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## Actuarial risk assessment of expected fatalities attributable to carbon capture and storage in 2050

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**Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »**

**Defines the « wedge of CCS at baseload coal power plants » scenario and summarizes its expected fatalities**

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**Blue cells:** Numerical assumptions defining the scenario

**Scenario parameters : Coal needed for the wedge of CSC at baseload coal plants**

**1** Gt C emissions avoided  
3,67 Gt CO2 emissions avoided A

**20%** Energy penalty = p  
**90%** Capture efficiency = e

4,17 Gt CO2 baseline B = A / a  
5,00 Gt CO2 generated G = g B  
4,50 Gt CO2 stored S = s B

**2,38** t CO2 generated by t of coal (bituminous grade)

2050	2,101 Gt of coal consumed in 2050
2025	0,879
2015	0,391
2007	

**Carbon dioxide emissions and coal types**

Source: [http://www.ccsd.biz/PSE\\_Handbook/5/3/](http://www.ccsd.biz/PSE_Handbook/5/3/)

Coal Types	Specific Energy(a) MJ/kg	Carbon Content (b) gC/MJ	CO2 emissions		
			kgCO2/MJ	kgCO2/kg coal	
Lignite		9,3	27,6	0,10	0,93
Sub bituminou		18,1	26,2	0,10	1,72
Bituminous		25,4	25,8	0,09	2,38

a) IEA Coal online

b) IPCC 1996

**Scenario parameters : Capture**

**1500** Total number of capture sites in our Wedge scenario.

**5** **10** Workers exposed to the risk at each capture site. Range representing « a fraction of the workforce of a modern coal power plant ».  
7500 15000 Workers on capture sites

**Scenario parameters : Shipping**

Coal	CO2	
<b>15%</b>	<b>10%</b>	Fraction shipped
0,32	0,45	Quantity shipped, Gt in 2050
<b>4500</b>	<b>5000</b>	Average trip, Nm
1,42	2,25	Transport, Tt Nm in 2050

## Wedge

### Scenario parameters : Pipeline CO2

90% Fraction pipelined (= not shipped)

Year	km	Mt
2007	1	3
2015	50	15
2025	100	190
2050	100	4050

### Scenario parameters : Injection and storage

15000 Injection wells  
 500 Storage sites  
 90% onshore  
 450 Onshore storage sites  
 30 Active injection wells at each site  
 0,30 Mt injected per well

Year	Sites	Wells	Wells/site	Mt Injection	kt CO2/yr Inject/well
2007		3	12	4	3
2015		15	50	3,33	15
2025		50	667	13,33	200
2050		500	15000	30	4500

10 30 Full time workers per site for operation, monitoring, development, maintenance...  
 5000 15000 Workers on injection sites

### Scenario parameters : population over storage

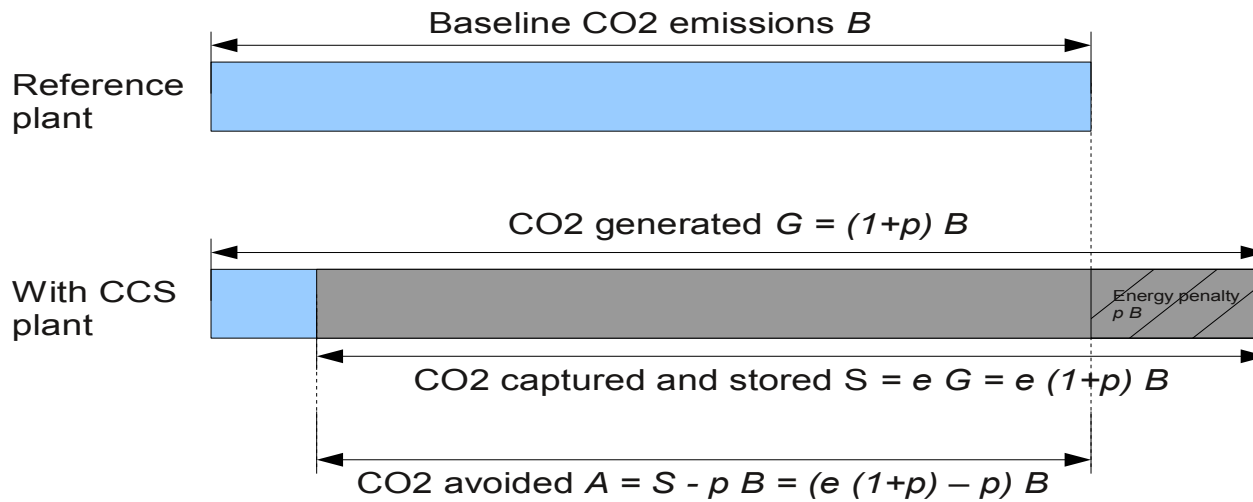
25 100 km<sup>2</sup> footprint of a storage site  
 20 20 Inhabitants / km<sup>2</sup> over storage sites  
 500 2000 Inhabitants in the footprint zone  
 225000 900000 Persons exposed to storage sites, worldwide

**Mathematical note on CCS and CO2 accounting**

Graphically explained by the figure below, based on Figure RID 2 in IPCC SRCCS  
 The baseline is defined as the nominal capacity of the reference coal plant, without CCS

Knowing  $e$  and  $p$ , we have:

- 120% Generation relative to baseline  $g = 1 + p$
- 108% Fraction captured (and stored) compared to baseline  $s = e g = e (1 + p)$
- 88% Fraction avoided compared to baseline  $a = s - p = e (1 + p) - p$



Wedge

Mining

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »

This spreadsheet computes global expected fatalities in the mining industry due to the fact that CCS allows the use of coal.

