Actuarial risk assessment of expected fatalities attributable to carbon capture and storage in 2050
Minh Ha-Duong, Rodica Loisel

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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
- 4.17 Gt CO2 baseline B = A / a
- 5.00 Gt CO2 generated G = g B
- 4.50 Gt CO2 stored S = s B

Carbon dioxide emissions and coal types

<table>
<thead>
<tr>
<th>Coal Types</th>
<th>Specific Energy(a) MJ/kg</th>
<th>Carbon Content (b) gC/MJ</th>
<th>CO2 emissions kgCO2/MJ kgCO2/kg coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>9.3</td>
<td>27.6</td>
<td>0.10</td>
</tr>
<tr>
<td>Sub bituminous</td>
<td>18.1</td>
<td>26.2</td>
<td>0.10</td>
</tr>
<tr>
<td>Bituminous</td>
<td>25.4</td>
<td>25.8</td>
<td>0.09</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Coal</th>
<th>Carbon</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>0.32</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>4500</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>1.42</td>
<td>2.25</td>
<td></td>
</tr>
</tbody>
</table>

Fraction shipped
Quantity shipped, Gt in 2050
Average trip, Nm
Transport, Tt Nm in 2050
### Scenario parameters: Pipeline CO2
90% Fraction pipelined (= not shipped)

<table>
<thead>
<tr>
<th>Year</th>
<th>km</th>
<th>Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2015</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>2025</td>
<td>100</td>
<td>190</td>
</tr>
<tr>
<td>2050</td>
<td>100</td>
<td>4050</td>
</tr>
</tbody>
</table>

### Scenario parameters: Injection and storage

<table>
<thead>
<tr>
<th>Year</th>
<th>Sites</th>
<th>Wells</th>
<th>Wells/site</th>
<th>Mt</th>
<th>Injection</th>
<th>kt CO2/yr Inject/well</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>3</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>15</td>
<td>50</td>
<td>3,33</td>
<td>15</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td>50</td>
<td>667</td>
<td>13,33</td>
<td>200</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td>500</td>
<td>15000</td>
<td>30</td>
<td>4500</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

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

### Scenario parameters: population over storage

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>100</td>
<td>km²</td>
<td>footprint of a storage site</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td></td>
<td>20 Inhabitants / km² over storage sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
<td></td>
<td>2000 Inhabitants in the footprint zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>225000</td>
<td>900000</td>
<td>Persons exposed to storage sites, worldwide</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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  $s = e \cdot g = e \cdot (1 + p)$
- 88% Fraction avoided compared to baseline  $a = s - p = e \cdot (1 + p) - p$

Reference
plant

Baseline CO2 emissions $B$

With CCS
plant

CO2 generated $G = (1 + p) \cdot B$

CO2 captured and stored $S = e \cdot G = e \cdot (1 + p) \cdot B$

CO2 avoided $A = S - p \cdot B = (e \cdot (1 + p) - p) \cdot B$
Wedge
Historical stats for the US coal mining industry

