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RISK ASSESSMENT FOR VESSELS AFFECTED BY CORROSION

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Abstract

The widely used engineering decisions concerning the performance of technological equipment for process industries are usually deterministic. Since the early 1990s probabilistic methods and risk assessment are now well established tools for assessing the behavior of many chemicals or processing installations. The paper presents a probabilistic approximation procedure for the risk assessment, suitable for technological equipment. It is reported like a risk of failure for a tank vessel type during its serviceable life, associated with structure's strength and corrosion defects. Simulation technique of a performance function, named the limit state function (LSF), which includes the main operating and dimensional parameters of the structure, was preferred. It was conducted according to the direct simulation method named *Latin Hypercube Sampling* (LHS) and a well-known reliability method, the FORM/SORM method (First Order Reliability Method/Second Order Reliability Method). For the first, a professional analysis package *Crystal Ball 2000-free trial version* was used to perform the simulation. For the second, one's self developed procedure built on the principle of the FORM, named *cyclic recursive method for risk assessment*, implemented in *MATLAB* package was used to perform the simulation. The limit state function is carried out using several already published failure models. The corrosion decay model and corrosion rate is done based on experimental values. The uncertainty and variability of the variables and parameters on which the model depends are evaluated by a sensitivity analysis. Finally, the study estimates the risk of damage as the failure probabilities for a number of different scenarios.

Keywords: thin walled pressure vessels, probability of failure, limit state function, corrosion rates, Latin Hypercube Sampling, FORM.

1. Introduction

The behavior of technological equipment for process industries, particularly of thin walled pressure vessels (*TWPV*), under operating conditions are always affected by variations and uncertainties: fluctuations and variations in service loading, scatters in material properties and manufacturing process, uncertainties regarding the analytical models, continuous chemical degradation and so on. The widely used engineering decisions concerning the performance of technological equipment for process industries are usually deterministic. These deterministic models provide a difficulty in handling variations and uncertainties in service conditions, or regarding the continuous degradation of these structures. On the other hand these deterministic approaches are made in the presence of many uncertainties and variability concerning the main variables. Probabilistic methods and risk assessment are now a well-established tools for assessing the behavior of many chemical or processing installations. Since the early 1990s, probabilistic and quantified risk assessment is routinely applied to designs in many areas. The most common definitions for 'risk' are [7, 20]:

- a combination of the likelihood and the consequences of a future event;
- the failure probabilities for a number of different scenarios;
- the product between the probability of occurrence and the quantified consequence of a future event: Risk $=$ function$(p_f \times \text{Consequences}) \approx p_f \times$ Consequences;

The aim of this paper is to present a procedure for risk assessment, based on the second definition, suitable for chemical engineers in the stage of a preliminary risk analysis, to avoid major technological incidents. It is reported like a risk of failure for a tank vessel type during its serviceable life, associated with structure's strength and corrosion defects.

The real load carrying capacity and hence the risk or the level of safety of these structures diminish with time and become uncertain due especially to the accumulation of corrosion decay. In order to maintain an acceptable level of safety for *TWPV* it is necessary to determine the variation of strength with time. The thickness losses and the diminishing of real strength section were assumed as the dominant influences. The rate of corrosion may be non-uniform or difficult to predict. Usually, according to design standards [9, 17, 19] a constant preventive value of corrosion damaged material is taken into account at the design stage. Often these values are too general and may have a high degree of uncertainty.

Structural reliability analyses of structures are among the main methods to minimize the cost of maintenance and to avoid technological incidents. Briefly, the reliability of an engineering system can be defined as its ability to fulfill its design purpose for a time period. The reliability of a structure can be viewed as the probability of its satisfactory performance under specific service conditions within a time period. There are two major categories of methods used to estimate the probability of failure: *analytical techniques* and *random sampling* methods. Structural reliability analysis can be used for the prediction of the probability of failure for any technological equipment at any time during the service life. These analyses correspond to an equivalent reliability index. According to previous statements and several already published papers [4], [6], [11]–[14], three major models for the failure probabilities may be mentioned: one based on deterministic methods which leads to the prediction of the remaining strength: another based on the estimation of the remaining life and the last based on the probability of failure, or the risk assessment reported to the original structure. In this paper the assessment for only the analytical techniques and random sampling methods do the probability of failure. For simplicity, in these papers and in many others, separate possible modes of failure were considered.

