08	5.4 (4.8–6.0)	48 (41–55)	5.3	52	1.9	70	45	99
	Support activities for oil and gas operations	213112	3.6E+08	2.4 (2.1–2.7)	17 (16–21)	2.3	18	1.0	32	27	97
	Oil and gas extraction	211	2.6E+08	2.0 (1.7–2.4)	20 (12–21)	1.9	18	0.8	24	14.4	91
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	1.1E+08	3.7 (3.3–4.2)	28 (22–33)	3.6	30	0.9	29	2.2–3.3–4.4	48–50–69
	All other industrial machinery manufacturing	333298	5.8E+07	6.7 (5.6–7.9)	72 (56–84)	6.3	69	1.7	64	2.1–4.9–7.6	25–51–78
	Pump and pumping equipment manufacturing	333911	5.8E+07	6.0 (5.4–6.6)	63 (54–72)	5.5	62	1.2	44	0.0–3.4–6.9	0–39–68
	Air and gas compressor manufacturing	333912	4.3E+07	5.0 (4.2–5.8)	51 (38–62)	4.7	49	1.2	41	0.0–4.6–9.2	0–31–53
	All other miscellaneous general purpose machinery manufacturing	333999	8.2E+07	5.6 (4.9–6.3)	58 (49–67)	5.2	58	1.5	56	0.0–2.4–4.9	0–36–64
	All other basic organic chemical manufacturing	325199	7.1E+07	2.5 (2.2–2.9)	18 (16–22)	2.0	16	0.7	23	1.7–4.0–6.2	25–58–78

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Table 5
International Oil and Gas Producers Association average worker safety measures for 2003–2007 for the world, North America and the United States, as available or calculable, in BLS unit. Averages based on weighting by number of hours worked each year.

	Injury cases		Lost time injury cases		Fatalities due to injury	
	/100 FTE	Work hours (millions)	/100 FTE	Work hours (millions)	/100,000 FTE	Work hours (millions)
World						
Total	**0.64**	**2300**	**0.18**	**2550**	**8.10**	**2550**
Company	**0.45**	**543**	**0.15**	**667**	**4.01**	**667**
Contractor	**0.69**	**1800**	**0.20**	**1890**	**9.55**	**1890**
Onshore	**0.57**	**1760**	**0.17**	**1970**	**8.58**	**1970**
Offshore	**0.84**	**535**	**0.22**	**582**	**6.46**	**582**
Exploration	**0.59**	**60**	**0.17**	**64**	**7.83**	**64**
Drilling	**1.09**	**249**	**0.31**	**281**	**10.21**	**281**
Production	**0.72**	**689**	**0.21**	**850**	**5.55**	**850**
Other/construction	**0.43**	**657**	**0.12**	**690**	**7.34**	**690**
North America						
Total	**1.04**	**300**	**0.18**	**303**	**6.25**	**303**
Company	0.46	119	0.12	119	1.01	119
Contractor	1.36	184	0.21	184	11.11	184
Onshore	1.07	226	0.18	226	5.50	226
Offshore	0.82	77	0.17	77	11.91	77
Exploration	0.54	6	0.05	6		
Drilling	1.45	34	0.29	47		
Production	1.09	68	0.15	94		
Other/construction	0.55	31	0.12	45		
US						
Total			**0.18**	**193**		

Numbers in bold text available in the OGP reports.
Numbers in plain text calculated from values in the OGP reports.
Data for only one category is reported for the US.
Fatality rates were not removed from injury and lost time injury incident rates for North America industry sectors as necessary to fully convert to BLS units because fatality rates for those sectors were not reported.
2006 lost time injury case rate for other/construction not included in averages because it is an order of magnitude greater than the rate for other years and it is greater than the 2006 injury rate.
The lost time injury case work hours for the United States is not reported for 2007, and so the case rate and work hour average shown does not include data from 2007.

fatality rate are generally akin to the BLS injury case rates. Both the OGP term “incident” and the BLS term “case” refer to a single event causing one or multiple injuries to a worker. The main differences are that OGP incidences include fatalities while BLS cases do not, and the OGP rates are reported per a different number of work hours than the BLS rates. All OGP rates presented in this report have been converted to BLS rate units to the extent possible (see Table 5 for exceptions) for consistency. A table with conversions between BLS and OGP units is provided in Appendix B (available in the supplementary material).

Table 5 presents the average OGP safety measures for North America during the study period converted to BLS units. The average safety measures and average number of hours worked for North America and the world are shown in Table 5. The average safety measures were calculated using the number of hours worked annually as a weight.

As mentioned, some breakdowns were not provided in the OGP report. Many of these were calculated from other breakdown measures provided. For instance the injury rate for drilling workers in North America was not reported, but was derived from the rates for company workers engaged in drilling as well as drilling contract workers in North America.

4.3. *National Petrochemical and Refiners Association*

The NPRA reports the rate of injury cases, and combines the days away from work case and fatality rate into one. However, the NPRA provides the absolute number of days away from work and fatality cases, as well as the total number of hours worked, so the annual work hours-weighted averages of injury, lost-time injury, and fatalities due to injury can be calculated. The average rates are presented in Table 6.

5. Analog industry results

Fig. 2 plots some of the percentiles for the BLS industry analog class worker health and safety rates given in Table 4. The injury and illness rate percentiles are plotted on the vertical axis. The “days away” case and fatality rate percentiles are plotted on the horizontal axis. For classes with multiple possible fatality rates shown in Table 4 the middle percentile is plotted on Fig. 2 only if the percentile range given on Table 4 is less than 25. The middle percentile results from assuming 1 fatality in all years for which no data was reported. The higher an industry class plots on Fig. 2, the higher its injury and illness rate compared to similar sized classes. The further to the right an industry class plots the more common are severe injuries and illnesses.