<table>
<thead>
<tr>
<th>t</th>
<th>Year</th>
<th>Miners</th>
<th>Fatalities</th>
<th>Source (a)</th>
<th>Source (b)</th>
<th>=D/E</th>
<th>log_FAR_US</th>
<th>OLS estimation of log (fatalities/production)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>const</td>
</tr>
<tr>
<td>1</td>
<td>1900</td>
<td>448.58</td>
<td>1489</td>
<td>268</td>
<td>5.55</td>
<td>1.71</td>
<td>1.86</td>
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<tr>
<td>2</td>
<td>1901</td>
<td>485.54</td>
<td>1574</td>
<td>292</td>
<td>5.40</td>
<td>1.69</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1902</td>
<td>518.2</td>
<td>1724</td>
<td>300</td>
<td>5.74</td>
<td>1.75</td>
<td>1.84</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1903</td>
<td>566.26</td>
<td>1926</td>
<td>356</td>
<td>5.42</td>
<td>1.69</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1904</td>
<td>593.69</td>
<td>1995</td>
<td>350</td>
<td>5.70</td>
<td>1.74</td>
<td>1.81</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1905</td>
<td>626.05</td>
<td>2232</td>
<td>391</td>
<td>5.71</td>
<td>1.74</td>
<td>1.79</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>1933</td>
<td>523.18</td>
<td>1064</td>
<td>383</td>
<td>2.78</td>
<td>1.02</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>1934</td>
<td>566.43</td>
<td>1226</td>
<td>417</td>
<td>2.94</td>
<td>1.08</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>1944</td>
<td>453.94</td>
<td>1298</td>
<td>683</td>
<td>1.90</td>
<td>0.64</td>
<td>0.52</td>
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</tr>
<tr>
<td>86</td>
<td>1985</td>
<td>197.05</td>
<td>68</td>
<td>884</td>
<td>0.08</td>
<td>-2.56</td>
<td>-2.17</td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>1986</td>
<td>185.17</td>
<td>89</td>
<td>890</td>
<td>0.10</td>
<td>-2.3</td>
<td>-2.25</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>1987</td>
<td>172.78</td>
<td>63</td>
<td>919</td>
<td>0.0686</td>
<td>-2.68</td>
<td>-2.33</td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>1988</td>
<td>166.28</td>
<td>53</td>
<td>946</td>
<td>0.06</td>
<td>-2.88</td>
<td>-2.42</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>1989</td>
<td>164.93</td>
<td>68</td>
<td>981</td>
<td>0.07</td>
<td>-2.67</td>
<td>-2.5</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>1992</td>
<td>153.13</td>
<td>55</td>
<td>998</td>
<td>0.06</td>
<td>-2.9</td>
<td>-2.76</td>
<td></td>
</tr>
<tr>
<td>106</td>
<td>2005</td>
<td>116.44</td>
<td>23</td>
<td>1131</td>
<td>0.02</td>
<td>-3.9</td>
<td>-3.98</td>
<td></td>
</tr>
<tr>
<td>107</td>
<td>2006</td>
<td>122.98</td>
<td>47</td>
<td>1055</td>
<td>0.04</td>
<td>-3.11</td>
<td>-4.08</td>
<td></td>
</tr>
<tr>
<td>108</td>
<td>2007</td>
<td>122.94</td>
<td>34</td>
<td>1039</td>
<td>0.03</td>
<td>-3.42</td>
<td>-4.18</td>
<td></td>
</tr>
</tbody>
</table>

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: http://www.iea.org/Textbase/stats/coaldata.asp?COUNTRY_CODE=29&Submit=Submit
F/C 1.64 This is the global fatality rate today

\[
\ln (F/C) = a + b t + c t^2
\]

1944 Year in which USA was at this fatality rate

(time solution of \[\ln (F/C) = a + b t + c t^2\] the other root is: -73.73)
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

\[ F/C = 0.0935 \]

The result: global coal mining industry fatality rate for 2050

<table>
<thead>
<tr>
<th>Summary results table: expected fatalities from coal mining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal mined Gt (scenario)</td>
</tr>
<tr>
<td>2.1</td>
</tr>
<tr>
<td>2.1</td>
</tr>
</tbody>
</table>

Engineering consistency check about the incremental quantity of coal

According to engineer Nhan T. Nguyen (pers. Com.)

- 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 CO2

Another view

- 920 kg CO2 / Mwh in 1997, Annex II countries
- 8760 h/yr
- 8059200 kg CO2 / MW / yr for a baseload plant
- 500 MW plant capacity
- 4.03E+006 t CO2/yr (divide by 1000 for kg to t)

A 500MW average plant emits 4 Mt CO2 per year

(source: Marion et al. CONTROLLING POWER PLANT CO2 EMISSIONS: A LONG RANGE VIEW)
## Total global production (Mt)

<table>
<thead>
<tr>
<th>Year</th>
<th>Hard coal</th>
<th>Brown coal/Lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008e</td>
<td>5848</td>
<td>951</td>
</tr>
<tr>
<td>2007</td>
<td>5442</td>
<td>956</td>
</tr>
<tr>
<td>2006</td>
<td>5205</td>
<td>914</td>
</tr>
<tr>
<td>2005</td>
<td>4934</td>
<td>906</td>
</tr>
<tr>
<td>2004</td>
<td>4629</td>
<td>879</td>
</tr>
<tr>
<td>2003</td>
<td>4231</td>
<td>893</td>
</tr>
<tr>
<td>1996</td>
<td>3734</td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>3489</td>
<td></td>
</tr>
<tr>
<td>1981</td>
<td>2796</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>2805</td>
<td></td>
</tr>
</tbody>
</table>

