Estimation of Failure Probability Using Fault Tree Analysis and Fuzzy Logic for CO_2 Transmission

Ahmed Ali Baig and Risza Ruzli

***Abstract*—In this paper a methodology is presented to estimate the probability of failure of CO_2 transporting pipeline. The causes of failure are analyzed using Fault Tree Analysis (FTA) and the scope of study is emphasized on the puncture or holiday formations in pipelines due to corrosion eventually leading to leakage of CO_2. For new systems the ambiguity in data or unavailability of failure data is one of the key problems encountered. Therefore a methodology is presented in this paper that uses expert's elicitation and converts it into crisp failure data using Fuzzy Logic approach. The combination of FTA with fuzzy logic will help in artificially generating the unavailable data. The puncture scenario of some existing CO_2 pipelines is also presented in this paper.**

***Index Terms*—Corrosion, CO_2 pipeline, corrosion simulation, fuzzy set theory, fault tree analysis.**

I. Introduction

During the last decade the effect of high concentration of CO_2 in the atmosphere (emission from various sources) has been a key point of discussion for the researcher over the world and different methods and techniques are being developed to capture CO_2 and store it in geological formations to reduce the greenhouse effect. Moreover this CO_2 can also be used for the extraction of oil from wells when the internal pressure of wells is reduced, also called as Enhanced Oil Recovery (EOR) [1]–[4]. It is not necessary that the storage site is near the capture facility therefore an effective transportation is required. Usually low volume of CO_2 over a short to medium distance can be carried out by motor carriers or water carriers but in case of large volume of CO_2 that is to be transported over a medium to far distance, use of pipeline is the most cost effective method. Initially the design of CO_2 pipe lines were made on the basis of natural gas pipe line systems but with passage of time and experience it was encountered that the behavior of CO_2 is very different from natural gas.

Risk assessment is commonly used to predict the reliability of complex systems, however it is difficult to estimate the precise failure probability for a new system due to insufficient data or vague characteristics of the system. So in the absence of such historical data, rough estimates of failure probabilities are assumed as known probabilities that lead to increased error in the results. So a method is required through which these probabilities may be deduced more accurately, FTA in combination with Fuzzy logic can be used for this purpose.

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II. FTA of Pipeline

Fault Tree Analysis (FTA) is commonly used for the estimation of reliability of systems. FTA is a top down deductive analysis in which the causes of an event are deduced. It gives a visual model of how equipment failure, human error and external factors have contributed towards an accident or event. It uses logical gates and small events to present the path of an accident through different steps and hence a fault tree is constructed for the particular event. The technical failures can be represented as basic event while human errors can be represented as intermediate events that may intensify to become a technical failure. The gates used can explain different ways in which the human-machine interaction may have resulted into an accident for e.g. AND gate means that both the initial events are needed to occur in for the intermediate event to occur while OR gate means only one of the initial event may become the cause of intermediate event [5]-[10]. The failure of pipelines usually happens in the form of cracks, leakages, punctures and ruptures due to the behavior of medium and environmental conditions. To ensure the safe operation of CO_2 pipeline, FTA is developed (shown in Fig. 1) for puncture case. 32 basic events are deduces with 42 minimal cut sets (MCSs).

Generally the lesser the degree of MCSs the higher will be the frequency of its occurrence. Therefore the cut sets with lower degree will be considered more than the others. The biggest hurdle is the availability of failure value for the basic events is not easily available, for this reason fuzzy logic comes handy and the data can artificially be generated using expert's opinion along with fuzzy logic.

III. Failure Probability of Basic Events

This information collected, still does not full fill our requirement of the research or it gives a vague image to a conclusive result. In such situations when assumption of probability values produce less accurate results, a new approach is used called the Fuzzy Logic based on Fuzzy Set Theory.