Fig. 2 indicates that capture industry construction workers, as represented by the “power and communication line and related structures construction” class, will have below median safety, mainly due to a high fatality rate that is endemic to the heavy and civil engineering construction industry.

Fig. 2 also indicates that the probability of worker injury or illness in the capture operation analog industries of electric power generation, petroleum refining and industrial gas manufacturing is below median to low, and the occurrence of severe injuries and illnesses is below median while the fatality rate is near median. Taken together, these industries have above median worker safety compared to other industries of similar size. However, as mentioned above, the safety rates do not account for contract work in these industries. Of these three analogs, safety data for contractors is only available for the petroleum refining industry.

The average hours worked by company employees in the NRPA annual safety reports is over 85% of the number of work hours estimated from BLS data for the petroleum refining class. This supports the NPRA statement that virtually all refining companies in the US

Table 6
National Petroleum Refiners Association work-hours weighted average safety measures for 2003–2007. Averages based on weighting by number of hours worked each year.

	Injury cases		Lost time injury cases		Fatalities due to injury	
	/100 FTE	Work hours (millions)	/100 FTE	Work hours (millions)	/100,000 FTE	Work hours (millions)
Total	0.94	233	0.20	232	5.83	233
Company	1.09	128	0.28	128	2.19	128
Contractor	0.77	106	0.11	105	10.23	106

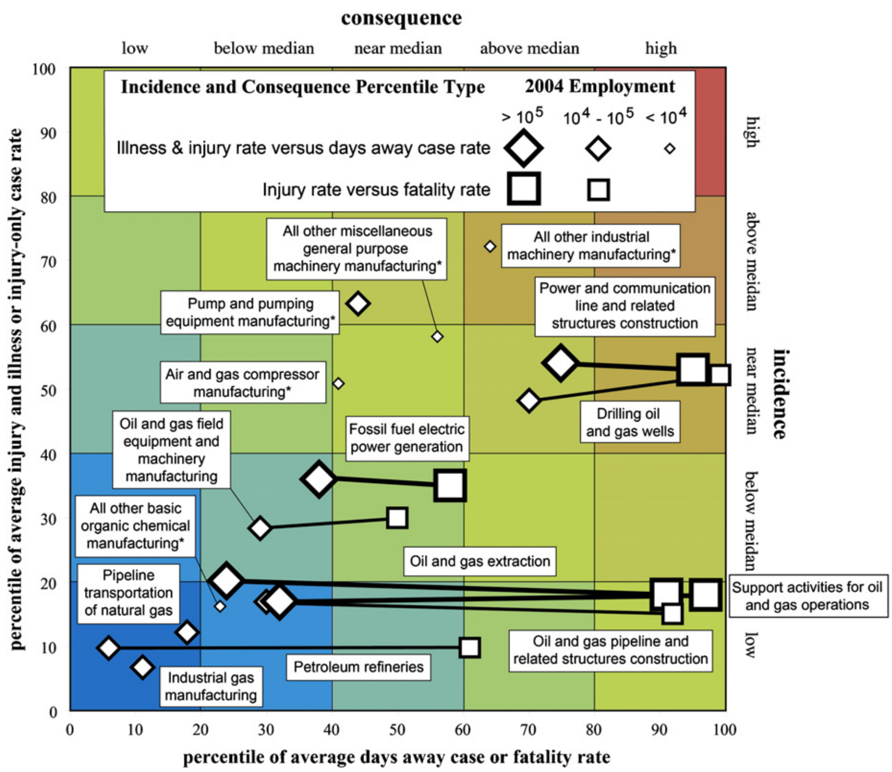

Fig. 2. Worker safety in CCS analog industry classes compared to similar size industry classes from United States Bureau of Labor Statistics data. The order of magnitude of employment in each industry class (assuming 2000 work hours per worker per year) is also shown. The order of magnitude of the asterisked manufacturing classes is reduced by one to reflect likely less significant potential participation in a future CCS industry.

submit safety data to the association. This is further supported by the close match between the average NRPA safety rates for companies shown in Table 6 to the BLS data for the petroleum refining class shown in Table 4. Further, these NRPA company rates fall in the same percentile as the BLS petroleum refining rates against the rates for the next 100 larger and smaller BLS classes by number of hours worked. These comparisons instill confidence that the contractor safety data reported by NPRA is representative of contractor safety in the industry as a whole.

Table 6 shows that the injury rate and lost time injury rate is lower for contractor than company workers in the petroleum refining industry. This lowers these rates for the industry taken in total. The lower injury rate still has the same percentile against rates from similar sized BLS classes though. The lower lost time rate is in the first percentile though as compared with the BLS petroleum refining industry rate percentile of 6 shown in Table 4. The contractor fatality rate is substantially higher than the company rate. This indicates the petroleum refining industry fatality rate is higher than reported for the petroleum refining class by the BLS. Still, the total industry fatality rate from the NPRA is just above the 48–65th percentile range for the BLS fatality rate for the petroleum refining industry shown in Table 4, and is only slightly higher than the 61st percentile position used for plotting. So overall the inclusion of contractors did not appreciably change the position of the petroleum refining industry with regard to worker safety relative to other industries as shown on Fig. 2.

Taking the worker safety results in the petroleum refining industry based on the NPRA data together with the results for the electric power generation and industrial gas manufacturing classes from the BLS data suggests that capture industry operational workers will have above median safety.

Fig. 2 indicates worker safety in the pipeline construction and operation portion of the storage industry will be above median by analogy to the oil and gas pipeline construction and operation industries.

Unlike for the capture industry for which analog contractor classes do not exist, there are separate classes for upstream companies (“oil and gas extraction”) and contractors (“drilling oil and gas wells” for instance). So the BLS data provides a reasonable perspective on worker safety in both. This perspective suggests worker injury and illness rates in storage field construction and operation will be below median, and the fatality rate among all involved classes, including companies and contractors, will be high.