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

## International Hard Coal Trade (Mt)

<table>
<thead>
<tr>
<th>Year</th>
<th>Steam</th>
<th>Coking</th>
<th>Total Trade</th>
<th>Share of trade</th>
<th>By ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>676</td>
<td>262</td>
<td>938</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>670</td>
<td>247</td>
<td>917</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>593</td>
<td>222</td>
<td>815</td>
<td>16%</td>
<td>15%</td>
</tr>
<tr>
<td>2005</td>
<td>548</td>
<td>227</td>
<td>775</td>
<td>16%</td>
<td>14%</td>
</tr>
<tr>
<td>2004</td>
<td>541</td>
<td>188</td>
<td>609</td>
<td>13%</td>
<td>15%</td>
</tr>
<tr>
<td>2000</td>
<td>421</td>
<td>187</td>
<td>608</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>318</td>
<td>196</td>
<td>513</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>297</td>
<td>186</td>
<td>484</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990</td>
<td>299</td>
<td>199</td>
<td>898</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Steam coal</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Coking coal</th>
<th></th>
<th></th>
<th></th>
<th>Total Mt</th>
<th>billion ton mile average trip (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atlantic</td>
<td>Pacific</td>
<td>Atlantic</td>
<td>Pacific</td>
<td></td>
<td></td>
<td>Atlantic</td>
<td>Pacific</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2006</td>
<td>240</td>
<td>330</td>
<td>72</td>
<td>129</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>771</td>
<td>3540</td>
</tr>
<tr>
<td>2005</td>
<td>219</td>
<td>289</td>
<td>72</td>
<td>129</td>
<td></td>
<td></td>
<td>674</td>
<td>2960</td>
<td>4392</td>
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<tr>
<td>2004</td>
<td>210</td>
<td>274</td>
<td>67</td>
<td>123</td>
<td></td>
<td></td>
<td>512</td>
<td>2509</td>
<td>4900</td>
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<td></td>
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</tr>
<tr>
<td>2000</td>
<td>157</td>
<td>187</td>
<td>70</td>
<td>98</td>
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<td>437</td>
<td></td>
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<tr>
<td>1996</td>
<td>125</td>
<td>139</td>
<td>70</td>
<td>103</td>
<td></td>
<td></td>
<td>420</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1995</td>
<td>120</td>
<td>129</td>
<td>68</td>
<td>103</td>
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<td></td>
<td>383</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1994</td>
<td>108</td>
<td>111</td>
<td>66</td>
<td>98</td>
<td></td>
<td></td>
<td>275</td>
<td></td>
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</tr>
<tr>
<td>1986</td>
<td>74</td>
<td>59</td>
<td>61</td>
<td>81</td>
<td></td>
<td></td>
<td>275</td>
<td></td>
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</tr>
<tr>
<td>1985</td>
<td>76</td>
<td>55</td>
<td>61</td>
<td>83</td>
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<td>240</td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

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-miles)

**Source**: Table 5 in UNCTAD, Review of Maritime Transport 2009. ([link](#))

<table>
<thead>
<tr>
<th>Year</th>
<th>Crude plus products</th>
<th>Iron ore</th>
<th>Coal</th>
<th>Grain</th>
<th>5 main dry bulks</th>
<th>Other dry cargoes</th>
<th>World total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>5597</td>
<td>890</td>
<td>6487</td>
<td>1093</td>
<td>481</td>
<td>475</td>
<td>2049</td>
</tr>
<tr>
<td>1980</td>
<td>8385</td>
<td>1020</td>
<td>9405</td>
<td>1613</td>
<td>952</td>
<td>1087</td>
<td>3652</td>
</tr>
<tr>
<td>1990</td>
<td>6261</td>
<td>1029</td>
<td>7290</td>
<td>1978</td>
<td>1849</td>
<td>1073</td>
<td>5259</td>
</tr>
<tr>
<td>2000</td>
<td>8180</td>
<td>1319</td>
<td>9499</td>
<td>2545</td>
<td>2509</td>
<td>1244</td>
<td>6638</td>
</tr>
<tr>
<td>2001</td>
<td>8074</td>
<td>1345</td>
<td>9419</td>
<td>2575</td>
<td>2552</td>
<td>1322</td>
<td>6782</td>
</tr>
<tr>
<td>2002</td>
<td>7848</td>
<td>1394</td>
<td>9898</td>
<td>2731</td>
<td>2549</td>
<td>1241</td>
<td>6879</td>
</tr>
<tr>
<td>2003</td>
<td>8390</td>
<td>1460</td>
<td>9850</td>
<td>3035</td>
<td>2810</td>
<td>1273</td>
<td>7118</td>
</tr>
<tr>
<td>2004</td>
<td>8795</td>
<td>1545</td>
<td>10340</td>
<td>3444</td>
<td>2960</td>
<td>1350</td>
<td>9521</td>
</tr>
<tr>
<td>2005</td>
<td>8875</td>
<td>1652</td>
<td>10527</td>
<td>3918</td>
<td>3113</td>
<td>1686</td>
<td>9119</td>
</tr>
<tr>
<td>2006</td>
<td>8983</td>
<td>1758</td>
<td>10741</td>
<td>4192</td>
<td>3540</td>
<td>1822</td>
<td>9976</td>
</tr>
<tr>
<td>2007</td>
<td>9214</td>
<td>1870</td>
<td>11084</td>
<td>4544</td>
<td>3778</td>
<td>1927</td>
<td>10676</td>
</tr>
<tr>
<td>2008</td>
<td>9300</td>
<td>1992</td>
<td>11292</td>
<td>4849</td>
<td>3905</td>
<td>2029</td>
<td>11209</td>
</tr>
</tbody>
</table>