Simulation technique of a performance function structure named the limit states function (LSF) was preferred. This *LSF* represents the total performance of the structure and includes the main operating and dimensional parameters of the pressure vessel. Variations and uncertainties in service loading, scatters in material properties, analytical models, chemical degradation generally fall into one of two categories: probabilistic or possibilistic. Probabilistic techniques are characterized by the use of random variables to describe the various sources of uncertainty and are often referred to as reliability methods by structural engineers. This involves the formulation of a limit state function (*LSF*), in terms of a number of basic random variables. This assessment is reported to the structure of the *TWPV* and is based on a deteriorating active corrosion decay, suitable for chemical engineers.

Simulations were conducted according to the direct simulation method named *Latin Hypercube Sampling* (LHS) and a well-known reliability method, the FORM/SORM method (First Order Reliability Method/Second Order Reliability Method). For the former, a professional analysis package the *Crystal Ball 2000-free trial version* was used to perform the simulation. For the latter one's self developed procedure, built on the principle of the FORM, named c*yclic recursive method for risk assessment* implemented in *MATLAB* package was used to perform the simulation. The limit state function is carried out using several published failure models. The corrosion decay model and corrosion rate is done based on experimental values. The uncertainty and variability of the variables and parameters associated with corrosion defects, on which the model depends, are evaluated by a sensitivity analysis. The main stages of this approach are:

- establishing the corrosion decay model reported to an active experimental corrosion test;
- establishing the *TWPV* failure function;
- establishing the probability of failure based on the *LSF*.

A lot of parameters which define both the imposed technological loads or the strength of structure, such as material properties, rate of corrosion, operating pressure, real strength section, etc. may vary in a large domain. The model and the *LSF* proposed contain some idealizations and assumptions, which can introduce additional uncertainties. A sensitive analysis of variance reduction of the *LSF* to the basic dependent variables was performed. It is necessary to identify the most important variables in failure analysis, so the model could be improved by focusing on the most critical parameters. To check the model, the decrease in safety and the increase of risk a *TWPV* will be studied considering probabilistical distributions for all the loading and strength parameters. Finally, the study estimates the risk of damage as the failure probabilities for a number of different scenarios. This type of analysis is recommended for chemical engineers to work out optimal inspection and maintenance schedules.

2. Theoretical Approach

2.1. *General Statements for the Probability of Failure*

2.1.1. *Latin Hypercube Sampling (LHS)*

Latin hypercube sampling is a stratified sampling scheme, along the entire domain of random variables, designed to ensure that the upper or lower ends of the distributions used in the analysis are well represented. The direct *simulation* m*ethods* are techniques of approximating the output of a model through repetitive random application of a model's algorithm. In the context of the *cumulative distribution function* of a real-valued random variable X the output of the model may be generally defined as $P(x) = \text{Prob}\,\{X \leq x\}$.

The corresponding notion for a multidimensional random vector $(X_1, X_2, \ldots, X_n)$ is the *joint cumulative distribution function* $P(x_1, x_2, \ldots, x_n) = \text{Prob}\,\{X_i \leq x_i \rightarrow \text{ for } \cdots \text{ all } \cdots i = 1 \ldots n\}$.

Considering the *joint density function* we have the relationship:

$$\text{Prob}\,\{x \in D\} = \int_D f\,(x_1, x_2, \ldots, x_n) \cdot \mathrm{d}x_1 \cdot \mathrm{d}x_2 \cdots \mathrm{d}x_n, \tag{1}$$

where $D \subset R^n$ for any Lebesgue measurable subset.