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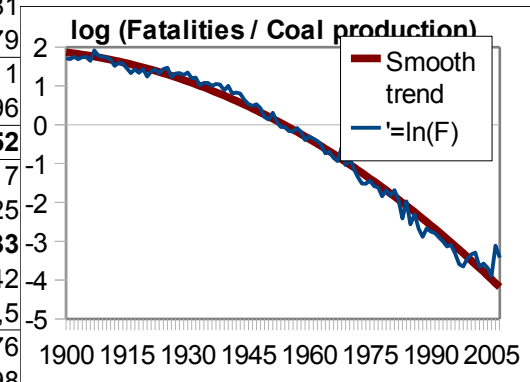
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**Historical stats for the US coal mining industry**

Source (a) <http://www.msha.gov/stats/centurystats/coalstats.asp>

Source (b) [http://www.eia.doe.gov/cneaf/coal/page/fig1\\_us\\_historical\\_production\\_bar\\_chart.xls](http://www.eia.doe.gov/cneaf/coal/page/fig1_us_historical_production_bar_chart.xls)

t	Year	Source (a) Miners	Source (a) Fatalities	Source (b) Coal_Prod_Mt	=D/E FAR_US	'=ln(F) log_FAR_US	Smooth trend a + b t + c t <sup>2</sup>	OLS estimation of log (fatalities/production)		
								const	1,8741	a
								time	-0,0116	b
								timesq	-0,0004	c
1	1900	448,58	1489	268	5,55	1,71	1,86			
2	1901	485,54	1574	292	5,40	1,69	1,85			
3	1902	518,2	1724	300	5,74	1,75	1,84			
4	1903	566,26	1926	356	5,42	1,69	1,82			
5	1904	593,69	1995	350	5,70	1,74	1,81			
6	1905	626,05	2232	391	5,71	1,74	1,79			
34	1933	523,18	1064	383	2,78	1,02	1			
35	1934	566,43	1226	417	2,94	1,08	0,96			
<b>45</b>	1944	453,94	1298	683	<b>1,90</b>	0,64	<b>0,52</b>			
86	1985	197,05	68	884	0,08	-2,56	-2,17			
87	1986	185,17	89	890	0,10	-2,3	-2,25			
<b>88</b>	1987	172,78	63	919	<b>0,0686</b>	<b>-2,68</b>	<b>-2,33</b>			
89	1988	166,28	53	946	0,06	-2,88	-2,42			
90	1989	164,93	68	981	0,07	-2,67	-2,5			
93	1992	153,13	55	998	0,06	-2,9	-2,76			
106	2005	116,44	23	1131	0,02	-3,9	-3,98			
107	2006	122,98	47	1055	0,04	-3,11	-4,08			
108	2007	122,94	34	1039	0,03	-3,42	-4,18			



**The global coal industry in:**

2007

Fatalities	11000	Source: Drexler et al. (2008) ICEM report on research, activities and developments, page 20
Production (Mt)	6691,05	Source: <a href="http://www.iea.org/Textbase/stats/coaldata.asp?COUNTRY_CODE=29&amp;Submit=Submit">http://www.iea.org/Textbase/stats/coaldata.asp?COUNTRY_CODE=29&amp;Submit=Submit</a>
F/C	1,64	This is the global fatality rate today
ln (F/C)	0,497	
time index	45,42	(Positive t solution of $\ln(F/C) = a + b t + c t^2$ )
	<b>1944</b>	Year in which USA was at this fatality rate
		(the other root is: -73,73)

## Mining

### Extrapolation of the global average coal mining fatality rate to 2050

Assumption (A): The global coal industry fatality rate per Mt converges to the rate recorded in the USA, averaged over 1990-2007

F/C **0,0383**

Assumption (B): The global coal industry fatality rate per Mt declines along the same historical curve as the USA

Target year: 2050

Years later: 43

Time index 88,42

1987 Year for which we lookup the USA fatality rate

Adjusted value -2,37 The log fatality rate at this time index, using the smoothed curve

F/C **0,09351** The result: global coal mining industry fatality rate for 2050

<b>Summary results table : expected fatalities from coal mining</b>			
Coal mined Gt (scenario)	Fatality rate per Mt mined	Expected fatalities In 2050	
2,1	0,0383	81	Convergence to USA 1990-2007
2,1	0,0935	196	Safety progress follows the USA curve

### Engineering consistency check about the incremental quantity of coal

*According to engineer Nhan T. Nguyen (pers. Com.)  
for a future (2021) High Efficiency (45%) IGCC power plant*

500 MW coal-based power plant needs

1,08 Mt bituminous coal

Proportionality suggests that

800 GW that correspond to one CCS wedge would need

1731,2 Mt bituminous coal

According to the table above, this would emit

4,12 Gt CO<sub>2</sub>

Another view

920 kg CO<sub>2</sub> / Mwh in 1997, Annex II countries

8760 h/yr

8059200 kg CO<sub>2</sub> / MW / yr for a baseload plant

500 MW plant capacity

4,03E+006 t CO<sub>2</sub>/yr (divide by 1000 for kg to t)

(source : Marion et al. CONTROLLING POWER PLANT CO<sub>2</sub> EMISSIONS:  
A LONG RANGE VIEW)

A 500MW average plant emits 4 Mt CO<sub>2</sub> per year

## Shipping coal

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »

This spreadsheet provides evidence to support the coal shipping scenario assumptions (see Shipping CO2 sheet for fatalities estimates).

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### How much coal is shipped in international trade ?

#### Total global production (Mt)

Source: <http://www.worldcoal.org/resources/coal-statistics/>

	Hard coal	Brown coal/Lignite
2008e	5848	951
2007	5442	956
2006	5205	914
2005	4934	906
2004	4629	879
2003	4231	893
1996	3734	
1990	3489	
1981	2796	
1980	2805	

Approx. 13% of hard coal production (717 Mt) is used by the steel industry

#### International Hard Coal Trade (Mt)

Source IEA - [www.iea.org](http://www.iea.org)

	Steam	Coking	Total Trade	Share of trade	By ship
2008	676	262	938	16%	
2007	670	247	917	17%	
2006	593	222	815	16%	15%
2005	548	227	775	16%	14%
2004	541	188	609	13%	15%
2000	421	187	608	14%	
1996	318	196	513		
1995	297	196	494		
1990	299	199	898		

In the scenario, we assume that 15% of coal used will be shipped



## Shipping coal

### How far is coal shipped ?

#### Development of seaborne trade (Mt)

Source SSY - [www.ssyonline.com](http://www.ssyonline.com)

	Steam coal		Coking coal		Total Mt	billion ton mileaverage trip (miles)	
	Atlantic	Pacific	Atlantic	Pacific			
2006	240	330	72	129	771	3540	4591
2005	219	289	72	129	709	3113	4391
2004	210	274	67	123	674	2960	4392
2000	157	187	70	98	512	2509	4900
1996	125	139	70	103	437		
1995	120	129	68	103	420		
1994	108	111	66	98	383		
1986	74	59	61	81	275		
1985	76	55	61	83	275		
1984	66	39	56	79	240		

Over 1986-2006, seaborne steam coal trade has increased on average by about 7.5% p.a.