Significance of using Fuzzy Set Theory: Fuzzy logic might be the most effective way when a very little quantitative information is available regarding the probabilities. It deals with imprecise scenarios like 'less/more', 'high/low', 'hot/cold' etc. rather than crisp or quantified values. Fuzzy set, here, will be used to convert this imprecise estimation of experts to a quantified number. It uses a degree if association (between 0 and 1) with the linguistic term, for example: to what degree a hot object is hot or how much less or more will be? So this qualitative

information like less, more, hot, warm, etc. can be calculated into a quantified value. In real life we use qualitative statements, which mean most of the human decisions are based on qualitative and possibility terms rather than probabilistic terms. The biggest advantage here from fuzzy logic is that it works on possibilistic terms and converts them into probabilistic values. In contrast to other approaches fuzzy logic is a simplified platform that is successful when less information is present and reduced developmental time is required to generate the output.

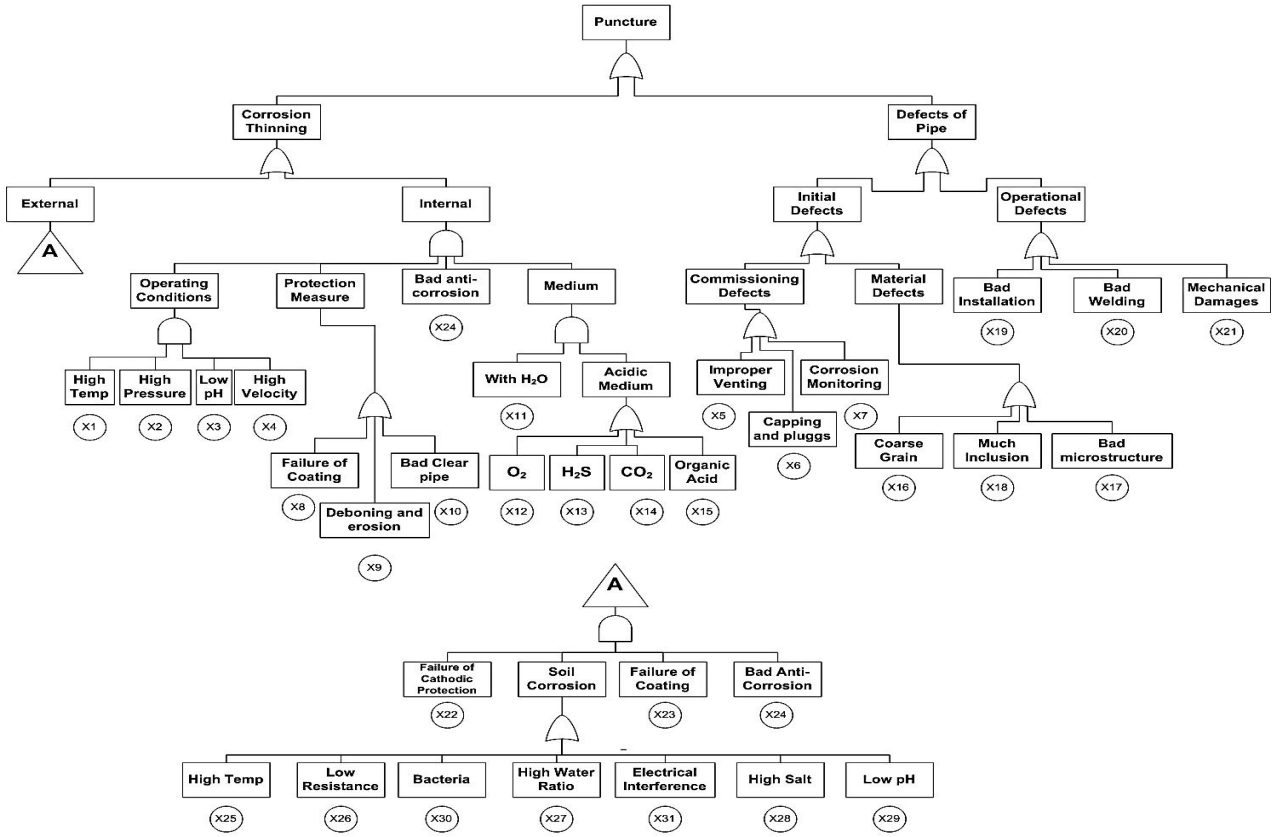

Fig. 1. FTA of pipeline

TABLE I: CORROSION SIMULATION AND RESULTS

Sr.#	Information	Cortez Pipeline	Fauji Fertilizer Co. Pvt. Ltd
1.	Location	USA, from the McElmo Dome natural source to the Wasson oil field.	Pakistan,Mirpur Mathelo, Distt. Ghotki Sindh.
2.	Dimensions	30inch diameter, 808km length	36 inch diameter
3.	Operating Conditions	Temperature:48 ℃ Pressure:135 bar Diameter:30” Velocity:0.192 m/s	Temperature:48 ℃ Pressure:0.29 bar Diameter:36” Velocity:0.367 m/s
4.	Composition	CO_2:96%(121bar) H_2S:20 ppm O_2:0 ppm HAc:0.21 ppm pH:6.5	CO_2:95% (0.27 bar) H_2:0.45% N_2:1.5 % HAc:0.68 ppm pH:6