The upstream industry injury rates from the BLS shown in Table 4 are considerably higher than those from the OGP shown in Table 5. For instance the BLS oil and gas extraction class injury and lost time due to injury case rates are 1.9 and 0.8 per 100 full time equivalent workers, respectively, but the OGP North America company injury and lost time due to injury case rates are 0.46 and

Table 7
Oil and gas extraction class average rates for 2004–2007 by company size.

# of employees	Injury case rate/100 FTE	Lost time injury and illness case rate/100 FTE
11–49	3.3	1.4
50–249	2.4	0.7
250–999	1.7	0.5
1000+	0.6	0.2

0.18 per 100 full time equivalent workers, respectively. This is a difference of about a factor of four for both rates.

The difference in the geographic area of coverage of the BLS and OGP data could explain the difference between those results. However, the OGP lost time due to injury case rate was the same for the US and North America, and the average US work hours reported in association with this rate is about two thirds of that for North America as a whole. These suggest the rates outside of the US in North America are not very different, and in any event data from the US dominates the North America results due to the relatively larger work hour basis of the former.

Another possible explanation for the contrast between the OGP and BLS results is that the OGP data is generally based on submissions from larger companies in the industry (listed in Appendix B in the supplementary material). Table 7 shows rates for the oil and gas extraction class by company size. For oil and gas extraction companies with greater than 1000 employees, the average "injury" and "lost time due to injury" case rates were 0.6 per and 0.2 per 100 full time equivalent workers, respectively, which are in close agreement with the OGP rates for North America. This indicates the OGP rates are useful for assessing the relative safety rates between portions of the upstream industry, but not the absolute rates that occur in the industry.

The OGP data on Table 5 show that company workers generally experience greater safety than contract workers. This is in accord with the BLS data on Table 4 for the "oil and gas extraction" class, which includes exclusively companies, as compared to the other storage classes, which include exclusively contractors. The OGP data show progressively greater worker safety from drilling to production to other to exploration. This agrees with the BLS data showing drilling is the least safe industry class involved in oil and gas extraction. A similar comparison is not possible between the other OGP sectors and BLS classes because there is not a one-to-one correlation. Table 5 also shows that while the injury rate offshore is lower than onshore, the fatality rate is higher offshore indicating greater injury consequences in that environment.

Of the industries likely to manufacture a significant amount of equipment for CCS, the air and gas compressor, pump and pumping equipment, oil and gas field equipment and machinery and all other miscellaneous general purpose machinery classes have below to above median injury and illness, and days away due to injury rates, and so about median safety for manufacturing as a whole as shown on Fig. 2. The capture fluid manufacturing industry has a low injury and illness rate and a low to below median days away rate, and so high safety.

Taking all the analog industry class results together in consideration of the relative level of employment in each industry suggests the CCS industry as a whole will have below median injury and illness rates, below median rates of severe injury resulting in days away from work, and high fatality rates. These analog results suggest overall worker safety in the CCS industry will be slightly above median.

Fig. 2 also shows the 2004 employment of each class in full time equivalent workers. The employment totals shown for classes whose worker population is likely to only be expanded, rather than largely replicated for a CCS industry, have been adjusted down an order of magnitude. Given the findings shown in Table 2, this applies to all the manufacturing classes except "oil and gas field machinery and equipment manufacturing." The other manufacturing classes considered in this study make equipment and chemicals used in a broad number of other industries and so their employment will likely rise only relatively incrementally in response to the development of a CCS industry. In contrast the "oil and gas field machinery and equipment manufacturing" industry makes equipment only for oil and gas production. Presuming CCS needs similar equipment employment in this industry is likely to grow significantly if a CCS industry is to develop.

6. Discussion of analogs versus carbon capture and storage

The percentile range at the 95% confidence interval for the injury and illness rate is less than 10 for the majority of the eight largest analog classes by employment, and all have a range less than 20. In fact all the analogs have a confidence interval less than 20 except two of the manufacturing classes. These two classes are relatively small by employment, and unlike the non-manufacturing classes are unlikely to be substantially replicated if CCS attains a size significant relative to greenhouse gas production. This indicates that comparitize injury and illness rate results are reasonably robust.

For seven of the fifteen classes considered, the fatality rate percentile range is greater than 25, indicating the result is not very robust. Five of these seven are manufacturing classes, for which there is one class that has a reasonably robust percentile range. One of the seven is one of the three capture operation analogs. The other two have reasonably robust to robust percentiles. The final of the seven is the pipeline operation analog, for which there is no other analog with a robust percentile. So the main consequence of the non-robust fatality rates regards elimination of any information on the fatality rate for pipeline operations.

In order for the lost-time injury and fatality rates to be valid metrics of severity, the causes of those events must be the same as the causes of injuries in general. This is known as the "common cause" hypothesis. Research suggests that this hypothesis is correct to a first order (Wright and van der Schaaf, 2005). However, this does not account for process differences between the analog industries and the CCS industry.

6.1. Analog process differences

The main process difference is that the oil and gas industry analogs are primarily involved with flammable fluids, while CCS is not. The main risk presented by CO_2 is asphyxiation, but this is also a risk with many of the fluids in the analog industries, particularly in confined spaces. In addition, anecdotal evidence suggests the asphyxiation hazard of CO_2 in industrial settings is considerably less than the explosion hazard of the fluids in the analog industries. For instance Skinner (2003) discusses five CO_2 blowouts during drilling with no attendant worker injuries. Duncan et al. (2009) discusses a CO_2 pipeline rupture by a backhoe operator who escaped unharmed. Further, most of the capture processes under consideration involve media that are not flammable, such as the currently prevailing capture fluid of aqueous monoethanolamine (MEA; Herzog et al., 2009; The National Institute of Occupational Safety and Health, 2010).

