Available online at www.sciencedirect.com
ScienceDirect
ISA Transactions 46 (2007) 119–126
www.elsevier.com/locate/isatrans

Study of a risk-based piping inspection guideline system

Shiaw-Wen Tien[a], Wen-Tsung Hwang[a,*], Chih-Hung Tsai[b]

[a] Graduate Institute of Technology Management, Chung-Hua University, No. 707, Sec. 2, Wu-Fu Road, Hsinchu, Taiwan 30012, ROC
[b] Department of Industrial Engineering and Management, Ta-Hwa Institute of Technology, No. 1, Ta-Hwa Road, Qionglin Shiang, Hsin-Chu County, Taiwan 30740, ROC

Received 29 July 2005; accepted 23 June 2006
Available online 2 February 2007

Abstract

A risk-based inspection system and a piping inspection guideline model were developed in this study. The research procedure consists of two parts—the building of a risk-based inspection model for piping and the construction of a risk-based piping inspection guideline model. Field visits at the plant were conducted to develop the risk-based inspection and strategic analysis system. A knowledge-based model had been built in accordance with international standards and local government regulations, and the rational unified process was applied for reducing the discrepancy in the development of the models. The models had been designed to analyze damage factors, damage models, and potential damage positions of piping in the petrochemical plants. The purpose of this study was to provide inspection-related personnel with the optimal planning tools for piping inspections, hence, to enable effective predictions of potential piping risks and to enhance the better degree of safety in plant operations that the petrochemical industries can be expected to achieve. A risk analysis was conducted on the piping system of a petrochemical plant. The outcome indicated that most of the risks resulted from a small number of pipelines.

Keywords: Risk-based inspection (RBI); Rational unified process (RUP); Damage factors; Damage models; Damage positions

1. Introduction

Statistics indicate that piping damage accounts for the greatest proportion of equipment damage in petrochemical plants [1]. There are two common reasons for this: (1) large volume of piping, (2) heavy reliance on the inspection specialists who are familiar with the working environment, professional analysis, and improvements necessary to attain efficient inspection planning. This strategy of inspection controlled the inspection timing and the inspection measures. It not only controlled the levels of safety, management, efficiency and quality, but it also dictated the bottom line costs.

During traditional inspection strategy, either using destruction testing methods or in non-destruction testing, some damage may be found, but not for most potential hazards. The way to solve this common situation fundamentally is nothing more than to understand the possible types of damage before determining proper inspection technology. The optimal inspection strategy suggested by the piping inspection guideline system developed by this research was based on corrosion types and damaged area of piping. Following Table 1 is its comparison with the creativity of current systems.

This study aimed at developing an application based on the concept of risk-based inspection (RBI), which provided accurate inspection planning. The application was built with a piping inspection database for different piping positions and corrosion types. Through effective utilization of the analysis software, inspection specialists at the petrochemical plants are able to make more accurate and professional assessments while applying adequate inspection techniques at the best time intervals during the implementation of inspection strategies.

RBI technology prioritizes inspection planning by calculating the risk value, and then the technology effectively implements an inspection programme. Additionally, RBI reallocates the inspection and maintenance resources to high-risk equipment items while paying appropriate attention to the low-risk equipment items as well. The RBI methodology and work process is depicted diagrammatically in Fig. 1.

* Corresponding author. Tel.: +886 3 5186 080x6751; fax: +886 3 5186 593.
E-mail addresses: wtsung@cc.kyu.edu.tw, wt.hwang@hotmail.com (W.-T. Hwang), ietch@thit.edu.tw (C.-H. Tsai).