5.	Corrosion Protection	Fusion Bonded Epoxy	none
6.	Material	Carbon Steel (API-5LX-65)	Carbon Steel
7.	Corrosion Rate	109.1 mm/yr. 100% CO_2 Corrosion	0.8mm/yr. 96.93% CO_2 Corrosion 1.06% pH Contribution 0.14% H_2O Contribution

Case studies will be made on different CO_2 based pipelines, for which the reliability data is available and then the same data will be generated using this method. For our research different experts are bought into indirect interaction regarding the discussion on the probability if an event. A defined advisory table is given to every expert and their judgment is noted to specify the final results. Since the experts cannot give a quantified value so the decisions are acquired in the form of categories for e.g. “High”, “Medium”, “Low” etc. [10]-[14]. For the purpose of acquiring a better opinion from the experts, Corrosion Simulations will be made on the case studies using “FREECORP V1.0” Corrosion simulation software (Shown in Fig. 2), specialized for CO_2 corrosion to increase the quality of expert’s judgment. Table I shows the result of corrosion simulation made on two pipelines using CO_2 medium.

The process of probability of basic event estimation using fuzzy logic is carried out in 4 steps [10]:

1) Selection of the Experts and developing the questionnaire is the 1st step to this process .Experts from different fields is selected to judge the probability of the events under assessment. Therefore an advisory table is generated to note the judgment of the experts. Then these experts are evaluated for introducing the weighting factor because every expert differs in opinion and the levels of expertise are different. The factor may include the following details(Fig. 3):

