Journal of Civil Engineering and Environmental Technology
Print ISSN: 2349-8404; Online ISSN: 2349-879X; Volume 1, Number 2; August, 2014 pp. 51-56

http://www.krishisanskriti.org/jceet.html

Risk Assessment from Injection of Carbon Dioxide into Sea

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Abstract: **Capturing of CO_2 from various industries and injecting into deep ocean water is being considered as a mitigating technique for decreasing the CO_2 concentration in the atmosphere. However, this leads to the reduction in pH of water in Ocean nearby the site of injection which has a toxic effect on marine organisms .The exposure of CO_2 to Ocean water takes place through various routes such as pipeline failure or diffusion of the liquid CO_2 layer at the bottom of the ocean which leads to mortality of aquatic life due to sudden reduction in pH. Based on mortality data of various species as a function of pH, a model is formed in this paper to give an idea of the fraction of species that will get extinct on exposure from faulty pipeline or diffusion of liquid layer due to induced pH reduction. In addition to the suggested failure routes, this paper also gives some recommendations regarding risk management .**

Keywords: **Carbon Sequestration, Hazard Identification, Risk Assessment, Risk Zonation**

1. INTRODUCTION

Activities such as burning of fossil fuels and cement production have led to a significant increase in the CO_2 concentration in the atmosphere since the start of the industrial revolution (IPCC 2007). CO_2 being a strong and long-lived Green House Gas (GHG), its increased concentrations in the atmosphere has led to increase in the global temperature (IPCC 2007). Carbon Capture, Storage and Sequestration are now considered an important strategy to reduce the concentration of CO_2 in the atmosphere. Furthermore, the idea of injecting the captured CO_2 from industries and power plants into oceans is considered as a way to mitigate increase in atmospheric CO_2 concentrations (Israelsson et al. 2010). The injection of CO_2 into ocean is further believed to decrease the pH of the ocean by the following buffer equations (Auerbach and Caulfield 1997).

$$CO_2 + H_2O \leftrightarrow H_2CO_3, \quad H_2CO_3 \leftrightarrow H^+ + HCO_3^-,$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

About 50% of the CO_2 being emitted for two centuries has been absorbed by the oceans, leading to a surface pH drop of 0.1 (Raven et al. 2005). This drop may seem small but it implies a 30% rise in the H+ present in the surface water.Acidification of oceans is believed to pose a very dire threat to a wide range of aquatic life (Basallote et al. 2011). It has led to bleaching of corals as well as increased mortality among other aquatic species, some of which we will discuss in this paper. Acidification of the Ocean also implies reduced capacity to absorb more CO_2 from the atmosphere, which would mean increasing the atmospheric GHG concentration at a faster rate (Raven et al. 2005).

2. OBJECTIVE AND SCOPE

To determine the risk posed to species living at intermediate depths in the ocean because of injection of CO_2 into the ocean beds. As a part of this paper we will identify the routes through which the various species can be exposed to reduced pH, resulting from the anthropogenic injection activity. We will determine not the risk posed to a certain species, but the number of species getting extinct as pH decreases. For performing Risk Assessment from injection of CO_2 into sea water, we have made some assumptions. We have assumed that the injection of CO_2 is being done near the bottom surface the ocean. A liquid layer of CO_2 is being formed due to the high pressure at that layer. The bottom of the ocean, because of nearly zero sunlight and other factors is assumed to be uninhabitable, thus it is the ideal place for injecting CO_2. We have considered failures to be the leakage or bursting of the pipeline that is transferring the CO_2 from the storage tank to the bottom of the ocean. Another route of failure is the diffusion of the CO_2 liquid layer in the upward direction. Both of these will lead to reduction of pH at the intermediate depths in the ocean.

3. MATERIAL AND METHOD

For the Risk Assessment we followed the standard procedure (Haas et al. 1999). We have taken data from literature to directly link pH levels to 100% mortality for the chosen 33 species of marine life that are at risk due to pipe leakage, bursting or diffusion of CO_2 from the liquid layer formed at the bottom of the ocean.