In the scenario, we assume that average trip will be 4500 miles

#### World seaborne trade in ton-miles, selected years (billions of ton-mSource: Table 5 in UNCTAD. Review of Maritime Transport 2009. [link](#))

Year	Oil									World total
	Crude	Products	Crude plus products	Iron ore	Coal	Grain	5 main dry bulks	Other dry cargoes		
1970	5597	890	6487	1093	481	475	2049	2118	10654	
1980	8385	1020	9405	1613	952	1087	3652	3720	16777	
1990	6261	1029	7290	1978	1849	1073	5259	3891	16440	
2000	8180	1319	9499	2545	2509	1244	6638	6790	22927	
2001	8074	1345	9419	2575	2552	1322	6782	6930	23131	
2002	7848	1394	9898	2731	2549	1241	6879	7395	23516	
2003	8390	1460	9850	3035	2810	1273	7118	7810	25124	
2004	8795	1545	10340	3444	2960	1350	9521	8335	26814	
2005	8875	1652	10527	3918	3113	1686	9119	8730	28376	
2006	8983	1758	10741	4192	3540	1822	9976	9341	30058	
2007	9214	1870	11084	4544	3778	1927	10676	9665	31425	
2008	9300	1992	11292	4849	3905	2029	11209	10245	32746	

#### Summary table : expected fatalities for shipping coal

Activity level	Fatality rate	Fatalities	
Tt Nm in 2050			
1,42	2,9	4,2	Extrapolated from tanking
1,42	10,9	15,5	Extrapolated from all goods trade

## Trains

**Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »**

**This spreadsheet provides evidence to support the coal rail transport scenario assumptions**

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### How much railroad activity to transport the coal in the scenario ?

2,101 Gt of coal (lignite) consumed in 2050

85% Fraction transported by train

1,79 Gt transported by train

10000 t of coal per unit train

In USA, a typical unit train is 100 to 120 cars long, each holding 100 to 115 (short) tons of coal. <http://www.wsgs.uwyo.edu/coalweb/trains/unit.aspx>

178 571 number of train trips

119 train trips per power plant per year

500 km, average trip

In USA, average distance shipped per ton of coal, grew from about 430 miles in 1979 to about 700 miles in 1997.

Reference: Energy Information Administration. <http://www.eia.doe.gov/cneaf/coal/ctrdb/tab34.html> Accessed 2011-02-03

In China, average coal transportation distance increased from about 400 km in 1978 to about 600 km in 2008.

Reference: Tu (2010) [http://www.glenbradford.com/files/Stocks/Summary\\_China\\_Coal\\_Value\\_Chain\\_J.Tu\\_Draft.pdf](http://www.glenbradford.com/files/Stocks/Summary_China_Coal_Value_Chain_J.Tu_Draft.pdf), figure 2 page v

8,93E+07 Train km

5,55E+07 Train miles

### Railroad accident statistics in the US

<http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/tenyr1a.aspx>

#### Class I RAILROADS Accident/Incident overview

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
ACCIDENTS/ INCIDENT	9502	8435	8345	8585	8336	7888	7573	6940	5482	5390
Total fatalities	629	639	590	613	577	622	546	505	412	460
Employee on duty deaths	15	15	13	18	18	8	10	15	12	9
Trespasser deaths, not at HRC	327	356	345	318	300	362	305	291	250	275
Highway-rail Xing incidents deaths	277	251	223	264	241	246	220	195	140	171
	44%	39%	38%	43%	42%	40%	40%	39%	34%	37%
Train miles	5,4E+8	5,5E+8	5,6E+8	5,8E+8	6,0E+8	6,1E+8	5,9E+8	5,8E+8	4,8E+8	5,1E+8
a/i rate	17,7	15,3	14,8	14,7	13,9	12,8	12,8	12,0	11,5	10,5
Fatality rate (per million train miles)	0,56	0,51	0,44	0,51	0,46	0,42	0,41	0,37	0,34	0,36
Fatality rate (per million train km)	0,91	0,83	0,7	0,81	0,74	0,68	0,65	0,59	0,55	0,58

Previous decades had higher rates.

[http://www.drsc.org/Research/AAR\\_Info+Publications/PETER\\_FRENCH\\_RAIL\\_SAFETY\\_STATS\\_011706.pdf](http://www.drsc.org/Research/AAR_Info+Publications/PETER_FRENCH_RAIL_SAFETY_STATS_011706.pdf)

### Railroad accident statistics in Europe

In 2004, EU-25

The number of fatalities per million train-kilometers

(excluding suicides) varied from ~0 (Ireland & Luxembourg) to ~2.8 (Portugal). Six countries were above 1.

## Trains

The average was 0.92 in 2004, and 1.13 in 2005.

Simo Pasi (2006) Rail transport accidents in the European Union in 2004, Eurosta Transport, "Statistics in Focus"

[http://www.eds-destatis.de/en/downloads/sif/inz\\_06\\_06.pdf](http://www.eds-destatis.de/en/downloads/sif/inz_06_06.pdf) , FR version [http://epp.eurostat.ec.europa.eu/cache/ITY\\_OFFPUB/KS-NZ-06-006/FR/KS-NZ-06-006-FR.PDF](http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NZ-06-006/FR/KS-NZ-06-006-FR.PDF)

Piazza, Mihm and Cassir (2006) Developing CSTs for the European Railway System

IRSC 2006, Dublin [http://www.intrailsafety.com/Dublin/presentations\\_AM\\_23\\_Oct/03\\_R\\_Piazza\\_P\\_Mihm\\_C.Cassir.pps](http://www.intrailsafety.com/Dublin/presentations_AM_23_Oct/03_R_Piazza_P_Mihm_C.Cassir.pps)

### In France

EPSF (2010) Rapport sur la sécurité du réseau ferré national

[http://www.securite-ferroviaire.fr/fr/modules/cms/fichiers/403/rapport\\_securite\\_2009.pdf](http://www.securite-ferroviaire.fr/fr/modules/cms/fichiers/403/rapport_securite_2009.pdf)

2006	2007	2008	2008
0,197	0,141	0,118	0,119 Serious injuries
0,193	0,173	0,163	0,159 Fatalities per million train-km (excl. Suicides)
0,024	0,020	0,020	0,018 Travelers
0,075	0,073	0,072	0,072 Level crossings users
0,087	0,062	0,068	0,066 Trespassers
0,008	0,006	0,005	0,004 Workers
0,000	0,013	0,008	0,007 Others

### Normative european targets (FWSI / million train-km / year)

0,08 Employees  
 0,74 Level crossing users  
 0,02 Others  
 2,3 Trespassers  
 2,51 Whole society

European Railway Agency (2009) Common Safety Targets

<http://www.era.europa.eu/Core-Activities/Safety/Pages/common-safety-targets.aspx>

ERA recommendation on the first set of Common Safety Targets as referred to in Article 7 of Directive 2004/49/EC