0019-0578/$ - see front matter
doi:10.1016/j.isatra.2006.06.006

Table 1
Comparison of current industrial practice

Items of comparison		Current technology and systems and The system of development by this study	
Damage mechanism for piping	Corrosion types	Existing but not for piping	For pipeline corrosive type and damaged models
	Position of inspection	None	Stipulating required inspection location reference
The analysis of failure consequence for piping	Consequence of failure	Qualitative analysis result	The result of qualitative and semiquantitative analysis
	Likelihood of failure	Qualitative analysis result	The result of qualitative and semiquantitative analysis
	Priority	Yes	Yes
Risk ranking for piping	Standards and procedures	Not consistent with API 581 calculation method	In compliance with API 581 and ASM V. 17
	Analysis of consequence	Risk will only be presented by the change of time	Provide the results focused on opinions
	Model of diagram	Risk matrix	Versatile type of diagram
Provision of the planning for inspection methods for piping	Data integration	Low	High
	Data model	With limitation	Analysis of multiple view
	Interface of graphics	Complex interface of operation	Excellent, easy for maintenance

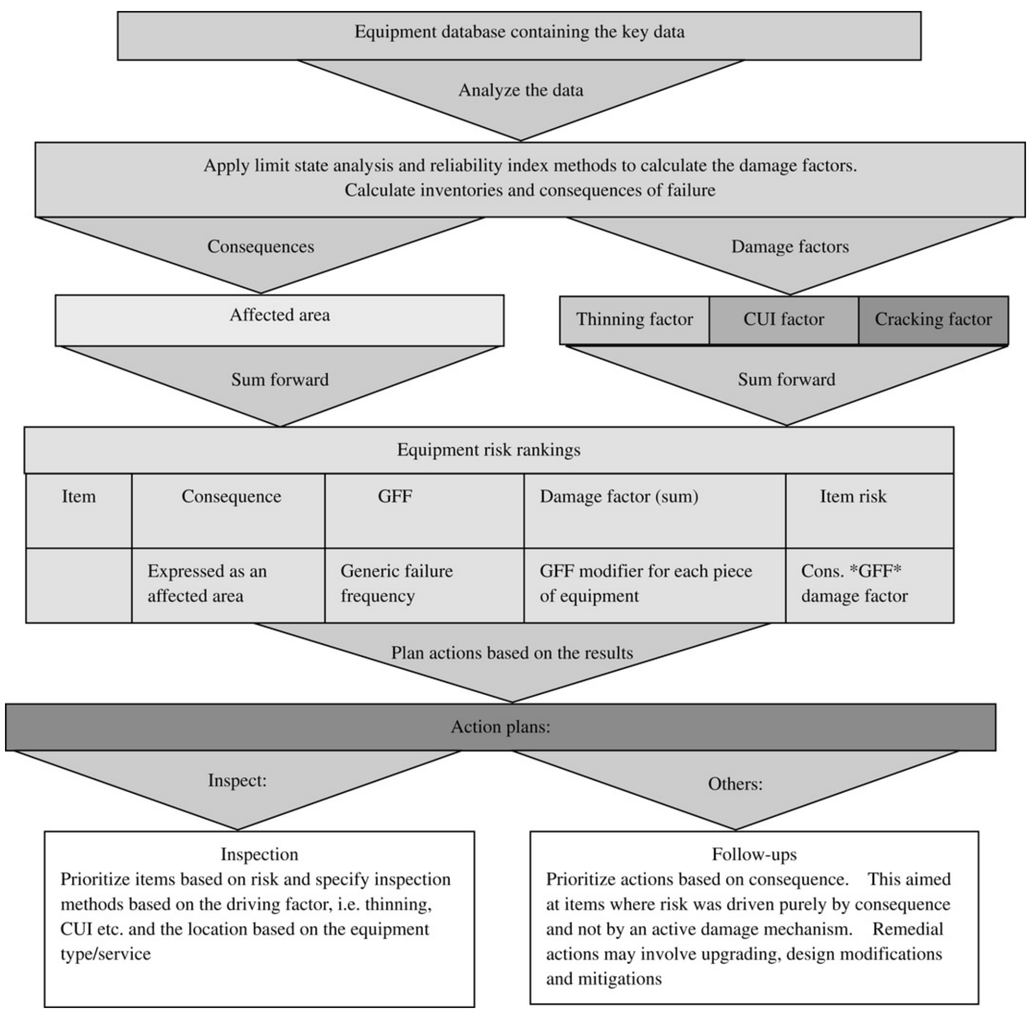

Fig. 1. RBI methodology and applications.