3.1 Hazard identification

The process of sequestering CO_2 emitted from industries and power plants deep in the ocean bed involves risk to the marine life because of reduction in the pH. The successful or ideal situation would be a 100% transfer of all the CO_2 from the storage tank to the ocean bed, followed by a formation of a liquid layer under high pressure (Levine et al. 2009). This layer should not diffuse into upper regions of the oceans that are hosted by various aquatic species. But these species are at risk because of leakages or bursting of the long pipeline. Anothersignificant factor is the diffusion of CO_2 from the liquid layer formed at the bottom of the ocean. We will study the mortality of the 33 species, considered as a function of pH change for a 24 hours exposure.

Table 5: pH for 100% mortality for affected species

Species	pH for 100% Mortality	Refrences
Salmo gairdneri (rainbow trout), Embryos	4.49	(Kwain 1975)
Salmo gairdneri (rainbow trout)	4.60	(Hulsman et al. 1983)
Sander vitreus, Egg	6.00	(Hulsman et al. 1983)
Sander vitreus, Before the eyed-egg stage	5.40	(Hulsman et al. 1983)
Yolk-sac larvae	4.60	(Hulsman et al. 1983)
Yolk-stage	4.43	(Schofield 1976)
S. trutta morpha trutta	5.19	(Schofield 1976)
Salmonidae	5.25	(Schofield 1976)
Rhitrogena semicolorata (Curtis)	4.70	(McCahon and Brown 1989)
Baertis rhodani (Pictet)	4.70	(McCahon and Brown 1989)
Isoperla grammatica (Poda)	4.70	(McCahon and Brown 1989)
Bullheads (Cottus gobio)	4.70	(McCahon and Brown 1989)
Charr (salvelinus fontinalis)	4.70	(McCahon and Brown 1989)
Trout (salmo trutta)	4.70	(McCahon and Brown 1989)
Oncorhynchus mykiss (rainbow trout)	3.83	(Molony 2001)
Salmo trutta (brown trout)	3.63	(Molony 2001)

Table 6: pH for 100% mortality of affected species

Species	pH for 100% Mortality	Refrences
Crenobia alpina (Dana)	5.00	(Fjellheim and Raddum 1990)
Otomesostorna auditivurn(Pless.)	5.00	
Anodonta sp.	5.50	
Margaritana margaritifera L.	5.50	
Sphaerium spp.	5.00	
Pisidium spp.	4.70	
Lymnaea peregra (Muller)	5.50	
Planorbis spp.	5.50	
Helobdella stagnalis (L.)	5.00	
Theromyzon tessulatum (O.F. Muller)	5.50	
Glossiphonia complanata (L.)	5.50	
Haemopis sanguisuga (L.)	5.50	
Lepidurus arcticus Kroyer	5.50	
Gammarus lacustris Sars	5.50	
AseUus aquaticus (L.)	5.00	
Daphnia magna Straus	5.00	
Daphnia longispina O.F. Muller	5.00	

3.2 Risk Characterization

Based on the pH for 100% mortality for the 33 species considered, we can fit a model for comparing the pH (reduction) and the decrease in number of species that survive.

← Table 7: pH v/s mortality for 33 species considered

pH (X_i)	Species with 100% Mortality (Y_i)
3.5	33
4	31
4.5	29
5	20
5.5	10
6	1
6.5	0