In the context of previous statements the performance function can be expressed in terms of basic random variables Xi for relevant loads, operating conditions and structural strength. Mathematically, the performance function Z can be described as

$$Z = Z(X_1, X_2, \ldots, X_n), \tag{2}$$

where Z is called the limit state function (LSF) of interest. The unsatisfactory performance limit state of interest can be defined as $Z \leq 1$. Accordingly, with $Z < 1$, the structure is in the unsatisfactory performance state and when $Z > 1 \approx D$ it is in the safe state. If the joint probability density function for the basic random variables Xi 's is $f_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots, x_n)$ then the unsatisfactory performance probability P_U of a structure can be given by the integral:

$$P_u = \iint_D \cdots \iint f_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots, x_n) \cdot \mathrm{d}x_{x_1} \cdot \mathrm{d}x_2 \cdots \mathrm{d}x_n, \tag{3}$$

where the integration is performed over the domain D in which $Z > 1 \approx D$. In general, the joint probability density function is unknown and the integral is a difficult and cumbersome task.

Due to the difficulties in solving this integral (3) for practical purposes alternate methods of evaluating P_U are required. One of these methods is the direct simulation method named *Latin Hypercube Sampling* (LHS). This simple and intuitive method consists in calculating (2) for a great number of combinations of

X_i. The combinations, called ‘trials’, are randomly sampled from the probability distribution of each X_i, by means of the standard random-generator functions implemented on any modern computer.

The probability P_U according to the performance function of (2) is provided by the integral of (3). Smaller unsatisfactory-performance probabilities require larger numbers of simulation cycles. Assuming N_U to be the number of simulation cycles for which $Z < 0$ in total N simulation cycles, unsatisfactory performance probability P_U of a structure given by the integral (2) can be expressed as:

$$P_U = N/N_U. \tag{4}$$

2.1.2. *Cyclic Recursive FORM Concept*

It is an alternative method built on the principle of the First Order Reliability Method (FORM). Based on its principle this cyclic recursive algorithm belongs to the *Most Probable Point* (*MPP*) methods. The starting point is the establishment of a performance function, which gives the relation between the chosen performance and the inputs of the model. This function ($LSF = G$), may be explicit or implicit. The *limit state function* depends on a set of governing parameters, which includes a vector of random variables, **x**. The random variables may represent inherent randomness, parameter uncertainty, or a combination of both.

Assume ‘n’ as the number of the system input variables, random variables ‘x_i’ in the *LSF* and a formal expression for this limit state function in real *Euclidean* R^n space is:

$$LSF = g_j(x_i) : R^n \to R \ (i = 1, 2, \ldots, n;\ \ j = 1, 2, \ldots, m,\ \text{and } m < n). \tag{5}$$

The failure surface [10, 16] or the limit state (a set defined by the locus of points $G(x)$) is defined as $G(x) = g_0$ or simply $G(x) = 0$. This is the boundary between the safe and failure regions in the random variables space: a region Ω, where combinations of system parameters lead to an unacceptable or unsafe system response and a safe region Ω where system response is acceptable. When $G(x) > 0$, the system is considered safe and when $G(x) < 0$, the system can no longer fulfill the function for which it was designed.

Only for simplicity, *Fig. 1* shows the elementary concepts for a particular state, a two dimensional problem. The use of the terms ‘failure’ is also customary, since only the likelihood of a particular system state may be of interest rather than system failure. The probability of system failure p_f is defined as the probability of the event that the system can no longer fulfill its function and is given by the expression:

$$p_f = P\{G(x) < 0\} \tag{6}$$

generally calculated by the integral

$$p_f = \iint_{G(x)<0} \ldots \int f(x)\,\mathrm{d}x, \tag{7}$$

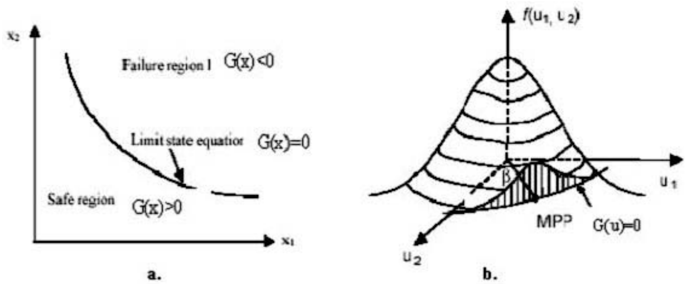

Fig. 1.

where $f(x)$ is the joint probability density function (*PDF*) of x and the probability is evaluated by the multidimensional integrals over the failure region $G(x) < 0$.