In contrast, explosions and burns make up a significant portion of the hazard in the petroleum refining industry. For instance, the one aforementioned explosion at a BP refinery in 2005 accounted for more than half of the contractor fatalities and almost half of all the fatalities reported by the NPRA during the study period. This suggests injury consequences in the capture industry will be significantly lower than in the petroleum refining industry, which itself has slightly above median safety.

Presumably the use of combustible and flammable fuels in the electric power generation industry elevates its risk relative to capture as well. Risk in this industry also accrues from its primary process, heat from combustion, and its primary product, electricity. While only a small percentage of injuries are due to electrocution (0.68% from 1995 to 2007), it caused almost a quarter of the fatalities while contact with heat caused 4% of fatalities (EPRI, 2008). EPRI (2008) does not break out the cause of fatalities at generation facilities, and so it is possible most electrocution fatalities occurred at transmission lines outside of generating stations. Still, the absence of such high temperatures and relatively less electrical current in the capture industry suggests it will be less risky than the electric power generation industry, which again suggests it will have above median safety.

As mentioned, most industrial gas is produced by cryogenic separation and delivered at cryogenic temperatures. The three main products are oxygen, nitrogen and carbon dioxide. Oxygen is more hazardous than carbon dioxide owing to its promoting the combustion of other substances, but otherwise the main fluids in the industrial gas manufacturing industry are similarly innocuous to those in the capture industry.

Companies in the industrial gas manufacturing industry also transport their product to their clients. One means of transport is by pipeline, and so this aspect of the industrial gas manufacturing industry is likely similar to safety in CO_2 pipeline transport. However, the other main means the industrial gas manufacturing industry uses for transporting its product is trucking, either by tanker or cylinder delivery. This activity carries high risk, as indicated by rates for the local, specialized freight trucking class (code 48422). This class has a median injury and illness rate for its size, but around 90th percentile injury consequences (days away case and fatality rates). The capture industry will not involve product transportation by truck, and so will be relatively safer than the industrial gas manufacturing industry.

So all three capture analog industries have factors suggesting they have higher worker risk than will the capture industry. Still, these differences should not be over interpreted as most worker accidents are likely due to causes other than the differences discussed. Consideration of the analogies does support a finding that risk to workers in the capture operation industry will not be higher than in the analog industries though, and so worker safety in this industry will be above median to high.

Relative to the storage industry, the oil and gas production industry analog also involves the additional risk factor of explosions and burns from flammable fluids. For instance, 12% of worker fatalities during the study period in the oil and gas extraction, drilling, and support activities for oil and gas operations industries were due to explosions and burns (BLS, 2005, 2006, 2007, 2008, and 2009). The OGP reports 6% of fatalities worldwide were due to explosion and burns (OGP, 2009). The OGP only reported the cause of lost time injuries after 2004, but for these three years in the study period explosions and burns caused 4–5% of such injuries.

This suggests the storage industry will have slightly lower accident consequences and so lower risk than the upstream industry. This difference will obviously be quite significant for individual workers who will not be subject to fire and/or explosion, such as that which killed 11 workers during the Macondo well blowout in the Gulf of Mexico in 2010. This will translate into a relatively small shift down in risk for the storage industry as a whole, though, compared to the upstream industry. For instance transportation incidents caused a third of the worker fatalities worldwide reported to the OGP in the study period (OGP, 2009), with the death of 10 workers in a single helicopter accident offshore of the US while traveling to a drill ship in 2004 a particularly tragic event (OGP, 2005).

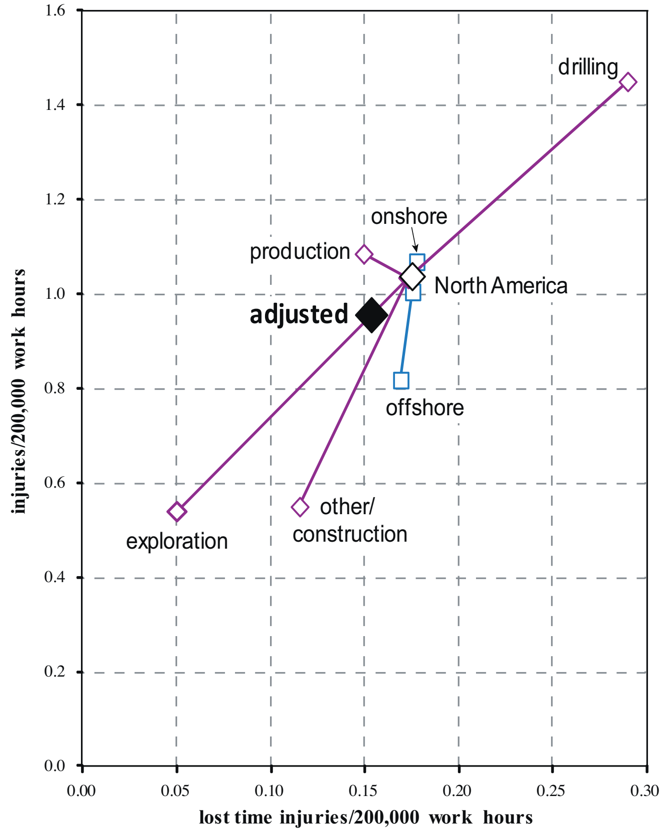

Fig. 3. Oil and gas production industry safety measures for North America from International Oil and Gas Producers Association data. The onshore-offshore and industry sector centroids vary from the North America average due to differences in the completeness of data coding for each breakdown as reported to the OGP. The marker labeled "adjusted" was calculated by doubling exploration and halving drilling effort.