RBI is beneficial for increasing the operating time of a plant or, at the very least, keeping risks at the existing or acceptable levels [2]. RBI takes into account the conditions of the plant without risk of restraining matters and computes the failure probability and consequences of every event with the condition that could occur. Risk is the result of failure probability and is used to locate any specific equipment items that are in the most need of inspection. A detailed consideration is undertaken for

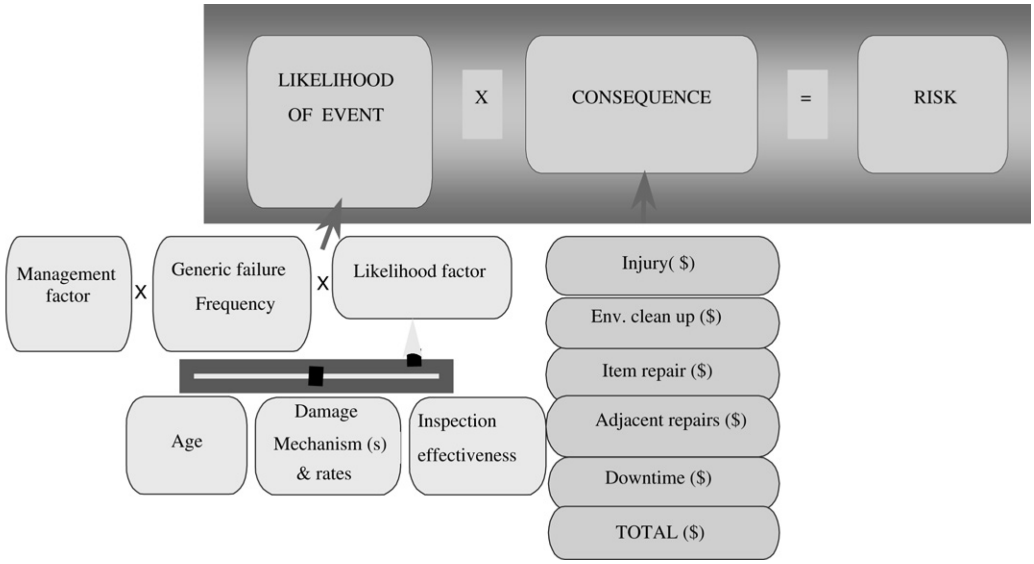

Fig. 2. Risk analysis model.

every corroded or failed machinery component. Thus, a suitable inspection plan can be developed through recommendations for inspection measure, category and frequency.

A fully integrated RBI system must comprise inspection activity, inspection data collection, update and continuous quality improvement. Risk analysis is an investigation of particular equipment in a precise time frame. Fig. 2 illustrates the essential elements that require input in order to conduct the analysis of quantitative RBI [3]. Similar to any risk-based research, the two main elements of quantitative RBI analysis are estimated by the probability of occurrence and the consequence of events.

Rational unified process (RUP) [4] is an iterative development process that provides the developers with a precise measure for assigning development related jobs and responsibility. Additionally, the RUP can be considered an adaptable process framework that can be adjusted or expanded according to the needs of the developers and creators.

The RUP model adopted in this study includes the requirements management that contains the systematic measure for guiding, organizing, communicating and managing the changes. It also is a use-case-driven approach, which means that use cases defined for the system can serve as the foundation for the rest of the development process. Use cases play an important role in several of the process workflows, especially requirement, design, test and management [4].

2. Research structure

The procedure of this study was divided into two sections. First, information collection and analysis were performed. Then, the system models were constructed accordingly.

2.1. The building of RBI model for piping

The procedure for building an RBI model for piping in the petrochemical industries includes collecting and analyzing the related domestic and international data, as well as confirming the standard for verification [5,6].

In this section, the information collection structure for the qualitative RBI analysis is clarified. The following information is collected and defined to derive a qualitative risk-based inspection system, as shown in Fig. 3.