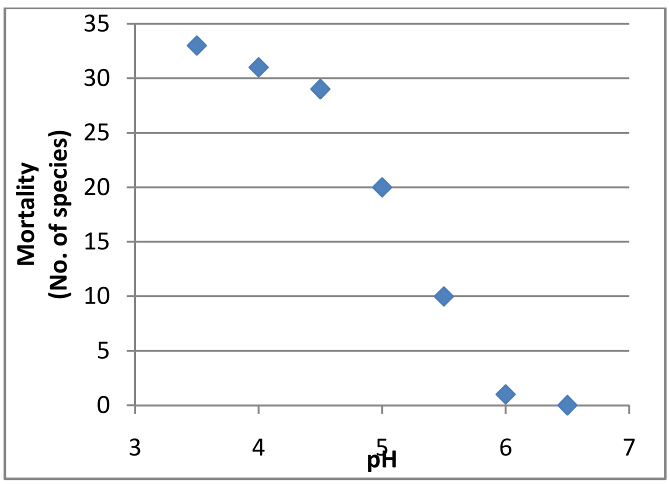


Figure 1: Plot based on mortality data for species considered

Model fitting for pH v/s mortality

Assuming that pH and number of species that have 100% mortality follow a linear model, we will find the value of slope and the intercept using linear regression. The assumption is rooted in the pattern followed by the scatter diagram based on the actual values. We have considered only the pH ranging from 3.5 to 6.5 for developing the model. $Y = MX + C$ Where, Y is the number of species that have 100% mortality at the given pH

X is the value of pH

We know that $M = \frac{\sum(X_i Y_i) - \frac{\sum(X_i)\sum(Y_i)}{n}}{(\sum X_i^2) - \frac{(\sum X_i)^2}{n}}$ $C = \frac{\sum Y_i}{n} - \frac{m(\sum X_i)}{n}$; $\Sigma X_i = 35$; $\Sigma Y_i = 124$; $\Sigma X_i Y_i = 531$; $\Sigma X_i^2 = 182$, On solving the equation, $M = \frac{531 - \frac{(35)*(124)}{7}}{(182) - \frac{(35)^2}{7}}$ = -12.71; $C = \frac{124}{7} - \frac{(-12.71)*(35)}{7}$ = 81.26 $Y = -12.71X + 81.26$

$Mortality = -12.71 pH + 81.26$ Mortality Fraction $= -0.39 pH + 2.46$

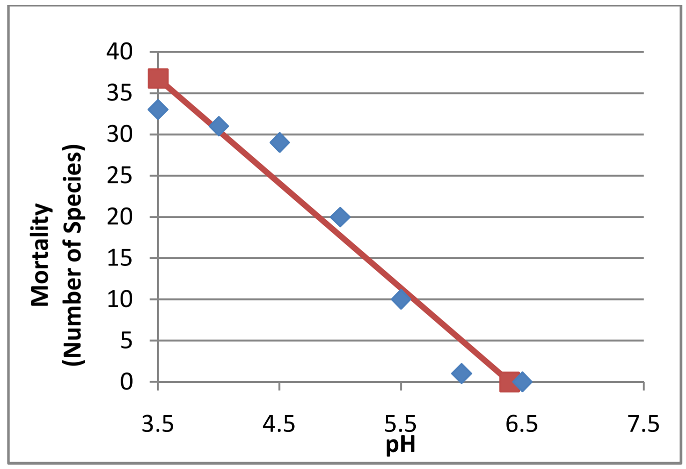


Figure 2: Linear m model for pH v/s Mortality

3.3Risk Zonation

In case of bursting of the pipeline that is carrying CO_2 from the tank to the bottom of the ocean, we have assumed the plume to be circular in shape in the horizontal plane. Based on a model generated in literature, as shown in Table 4 (Caulfield and Adams 1997) we have also assumed that the variation of pH is linear with the distance from the pipeline. In our case we have assumed that the minimum pH is 3.0 at the pipeline and increase linearly outwards. We can thus find the relation between the mortality of 33 species considered as a function of the distance from the bursting point of the pipeline.

Table 8: pH as a function of distance from point source

pH	Distance from pipeline 'r' (km)
6.4	5
6.6	10
6.8	15
7	20

Since we have assumed a linear decrease in pH in our case as well, $pH = mr + c$, From the above table we can find the slope, m = 0.04, Based on our assumption, pH at the pipeline is 3.0,

