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ABSTRACT

Corrosion under insulation (CUI) is found to be a major problem for insulated piping systems in refineries, petrochemical and gas processing plants. Since those pipes carry hydrocarbons or other dangerous process fluids, gradual thinning due to CUI may cause the pipes to leak, leading to a hazardous situation. Due to the nature of CUI which is hidden, the challenge is in the monitoring, detection and, hence, prediction of CUI. Also, due to scarcity of data, the current CUI inspection and maintenance strategy adopts the risk-based inspection (RBI) approach where the assessment of the probability of failure for CUI adopts either the qualitative or semi-quantitative methods. These approaches were highly subjective and to overcome this drawback, the quantitative approach is usually employed where this approach bases the failure probability estimates on historical failure data.

This study presents a methodology for quantitatively estimating the probability of failure of piping systems subject to CUI based on the type of data available. In the absence of failure data and wall thickness data, logistic regression model was proposed by considering the inspection data as a binary data. When the wall thickness data is available, the probabilistic models, namely degradation analysis, structural reliability analysis and Markov chain model, were proposed.

The study recommended that for the case where wall thickness data is minimal, a good model that can be used for quantitative risk assessment is the structural reliability analysis. If more wall thickness data is available, degradation analysis and Markov chain model are the potential models. This study also demonstrated that the logistic regression model is not applicable for quantitative risk assessment. In summary, the quantitative approach is necessary as a means for quantitatively establishing future reliability for piping systems subject to CUI. Even though applying the quantitative method is optional in the current RBI analysis, quantitative risk assessment is, in fact, now a required element of the maintenance optimization methodology.

ABSTRAK

Kakisan di bawah penebatan (CUI) didapati menjadi satu masalah utama untuk sistem-sistem perpaipan tertebat di kilang penapis, kilang petrokimia dan pemprosesan gas. Oleh kerana paip-paip itu menyalirkan hidrokarbon atau cecair-cecair proses berbahaya, pengurangan ketebalan paip secara beransur-ansur yang disebabkan oleh CUI boleh menyebabkan paip-paip untuk bocor, seterusnya membawa kepada satu keadaan berbahaya. Disebabkan sifat CUI yang tersembunyi, cabaran telah dihadapi untuk mengawas, mengesan dan meramal CUI. Dan juga disebabkan oleh kekurangan data, kaedah pemeriksaan CUI dan strategi penyelenggaraan telah mengikut kaedeh pemeriksaan berasaskan risiko (RBI) di mana penilaian kebarangkalian kegagalan disebabkan oleh CUI mengambil salah satu kaedah-kaedah kualitatif atau separa kuantitatif. Pendekatan-pendekatan ini amat subjektif dan untuk mengatasi kelemahan ini, pendekatan kuantitatif biasanya diambil di mana pendekatan ini berdasarkan anggaran kebarangkalian kegagalan menggunakan sejarah data kegagalan.

Kajian ini membentangkan satu kaedah secara kuantitatif untuk menganggarkan kebarangkalian kegagalan sistem-sistem perpaipan tertakluk kepada CUI berdasarkan jenis data yang boleh didapati. Tanpa data kegagalan dan data ketebalan dinding paip, model regresi logistik adalah dicadangkan dengan mempertimbangkan data pemeriksaan sebagai data perduaan atau data ‘binary’. Bila data ketebalan dinding tersedia ada, model-model kebarangkalian, iaitu analisis degradasi, analisis kebolehpercayaan struktur dan model Markov, telah dicadangkan.

Kajian mencadangkan untuk kes di mana data ketebalan dinding adalah minimum, model yang baik yang boleh digunakan untuk penilaian risiko kuantitatif ialah analisis kebolehpercayaan struktur. Jika lebih banyak data ketebalan dinding tersedia ada, analisis degradasi dan model Markov adalah model-model potensi. Kajian ini juga mendemonstrasikan yang model regresi logistik tidak boleh digunakan

untuk penilaian risiko kuantitatif. Rumusannya, pendekatan kuantitatif adalah perlu sebagai satu cara untuk meramal secara kuantitatif kebolehpercayaan di masa akan datang untuk sistem-sistem perpaipan tertakluk kepada CUI. Walaupun kaedah kuantitatif dalam analisis RBI adalah sebagai salah satu pilihan yang ada, penilaian risiko kuantitatif kini adalah satu kaedah yang dikehendaki untuk pengoptimuman penyelenggaraan.