HASOFER and LIND had proposed the concept of the *Most Probable Point* (*MPP*) to approximate the integration (7). This point referred as the *most probable point* (MPP) is the point on the limit state that lies closest to the origin. There is a direct relationship between this point or the safety index β and the probability of failure:

$$p_f = \Phi(-\beta). \tag{8}$$

When it is used in the context of $p_f = \Phi(-\beta)$ it is assumed that $\beta > 0$. In general, this relationship (8) is only approximate, but in the unique case of a linear combination of Gaussian (i.e., with a Gaussian probability distribution that has zero mean and unit variance) distributed random variables, where $\Phi(\ldots)$ is the cumulative normal density function, the relationship is exact. Each random variable must be transformed into a standard normal Gaussian random variable. The mapping matches the physical value of vector **x**, for each random variable, with a standard normal vector variable, **u**, by matching probability levels of the cumulative distribution function. The result is the transformation of calculating the probability of failure into standard-normal space (*u-space*). The new limit function in the standardized normal space $u_i = \{u_1, \ldots, u_n\}$, in terms of reduced variables, is given by the expression:

$$LSF = g_j(u_i) : R^n \to R \ (i = 1, 2, \ldots, n;\ \ j = 1, 2, \ldots, m, \text{ and } m < n). \tag{9}$$

The point on the limit state that lies closest to the origin, $u^* = (u_1^*, u_2^*, \ldots, u_n^*)$ referred as *MPP* must be evaluated. In general the minimum distance from the point u^* to the limit state $g_j(u_i) = 0$ is a straightforward nonlinear constrained optimization problem:

$$\text{Minimize: } d = \left[\sum_1^n u_i^*\right]^{0.5} = (u^{*T} u^*)^{0.5}$$

$$\text{Subject to: } g_j(u_i) = 0. \tag{10}$$

The reduced variables corresponding to the *MPP* can be found in a number various of ways following approaches involving iterative, vectorial or gradient solutions [10, 15, 16]. Generally, for an ‘*n*’ dimensional problem, the *n* random variables form an *n*-space of all possible combinations of values. A feature of the *MPP* method is that it provides a built-in sensitivity analysis. Sensitivity measures, when used in the context of the analytical methods, are often referred to as *importance factors*. The magnitudes of these factors characterize the impact of each of the random variables on the safety index and thereby, their impact on the probability of failure. This feature has been used to quantify the influence on the calculated risk of uncertainties in the input quantities, for each of the consequence models. Based on some previous related works [10, 13] the unimportant quantities can be screened out, allowing the importance of the remainder to be quantified by means of progressively more accurate methods. The proposed *cyclic recursive FORM* method [3], works on the base of the dual Lagrangean operator in the standard normal reduced space and with a successive distance approach. It is applied to find the minimum distance to the limit state $g_j(u_i) = 0$. The main stages of this *cyclic recursive algorithm* are:

- the first step is a random sampling procedure in agreement with the original distribution of all the input variables;
- perform a sensitivity analysis to establish dominant ‘*k*’ variables;
- transform the problem of *MPP* searching into one dual Lagrangean problem;
- check the concordance between the probability of failure and the probabilistic sensitivity.

Obviously these *MPP* points must to belong to the domain of random sampling points and to satisfy the system of *Eqs.* (10). This cyclic algorithm will be stopped when no significant changes in concordance between the probability of failure and the probabilistic sensitivity will be realized.

2.2. General Assumptions

To avoid some cumbersome approaches unnecessary for the purpose of this paper only general design standard limitations [9, 17] are utilized. For simplicity the following idealizations and assumptions were considered:

- basic variables: material properties, constructive dimensions, rate of corrosion, wall thickness, service life, etc. are assumed to be random variables;
- at any stage the loads acting on components are assumed to be stationary and ergodic;
- any estimator is statistic, hence any estimated parameter is a random variable;
- the random variables were assumed to be statistically independent – just for simplicity.