- Piping factor (PF): Evaluates the quantity and type of the equipment and estimates the possible risk range.
- Damage factor (DF): Assesses the risk of the existing or potential damage mechanism of the equipment.
- Inspection factor (IF): Estimates the validity of the inspection planning for equipment damage.
- Condition factor (CF): Examines the validity of plant maintenance and the quality of execution.
- Process factor (PF): Appraises the potential or abnormal operation conditions that might cause uncontrollable events.
- Mechanical design factor (MDF): Scrutinizes certain design problems of the equipment.

2.2. Knowledge database for risk calculation

In typical RBI research conditions, the construction and collection of data were focused on the equipment. The risk types and probability were categorized and ranked in order to select the high-risk equipment and to eliminate the nonrisk and low-risk ones. Then, the actions taken on high-risk equipment were examined for a decision on whether or not to adjust the standard models and directions.

As the configuration of the risk analysis model is based on determining the corrosion type, differentiating risk consequence and probability, it is necessary to have an understanding of all the equipment involved in the process. This includes selecting the inspection range and inspection measures, and thus formulating appropriate inspection planning. These data could also be employed for inspection prioritization and corrosion management in order to meet the needs of an enterprise's optimal risk management procedure, taking into consideration the optimal costs.

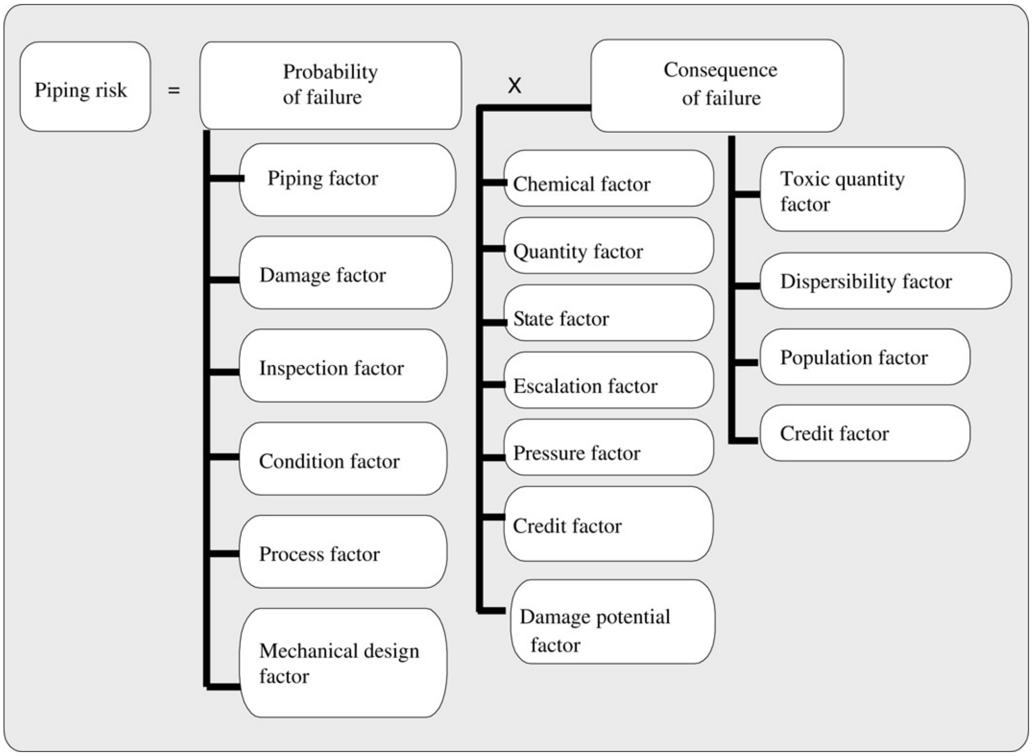

Fig. 3. Data collection and definition in the calculation of the risk for piping.

The system analysis process in this research is constructed in accordance with the international standards of API 581 and local factors of qualitative measures taken in domestic industries [5,7,8]. Fig. 3 demonstrates that the qualitative measure mainly focuses on the inspection of failure probability and failure consequences [7].