<http://www.era.europa.eu/Document-Register/Pages/recommendation-first-set-common-safety-targets.aspx>

### **Share of fatalities in FWSI (fatalities and weighted serious injuries)**

10 serious injury statistically equivalent to 1 fatality

In UK WSI < F for the main risks (trespass & level crossing)

See also data above for France

75% Share of F in FWSI

<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:150:0011:0019:EN:PDF>

<http://www.rssb.co.uk/SiteCollectionDocuments/pdf/reports/strategic%20safety%20%20plan%20%202009-14.pdf>

Trespassing is a crime, we don't attribute these fatalities to CCS but to alcohol, stupidity and depression

0,84 FWSI per million train-km European common target « Employees + level crossing users + other »

0,63 Fatalities per million train-km, excluding trespassers and suicides, European Common Safety target

### **Summary table : expected fatalities from coal on railroads**

Mkm	Fatality rate	Fatalities	
89,3	0,63	56	2009 ECS target are realised
89,3	0,91	81	The 2001 USA risk rate applies

**Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »**

**This spreadsheet computes global expected fatalities to capture the CO2**

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**Method 1: Industrial carbon dioxide use**

	120	100 Mt CO2/year	Sources (a) (b)	Source (c)
	12 Fatalities from the two chemical accidents recorded in 1926	1997 Period	Source (d)	
		72 Years		
Source (a)	IPCC (2005) SRCCS main report says 115 in 7.3.4. Numbers on table 7.2 add up to 152.6 with a large uncertainty and include artificial CO2.			
Source (b)	IPCC (2005) SRCCS Technical Summary says 120 in section 7.			
Source (c)	Conclusion of Aresta & Tommasi (1997) Carbon dioxide utilisation in the chemical industry, Energy Convers. Mgmt, v 38:S373-S378			
Source (d)	Khan & Abbasi (1999) Major accidents in process industries and an analysis of causes and consequences Journal of Loss Prevention in the Process Industry 12:361-378			

**Summary table : expected fatalities in 2050 to capture the CO2**

Qty captured	Risk rate	Expected	
Gt CO2	Gt <sup>-1</sup> a <sup>-1</sup>	Fatalities	
4,5	1,4	6,3	Accident record, low case
4,5	1,7	7,5	Accident record, high case

**Method 2: Fatalities from utilities in large economies**

In industrialized countries, 3 to 14 fatalities per year, per 100,000 workers can reasonably be expected.

This range is a guesstimate based on the table below, which is a descriptive statistics summary of the data to the right --->

	n	Min	Average	Max
<b>UK</b>	25	0	2,1	4,4
<b>USA</b>	4	4	5,0	6
<b>France</b>	31	1,7	13,0	31,9
<b>Canada</b>	14	10,5	14,2	19,7
<b>Italy</b>	16	1	3,6	7
<b>Japan</b>	38	0	2,8	16
<b>China</b>	18	6,1	16,8	27,3

**Summary table : expected fatalities in 2050 to capture the CO2**

Workers	Fatality rate	Fatalities	
7500	3	0,23	Worker's safety, low case
15000	14	2,1	Worker's safety, high case

**Rates of fatal injuries (Raw data)**

Source: International Labor Organisation, LABORSTA database. [http://laborsta.ilo.org/data\\_topic\\_E.html](http://laborsta.ilo.org/data_topic_E.html) (accessed 2009-02-06)  
 Query: By Topic / Occupational injuries - 8B. Rates of occupational injuries, by economic activity.  
 1969-present, for the 10 largest economies.  
 Row selected: Economic activity code 4 (in ISIC revision 2) or E (in ISIC revision 3), meaning Electricity, gas and water  
 Note: Data for Germany, India and Russia were not available or useable.

		1969	1970	1971	#####	2004	2005	2006	2007
UK	4				#####				
	E				#####	0	1	,,,	,,,
USA*	E				#####	6	4	6	,,,
France**	4	0,136	0,231	0,207	#####				
	E				#####	,,,	,,,	,,,	
Canada*	E				#####	12,8	18,4	19,7	
Italy*	E				#####	2	2	3	,,,
Japan***	4	0,06	0,06	0,08	#####				
	E				#####	0	0	0	0
China*	4				#####	17,7	14,2		
Brazil*	E				#####	6,0	,,,	,,,	,,,

\* Per 100.000 workers employed.

\*\* Per 1000 workers employed, excluding agents of public gas and electricity services.

\*\*\* Per 1.000.000 hours worked. According to [http://en.wikipedia.org/wiki/Japanese\\_work\\_environment](http://en.wikipedia.org/wiki/Japanese_work_environment), the average number of hours worked in Japan was 2150/yr in 1986, and 1889 in 1995. Therefore 200 is the conversion factor to 100.000 workers employed: Assuming that 1 worker does 2000 hours, then a million hours is 500 workers employed.

**Rates of fatal injury (all rows per 100.000 workers)**

		1969	1970	1971	#####	2004	2005	2006
UK					#####	0,0	1,0	
USA					#####	6,0	4,0	6,0
France		13,6	23,1	20,7	#####			
Canada					#####	12,8	18,4	19,7
Italy					#####	2,0	2,0	3,0
Japan		12,0	12,0	16,0	#####	0,0	0,0	0,0
China					#####	17,7	14,2	
Brazil					#####	6,0		

**Summary table**

n	Min	Max	Average
25	0	4,4	2,12
4	4	6	5
31	1,7	31,9	13,03
14	10,5	19,7	14,21
16	1	7	3,63
38	0	16	2,84
18	6,1	27,3	16,75
1	18,6	18,6	18,6

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »

This spreadsheets analyzes the risk of pipelines

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Following IPCC (2005), we consider the yearly incident rate as Number/km, not Number / Mt / km

**Evidence from the US pipelines networks**

Updated statistics of pipeline incident in the USA

	Natural gas Transmission	Hasardous liquids	CO2
Start	1986	1986	1990
End	2009	2009	2009
Duration (years)	24	24	20
# significant incidents	2 318	4 088	20
# fatalities	65	54	0
Network length (1000km)	522	255	6,2
Observation basis (Mkm yr)	12,532	6,113	0,123
Incidents /Mkm / yr	184,97	668,73	162,09
Fatalities / Mkm / yr	5,2	8,8	0,0

**Homogenous Poisson Process statistics**

Fail free duration	Desired confidence	MTBF at this conf. Level	Upper rate of failure
0,123	95%	0,0412	24,3

**Assumptions from the 2050 scenario**

Sites	Distance km	Total network size Mkm
1500	100	0,15

**Summary table : expected 2050 fatalities from pipelines**

Mkm	Fatality rate	Fatalities	
0,15	5	0,75	Lower expectation
0,15	50	7,5	Upper expectation

Table data sources:

US Department of Transportation, Office of Pipeline Safety. Natural Gas Pipeline Operators Incident Summary Statistics by Year 1/1/1986 – 12/31/2008 (accessed 2010-02-18) ([link](#))

Hazardous liquid pipeline operators accident summary statistics by year (accessed 2010-02-18) ([link](#))

The 20 significant incidents, 0 fatalities for CO2 pipes were obtained by looking up the PHMSA data files directly, see table to the right.