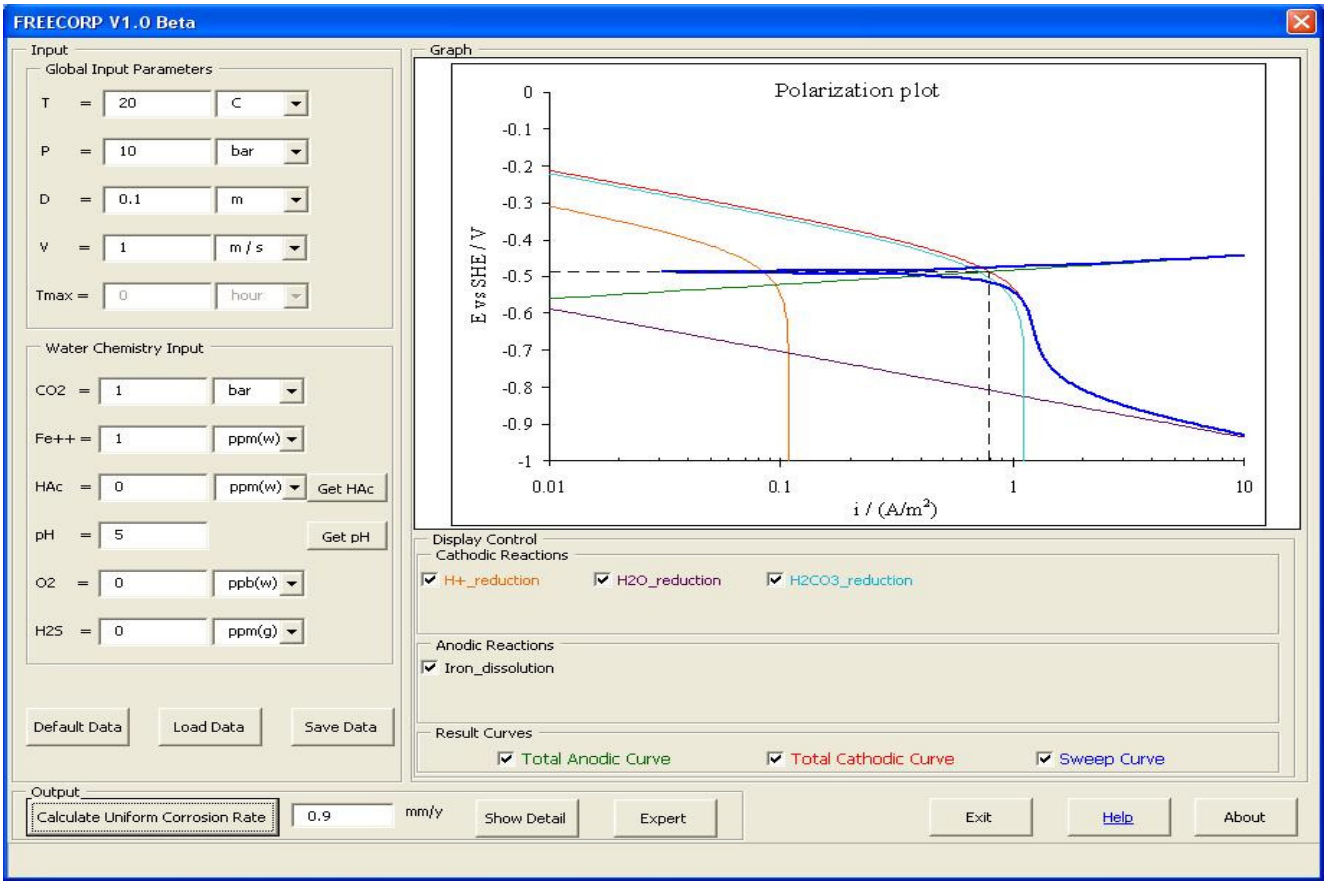

Fig. 2. FREECROP simulation sample

Fig. 3. Elements of expert's Wt. factor

Weightage score can be generated by using Table II of scores:

TABLE II: WT. FACTOR TABLE

Title/Designation	Wt.	Work Experience	Wt.	Education	Wt.	Age	Wt.
Professor /Sr. Manager	5	>30	5	Doctorial.	5	>50	5
Associate Prof./Manager	4	20-30	4	Masters	4	40-50	4
Assistant Prof./Assistant Manager	3	10-20	3	Bachelors	3	30-40	3
Lecturer/Sr. Officer	2	5-10	2	Technical college	2	25-30	2
Worker/Officer	1	>5	1	Graduate	1	<25	1

*For e.g. An MSc. Manager of age 55 with experience of 25 year will have weightage of **17**. Weightage factor* $= \frac{Wt.score\ of\ the\ expert}{\sum Wt.scoreof\ all\ experts}$

Once the scores are set then all the information gathered in the former study will be manipulated into a questionnaire paper for the experts to fill the answers that are projecting their expert opinion. This questionnaire consists of all the data on which a pipe system is running and the simulated data on corrosion that depicts the state of the pipeline. The results in terms of ambiguous terms (like high, low & medium) from this questionnaire will then be converted to form the final result of the research.