Another source of risk reduction in the storage industry compared to the oil and gas production industry is drilling target conditions. The majority of storage wells will be drilled to normally pressured saline aquifers with little or no buoyant fluids or hydrocarbon reservoirs with residual buoyant fluids that are under pressured due to depletion. This will further reduce the risk of a well blowout while installing wells, which can contribute to other fatality causes, such as falls.

The lack of explosion and burn hazard in the storage industry versus the upstream oil industry and the different fluid types and/or pressure conditions of the drilling targets all suggest worker safety in the storage industry will be greater than in the upstream industry.

6.2. *Storage analog sector mix and geographic differences*

As mentioned, different functional sectors in the upstream oil and gas industry can be defined, such as exploration, drilling, and field operation. The OGP injury rate relative to the lost time injury rate for different functional industry sectors in North America is plotted in Fig. 3. In this illustration, the higher the sector plots the higher its injury rate and the further to the right the more severe the injuries on average.

The relative effort in exploration, drilling, field operation and other activities, such as construction, will be somewhat different in the storage industry as compared to the upstream oil and gas industry. The value derived per pore volume containing oil or gas is almost certain to be higher than for storing CO_2. These economics promote investing in higher sweep efficiency in the upstream industry than is likely in the storage industry. In other words, given subsurface heterogeneity, wells in the upstream industry are installed to access smaller subsurface volumes than will likely be the case in the storage industry.

In addition, the viscosity of CO_2 at typical reservoir storage conditions is similar to natural gas (Oldenburg, 2002), which is an order of magnitude less than water and one to several orders of magnitude less than crude oil. Yet the density of CO_2 at these conditions is closer to oil than natural gas. The average operating pressure difference between the base of the well and the reservoir in storage fields is likely to be similar to that in oil and gas fields. Therefore average CO_2 mass injection rates per well will be significantly higher than average fluid mass production rates from oil wells (due to the lower viscosity of CO_2) and natural gas wells (due to the higher mass density of CO_2).

So the economics and physics of storage cumulatively suggest fewer wells will be required per mass of CO_2 stored than per oil or gas mass produced. Consequently the storage industry will likely be less drilling intensive than the upstream industry relative to the effort in the other functional sectors.

Ongoing monitoring of stored CO_2 to verify storage integrity is part of the regulatory framework for permitting a CO_2 storage injection well in the United States (Federal Register, 2010). A variety of methods will be used for monitoring, including various geophysical methods, such as time lapse seismic reflection, gas monitoring methods, such as eddy covariance, remote aerial sensing, such as interferometric synthetic aperture radar, and subsurface pressure monitoring and fluid sampling (National Energy Technology Laboratory, 2009). These methods will be used to monitor not just the reservoir, but above and lateral to the reservoir as well. Most of these are the same or similar methods to those used in oil and gas exploration. The requirement for periodic monitoring over a large area/volume during and after CO_2 injection indicates storage will involve a relatively higher exploration-type effort than in the upstream industry.

Fig. 3 shows the OGP industry safety rates adjusted by halving the amount of drilling effort and doubling the amount of exploration effort. This provides some perspective on storage industry worker safety based upon qualitatively accounting for the different sector proportions relative to the upstream industry. As indicated by Fig. 3, the downward shift in risk is moderate because exploration and drilling are relatively small portions of total labor. The cumulative shift downward in risk by also considering process, material and condition differences discussed in the previous section would further reduce risk. However, the reduction still would probably not rise to a substantial level because most of the risk is due to factors storage would have in common with the analogs, such as construction activities and worker transportation.

A bit less than half the oil in North America was produced offshore during the study period (EIA, 2009c, 2010a,b) and a bit less than a fifth of natural gas was produced offshore (US Energy Information Administration (EIA), 2009c, 2010b,c,d). About half of the large stationary CO_2 point sources are in states more than 100 miles from an ocean in their entirety (National Energy Technology Laboratory, 2008). Interestingly, Table 5 indicates only about a quarter of labor effort takes place offshore. This suggests either the OGP reports are biased against offshore or offshore production is more efficient in terms of labor input. Given that larger companies tend to participate in the OGP and these are probably more heavily involved offshore because it is capital intensive, the hypothesis that offshore production is more labor efficient seems more likely.

In any event, it seems unlikely that the percentage of CO_2 stored offshore would be as high as the percentage of oil and gas produced offshore due to the geographic distribution of sources and the greater capital expense of operating offshore. This suggests that the worker safety data from OGP could be adjusted to qualitatively explore the consequence of a greater portion of work onshore, similar to the adjustment considered for different sector proportions. However, Fig. 3 shows that the injury and lost time injury rates for North America as a whole are already close to the North America onshore measures, so such adjustment would not result in much change. In contrast, a comparison of the North America onshore versus offshore fatality rates shown in Table 5 indicates that to the extent storage is relatively more focused on shore it will have a significantly lower worker fatality rate.

7. Public safety implications

The differences between the analog and CCS industry inform a perspective on the public safety of CCS versus the analog industries or industries in general. Industrial risk to the public largely accrues from off-site occurrence of industry hazards. One source of risk to the public is transportation of people, equipment and supplies in the CCS industry, as currently in the analog industries. Another source is accidental or by design off-facility migration of constituents, such as leakage from oil and gas pipelines and wells, pollutants emitted from petroleum refineries, and emissions from fossil fueled power generation stations.