For average network length computations, see tables to the right

References interesting but not used

Dooley JJ, Dahowski RT, Davidson CL, 2008, «Comparing existing pipeline networks with the potential scale of future U.S. CO2 pipeline networks», doi:10.1016/j.egypro.2009.01.209

The ENSAD database at PSI. <http://gabe.web.psi.ch/research/ra/>

John Gale and John Davison (2004) Transmission of CO2—safety and economic considerations. *Energy* 29:1319-1328 ([link](#))

Jo Y.D., Crowl D.A., 2008, « Individual risk analysis of high-pressure natural gas pipelines », *Journal of Loss Prevention in the Process Industries*, 21: 589-595.

Note: in UK CO2 pipeline are designed similarly to natural gas transportation

<http://www.hse.gov.uk/pipelines/resources/designcodes.htm>

## Pipelines

### In the US, are CO2 incidents more or less likely to cause fatalities ?

	Natural gas Transmission	Hasardous liquids	CO2		
Fatalities / incident	0,0280	0,0132	0,0000		
Incidents without fatalities (at least)	2253	4034	20		
The probability that an serious incident has no victim is larger than	97,20%	98,68%	100,00%	90,00%	86,00%
Probability that the number of incidents in \$E\$37 all have No fatalities			100,00%	12,16%	4,90%

We have a run of 20 incidents without fatality.

But even if a significant CO2 incident has 10% probability of causing at least one fatality, there is more than 10% probability that the observed run of 20 incidents without victims is just luck.

If we want the 95% confidence level, we can only say that the probability that a serious incident with a CO2 pipeline causes a fatality is less than 14%.

In other words, we do not have enough observations to compare statistically the lethality of CO2 pipelines incidents with the lethality of other pipelines accidents.

### Evidence from European networks

Ancien (a) Concawe Oil Pipelines Management Group's Special Task Force on oil pipeline spillages (OP/STF-1), 2007, "Performance of European crosscountry oil pipelines, . Statistical summary of reported spillages in 2005 and since 1971", Brussels.

Source (a) [Concawe Report No. 7/08](#). Performance of European cross-country oil pipelines - statistical summary of reported spillages in 2006 and since 1971

27 Oil Pipeline in Western Europe (average from Figure 1 page 3, thousand km)  
 37 Period 1971 2006  
 14 Total Fatalities, section 3.1 page 7, all « Workers »  
**0,0140** Fatalities per 1000 km per year

Pipelines

Imperial-metric distance unit conversion factor

1,61 km

1 mile

**Natural gas transmission pipeline annual mileage**

*Unit: 1000 miles*

Year	N° of records	Onshore	Offshore	Total transmiss	onshore	offshore	total gathering	total pipe	(in Km)
1984	885	277,6	7,35	284,95	33,29	3,67	36,96	321,92	518,07
1985	952	282,75	7,72	290,46	33,73	1,74	35,47	325,93	524,54
1986	1,01	280,67	9,29	289,96	29,74	1,96	31,7	321,65	517,65
1987	963	284,24	7,62	291,86	29,65	2,48	32,13	323,99	521,41
1988	1,02	280,25	7,91	288,16	28,94	3,1	32,04	320,2	515,32
1989	1,03	279,73	8,2	287,93	29,6	2,55	32,14	320,07	515,1
1990	1,11	283,88	8,11	291,99	29,27	3,15	32,42	324,41	522,09
1991	1,21	285,3	8,57	293,86	29,01	3,7	32,71	326,58	525,57
1992	1,18	283,07	8,4	291,47	28,91	3,72	32,63	324,1	521,58
1993	1,13	285,04	8,22	293,26	28,43	3,63	32,06	325,32	523,55
1994	1,23	293,44	8,11	301,55	27,4	3,91	31,32	332,86	535,69
1995	1,27	288,85	8,1	296,95	26,67	4,26	30,93	327,88	527,67
1996	1,25	285,34	6,85	292,19	24,86	4,76	29,62	321,8	517,89
1997	1,35	287,75	6,63	294,37	28,3	6,16	34,46	328,83	529,21
1998	1,17	295,61	7,11	302,71	23,49	5,67	29,17	331,88	534,11
1999	1,18	290,1	6,02	296,11	26,36	5,92	32,28	328,39	528,49
2000	1,17	293,72	5,24	298,96	21,88	5,68	27,56	326,52	525,48
2001	1,35	284,91	5,54	290,46	17,73	3,88	21,61	312,07	502,23
2002	1,47	297,21	6,33	303,54	16,98	5,58	22,56	326,1	524,81
2003	1,47	295,55	6,28	301,83	16,43	6,33	22,76	324,59	522,37
2004	1,43	296,86	6,24	303,22	17,27	7,41	24,73	327,95	527,78
2005	1,48	294,68	5,86	300,66	16,03	7,37	23,4	324,06	521,53
2006	1,49	293,61	6,7	300,46	13,1	7,33	20,43	320,89	516,42
2007	1,45	294,73	6,2	301,17	12,57	7,12	19,7	320,86	516,38
2008	1,48	295,22	6	301,22	12,99	7,23	20,22	321,44	517,31
								<b>522,16</b>	

**Carbon dioxide systems, jan 12, 2010**

	No of records	Onshore	Offshore	Total pipe (mi)	Total pipe (1000 km)
2004	21	3408	0	3408	5,48
2005	27	3718	127	3846	6,19
2006	29	3827	0	3827	6,16
2007	31	3884	0	3884	6,25
2008	30	4202	0	4202	6,76
		<b>Average, 2004-2008</b>			<b>6,169</b>

Source: PHMSA Office of Pipeline Safety Natural Gas Transmission Pipeline Annual Mileage [\(link\)](#)

**Average 1986-2007**





## Shipping CO2

**Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »**

**This spreadsheet computes global expected fatalities attributable to shipping CO2 in the wedge scenario**

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### Method 1. Oil tanking statistics: we consider the average FAR/ Mt-miles in oil trade by tankers for 1978-2001