2) Conversion of these ambiguous terms into Fuzzy No's is the 2nd step. Because the experts applied linguistic terms to judge failure probability of the pipeline installation, a numerical approximation system was proposed to systematically convert linguistic terms to their corresponding fuzzy numbers [13]. Even if the number of terms allowed is same, the actual verbal terms may be slightly different. It is also worth noting that even the same term such as 'high' is used, the fuzzy numbers graphed are quite different from one

scale to another (shown in Fig. 4). This reflects the fact that the same linguistic term may possess different meanings on different occasions.

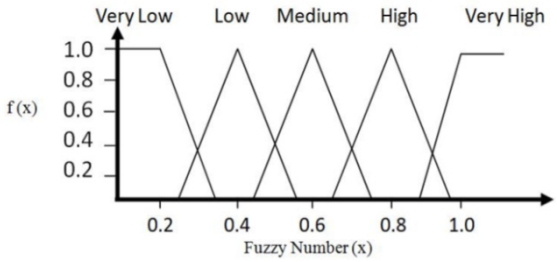

Fig. 4. Triangular fuzzy No.

Here a triangular fuzzy number can be defined by a triplet (n1, n2, n3) with a membership function f(x) and x as the fuzzy number. The membership function f(x) is defined as:

$$f(x) = \begin{cases} 0, & x < n1 \\ \dfrac{x-n1}{n2-n1}, & n1 \le x \le n2 \\ \dfrac{x-n3}{n2-n3}, & n2 \le x \le n3 \\ 1, & x > n3 \end{cases}$$

3) Converting fuzzy number into fuzzy possibility score. When fuzzy ratings are incorporated into FTA problem, the final ratings are also fuzzy numbers. In order to determine relationship among them, fuzzy number must be converted to a crisp score, named as fuzzy possibility score (FPS). FPS represents the most possibility that an expert believe occurring of a basic event. In sum, an algorithm of the multi-person multi-criteria decision making with fuzzy set approach is given in the following.

- Chose the appropriate linguistic variables for the importance weight of the criteria and the linguistic ratings for alternatives or cases with respect to criteria.
- Aggregate the weight of criteria to get the aggregated fuzzy weight of criterion, and pool the expert's opinions to get the aggregated fuzzy rating of the cases.
- Construct the fuzzy decision matrix and the normalized fuzzy decision matrix.
- Construct the weighted normalized fuzzy decision matrix.
- Determine Fuzzy Positive Ideal Solution (FPIS).
- All these steps will be carried out during the research when data collection is made and fuzzy set theory is applied to it.
- Transforming fuzzy possibility score into fuzzy failure probability (FFP). Possibility score must be transferred to fuzzy failure probability. Using the given correlation the possibility score can be converted to Fuzzy Failure Probability (FFP) [10].

$$FFP = \frac{1}{10^k} \begin{cases} FPIS \neq 0 \\ 0 \quad FPIS = 0 \end{cases}$$

where, $k = \left[\dfrac{(1-FPIS)}{FPIS} \right]^{\frac{1}{3}}$

Case studies will prove after the sensitivity analysis that to what extent this method is reliable for estimating the reliability data of new systems and what other improvements are required for this method to produce required results.

IV. Calculations

The probability of the basic events obtained from the expert opinion is given in Table III.

TABLE III: Failure Probabilities of Basic Events

Basic Events	Probability of Failure	Basic Events	Probability of Failure
X1	0.00148	X17	0.000264
X2	0.003466	X18	0.00031
X3	0.000223	X19	0.0237
X4	0.000153	X20	0.000887
X5	0.002323	X21	0.000548
X6	0.001101	X22	7.9×10^{-5}
X7	0.000125	X23	0.000704
X8	0.002739	X24	7.9×10^{-5}
X9	0.00031	X25	0.000125
X10	0.000223	X26	3.10×10^{-4}
X11	7.9×10^{-5}	X27	0.001485
X12	0.00977	X28	6.59×10^{-3}
X13	0.007045	X29	0.002323
X14	0.005	X30	7.9×10^{-5}
X15	0.02378	X31	0.00048
X16	0.000418		