### Summary table: expected fatalities for shipping coal

<table>
<thead>
<tr>
<th>Activity level</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tt Nm in 2050</td>
<td>1.42</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>1.42</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Extrapolated from tanking

Extrapolated from all goods trade
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
- 178 571 number of train trips
- 500 km, average trip

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](http://www.wsgs.uwyo.edu/coalweb/trains/unit.aspx)

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


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


### Railroad accident statistics in the US

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


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


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

In France

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.197 0.141 0.118 0.119 Serious injuries</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0.193 0.173 0.163 0.159 Fatalities per million train-km (excl. Suicides)</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>0.024 0.020 0.020 0.018 Travelers</td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>0.075 0.073 0.072 0.072 Level crossings users</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.087 0.062 0.068 0.066 Trespassers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.008 0.006 0.005 0.004 Workers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.000 0.013 0.008 0.007 Others</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Category</th>
<th>Target (FWSI / million train-km / year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employees</td>
<td>0.08</td>
</tr>
<tr>
<td>Level crossing users</td>
<td>0.74</td>
</tr>
<tr>
<td>Others</td>
<td>0.02</td>
</tr>
<tr>
<td>Trespassers</td>
<td>2.3</td>
</tr>
<tr>
<td>Whole society</td>
<td>2.51</td>
</tr>
</tbody>
</table>

European Railway Agency (2009) Common Safety Targets

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

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

| Share of F in FWSI | 75%                                    |

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

<table>
<thead>
<tr>
<th>Mkm</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.3</td>
<td>0.63</td>
<td>56</td>
</tr>
<tr>
<td>89.3</td>
<td>0.91</td>
<td>81</td>
</tr>
</tbody>
</table>

2009 ECS target are realised
The 2001 USA risk rate applies
This spreadsheet computes global expected fatalities to capture the CO2

Method 1: Industrial carbon dioxide use

<table>
<thead>
<tr>
<th>Sources</th>
<th>120 Mt CO2/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>12 Fatalities from the two chemical accidents recorded</td>
</tr>
<tr>
<td>(b)</td>
<td>Source (c)</td>
</tr>
<tr>
<td>(c)</td>
<td>1926 1997 Period 72 Years</td>
</tr>
</tbody>
</table>

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


Summary table: expected fatalities in 2050 to capture the CO2

<table>
<thead>
<tr>
<th>Qty captured</th>
<th>Risk rate</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gt CO2</td>
<td>Gt⁻¹ a⁻¹</td>
<td>Fatalities</td>
</tr>
<tr>
<td>4,5</td>
<td>1,4</td>
<td>6,3 Accident record, low case</td>
</tr>
<tr>
<td>4,5</td>
<td>1,7</td>
<td>7,5 Accident record, high case</td>
</tr>
</tbody>
</table>

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 guess estimate based on the table below, which is a descriptive statistics summary of the data to the right

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

Summary table: expected fatalities in 2050 to capture the CO2

<table>
<thead>
<tr>
<th>Workers</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>7500</td>
<td>0,23</td>
<td>Worker’s safety, low case</td>
</tr>
<tr>
<td>15000</td>
<td>2,1</td>
<td>Worker’s safety, high case</td>
</tr>
</tbody>
</table>
## Rates of fatal injuries (Raw data)


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.