2.3. *Corrosion Decay Model*

Corrosion decay model is reported to be based on experimental corrosion rate. The rate of corrosion in a specific technological environment has been obtained using experimental tests of samples, based on the detailed measurements of surface and the weight lost. Simplifying the stochastic corrosion conditions we assume it to be stationary [1, 5]. From a statistical characterization the parameters of distribution for corrosion rate were obtained. To avoid technological incidents in the stage of a preliminary design analysis, chemical engineers are much interested to know what threats occur and what are the results, the locations and the details. Therefore, according to several published papers [1, 5, 11], the rate of penetration corresponding to a uniform and local continuous corrosionis defined for simplicity by the following expression:

$$V_C = 8760 \times \left(\frac{\Delta G}{A \times T_C}\right) \times (1/\rho);\ \text{[mm / year]}, \tag{11}$$

where ΔD is the lost weight [g], A is the sample surface [m^2], T_C is the exposure time [hours], ρ is the sample density [kg/m^3]. The rate of penetration, V_C, or the thickness loss parameter is considered as random variables, usually normally distributed [1, 2, 5]. Accordingly, this change in depth, the thickness of corroded wall may be considered also like a normally distributed random variable. Based on previous presumptions and other related papers [1, 4, 9, 19] a linear growth with time is considered for the defect size and implicitly for the local thickness loss parameter. The real thickness of the *WTPV*'s wall may be done by the expression:

$$s_e = s_O - V_C \times T_U; [mm] \tag{12}$$

where s_0 is the initial sample thickness, T_U is the service life.

2.4. *Failure Model*

Failure pressure model is reported to an unflawed cylindrical vessel subjected to inner pressure. Two main failure criteria are recognized: failure due to yielding and failure due to fracture when an existing crack extends. For simplicity and according to general design standards in this study only the first failure criteria was considered. The design of a *TWPV* subjected to internal pressure requires two modes of failure: one when the deformations become excessive and the second when a higher pressure occurs. The second mode of failure takes the form of bursting the vessel and it is much more adequate to technological circumstances of running processes in industries. The critical load model used in this paper is derived from a deterministic model. Based on general design standards [9, 17, 19], after some minor developments, the current effective vessel's stress at operating conditions is written as:

$$\sigma_e = p_e \times (D_e + (s_0 - V_C \times T_U))/(2\varphi \times (s_0 - V_C \times T_U));\ \text{[MPa]}, \tag{13}$$

where D_e is the outer nominal diameter of cylindrical vessel, p_e is the operating pressure, 2φ is the welding conditions factor. According to the idea of global probabilistical model of failure, initial sample thickness s_0, was replaced with the real thickness of the *TWPV*'s wall expression (12).

2.5. Limit State Function (LSF)

The limit state function is defined as the difference between the *TWPV's* admissible strength of material at operating conditions and the *TWPV's* failure effective stress:

$$LSF = \sigma^t_{\text{am}} - \sigma_e. \tag{14}$$

The *TWPV*'s admissible strength of material at operating conditions was defined as threshold values for the pressure vessel failure probability. Risk assessment, including the failure of *TWPV*, is judged on the basis of limit state function. On the basis of limit state function two clear stages may be defined. One is defined by $LSF > 0$ for safe working and the other is defined by $LSF \leq 0$ for possible failure. A general form of the *LSF* based on previous expressions (11)-(14), a function of random variables, suitable for probabilistic analyses are:

$$LSF(P_{\text{cro}}, P_e, T) = LSF(P_e, D_e, s_0, V_C, T_U, 2\varphi, \sigma^t_{\text{am}}). \tag{15}$$

In spite of some correlation, which can be expected between variables, according to general assumptions these random variables were assumed to be statistically independent just for simplicity.

3. Numerical Approaches

The numerical analysis was carried out for a pressure vessel working a technological process of aliphatic organic acid in the stage of catalysis of propionic acid synthesis. The main parameters of the pressure vessel and the operating technological conditions are shown in *Table 1*.

3.1. Corrosion Test

The rate of corrosion in one specific technological environment has been obtained using experimental test data based on the detailed measurements of the surface and the weight loss of the samples (*Table 2*). The samples were introduced with a total immersion in the catalysis reactor, under processing conditions. Using deterministic/statistic methods, according to some previous papers [1, 2, 19] the rate of corrosion, V_C, expressed by the penetration index is emphasized. The standard statistical characterization of these values (*Table3*) allows us to assume a normal distribution for the rate of penetration, V_C.