Failure probability is calculated by attaining the number of affected equipment, the possible cause of damage (e.g. general corrosion, weary cracks, high-temperature deterioration), the appropriateness of the inspection measure and process/design functions. Failure consequences focused on the two categories of risk, fire/explosion and poisonous gas. Fire/explosion risk accounts for the chemical substances' physical properties, leakage and release, and release types and protection. Poisonous gas risk involves the calculation of the amount of toxic chemicals released, the spreading range, the population density, isolation, etc. The design of the database is defined and categorized accordingly.

Risks are classified by the distribution of likelihood and consequence as shown in Fig. 4. Among which, categories 1, 2, 3, 4 and 5 represent the likelihood of failure from 1 to 5 in an increasing order. The consequence category A, B, C, D and E represents the consequence of failure from A to E in an increasing order for clearly taking hold of the distribution of the piping risks [3].

2.3. The construction of a risk-based inspection model for piping

Failed piping will affect the accuracy of inspection measures. The main effected factors include corrosion type, inspection measure and inspection position [6,8]. The categorization of the data helps to configure the database of root cause factor analysis for piping risk inspections. After appropriate screenings, selections for optimal nondestructive inspection measures are proposed [7]. Fig. 5 illustrates the structure of the RBI guideline model for piping.

The purpose of defining the probability of failed pipes was to provide the amendment mechanism for coping with the effects caused by different operating environments and management conditions at various processing plants. This probability was determined by frequency failure and other specific factors in the field. The calculations were further determined by equipment and management factors, as listed below.

1. *Failure frequency*: The failure frequency database has recorded the history of all equipment failures. These records could be originated from different sources, including computer application software or forms in current use. Records of failure frequency were made according to different equipment types and pipe diameters.
2. *Specific field adjustment factor*: Different plants may have different effects on risk probability of failure. In API 581, the adjustment factor has been divided into two parts—equipment factor and management system factor [7].
3. *Equipment factor*: The equipment factor defines the specific conditions that directly affect equipment failure frequency. These conditions are divided into four types:
   - (i) *Technical subfactor*: Reviews the material, environment and inspection planning, and focuses on its damage rate and effectiveness.
   - (ii) *Overall subfactor*: Reviews all the elements that affect the entire facility, and focuses on observing the

Likelihood category

Likelihood factor	Likelihood category
1–15	1
16–25	2
26–35	3
36–50	4
51–75	5

Consequence category

Consequence factor	Consequence category
0–19	A
20–34	B
35–49	C
50–70	D
> 70	E

Fig. 4. Ranking criteria.