### Rates of fatal injuries per 1000 workers employed, excluding agents of public gas and electricity services

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>4</td>
<td>E</td>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>4</td>
<td>0.136</td>
<td>0.231</td>
<td>0.207</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>4</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>E</td>
<td>12.8</td>
<td>18.4</td>
<td>19.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>4</td>
<td>0.06</td>
<td>0.06</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>4</td>
<td>17.7</td>
<td>14.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 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.

### Summary table

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>0.0</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>6.0</td>
<td>4.0</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>13.6</td>
<td>23.1</td>
<td>20.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>12.8</td>
<td>18.4</td>
<td>19.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>2.0</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>12.0</td>
<td>12.0</td>
<td>16.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>17.7</td>
<td>14.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summary table</th>
<th>n</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>25</td>
<td>4</td>
<td>4.4</td>
<td>2.12</td>
</tr>
<tr>
<td>USA</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>France</td>
<td>31</td>
<td>1.7</td>
<td>31.9</td>
<td>13.03</td>
</tr>
<tr>
<td>Canada</td>
<td>14</td>
<td>10.5</td>
<td>19.7</td>
<td>14.21</td>
</tr>
<tr>
<td>Italy</td>
<td>16</td>
<td>1</td>
<td>7</td>
<td>3.63</td>
</tr>
<tr>
<td>Japan</td>
<td>38</td>
<td>0</td>
<td>16</td>
<td>2.84</td>
</tr>
<tr>
<td>China</td>
<td>18</td>
<td>6.1</td>
<td>27.3</td>
<td>16.75</td>
</tr>
<tr>
<td>Brazil</td>
<td>1</td>
<td>18.6</td>
<td>18.6</td>
<td>18.6</td>
</tr>
</tbody>
</table>
Evidence from the US pipelines networks

Updated statistics of pipeline incident in the USA

<table>
<thead>
<tr>
<th>Natural gas Transmission</th>
<th>Hazardous liquids</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>1986</td>
<td>1986</td>
</tr>
<tr>
<td>End</td>
<td>2009</td>
<td>2009</td>
</tr>
<tr>
<td>Duration (years)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td># significant incidents</td>
<td>2 318</td>
<td>4 088</td>
</tr>
<tr>
<td># fatalities</td>
<td>65</td>
<td>54</td>
</tr>
<tr>
<td>Network length (1000km)</td>
<td>522</td>
<td>255</td>
</tr>
<tr>
<td>Observation basis (Mkm yr)</td>
<td>12,532</td>
<td>6,113</td>
</tr>
<tr>
<td>Incidents /Mkm / yr</td>
<td>184.97</td>
<td>668.73</td>
</tr>
<tr>
<td>Fatalities / Mkm / yr</td>
<td>5.2</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Homogenous Poisson Process statistics

<table>
<thead>
<tr>
<th>Fail free duration</th>
<th>Desired confidence</th>
<th>MTBF at this conf. Level</th>
<th>Upper rate of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.123</td>
<td>95%</td>
<td>0.0412</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Assumptions from the 2050 scenario

<table>
<thead>
<tr>
<th>Sites</th>
<th>Distance km</th>
<th>Total network size Mkm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1500</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

Summary table : expected 2050 fatalities from pipelines

<table>
<thead>
<tr>
<th>Mkm</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>5</td>
<td>0.75</td>
</tr>
<tr>
<td>0.15</td>
<td>50</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower expectation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper expectation</td>
</tr>
</tbody>
</table>

Table data sources:
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
The ENSAD database at PSI. http://gabe.web.psi.ch/research/ra/
Note: in UK CO2 pipeline are designed similarly to natural gas transportation http://www.hse.gov.uk/pipelines/resources/designcodes.htm
In the US, are CO2 incidents more or less likely to cause fatalities?

<table>
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<th>Incident Type</th>
<th>Natural gas Transmission</th>
<th>Hazardous liquids</th>
<th>CO2</th>
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<td>0,0280</td>
<td>0,0132</td>
<td>0,0000</td>
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<tr>
<td>Incidents without fatalities (at least)</td>
<td>2253</td>
<td>4034</td>
<td>20</td>
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</tbody>
</table>

The probability that a serious incident has no victim is larger than 97,20% for Natural gas Transmission, 98,68% for Hazardous liquids, 100,00% for CO2.

Probability that the number of incidents in $E$37 all have No fatalities is 100,00% for Natural gas Transmission, 12,16% for Hazardous liquids, 4,90% for CO2.