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
CUI	Corrosion under insulation
COV	Coefficient of variation
FE	Equipment modification factor
FM	Management systems evaluation factor
FORM	First-order reliability method
FOSM	First order second moment
iid	Independent and identically distributed
ISGSS	Intergranular stress corrosion cracking
LOCA	Loss of coolant accident
LSF	Limit state function
MCS	Monte Carlo simulation
MLE	Maximum likelihood estimation
MTBF	Mean time between failures
NDE	Non-destructive examination
NDT	Non-destructive testing
PFM	Probabilistic fracture mechanics
PRAISE	Piping Reliability Analysis including Seismic Events
PSQUIRT	Probabilistic Seepage Quantification of Upsets in Reactor Tubes
RBI	Risk-based inspection
TML	Thickness measurement location

NOMENCLATURES

General Notation

$\mathrm{t}_{\mathrm{actual}}$	Actual pipe thickness measured at the time of inspection for a given location (in mm)
$\mathrm{t}_{\mathrm{required}}$	Required pipe thickness at the same location as $\mathrm{t}_{\mathrm{actual}}$ computed by the design formulas before corrosion allowance and manufacturer's tolerances are added (in mm)
$\mathrm{t}_{\mathrm{initial}}$	Initial pipe thickness at the same location as $\mathrm{t}_{\mathrm{actual}}$ measured at initial installation or at the commencement of new corrosion rate environment (in mm)
$\mathrm{t}_{\mathrm{previous}}$	Pipe thickness at the same location as $\mathrm{t}_{\mathrm{actual}}$ measured during one or more previous inspections (in mm)
$\mathrm{t}_{\mathrm{nominal}}$	Nominal pipe thickness (in mm)

Symbols for Logistic Regression Model

Y	Binary response (either 0 or 1)
$f(z)$	Logistic function
z	Linear sum of the independent variables
n	Number of independent variables
$x_1, x_2, \ldots x_n$	Independent variables of interest
$\beta_0, \beta_1, \ldots \beta_n$	Coefficient for each independent variable

Symbols for Degradation Analysis

t	Time
$d(t)$	Pipe wall thickness at time t
a	Corrosion rate (in mm/yr)
b	Pipe nominal thickness (in mm)
$f(t)$	Probability density function
$F(t)$	Cumulative density function

Symbols for Structural Reliability Analysis

$g(x)$	Limit-state function or a failure function
x_n	Basic random variables
n	Number of random variables
R	Resistance

S	Load
$f_R(\sigma)$	Probability density function of resistance R
$f_S(\sigma)$	Probability density function of load S
$f_n(x_n)$	Probability densities of the basic variables x_n
$f_{RS}(r, s)$	Joint probability density function of $f_R(r)$ and $f_S(s)$
p_f	Probability of failure
F	Failure domain
μ	Mean
σ^2	Variance
N_H	Total number of trials where failure has occurred in MCS
N	Total number of trials conducted in MCS
β	Reliability index
$\Phi(.)$	Cumulative distribution function of a variable
S	Material strength (in MPa)
P	Operating pressure (in MPa)
D	Outer diameter of the pipe (in mm)
t	Pipe wall thickness (in mm)
T	Number of years in service (in years)
$d(T)$	Depth of corrosion in at time T (in mm)
l	Axial length of corrosion defect (in mm)
CR	Corrosion rate (in mm/yr)

Symbols for Continuous-time Markov Model

ϕ	Occurrence rate of flaw
λ	Occurrence rate of a leak from a flaw state
ω	Inspection and repair rate of a flaw state