2322 Fatalities on the period 1978-2001 from oil tanker incidents (Ranheim 2002)

24 Period duration

8258 Gt miles of oil (crude+products) shipped by tankers – average 1978-2001 (see table below)

11,7 fatality per Tt-miles-yr

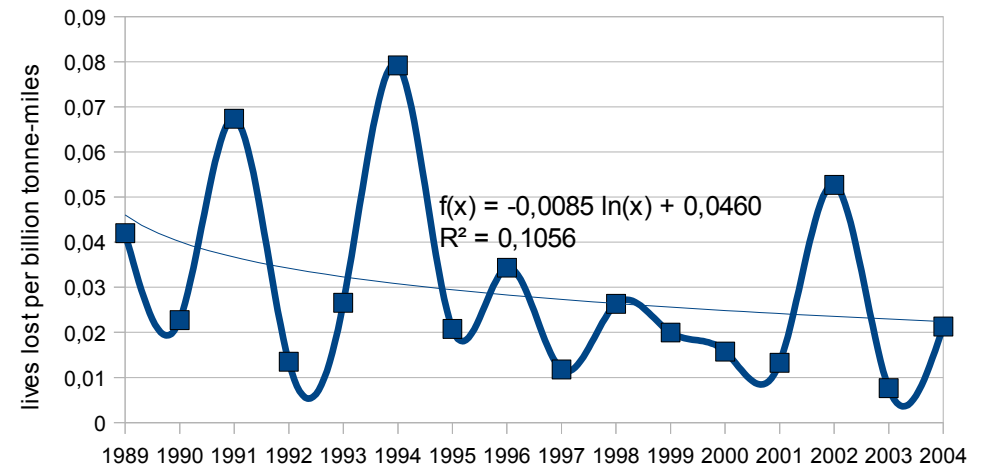
Oil (crude+products)	World seaborne trade in Gt-miles (Table reproduced from IMO 2005 Facts and figures p. 6, citing data from Fearnleys Review, 2004)	
1970	6487	
1975	9727	
1980	9405	<u>Weighted average</u>
1985	5157	75-80 9566
1990	7821	80-85 7281
2000	10265	85-90 6489
2001	10179	90-00 9043
2002	9898	00-01 10222
		78-01 <b>8258</b>

### Method 2. Shipping/ World Trade statistics

	Year	Fatalities*	Total trade**	Fatality rate	Log. Tendency
1	1989	688	16385	0,0420	0,0460
2	1990	389	17121	0,0227	0,0401
3	1991	1204	17873	0,0674	0,0367
4	1992	246	18228	0,0135	0,0342
5	1993	504	18994	0,0265	0,0323
6	1994	1552	19600	0,0792	0,0308
7	1995	419	20188	0,0208	0,0295
8	1996	710	20678	0,0343	0,0283
9	1997	257	21825	0,0118	0,0273
10	1998	566	21492	0,0263	0,0264
11	1999	439	21990	0,0200	0,0256
12	2000	373	23693	0,0157	0,0249
13	2001	317	23891	0,0133	0,0242
14	2002	1274	24172	0,0527	0,0236
15	2003	197	25844	0,0076	0,0230
16	2004	589	27635	0,0213	0,0224
	<b>Total</b>	<b>9724</b>	<b>339609</b>	<b>0,0286</b>	
62	2050				

0,0109 E)

**Fatality rate**  
World seaborne trade



## Shipping CO2

Source: \* Fatalities: IMO 2005 FSI.3/Circ.6. \*\* Total world seaborne trade (billion tonne-miles): Fearnley annual Review 2004, p.49

### Analysis of the trend, for extrapolation

According to Ranheim (2002), the trend in fatalities is declining. 775 in the second 12 year half of the series, versus 1617 in the previous 12 years.

However the number of tanker incidents increased again during 2002-2007, see chart, source (a).

And over 2002-2007, the table below sums up to 229 fatalities.

#### Recent data (include descriptions)

Fatalities in recorded tanker incidents – all types and sizes

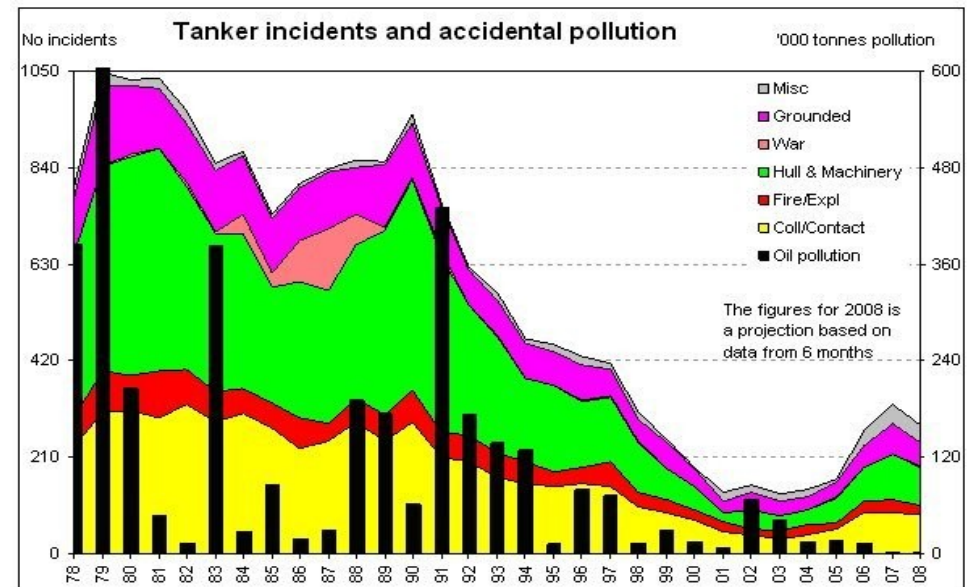
2008->27/5	33
2007	61
2006	40
2005	26
2004	65
2003	21
2002	16

Sources: Compiled by E. Ranheim at Intertanko, based on reports from LMIU, published at:

- (a) <http://www.themaritimefoundation.com/templates/Page.aspx?id=44456>
- (b) <http://www.themaritimefoundation.com/templates/Page.aspx?id=43302>
- (c) <http://www.themaritimefoundation.com/templates/Page.aspx?id=44172>
- (d) <http://www.themaritimefoundation.com/templates/Page.aspx?id=42406>

Period	Fatalities*	Annual average	
1978-1989	1617	134,75	
1990-2001	775	64,58	2,09
2002-2007	229	38,17	1,69

\*Ranheim (2002) The table suggests that safety improved by a factor 2 over 78-89, then by 1.7 over 90-01. We extrapolate a factor 4 over 2002-2050.