The values from our results may be compared to natural gas pipeline and the analysis implies that CO_2 pipelines show more adverse effects in the presence of water, however, the mechanical aspects such as installation, welding, mechanical damages and external damages can be assumed to have same failure rates as of the natural gas. Some literature stated that above ~600ppm the corrosion rate of CO_2 increases drastically and the new surface of carbon steel react very actively to the CO_2. Water mixture results in the formation of carbonic acid that rapidly decreases the pH of the system. Expert's showed major concern with other contaminants like O_2, SO_2, and H_2S etc. also aggravate the corrosion and contribute to the failure of pipeline. Similarly the organic acids such as acetic acid and naphtanic acids that are derived in from the down hole of the CCS facility (underground confirmation or well) reduce the life of the pipe and other equipment. In comparison to natural gas pipe line, CO_2 pipeline shows higher puncture failure rate of ~3×10^{-2} year^{-1}.

Comparative Study and Discussion: In [15], a comparison of failure probabilities of pipeline at different design factors is estimated and the result shows that the failure probability lies between 1×10^{-1} to 3×10^{-2} , which means that a CO_2 transporting pipeline ranges in the class of pipelines that are most probable to failure. In 1996 an analysis was made for sour gas pipeline failure rates that showed severe results in pipeline failure rates due to internal and external corrosion [16]. A failure rate of

8.4×10^{-3} for external corrosion and $0.3\times10^{-3}$for internal corrosion was presented, these high values indicated that appropriate measure for the protection of pipeline were not in practice, however our concern is the values of failure rates that can still be compared to CO_2 transporting pipeline. The expert's opinion shows that the probability of a pipeline to fail increases slowly in early 15 to 20 year but the exponential increase occurs at the age of 20 to 25 year (as shown Fig. 5). The decision of using natural gas pipeline data for CO_2 transportation is still questionable.

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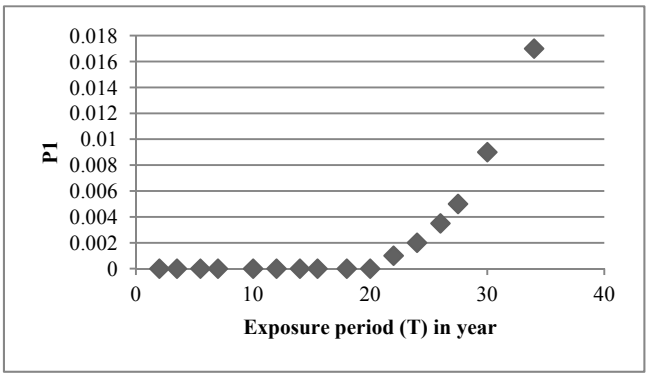

Fig. 5. Failure probability Vs age of pipeline

V. Conclusion

Different methods and techniques are used for the safety and risk assessment of complex systems. These analyses depend upon the detailed data from the past experiences. The literature review suggests that when accurate data is not available then techniques like Fuzzy logic and FTA, will give quantified results for the risk assessment. To decrease human errors a weight age factor was introduced in the methodology along with the triangular/trapezoidal fuzzy approach to calculate the probability of failure of a CO_2 pipeline. This methodology effectively describes the effect of operating conditions, pH, impurities and corrosion rate that cause drastic changes in the failure probability. The proposed method will produce reasonable result that will fulfill the present need of knowledge in this area of research. Moreover, it is seen that CCS pipeline designed on natural gas pipeline data will not perform at maximum efficiency.

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References

[1] L. Jennifer and L. Berkeley, "Natural and Industrial Analogues for Release of CO_2 from Storage Reservoirs: Identification of Features, Events, and Processes and Lessons Learned," 2006.

[2] Z. Liang, W. Shu, Z. Li, R. Shaoran, and G. Qing, "Assessment of CO_2 EOR and its geo-storage potential in mature oil reservoirs, Shengli Oilfield, China," *Petroleum Exploration and Development*, vol. 36, issue. 6, pp. 737–742, December, 2009.