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


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
### Natural gas transmission pipeline annual mileage

<table>
<thead>
<tr>
<th>Year</th>
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<th>Offshore</th>
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<th>onshore</th>
<th>offshore</th>
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**Carbon dioxide systems, Jan 12, 2010**

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**Average 1986-2007**

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Source: PHMSA Office of Pipeline Safety Natural Gas Transmission Pipeline Annual Mileage [link]
### Liquid Pipeline Operator Total National Mileage

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**Average 1986-2007:** 254,71

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### Database report on CO2 pipeline spills in the US.

Source: PHMSA Significant Incident Data Assess database [link]

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Significant incidents: 14

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Page 12
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

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Method 2. Shipping/ World Trade statistics

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<th>Fatality rate</th>
<th>Log. Tendency</th>
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Fatality rate

Extrapolation!
Shipping CO2


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

<table>
<thead>
<tr>
<th>Year</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>27/5</td>
</tr>
<tr>
<td>2007</td>
<td>33</td>
</tr>
<tr>
<td>2006</td>
<td>61</td>
</tr>
<tr>
<td>2005</td>
<td>40</td>
</tr>
<tr>
<td>2004</td>
<td>26</td>
</tr>
<tr>
<td>2003</td>
<td>65</td>
</tr>
<tr>
<td>2002</td>
<td>21</td>
</tr>
<tr>
<td>2002</td>
<td>16</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Period</th>
<th>Fatalities*</th>
<th>Annual average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978-1989</td>
<td>1617</td>
<td>134.75</td>
</tr>
<tr>
<td>1990-2001</td>
<td>775</td>
<td>64.58</td>
</tr>
<tr>
<td>2002-2007</td>
<td>229</td>
<td>38.17</td>
</tr>
</tbody>
</table>

*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.

Summary table: expected fatalities for shipping CO2

<table>
<thead>
<tr>
<th>Shipping</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Tt Nm</td>
<td>Fat/Tt Nm</td>
<td>2050 expected</td>
</tr>
<tr>
<td>2,25</td>
<td>2,9</td>
<td>7 Tanking, extrapolated</td>
</tr>
<tr>
<td>2,25</td>
<td>11</td>
<td>25 All goods, extrapolated</td>
</tr>
</tbody>
</table>

References and data sources on shipping

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.
**Figure 3 in the paper**

**Fatalities per 100 000 workers**

US oil and gas extraction industry

<table>
<thead>
<tr>
<th>Year</th>
<th>Drilled wells/100 workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>24 452</td>
</tr>
<tr>
<td>1994</td>
<td>21 427</td>
</tr>
<tr>
<td>1995</td>
<td>20 698</td>
</tr>
<tr>
<td>1996</td>
<td>22 432</td>
</tr>
<tr>
<td>1997</td>
<td>28 341</td>
</tr>
<tr>
<td>1998</td>
<td>23 825</td>
</tr>
<tr>
<td>1999</td>
<td>20 158</td>
</tr>
<tr>
<td>2000</td>
<td>29 063</td>
</tr>
<tr>
<td>2001</td>
<td>23 382</td>
</tr>
<tr>
<td>2002</td>
<td>27 689</td>
</tr>
<tr>
<td>2003</td>
<td>29 063</td>
</tr>
<tr>
<td>2004</td>
<td>36 777</td>
</tr>
<tr>
<td>2005</td>
<td>43 747</td>
</tr>
<tr>
<td>2006</td>
<td>50 842</td>
</tr>
<tr>
<td>2007</td>
<td>50825</td>
</tr>
<tr>
<td>2008</td>
<td>55670</td>
</tr>
</tbody>
</table>

**Sources**

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

   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**

<table>
<thead>
<tr>
<th>Workers</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>15000</td>
<td>30</td>
<td>4,5</td>
</tr>
</tbody>
</table>

**Summary table : expected fatalities from injection**

<table>
<thead>
<tr>
<th>Workers</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>15000</td>
<td>30</td>
<td>4,5</td>
</tr>
</tbody>
</table>