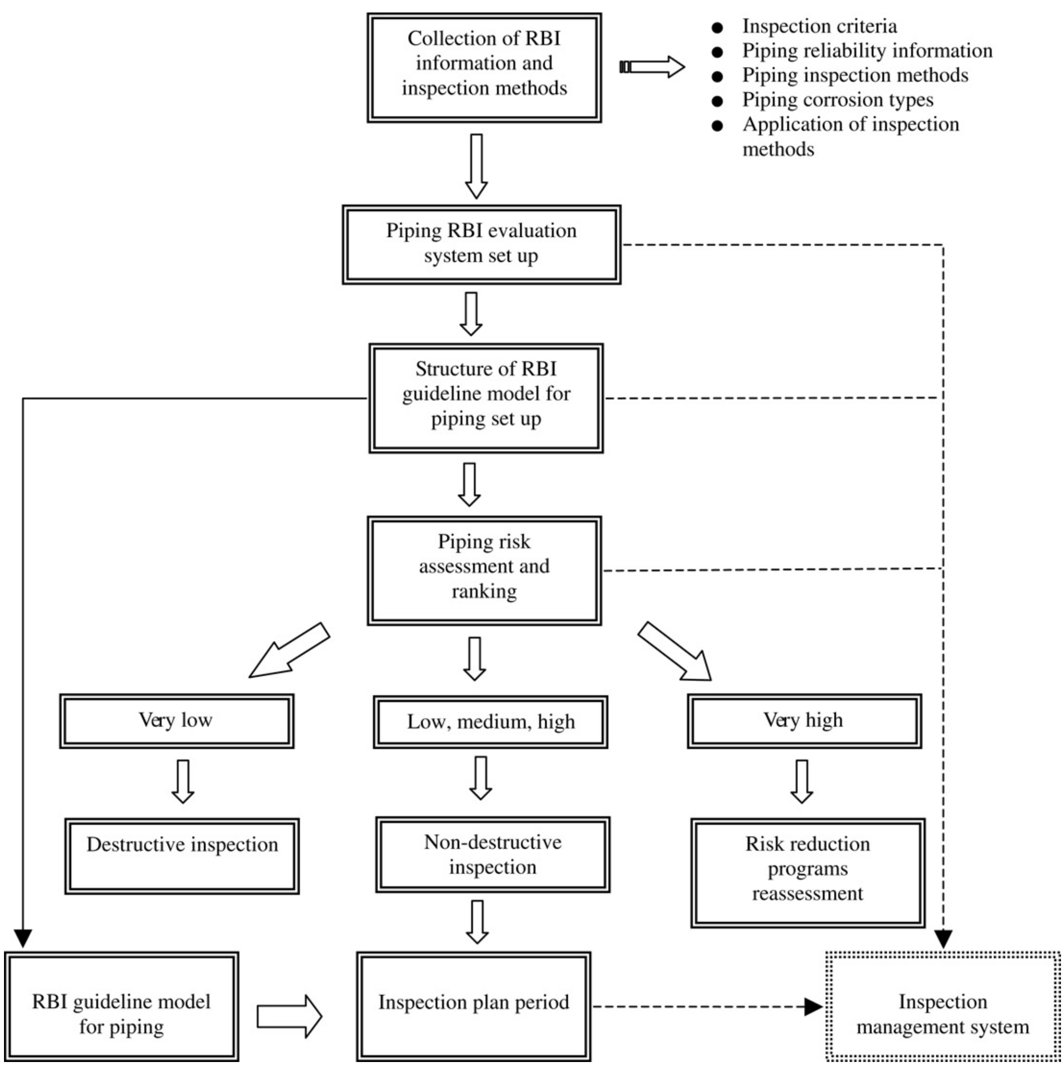

Fig. 5. Structure of RBI guideline model for piping.

plant condition, weather and the geographical activity surrounding the plant, such as earthquakes and other natural disasters.

(iii) *Mechanical subfactor*: Reviews the differences among the equipment items, and focuses on monitoring the complexity conditions, coding, life cycle, safety and vibration.

(iv) *Procedure subfactor*: Reviews and determines the integrity of the equipment and focuses on observing the continuity and stability of the equipment.

4. *Management system factor*: The implementation of industrial safety measures may also affect the integrity of the equipment to a certain degree. The process for RBI involves evaluating the facilities management system to further understand the management system's direct influence on the failure frequency of the equipment. The evaluation process includes a series of interviews of the staff for inspection, maintenance, production process and industrial safety.

This study discovered that some areas of risk assessment for industrial equipment could be expanded and systematized. However, the records of systematic data and inspection dispatch and logging have not been included. Thus, the functions of this model should at least include the following attributes:

1. *Management of static piping data*: Information (such as the updated version of basic equipment/piping data, design data, material information, inspection history, inspection criteria, schedule planning, associated equipment data, material-supplied data and background of personnel in charge) is effectively compiled and networked with inspection procedures, documents, graphic files, damage photos and monitored equipment data.
2. *Analysis of pipeline inspection*: A complete database that meets international standards is created to include calculation equations and material reference tables of ASME, API, BS, amongst other references. This function shall enable the automatic calculation of equipment design and allow minimum operational thickness to aid in comparing the corrosion rate, analysis of residual life cycle, and suggestion for the best timing of inspections.