[3] A. Mazzoldi, T. Hill, and J. J. Colls, "CO_2 transportation for carbon capture and storage: Sublimation of carbon dioxide from a dry ice bank," *International Journal of Greenhouse Gas Control*, vol. 2, issue 2, pp. 210–218, April 2008.

[4] R. Svensson, M. Odenberger, F. Johnsson, and L. Str, "Transportation systems for CO_2— application to carbon capture and storage," *Energy Conversion and Management,* vol. 45, issue 15-16, pp. 2343–2353, September, 2004.

[5] B. Ayyub, Risk analysis in engineering and economics. 2003.

[6] S. Arvanitogeorgos, "Risk analysis in industry", *ELINYAE*., 1999.

[7] G. L. L. Reniers, W. Dullaert, B. J. M. Ale, and K. Soudan, "The use of current risk analysis tools evaluated towards preventing external domino accidents," *Journal of Loss Prevention in the Process Industries*, vol. 18, issue 3, pp. 119–126, 2005.

[8] E. Hong, I. Lee, H. Shin, S. Nam, and J. Kong, "Quantitative risk evaluation based on event tree analysis technique: Application to the design of shield TBM," *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, vol. 24, issue 3, pp. 269–277, May 2009.

[9] *Haimen, Risk assessment, modeling and management*, 3rd ed. A John Wiley & Sons Inc. publication, 2009.

[10] D. Yuhua and Y. Datao, "Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis," *Journal of Loss Prevention in the Process Industries*, vol. 18, issue 2, pp. 83–88, March 2005.

[11] C. Carlsson, "Fuzzy multiple criteria decision making: Recent developments," *Fuzzy Sets and Systems*, vol. 78, issue 2, pp. 139–153, March, 1996.

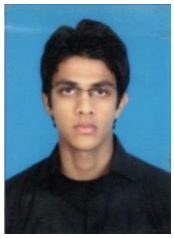
[12] A. Y. Odabas, "A new fuzzy multiple attributive group decision making methodology and its application to propulsion/ manoeuvring system selection problem," vol. 166, pp. 93–114, 2005.

[13] C. Chen, "Extensions of the TOPSIS for group decision-making under fuzzy environment," vol. 114, issue 1, pp. 1–9, August, 2000.

[14] L. A.Zadeh, *Fuzzy Set Theory as the basis for Possibility Theory*. North-Holland Publishing Co., 1978.

[15] J. Dawson, D. Jones, J. Hedger, and I. Colquhoun, "ENSURING CONSISTENT FACTORS OF SAFETY IN THE ASSESSMENT OF CORRODING PIPELINES," Corrosion 2002, Document ID. 02074, pp. 1–20, 2002.

[16] G. P. Systems, "Identification and Quantification of Failure Rates to Effectively Manage Sour Gas Production System," in *Proc. SPE Health, Safety and Environment in Oil and Gas Exploration and Production Conference*, pp. 177–183, 1996.



Ahmed Ali Baig was born in Kuwait on December 1, 1988. From the very beginning, Mr. Baig has been inspired by intellectuals and their accomplishments with respect to the welfare of the society and his dream to become of such intellectual, in order to do so, he completed his schooling from one of the highly reputable schools. His interest in engineering made him to select the pre-engineering course for his college and this decision directed his potential to become a Chemical & Process Engineer. In January 2012, with majors in Polymers and Petrochemical studies from NED University of Engineering and Technology Karachi, Pakistan, he was awarded the degree of Bachelors of Engineering.

Soon after his graduation and within no time his potential was recognized by one of the leading tyre industry named as "General Tyre and Rubber Co." Karachi, Pakistan. On April 22, 2012 he served his first day as Trainee Production Engineer (MTO, Management Trainee Officer). His thirst for knowledge made him accept the opportunity to work as a Research Scholar and pursue his Masters Degree in Chemical Engineering at Universiti Teknologi PETRONAS, Malaysia, where he is currently conducting his research in the field of Industrial safety.

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