**Lower expectation**

**Upper expectation**
### Injection

<table>
<thead>
<tr>
<th></th>
<th>31/12/10 Revenue</th>
<th>31/12/09 Revenue</th>
<th>Employees</th>
<th>R/E</th>
<th>Employees</th>
<th>R/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlumberger</td>
<td>27 447</td>
<td>22 702</td>
<td>108 000</td>
<td>$254 139</td>
<td>77 000</td>
<td>$294 831</td>
</tr>
<tr>
<td>Halliburton</td>
<td>17 973</td>
<td>14 675</td>
<td>58 000</td>
<td>$309 879</td>
<td>51 000</td>
<td>$287 745</td>
</tr>
<tr>
<td>Baker Hugues</td>
<td>14 414</td>
<td>9 664</td>
<td>53 100</td>
<td>$271 450</td>
<td>34 400</td>
<td>$280 930</td>
</tr>
<tr>
<td>Weatherford Int.</td>
<td>10 221</td>
<td>8 833</td>
<td>55 000</td>
<td>$185 836</td>
<td>52 000</td>
<td>$169 865</td>
</tr>
<tr>
<td>CGGVeritas</td>
<td>2 904</td>
<td>3 109</td>
<td>7 264</td>
<td>$399 780</td>
<td>7 500</td>
<td>$414 533</td>
</tr>
</tbody>
</table>

**Source:** annual reports available at
- [http://investorcenter.slb.com/phoenix](http://investorcenter.slb.com/phoenix)
- [http://ir.halliburton.com/phoenix.zhtml](http://ir.halliburton.com/phoenix.zhtml)
- [http://investor.shareholder.com/bhi/an](http://investor.shareholder.com/bhi/an)
- [http://www.cggveritas.com/default.aspx](http://www.cggveritas.com/default.aspx)

- **Minimum** $185 836
- **Maximum** $169 865
- **Revenue** $414 533

**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**
- **Maximum:** 24
- **Minimum:** 11

**Employees per site R/E 2009**
- **Maximum:** 26
- **Minimum:** 11

**Number of sites:** 500

**Total workers R/E 2010**
- **Maximum:** 11 838
- **Minimum:** 5 503

**Total workers R/E 2009**
- **Maximum:** 12 951
- **Minimum:** 5 307
Injection
Method 1: Minimum endogenous mortality risk increase

Negligible level of individual risk increase in MicroMort units:

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


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.

<table>
<thead>
<tr>
<th>Exposed population</th>
<th>Risk level</th>
<th>Expected fatalities in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>225000</td>
<td>1E-06</td>
<td>0,23 MEM, small footprint</td>
</tr>
<tr>
<td>900000</td>
<td>1E-06</td>
<td>0,90 MEM, large footprint</td>
</tr>
</tbody>
</table>

Method 2: Storage sites as artificial installations

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

<table>
<thead>
<tr>
<th>France</th>
<th>Europe (former period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1076</td>
<td>8558 Sites</td>
</tr>
<tr>
<td>38</td>
<td>153 Fatalities</td>
</tr>
<tr>
<td>17</td>
<td>17 Years</td>
</tr>
<tr>
<td>2,08E-003</td>
<td>1,05E-003 Fatalities per site per year</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Sites</th>
<th>Fatalities</th>
<th>Years</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>500000</td>
<td>403</td>
<td>17</td>
<td>(b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4,74E-005 Fatalities per site per year</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Onshore sites</th>
<th>Risk per site</th>
<th>Expected fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0,001</td>
<td>0,45</td>
</tr>
<tr>
<td>450</td>
<td>0,003</td>
<td>1,35</td>
</tr>
</tbody>
</table>
### Sources for method 2


Journal of Loss Prevention in the Process Industries 8, no. 2: 79-86. [http://dx.doi.org/10.1016/0950-4230(95)00008-O](http://dx.doi.org/10.1016/0950-4230(95)00008-O)