$\Rightarrow c = 3.0$

$\Rightarrow pH = 0.04r + 3.0$; 'r' is the distance from the pipeline

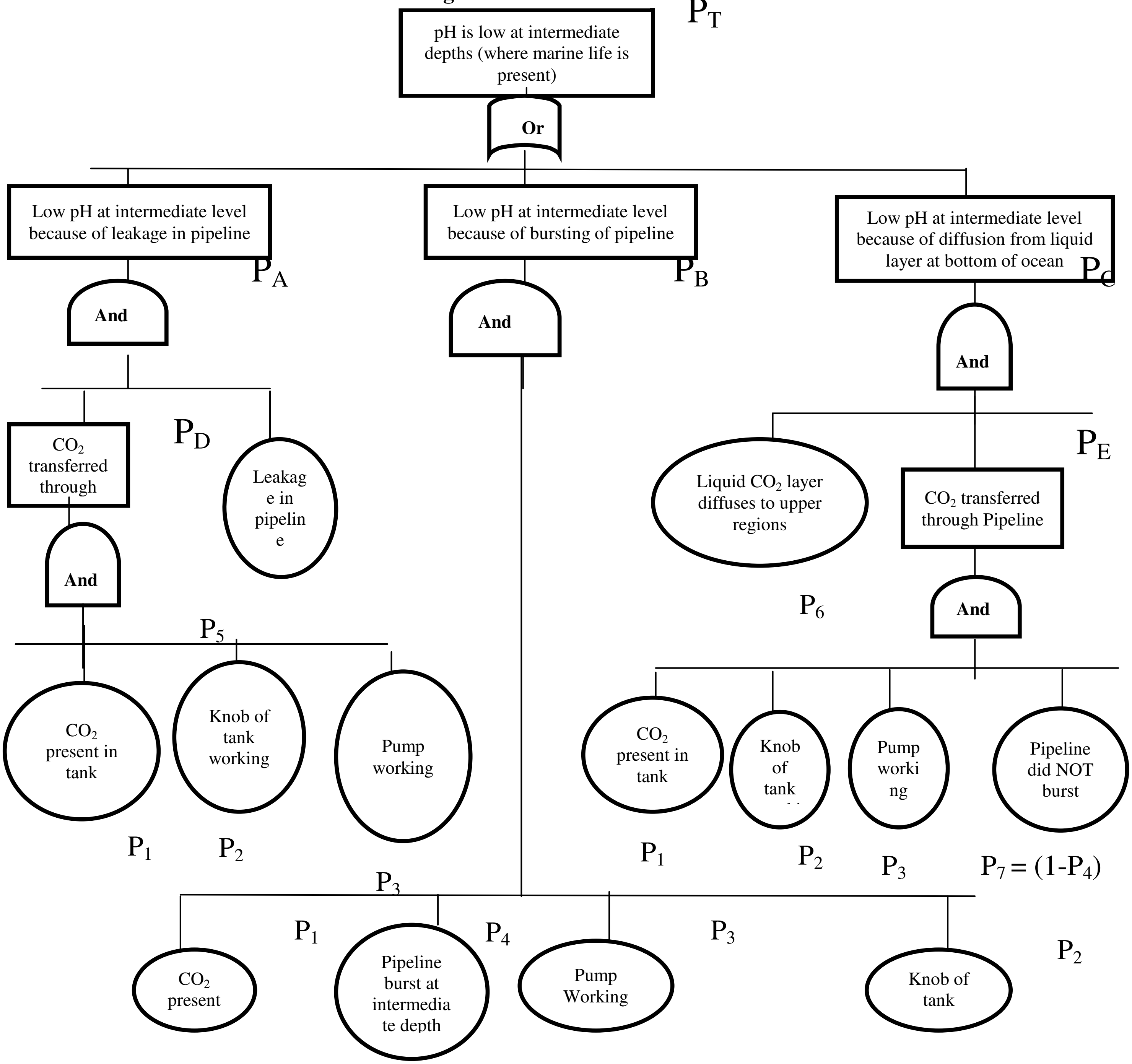
We have shown in the previous section that,

Mortality Fraction $= -0.39\,pH + 2.46$

$= -0.39 \times (0.04r + 3.0) + 2.46$, $= -0.016\,r + 1.29$

Mortality Fraction is '1' for $r = 18.13km$ Therefore, in a radius of 18.13 km all the species will have 100% mortality We can see from Figure 4 that the all the species at a radius of approximately 18km from the point of bursting in the pipeline will suffer 100% mortality. Based on the linear model that we have assumed, we can say that the effect of the bursting of pipeline can be hazardous for species living even more than 80 km away from the pipeline. This factor needs to be considered while planning any zone for injection of the pipeline. Ocean areas where less species are present in this diameter should be chosen to reduce the hazardous impacts.