While CCS facilities will also be subject to off-site migration, unlike in the oil and gas industry, the fluids, predominantly CO_2 and MEA, particularly in aqueous solution, are not flammable like most fluids in the oil and gas industry and some in the electric power generation industry, and are not strong oxidizers as is oxygen in the industrial gas manufacturing industry. The oil and gas industry also produces, processes and/or manufactures toxic gases such as hydrogen sulfide, sulfur dioxide and benzene. For these substances, the United States Occupational Health and Safety Administration 8 hour per day airborne permissible exposure limits (PEL) for workers is 20 parts per million by volume (ppm), 5 ppm, and 1 ppm respectively. In contrast CO_2 is not toxic to humans, but rather has a PEL of 5000 ppm due to being a simple asphyxiant. MEA does have a low PEL of 3 ppm, but it is a liquid at ambient conditions, which reduces the public health consequence of its release. Beyond this it appears the concentration of toxic co contaminants in the captured gas stream will be limited in the case of coal-fired power plants unless the stream is intentionally enriched with co contaminants as a means to dispose of them (Apps, 2006).

In addition, it is likely storage fields will be located further from population centers on average than are petroleum fields. As shown in Fig. 1, oil and gas fields have been developed in a number of relatively more populated counties. For instance a prolific quantity of oil has been produced from the Los Angeles Basin and production continues. This close proximity of oil field operations and an urban population has caused elevated public health concerns (Chilingar and Endres, 2004) and evacuations (Ragus, 2011; Rodriguez, 2011) that would largely be avoided in association with storage fields. This is because unlike hydrocarbon resources, which can only be developed where they occur, whether in a populated area or not, storage operators will have a choice where to develop storage fields. Such operators are unlikely to locate these fields in densely populated areas of the US for the foreseeable future due to the more favorable economics in less populated areas, such as for securing land for surface operations and conducting surface-based geophysical monitoring, as well as conferring with fewer stakeholder groups.

Capture facilities will likely be in approximately the same proximity to population as electric power generation stations and petroleum refineries for the simple reason that these analog facilities are for the most part where the bulk of CO_2 is available to be captured. While experience alone is not yet sufficient to determine the safety of pipelines from these plants to storage fields relative to ubiquitous natural gas and hazardous liquids pipelines (Ha-Duong and Loisel, 2011), modeling indicates the hazard area from a CO_2 pipeline rupture will be quite limited (Mazzoldi et al., 2011) in contrast to the potential for chemical combustion from natural gas pipeline ruptures and the hazard area from hazardous liquid pipeline ruptures.

8. Conclusions

Fifteen current US industries can serve as analogs for the prospective CCS industry in the US with regard to worker safety. While there are differences between these industries and the CCS industry, the safety statistics from the analog industries provide insight into the worker safety of a mature CCS industry in the US. The following conclusions can be drawn about worker and public safety in such an industry:

Worker injury and lost time rates in a mature CCS industry will be below the median and fatality rates will be high relative to all other industries, and so slightly decrease worker injury rates and slightly increase worker fatality rates in the US.

CCS worker safety will be better than in such common industries as heavy and civil engineering construction and much better than in other common industries such as truck and marine transportation.

Capture facility and pipeline construction worker safety will be below median compared to all industries, and will include a high fatality rate, but this will be due to the risk of construction in general rather than the specifics of carbon capture or transportation facilities.

Capture operation worker safety will likely be above median relative to all industries based on safety in the analog petroleum refining, fossil fuel electric power generation and industrial gas manufacturing industries.

Capture operation worker safety should be higher than in the analog industries due to capture not involving flammable, explosive and toxic volatile materials, electricity as a product, excessively low or high temperatures, or product transportation by truck as in the various analog industries.

Storage field worker injury rates will be below median and fatality rates will be high compared to all industries based on safety in the analog oil and gas production and transportation industries.

Storage field worker safety will be better than in the oil and gas production analog due to a relative lack of explosion and burn hazard, relatively lower fluid toxicity, lower proportion of drilling effort, relatively more geophysics effort, and relatively more on shore effort.

Storage well drilling worker safety will be below median compared to all industries. However safety will be somewhat greater than in oil and gas field drilling because storage drilling targets will have relatively less buoyant native fluid and lower pressure on average, and so blowouts will be less common.

The CCS industry will be safer for the public than the analog industries as a group. Its product and process materials are inflammable, not strongly oxidizing, less toxic and/or toxic but non-volatile as compared to those of the various analog industries. The storage fields will likely be relatively more removed from population centers than those of the analog oil and gas production industry, and pipeline ruptures will be of less consequence.

While it is early in the development of the CCS industry, it would be useful to establish an industry association that collects, analyzes and reports worker safety data similar to the activities of the OGP, NPRA and to a lesser extent EPRI. This would provide a potentially more complete perspective than provided by government safety data sources, which tend to more readily identify company rather than contractor safety in an industry. Such perspective would also allow more prompt action to mitigate against unforeseen unique risks that might occur as the CCS industry develops. Perhaps the Global CCS Institute could fulfill this role, or at least provide the starting point.

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Appendices A and B. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijggc.2012.06.009.

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Appendix B: Additional Tables

Table B-1. Annual hours worked in each industry class calculated by dividing BLS injury and illness cases by case rates during the study period

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713				2.7E+08	2.8E+08
	Fossil fuel electric power generation	221112				2.7E+08	2.6E+08
	Petroleum refineries	32411	1.5E+08	1.6E+08	1.4E+08	1.6E+08	1.6E+08
	Industrial gas manufacturing	32512	5.0E+07	5.0E+07	4.8E+07		3.5E+07
Transportation	Oil and gas pipeline and related structures construction	23712				1.8E+08	2.0E+08
	Pipeline transportation of natural gas	4862	5.0E+07	5.4E+07	5.2E+07	5.0E+07	5.0E+07
Storage	Drilling oil and gas wells	213111	1.2E+08	1.2E+08	1.5E+08	1.7E+08	1.8E+08
	Support activities for oil and gas operations	213112	3.0E+08	3.0E+08	3.4E+08	4.1E+08	4.4E+08
	Oil and gas extraction	211	2.4E+08	2.5E+08	2.5E+08	2.7E+08	2.8E+08
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	9.5E+07	9.7E+07	1.0E+08	1.1E+08	1.4E+08
	All other industrial machinery manufacturing	333298	5.6E+07	5.3E+07	6.2E+07	5.9E+07	5.9E+07
	Pump and pump-ing equipment manufacturing	333911	5.7E+07	5.8E+07	5.8E+07	5.9E+07	5.9E+07
	Air and gas compressor manufacturing	333912	4.1E+07	4.1E+07	4.1E+07	4.8E+07	4.6E+07
	All other miscel-laneous general purpose machin-ery manufacturing	333999	7.9E+07	7.9E+07	8.2E+07	8.8E+07	8.2E+07
	All other basic organic chemical manufacturing	325199	6.92E+07	6.96E+07	6.92E+07	7.27E+07	7.33E+07