This study covered the gathering of basic pipeline data, the inspection policy of RBI and the theoretical application of the pipeline life cycle evaluation. The concept of applying correct inspection methods and the comprehensive description of pipeline inspection management were major factors for the continual systematic development of a comprehensive expert pipeline inspection guideline system. This system, not only provided guidance for the pipeline inspection personnel but also enhanced the degree of safety in the plant.

3. Model design

In this study, a regular and systematic method provided by RUP was adopted for designing, developing and testing the models. The RUP template is also adopted to enable the description of structures from various perspectives. At the same time, the specific activities involved in the design process of the RUP components were taken as reference to determine the limitations and factors of this study. Key technical risks have been taken into consideration in this model design. The reusable components serve as the solution to similar problems for enhancing the overall productivity and quality of this study [4].

Generally speaking, RUP is related to the development and maintenance of software models. The modelled language of the unified model language (UML) graphics provides a tool to visualize, specify and structure the work. It also helps to document the work results. UML allows us to create the model blueprint in a standard way [9].

The development of this model is based on engineering theories and users' requirements. The first portion of the study focuses on the engineering theory. The second builds the practical system from theoretical foundations. The experience, collected from relevant users, is then included in the model development, in order to better meet enterprise requirements.

Gleaned from theories and users' requirements, the objectives of the model developed in the study were established as follows:

- provide easy to use piping registration tools for storing relevant factors related to piping and piping inspection;
- provide a method of risk evaluation that complies with API 581 for classifying piping risks;
- allow recording of various inspection programmes, inspection measurements and systematic calculations of corrosion rates with the remaining life;
- provide for proper inspection methods, according to system recommendations;
- provide accurate piping reports, including technical details, risk classification and risk distribution.

3.1. Model analysis

The object-oriented approach was used for model analysis, design and development. The development process of this model was constantly referenced to RUP and defined as the first iteration of RUP. Though only one iteration was generated for this development process, it still strictly followed RUP development procedures of complete analysis, design, development, testing and user feedback.

3.2. Analysis of object model

In addition to understanding the analysis of operational functions, the purpose of this study was to include a design model of data structure to support the requirements of analysis from the viewed data. Based on the usage terminology, the model had been divided into six parts—basic piping information, inspection interval and measured data, risk evaluation standards, risk evaluation information for piping, standards of inspection methods and data of inspection methods for pipes. Requirements for the model were listed as follows:

1. Basic piping information
   (a) Be able to readily identify piping by using piping codes.
   (b) Store and retrieve piping data, such as piping content, temperature, pressure, etc.

   (c) Be able to view all related pipes in the same window simultaneously.
2. Inspection interval and measured data for piping
   (a) Be able to define segments in a pipeline and to properly input each particular segment inspection data, including diameter, inspection time, piping wall thickness, tolerable thickness, etc. This is vital as specifications and limits of piping may be changed by its diameter.
   (b) Be able to calculate the estimated life of different piping segments by system.
   (c) Be able to set the overall estimated life for piping, using the shortest estimate of its segments.
3. Standards of risk evaluation for piping:
   (a) Conduct evaluation in accordance with the standards of API 581 risk evaluation.
   (b) Convert risk evaluation results to risk factors for more accurate calculations and predictions of the next piping inspection date.
4. Data for piping risk evaluation:
   (a) Implement risk evaluation on several piping items simultaneously.
   (b) Combine the results of risk evaluation and inspection data simultaneously to determine the next inspection date. However, these two sets of data may not always be available at the same time in general operation. Therefore, the system shall be able to deal with these two conditions independently as well.
   (c) In a survey of the risk evaluation, the question, the corresponding answer and the associated points shall be shown at the same time.
5. Standards of inspection methodology
   (a) Establish a standard of inspection methods, as piping positions and problem types differ.
   (b) Advantages and disadvantages for different inspection methods shall be made available for the user to choose objectively.
   (c) The standards of inspection methods can be edited by the specialist.
   (d) The standards of inspection methods will recommend fixed coding regulations for the plant.
6. Data for inspection methods for piping:
   (a) Establish proper inspection methods for different types of pipes.
   (b) Select from the inspection methods, suggested by experts, for differing pipe types.
   (c) Allow the user to add site-designed inspection methods.
   (d) Utilize similar inspection methods repeatedly for similar inspection position and types of equipment failures.