#### References and data sources on shipping

Ranheim E (2002) dans "Sécurité Maritime et protection de l'environnement" *Evolution et Perspectives* (Brest), p 68-77.

IMO (International Maritime Organization) Library Services (2005) *International Shipping and World Trade. Facts and figures*

IMO (2005) Casualty statistics and investigation. *Very serious and serious casualties for the year 2003. FSI.3/Circ.6 – 17/3/2005.*

The IMO database on marine casualty and incidents (not very useful)

Fearnley annual Review 2004

For global production and productivity, see UNCTAD « [Review of maritime transport](#) »

Casualties topic page on [Seasearcher](#), Lloyd's database.

#### Summary table : expected fatalities for shipping CO2

Shipping	Fatality rate	Fatalities	
CO2 Tt Nm	Fat/Tt Nm	2050 expected	
2,25	2,9	7	Tanking, extrapolated
2,25	11	25	All goods, extrapolated

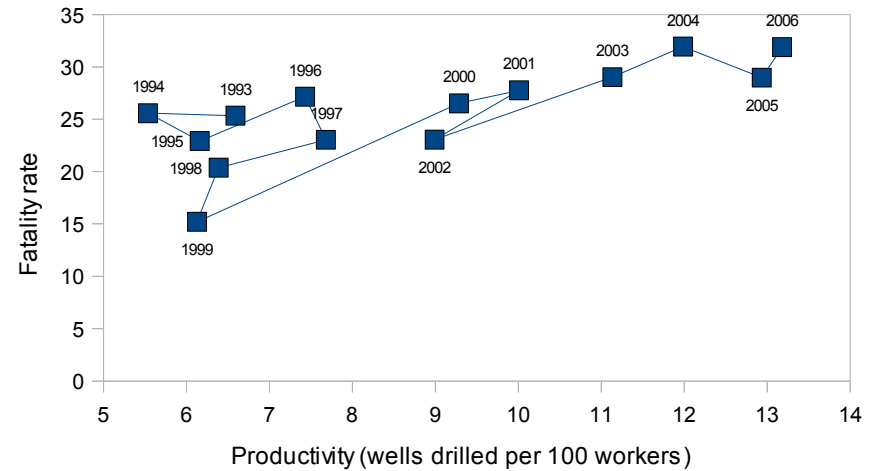
## Injection

**Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »**  
**This spreadsheet computes global expected fatalities attributable to the injection of CO2 in the wedge scenario**  
**(c) 2008-2011. Minh Ha-Duong. Rodica Loisel. CIRED** **Reproduction allowed. share alike. attribution.**

Source:	(a)	(a)	(a)	(b)	
Year	No of fatalities	No of workers	Rate per 100.000 workers	Drilled wells	Drilled wells/100 workers
1993	94	371 000	25,3	24 452	6,6
1994	99	387 000	25,6	21 427	5,5
1995	77	336 000	22,9	20 698	6,2
1996	82	302 000	27,2	22 432	7,4
1997	85	369 000	23,0	28 341	7,7
1998	76	373 000	20,4	23 825	6,4
1999	50	329 000	15,2	20 158	6,1
2000	83	313 000	26,5	29 063	9,3
2001	98	353 000	27,8	35 331	10,0
2002	71	308 000	23,1	27 689	9,0
2003	85	292 846	29,0	32 599	11,1
2004	98	306 863	31,9	36 777	12,0
2005	98	338 234	29,0	43 747	12,9
2006	123	385 803	31,9	50 842	13,2
2007				50825	
2008				55670	

**Figure 3 in the paper**

**Fatalities per 100 000 workers**  
**US oil and gas extraction industry**



### Sources

(a) Centers for Disease Control and Prevention. 2008. Fatalities Among Oil and Gas Extraction Workers --- United States, 2003--2006. MMWR 57(16):429-431.

Table 1, Available at <http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5716a3.htm>

(b) U.S. Energy Information Administration 2009. Annual Energy Review 2008. Report DOE/EIA-0364(2008)

Table 4.5 Crude Oil and Natural Gas Exploratory and Development Wells, 1949-2008. Column Total, Wells drilled. Available at <http://www.eia.doe.gov/emeu/aer/txt/ptb0405.html>

### Assumptions from the 2050 scenario

5000      15000 Workers on injection sites

<b>Summary table : expected fatalities from injection</b>			
Workers	Fatality rate	Fatalities	
5000	20	1	Lower expectation
15000	30	4,5	Upper expectation

## Injection

	31/12/10			31/12/09		
	Revenue (million \$)	Employees	R/E \$	Revenue (million \$)	Employees	R/E \$
Schlumberger	27 447	108 000	\$254 139	22 702	77 000	\$294 831
Halliburton	17 973	58 000	\$309 879	14 675	51 000	\$287 745
Baker Hugues	14 414	53 100	\$271 450	9 664	34 400	\$280 930
Weatherford International	10 221	55 000	\$185 836	8 833	52 000	\$169 865
CGGVeritas	2 904	7 264	\$399 780	3 109	7 500	\$414 533
Minimum			\$185 836			\$169 865
Maximum			\$399 780			\$414 533

Source : annual reports available at

<http://investorcenter.slb.com/phoenix>.  
<http://ir.halliburton.com/phoenix.zhtm>  
<http://investor.shareholder.com/bhi/ar>  
<http://annualreport.weatherford.com/>  
<http://www.cggveritas.com/default.aspx>

Injection per site                    8,8 million ton per year  
 Assumed injection fee            0,50 USD per ton of CO2  
 Revenue                                4,40 USD million per year

Employees per site	R/E 2010	R/E 2009
Maximum	24	26
Minimum	11	11

Number of sites                    500

Total workers	R/E 2010	R/E 2009
Maximum	11 838	12 951
Minimum	5 503	5 307

Injection

## Injection

zhtml?c=97513&p=irol-reportsannual  
l?c=67605&p=irol-reportsAnnual  
nuals.cfm

ox?cid=38&lang=2

**Electronic supplement to the manuscript « Expected fatalities foone wedge of CCS in 2050 »**

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### **Method 1: Minimum endogenous mortality risk increase**

Negligible level of individual risk increase in MicroMort units:

1

1 micromort is defined as a one in a million probability of dying next year. This is a negligible level because:

According to P. Fishbeck and D. Gerard « Death Risk Rankings » database, accessed at <http://www.deathriskrankings.com/> 2001-02-23,

the probability of dying for Females, aged 5-9 is 97 MicroMort in Western Europe, 106 in New England

This is the minimum across genders, region and age groups. So practically everybody is above 100 micromorts.