Table B-2. Rate of total recordable injury and illness cases (/100 FTE) from the BLS for each study year

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713				5.8	4.9
	Fossil fuel electric power generation	221112				3.9	3.4
	Petroleum refineries	32411	1.5	1.5	1.4	1.4	1.6
	Industrial gas manufacturing	32512	1.6	0.8	2.1		1.7
Transportation	Oil and gas pipeline and related structures construction	23712				2.6	2.5
	Pipeline transportation of natural gas	4862	2.4	2.6	2.7	2.4	2.0
Storage	Drilling oil and gas wells	213111	4.0	6.8	6.4	5.5	4.6
	Support activities for oil and gas operations	213112		2.7	2.8	3.2	2.7
	Oil and gas extraction	211	1.8	2.6	2.1	2.0	1.7
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	4.4	2.9	3.6	4.2	3.6
	All other industrial machinery manufacturing	333298	7.5	5.7	7.8	6.8	5.8
	Pump and pumping equipment manufacturing	333911	8.4	5.9	5.2	5.4	5.1
	Air and gas compressor manufacturing	333912	4.9	6.4	3.9	4.6	5.2
	All other miscellaneous general purpose machinery manufacturing	333999	6.1	4.8	5.1	6.4	5.6
	All other basic organic chemical manufacturing	325199	2.6	2.3	2.6	2.2	3.0

Table B-3. Rate of total recordable injury cases (/100 FTE) from the BLS for each study year

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713				5.6	4.7
	Fossil fuel electric power generation	221112				3.3	3.3
	Petroleum refineries	32411	1.2	1.2	1.2	1.3	1.4
	Industrial gas manufacturing	32512	1.6	0.8	2.0		1.6
Transportation	Oil and gas pipeline and related structures construction	23712				2.6	2.4
	Pipeline transportation of natural gas	4862	2.1	2.5	2.3	2.0	1.4
Storage	Drilling oil and gas wells	213111			6.3	5.4	4.5
	Support activities for oil and gas operations	213112		2.6	2.7	3.0	2.6
	Oil and gas extraction	211	1.6	2.4	2.0	2.0	1.6
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	4.2	2.8	3.5	4.1	3.5
	All other industrial machinery manufacturing	333298	6.2	5.3	7.6	6.5	5.5
	Pump and pumping equipment manufacturing	333911	7.4	5.3	4.8	5.2	4.9
	Air and gas compressor manufacturing	333912	4.3	6.0	3.7	4.3	5.0
	All other miscellaneous general purpose machinery manufacturing	333999	5.7	4.6	4.7	6.1	5.0
	All other basic organic chemical manufacturing	325199	2.2	2.0	2.3	1.8	1.8

Table B-4. Rate of days away due to injury or illness cases (/100 FTE) from the BLS for each study year

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713				2.2	1.9
	Fossil fuel electric power generation	221112				1.2	1.1
	Petroleum refineries	32411	0.4	0.4	0.4	0.5	0.3
	Industrial gas manufacturing	32512	0.9	0.1	0.9		0.4
Transportation	Oil and gas pipeline and related structures construction	23712				1.1	1.0
	Pipeline transportation of natural gas	4862	0.4	1.1	0.8	0.8	0.5
Storage	Drilling oil and gas wells	213111	1.5	2.8	2.0	1.6	1.7
	Support activities for oil and gas operations	213112	0.6	0.9	0.9	1.3	1.0
	Oil and gas extraction	211	0.6	0.9	0.9	0.5	1.0
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	1.2	0.8	0.8	1.0	0.8
	All other industrial machinery manufacturing	333298	2.8	1.5	1.5	1.2	1.3
	Pump and pump-ing equipment manufacturing	333911	1.4	1.3	1.3	0.9	1.3
	Air and gas compressor manufacturing	333912	1.1	1.6	0.8	1.1	1.2
	All other miscel-laneous general purpose machin-ery manufacturing	333999	1.6	1.2	1.6	1.6	1.4
	All other basic organic chemical manufacturing	325199	0.4	1.0	0.5	0.7	1.1

Table B-5. Fatalities due to injury from the BLS for each study year. Ranges based on a presumed reporting limit of 3.

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713	48	28	33	25	33
	Fossil fuel electric power generation	221112	5	7	4	4	5
	Petroleum refineries	32411	0-2	0-2	0-2	4	5
	Industrial gas manufacturing	32512	0-2	0-2	0-2	0-2	0-2
Transportation	Oil and gas pipeline and related structures construction	23712	15	9	22	21	12
	Pipeline transportation of natural gas	4862	0-2	0-2	0-1	0-2	0-2
Storage	Drilling oil and gas wells	213111	26	30	34	36	39
	Support activities for oil and gas operations	213112	41	37	46	62	61
	Oil and gas extraction	211	16	27	16	19	15
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	0-2	3	3	0-2	0-2
	All other industrial machinery manufacturing	333298	3	0-2	0-2	0-2	0-2
	Pump and pumping equipment manufacturing	333911	0-2	0-2	0-2	0-2	0-2
	Air and gas compressor manufacturing	333912	0-2	0-2	0-2	0-2	0-2
	All other miscellaneous general purpose machinery manufacturing	333999	0-2	0-2	0-2	0-2	0-2
	All other basic organic chemical manufacturing	325199	0-2	0-2	0-2	3	0-2

Table B-6. Rate of fatalities (/100,000 FTE) due to injury for each study year calculated from BLS data. Multiple values correlate to 0, 1 or 2 possible fatalities based on a presumed fatality reporting limit of 3.