### 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. 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?

<table>
<thead>
<tr>
<th>Year</th>
<th>Storage sites</th>
<th>Cumulative experience</th>
<th>New sites opened per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>3</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>2008</td>
<td>4,5</td>
<td>7,5</td>
<td>1,5</td>
</tr>
<tr>
<td>2014</td>
<td>13,5</td>
<td>66</td>
<td>1,5</td>
</tr>
<tr>
<td>2015</td>
<td>15</td>
<td>81</td>
<td>3,5</td>
</tr>
<tr>
<td>2016</td>
<td>18,5</td>
<td>99,5</td>
<td>3,5</td>
</tr>
<tr>
<td>2024</td>
<td>46,5</td>
<td>373,5</td>
<td>3,5</td>
</tr>
<tr>
<td>2025</td>
<td>50</td>
<td>423,5</td>
<td>18</td>
</tr>
<tr>
<td>2026</td>
<td>68</td>
<td>491,5</td>
<td>18</td>
</tr>
<tr>
<td>2038</td>
<td>284</td>
<td>2711,5</td>
<td>18</td>
</tr>
<tr>
<td>2039</td>
<td>302</td>
<td>3013,5</td>
<td>18</td>
</tr>
<tr>
<td>2040</td>
<td>320</td>
<td>3333,5</td>
<td>18</td>
</tr>
<tr>
<td>2041</td>
<td>338</td>
<td>3671,5</td>
<td>18</td>
</tr>
<tr>
<td>2042</td>
<td>356</td>
<td>4027,5</td>
<td>18</td>
</tr>
<tr>
<td>2043</td>
<td>374</td>
<td>4401,5</td>
<td>18</td>
</tr>
<tr>
<td>2044</td>
<td>392</td>
<td>4793,5</td>
<td>18</td>
</tr>
<tr>
<td>2045</td>
<td>410</td>
<td>5203,5</td>
<td>18</td>
</tr>
<tr>
<td>2046</td>
<td>428</td>
<td>5631,5</td>
<td>18</td>
</tr>
<tr>
<td>2047</td>
<td>446</td>
<td>6077,5</td>
<td>18</td>
</tr>
<tr>
<td>2048</td>
<td>464</td>
<td>6541,5</td>
<td>18</td>
</tr>
<tr>
<td>2049</td>
<td>482</td>
<td>7023,5</td>
<td>18</td>
</tr>
<tr>
<td>2050</td>
<td>500</td>
<td>7523,5</td>
<td>18</td>
</tr>
</tbody>
</table>
### Summary results table: expected fatalities from coal mining

<table>
<thead>
<tr>
<th>Coal mined (Gt) (scenario)</th>
<th>Fatality rate per Mt mined</th>
<th>Expected fatalities</th>
<th>In 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>0.0383</td>
<td>Convergence to USA 1990-2007</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>0.0935</td>
<td>Safety progress follows the USA curve</td>
<td></td>
</tr>
</tbody>
</table>

### Summary table: expected fatalities for shipping coal

<table>
<thead>
<tr>
<th>Activity level (Tt Nm in 2050)</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.42</td>
<td>2.9</td>
<td>4.2</td>
</tr>
<tr>
<td>1.42</td>
<td>10.9</td>
<td>15.5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mkm</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.3</td>
<td>0.63</td>
<td>56</td>
</tr>
<tr>
<td>89.3</td>
<td>0.91</td>
<td>81</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Qty captured (Gt CO2)</th>
<th>Risk rate (Gt-1 a-1)</th>
<th>Expected Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>1.4</td>
<td>6.3</td>
</tr>
<tr>
<td>4.5</td>
<td>1.7</td>
<td>7.5</td>
</tr>
</tbody>
</table>

### Summary table: expected 2050 fatalities from pipelines

<table>
<thead>
<tr>
<th>Mkm</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>5</td>
<td>0.75</td>
</tr>
<tr>
<td>0.15</td>
<td>50</td>
<td>7.5</td>
</tr>
</tbody>
</table>

---

Electronic supplement to the manuscript « Expected fatalities for one wedge of CCS in 2050 »
Summary of results (Table 4)
(c) 2008-2011. Minh Ha-Duong, Rodica Loisel. CIREP
### Results

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

<table>
<thead>
<tr>
<th>Shipping</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 Tt Nm</td>
<td>Fat/Tt Nm</td>
<td>2050 expected</td>
</tr>
<tr>
<td>2.25</td>
<td>2.9</td>
<td>7</td>
</tr>
<tr>
<td>2.25</td>
<td>11</td>
<td>25</td>
</tr>
</tbody>
</table>

6.6 24.6

**Summary table : expected fatalities from injection**

<table>
<thead>
<tr>
<th>Workers</th>
<th>Fatality rate</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>15000</td>
<td>30</td>
<td>4.5</td>
</tr>
</tbody>
</table>

1.0 4.5

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

<table>
<thead>
<tr>
<th>Exposed population</th>
<th>Risk level</th>
<th>Expected fatalities in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>225000</td>
<td>1E-06</td>
<td>0.23 MEM, small footprint</td>
</tr>
<tr>
<td>900000</td>
<td>1E-06</td>
<td>0.90 MEM, large footprint</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Risk per site</th>
<th>Expected fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.001</td>
<td>0.45</td>
</tr>
<tr>
<td>450</td>
<td>0.003</td>
<td>1.35</td>
</tr>
</tbody>
</table>

0.2 1.4

**Total** 149.7 338.2