Figure 3: Fault Tree



Fault Tree

$P_T = P_A + P_B + P_C$ $P_T = (P_D \times P_5) + P_B + (P_6 + P_E)$ $P_T = (P_1 \times P_2 \times P_3 \times P_5) + (P_1 \times P_2 \times P_3 \times P_4) + (P_1 \times P_2 \times P_3 \times P_6 \times P_7)$, Let $X = (P_1 \times P_2 \times P_3)$ 'Event X' implies that CO2 is present in the tank and the knob and pump are working.

$$P_T = (X \times P_5) + (X \times P_4) + (X \times P_6 \times P_7)$$

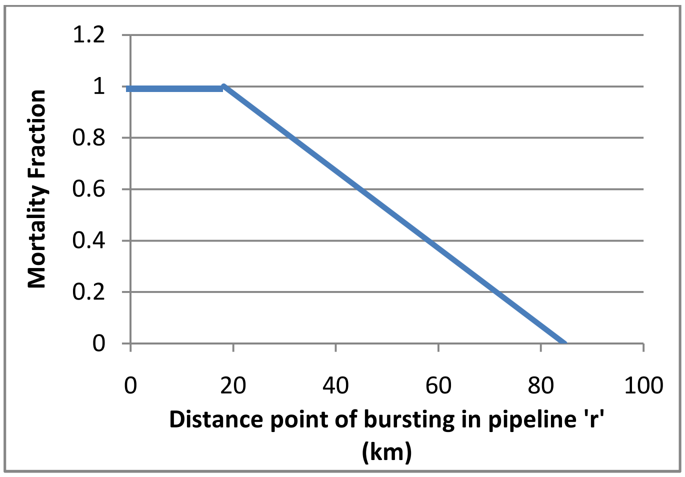


Figure 4: Mortality Fraction v/s distance from point of fault

3.4Risk Management and Communication

There is no peer review literature that deals with risk management from anthropogenic CO_2 injection. But, based on the fault tree analysis shown in this paper, it makes sense to address the bursting of pipeline as the most severe hazard for marine life living around the pipeline. Proper personnel should monitor the pressure in the pipeline at all times to ensure that events such as bursting do not occur. In case the pipeline does burst, all workers should follow a protocol to ensure minimization of impacts. Either automatic or quick manual sealing of the storage tank should take place, cutting down the supply of CO_2 to the pipeline. Leakages in pipeline may pose lesser risk for the marine life, but if it goes unnoticed the increased exposure time will increase the overall risk to the organisms living in the vicinity of the pipeline.Checks and repairs of the pipeline should take place on a routine basis to avoid such leakages and bursting. Equipment should be installed to measure the pressure at various depths in the pipeline. Aberrant readings should result in immediate investigation into the cause of pressure drop. All workers should be trained in risk minimization and disaster control.

4. RESULTS AND DISCUSSIONS

Based on data of 33 species (Table 1, 2) it was shown that the total extinction of a species from an affected area would depend on the pH linearly. The model is designed for a pH ranging from 3.5 to 6.5. As shown by Figure 2, the model deviates very less from the values based on literature review. This linear dependence would mean that the mortality fraction will decrease as we go away from the source of CO_2, that leads to reduction in the pH. Thus, It is crucial to take this impact diameter into consideration while designing a pipeline to inject CO_2 into deep ocean.Through Risk Zonation it was shown that distance from the pipeline and pH (on bursting) follows a linear relation. For 33 species that we took, the impact of bursting was found to have a mortality effect till more than 80 km away from the point of bursting and have 100% mortality upto 18.13 Km from the point of bursting of pipeline . Given that our size of sample of species is small, it can be said with confidence that in actual scenario the bursting of pipeline will have a wider impact zone. The Fault Tree Analysis suggests that routes that can impact marine life most are through leakage and bursting of pipeline and rather than diffusion from the liquid layer to upper regions. Risk management should involve vigilant monitoring of pressures, timely maintenance and skilled workers to handle the scenarios which involve failure events discussed above.

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