CCS industry segment	Industry class name	NAICS code	2003	2004	2005	2006	2007
Capture	Power and communication line and related structures construction	23713				18.8	23.4
	Fossil fuel electric power generation	221112				3.0	3.9
	Petroleum refineries	32411	0.0-1.4-2.7	0.0-1.3-2.5	0.0-1.4-2.8	5.1	6.2
	Industrial gas manufacturing	32512	0.0-4.0-8.0	0.0-4.0-8.0	0.0-4.2-8.4		0.0-5.7-11.3
Transportation	Oil and gas pipeline and related structures construction	23712				23.7	12.0
	Pipeline transportation of natural gas	4862	0.0-4.0-8.0	0.0-3.7-7.4	0.0-1.9	0.0-4.0-8.0	0.0-4.0-8.0
Storage	Drilling oil and gas wells	213111	43.3	48.6	46.3	43.0	42.7
	Support activities for oil and gas operations	213112	27.3	24.4	26.8	30.1	27.5
	Oil and gas extraction	211	13.1	21.9	12.9	14.1	10.6
Equipment and capture fluid manufacturing	Oil and gas field machinery and equipment manufacturing	333132	0.0-2.1-4.2	6.2	6.0	0.0-1.8-3.5	0.0-1.4-2.9
	All other industrial machinery manufacturing	333298	10.7	0.0-7.6	0.0-6.5	0.0-3.4-6.8	0.0-3.4-6.8
	Pump and pumping equipment manufacturing	333911	0.0-3.5-7.0	0.0-3.5-6.9	0.0-3.5-6.9	0.0-3.4-6.8	0.0-3.4-6.8
	Air and gas compressor manufacturing	333912	0.0-4.9-9.8	0.0-4.9-9.8	0.0-4.9-9.8	0.0-4.2-8.4	0.0-4.3-8.7
	All other miscellaneous general purpose machinery manufacturing	333999	0.0-2.5-5.1	0.0-2.5-5.1	0.0-2.4-4.9	0.0-2.3-4.6	0.0-2.4-4.9
	All other basic organic chemical manufacturing	325199	0.0-2.9-5.8	0.0-2.9-5.8	0.0-2.9-5.8	8.3	0.0-2.7-5.5

Table B-7. BLS and OGP safety rates and equivalencies

per	measures	BLS	OGP	measures	per
200,000 work hours	Total recordable non-fatal injury cases	TRC-Ir[a]	(TRIR-FAR/ 1,000)/5		
		(TRC-Ir + F-Ir/ 1,000) x 5	TRIR[b]	Total recordable incident (fatal and non-fatal injury) cases	1,000,000 work hours
200,000 work hours	Days-away from work cases due to non-fatal injury and illness	DAC-IIr[c]			
			LTIF[d]	Fatalities and lost time cases due to injury	1,000,000 work hours
200,000,000 work hours	Fatalities due to injury	F-Ir[e]	FAR x 2		
		F-Ir/2	FAR[f]	Fatalities due to injury	100,000,000 work hours

[a]total recordable cases - injury rate

[b]total recordable injury rate

[c]days away from work cases - injury or illness rate

[d]lost time injury frequency

[e]fatal injury rate

[f]fatal accident rate

Table B-8. Companies providing safety data to the OGP during the study period

Company	2003	2004	2005	2006	2007
ADNOC	X	X	X	X	
Agip KCO			X	X	
Amerada Hess	X	X	X		
Anadarko		X	X	X	X
BG	X	X	X	X	X
BHP	X	X	X		X
BP	X	X	X	X	X
Cairn Energy	X	X	X	X	X
Chevron			X	X	X
ChevronTexaco	X	X			
CNOOC	X	X	X	X	X
ConocoPhillips	X	X	X	X	X
Devon Energy	X	X			
Dolphin Energy			X	X	X
DONG	X	X	X	X	X
ENI	X	X	X	X	X
ExxonMobil	X	X	X	X	X
Gaz de France				X	X
GNPOC	X	X	X		
Hess Corporation				X	X
HOCOL	X	X	X	X	X
Hydro				X	
Kuwait Oil Company	X	X	X	X	X
Maersk	X	X	X	X	X
Marathon	X	X	X	X	X
Nexen Inc				X	X
Norsk Hydro	X	X	X		

Company	2003	2004	2005	2006	2007
OMV	X	X			X
Occidental	X	X	X	X	
Oil Search			X	X	
OMV			X	X	
PDVSA	X	X	X	X	
PEMEX	X	X			
Perenco					X
Petrobras				X	X
Petro-Canada	X	X	X	X	X
Petronas Carigali Sdn Bhd	X	X	X	X	X
Premier Oil	X	X	X	X	X
PTTEP	X	X	X	X	X
Qatar Petroleum	X	X	X	X	X
RasGas	X	X	X		X
Repsol	X	X	X	X	X
Saudi Aramco	X	X	X	X	X
Shell	X	X	X	X	X
Statoil	X	X	X	X	
StatoilHydro					X
TNK - BP			X	X	X
Total	X	X	X	X	X
Tullow Oil			X	X	X
VICO	X	X	X		
Wintershall				X	X
Woodside					X
Yemen LNG				X	X
Yukos	X	X			