Table 1. Working conditions and main sizes of pressure vessel

Parameter	Values	Mentions	Statistic/Probabilistic distribution of parameters
Outer nominal diameter D_e [mm]	1424	Reported to cylindrical area	LogNormal distribution
Design thickness s_0 [mm]	12	Initial thickness	LogNormal distribution
Admissible stress σ^t_{am} [MPa]	105	Stainless steel X10CrTi18.9 W1.4541 with yield stress ≈200 Mpa	Critical value
Operating temperature T[°C]	240	Maximum value	Normal distribution
Operating pressure P_e [MPa]	1.2	Maximum value	Normal distribution
Corrosion exposure time T_C [hours]	240	According [1,2]	Fixed value
Synthesis exposure time T_R [hours]	200–300	Average value	Weibull distribution
T_U – service life		Average value	LogNormal distribution
Technological mixture	(CH_3-CH_2-COOH); (C_2H_5I); $(CH_3-CH_2-COO-CH_2-CH_3)$		
All these parameters represent the average or extreme mean values.			

3.2. *Uncertainties of Parameters*

An experimental statistic characterization of all the parameters on which the limit state function (*LSF*) depend is not available. These parameters were set according to values known in practice or to values reported in literature [8, 9]. For this study some of these parameters, s_0, De, T_u, $K_S = 2\varphi$, are assumed to be lognormally distributed. According to the experimental corrosion test the real current thickness $s_e = s_O - V_C \times T_U \ldots$ [mm] may be assumed to be also normally distributed. The parameters of the model, include both variability and uncertainty, thus they can determine major changes in the probability of failure. The model and the system vector *LSF* $(P_e, D_e, s_0, V_C, T_U, 2\varphi)$ are simulated in lots of probabilistic assessments. Major concern focuses on the question of whether uncertainty and variability, both in defining *LSF* and in quantifying model parameters, are so large or difficult to characterize that the methodology fails. To reduce and avoid these weaknesses a sensitivity analysis, was carried out (*Fig.* 2–3). The magnitudes of these factors characterize the impact of each of the random variables on the probability of failure. The real main importance parameters seem to be s_0 (initial sample thickness) and p_e (operating pressure).

Table 2. Experimental corrosion variables values

Sample surface A [cm*cm]	Lost weight DG [g]	Corrosion rate V_c [mm/year]
23.64	0.011	0.0195
23.689	0.02	0.039
23.72	0.031	0.0586
23.764	0.035	0.0683
23.8	0.041	0.0779
23.84	0.05	0.0972
23.841	0.05	0.0972
23.86	0.06	0.1165
23.889	0.061	0.1166
23.919	0.08	0.155
24.015	0.09	0.1737
24.072	0.111	0.2118

Experimental analysis were done under processing conditions with 12 samples of stainless steel according [1, 5].

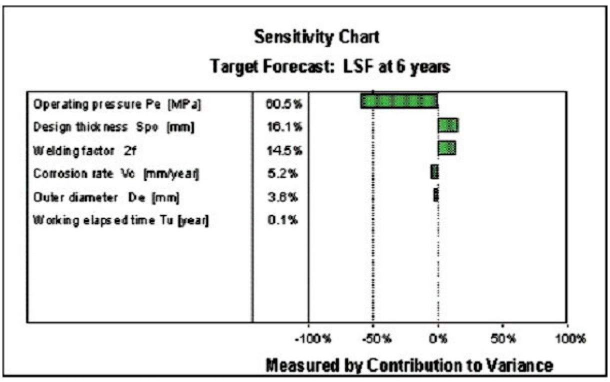

Fig. 2.

3.3. Results

The effects of corrosion decay on the safety of *TWPV* was done considering the trend of the probability of failure over the service life, during a period extent over 0…16 years.