#### **Summary table : expected fatalities in 2050 from storage, method 1**

Exposed population	Risk level	Expected fatalities in 2050
225000	1E-06	0,23 MEM, small footprint
900000	1E-06	0,90 MEM, large footprint

### **Method 2: Storage sites as artificial installations**

#### **Analogue with a risk level apparently greater than CO2 storage: Risk around dangerous installations (Seveso)**

France	Europe		Europe (former period)	
1076	8558 Sites	Source (a)	1860 Sites	Source (c)
38	153 Fatalities	Source (b)	14 Accidents per year	Source (c)
17	17 Years	Source (b)	2,3 Fatalities per accidents	Source (c)
2,08E-003	1,05E-003 Fatalities per site per year		1,73E-002 Fatalities per site per year	

#### **Analogue with a risk level apparently smaller than CO2 storage: Risk around common installations in France**

500000 Sites	403 Fatalities	17 Years	Source (b)
4,74E-005 Fatalities per site per year			

The above rates should be increased to account for underreporting (except those from source c), so the range is 0.01 – 0.0001

Because CO2 storage is regulated in-between these analogues, we assume that the accepted risk will be 0.001, in the (geometric) middle.

But we extrapolate a worst case 3 times as high, because EU societies are more risk averse than our 2050 world

#### **Summary table : expected fatalities in 2050 from storage, method 2**

Onshore sites	Risk per site	Expected fatalities	
450	0,001	0,45	Analogue, low risk
450	0,003	1,35	Analogue, high risk



## Storage

### Sources for method 2

- (a) Salvi, O., A. Jovanovic, C. Bolvin, C. Dupuis, C. Vaquero, D. Balos, et A-M. Villamizar. 2008. F-SEVESO. Study of the effectiveness of the Seveso II Directive. Final report. Contract n°070307/2007/476000/MAR/A3. Août 29. <http://ec.europa.eu/environment/seveso/review.htm>
- (b) Michel, Laurent. 2010. Inventaire 2009 des accidents technologiques. Bureau d'Analyse des Risques et Pollutions Industriels (BARPI), Ministère de l'Ecologie, de l'Energie, du Développement Durable et de l'Aménagement du Territoire. [http://www.aria.developpement-durable.gouv.fr/barpi\\_2963.jsp](http://www.aria.developpement-durable.gouv.fr/barpi_2963.jsp)
- (c) Haastrup, P, et H Romer. 1995. An analysis of the database coverage of industrial accidents involving hazardous materials in Europe. Journal of Loss Prevention in the Process Industries 8, no. 2: 79-86. [http://dx.doi.org/10.1016/0950-4230\(95\)00008-0](http://dx.doi.org/10.1016/0950-4230(95)00008-0)

### Remark on reliability testing and CO2 storage demonstration projects

If a fatality occurs too soon, it will be hard to justify that the risk per site is as low as 0.001 fatality per year.

According to the NIST/SEMATECH e-handbook of statistical methods (<http://www.itl.nist.gov/div898/handbook/apr/section3/apr311.htm>), to test statistically an MTBF of 1000 years with a 95% confidence level, one has to see the system working without failure for 3000 years. So when do we get 3000 years of storage experience in our scenario ?

Year	Storage sites	Cumulative experience	New sites opened per year
2007	3	3	1,5
2008	4,5	7,5	1,5
2014	13,5	66	1,5
2015	15	81	3,5
2016	18,5	99,5	3,5
2024	46,5	373,5	3,5
2025	50	423,5	18
2026	68	491,5	18
2038	284	2711,5	18
<b>2039</b>	<b>302</b>	<b>3013,5</b>	<b>18</b>
2040	320	3333,5	18
2041	330	3663,5	18
2042	340	3993,5	18
2043	350	4323,5	18
2044	360	4653,5	18
2045	370	4983,5	18
2046	380	5313,5	18
2047	390	5643,5	18
2048	400	5973,5	18
2049	410	6303,5	18
2050	500	7523,5	18

## Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »

## Summary of results (Table 4)

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Minimum Maximum

**Summary results table : expected fatalities from coal mining**

Coal mined Gt (scenario)	Fatality rate per Mt mined	Expected fatalities In 2050			
2,1	0,0383	81	Convergence to USA 1990-2007		
2,1	0,0935	196	Safety progress follows the USA curve	80,6	196,5

**Summary table : expected fatalities for shipping coal**

Activity level Tt Nm in 2050	Fatality rate	Fatalities			
1,42	2,9	4,2	Extrapolated from tanking		
1,42	10,9	15,5	Extrapolated from all goods trade	4,2	15,5

**Summary table : expected fatalities from coal on railroads**

Mkm	Fatality rate	Fatalities			
89,3	0,63	56	2009 ECS target are realised		
89,3	0,91	81	The 2001 USA risk rate applies	56,2	80,9

**Summary table : expected fatalities in 2050 to capture the CO2**

Qty captured Gt CO2	Risk rate Gt-1 a-1	Expected Fatalities			
4,5	1,4	6,3	Accident record, low case		
4,5	1,7	7,5	Accident record, high case		
Workers	Fatality rate	Fatalities			
7500	3	0,23	Worker's safety, low case		
15000	14	2,1	Worker's safety, high case	0,2	7,5

**Summary table : expected 2050 fatalities from pipelines**

Mkm	Fatality rate	Fatalities			
0,15	5	0,75	Lower expectation		
0,15	50	7,5	Upper expectation	0,8	7,5

Results

<b>Summary table : expected fatalities for shipping CO2</b>			
Shipping	Fatality rate	Fatalities	
CO2 Tt Nm	Fat/Tt Nm	2050 expected	
2,25	2,9	7	Tanking, extrapolated
2,25	11	25	All goods, extrapolated

6,6      24,6

<b>Summary table : expected fatalities from injection</b>			
Workers	Fatality rate	Fatalities	
5000	20	1	Lower expectation
15000	30	4,5	Upper expectation

1,0      4,5

<b>Summary table : expected fatalities in 2050 from storage, method 1</b>			
Exposed population	Risk level	Expected fatalities in 2050	
225000	1E-06	0,23 MEM, small footprint	
900000	1E-06	0,90 MEM, large footprint	
Onshore sites	Risk per site	Expected fatalities	
450	0,001	0,45	
450	0,003	1,35	

0,2      1,4

**Total                      149,7      338,2**