Table 3. One-sample Kolmogorov-Smirnov testfor the main corrosion variables

		Surface [cm*cm]	Lost weight [g]	Corrosion rate [mm/year]
N		12	12	12
Normal parametersa, b	Mean	23.83742	5.33E-0.2	0.1026083
	Std. Deviation	0.1272041	2.92E-02	5.63E-02
Most Extreme	Absolute	0.096	0.147	0.152
Differences	Positive	0.096	0.147	0.152
	Negative	−0.091	−0.074	−0.074
Kolmogorov-Smirnov *Z*		0.333	0.508	0.525
Asymp. Sig. (2-tailed)		1.000	0.959	0.945

[a] Test distribution is Normal
[b] Calculated from data.

Latin Hypercube Sampling

The trials were guided based on two principles: a maximum number of 100.000 trials and a control of precision defined by the minimum confidence parameters of 95% reported to mean and standard deviation. The sensitivity analysis, based on variance reduction, was carried out (*Fig.* 2). In the real space, the main importance parameters are p_e (operating pressure) and s_0 (initial sample thickness). Thus on the basis of probability histograms (*Fig.* 4) the probability of failure is done by:

$$\text{Probability of failure} = 1 - \text{Certainty} \Rightarrow 1 - 0.9685 = 0.0315. \qquad (16)$$

Cyclic Recursive FORM Method

The main variables in reduced space are determined on the basis of a sensitivity analysis according to the importance factors (*Fig.* 3). Generally, they are the same as in *LHS* but in a different ranking, most important is s_0 (initial sample thickness) and then p_e (operating pressure). Accordingly, for the critical value for *TWPV's* admissible strength of material and the expression of limit state (in reduced space) a probabilistic analysis was performed (*Fig.* 5). Simultaneously, the safety index β and the probability of failure was established. Checking the concordance between the probability of failure and the importance factors [3] associated with each of these points, the best probability associated with each of the safety indexes β (*Fig.* 3–6) arise on the following determinant model outputs:

U_2 reduced variable	U_3 reduced variable	Safety index β.
$-9.312049e - 001$	$1.004069e + 000$	$1.768694151e + 0000$

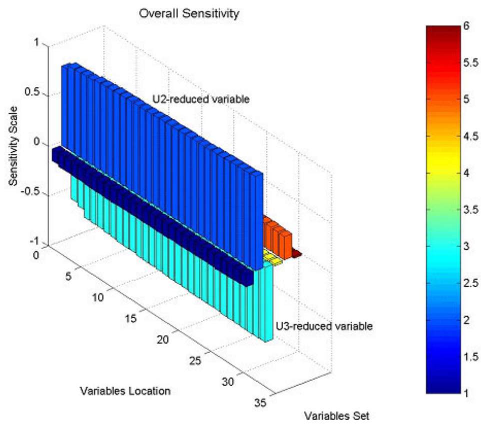

Fig. 3.

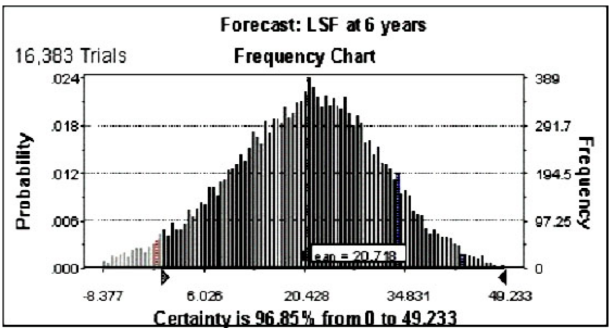

Fig. 4.

Thus, on the basis of *Eq.* (8) the probability of failure is done by:

$$\text{Probability of failure} = \Phi(-\beta) = 3.847246444e - 002. \tag{17}$$

3.4. *Discussions*

Comparatively the presented analyses, based on the proposed approaches, produce reasonable accurate results. Relative errors occur under 18%, but in the same rank of magnitude. Furthermore, the probability of failure obtained using the *cyclic recursive FORM approach* produces not only a single value (*Fig.*6); it produces an interval of the probability values. The boundaries of this interval may reflect to high uncertainty and variability of variables and may better characterize the probability of failure in the vicinity of tails of real or reduced parameters as random variables.

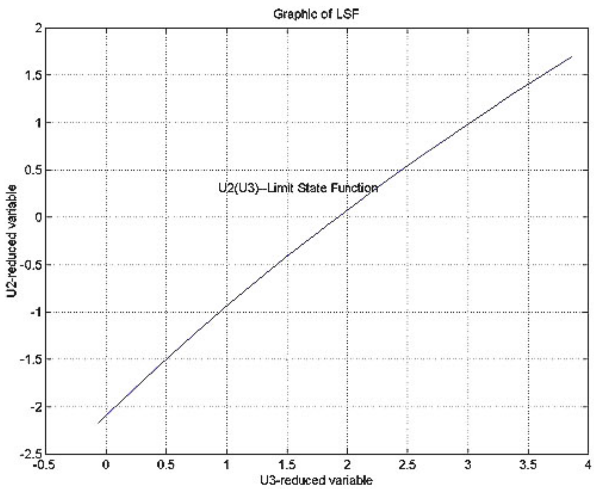

Fig. 5.

The results based on *LHS* trials reveal satisfactory forecast values for *LSF* (*Fig. 4*). These forecast values are greater than the critical value, $LSF = 0$, with a certainty more than 89.32%. The total overlay probability trends reveal a domain of possible average values of $LSF = 20.718$ for the limit sate. Regarding the risk of failure estimated on the bases of critical forecast values of the *LSF*, this is not insignificant, it exists.

According to Mc.Leods and Plewes's scale, this probability of failure suits on the scale of risk in the range between $10^{-2} \ldots 10^{-3}$. This risk is characterized as a reduced one. Due to the variations in service load during service elapsed time and especially the propagation of corrosion, damage can occur. It is possible that beyond the service stage the corrosion rate parameter V_C to become the most pronounced negative influence over the limit state function *LSF*. Hence, the containment of this damage becomes most important for the safety working life of the pressure vessel.

4. Conclusions

A large number of technological structures like pressure vessels are deteriorating by corrosion with time, due to process exposure. As a main result the carrying capacity diminishes with time and hence the level of risk of these structures increase. Using a corrosion decay model based on experimental data and a probabilistic assessment it is possible, more realistic, to decide when the structure becomes unsafe or the level of risk becomes too high. The paper introduces sampling and probabilistic algorithms for calculating the risk of failure, for corrosion deteriorating pressure vessel at any time during the service life. This example is not one very critical,

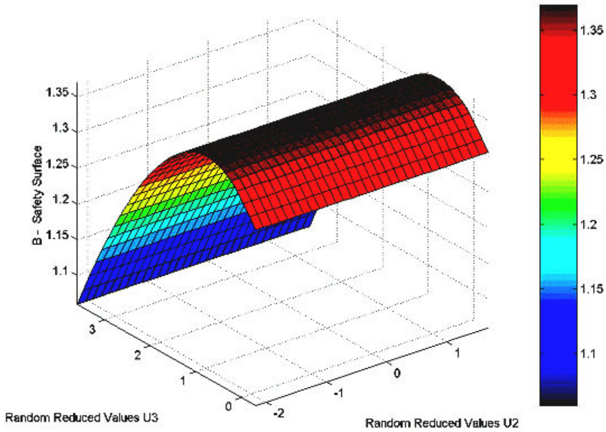

Fig. 6.

but in process industry there are many and more critical situations. Also it accents on the sensitivity analysis as a key factor which could have a profound impact on the risk estimate. The proposed methods and numerical results are observed to be reasonable accurate and efficient. The study possibly offers a greater reliability in life prediction. High values for safety factor β lead to low values for the risk of failure. Some approaches, like this, reduce the need for excessive safety margins in design and more cumbersome experimental and analytical approaches.

According to these previous conditions we can highlight that the limit state function is based on pure mechanical conditions. The risk of failure or the reduction in pressure vessel safety are major conditiones for the active corrosion defects. Using a corrosion decay model it is possible to establish a reliability-time profile for *TWPV* structure. These types of study become not only recommended, but also necessary for engineers, especially for chemical engineers to work out optimal safety decisions, inspection and maintenance schedules.

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