4. A case study

This study was developed out of the modelled language of UML graphics. In addition to understanding the analysis of operational functions, the purpose of this study was to include a design model of the data structure to support the requirements of the analysis from the viewed data. Mentioned by aforesaid object models analysis, the requirement of model development of this system primarily includes basic piping information, inspection interval and measured data, risk evaluation standards, risk evaluation information for piping, standards of inspection methods, data of inspection methods for pipes, etc. Take the risk evaluation information for piping, for example. We not only implemented RBI analysis for evaluating several piping items simultaneously but conducted an RBI analysis on the piping for the Naphtha Cracking Unit of a petroleum refinery in Taiwan.

Table 2
Numbers of piping analysis

Equipment type (unit: in.)	Total
PIPE < 2	3
PIPE-2	51
PIPE-4	145
PIPE-6	49
PIPE-8	51
PIPE-10	18
PIPE-12	40
PIPE-16	23
PIPE > 16	91
Grand total	471
Likelihood of failure	**Total**
1	433
2	22
3	8
4	4
5	4
Grand total	471
Consequence of failure	**Total**
A	12
B	58
C	168
D	233
E	0
Grand total	471

After assessing the P&ID of the factory, the pipeline sizes were converted and classified into Table 2 (471 pipelines underwent analysis). With the failure likelihood and failure effects defined accordingly, 433 pipelines were rated a failure likelihood of grade A; 22 pipelines were rated grade B; eight pipelines were rated grade C; four pipelines were rated grade D; and five pipelines were rated grade E. For most of the pipelines, since proper materials were chosen in accordance with the operating conditions, the probabilities of failure were relative low. The failure effects ratings were as follows: 12 pipelines were rated grade A; 58 pipelines were rated grade B; 168 pipelines were rated grade C; 233 pipelines were rated grade D; and no pipelines were rated grade E. Since the piping covered a large area, the failure effects were comparatively high.

The risk distribution is analyzed and shown in Fig. 6. The risk rate and quantity of the pipelines are given in Table 3. From these findings, it can be concluded that only a small number of pipelines, lower than 5%, were accounted for as middle/high risks. Thus, it can be assumed that for the small number of

LoF	CoF				
5	0	0	3	1	0
4	0	0	3	1	0
3	1	0	3	4	0
2	0	0	1	21	0
1	11	58	158	206	0
	A	B	C	D	E

Fig. 6. Risk distribution matrix.

Table 3
Case results on RBI studies

Risk contributions	Total	Percentage (%)
High	1	0.2
Medium–high	11	2.3
Medium	390	82.8
Low	69	14.6
Grand total	471	100.0

pipelines with higher risks, an adoption of effective inspection strategies can largely ward off the occurrence of future risks.

5. Conclusion

The objectives of RBI analysis research were to manage, predict and inspect the damage mechanisms. The results of this analysis should be adopted as a crucial element for overall inspection and maintenance planning. In an attempt to attain optimal results for research on RBI, it was essential to fully understand the difference between the RBI methodology and traditional measures. As in traditional measures, internal inspection of equipment was only performed once every few years. The internal and off-stream inspection requires less study as it was used merely to implement timely work. The drawback of internal inspections was that it requires a shutdown of operations and thus, interrupts production, which can be very costly.

The process of studying RBI requires more effort by definition. The reason for this is because it involves changing work procedures and developing an auditable management system. In order to amass a large quantity of accurate data, a comprehensive and reliable database becomes crucial. The RBI process provides exactly that. Even though the RBI process requires more effort in designing and operating computerized systems, it is still much more effective than the traditional method of analysis.

References

[1] Mahoney D. Large property damage losses in the hydrocarbon-chemical industries—A thirty-year review. 20th ed. New York: M & M Protection Consultants; 2003. p. 23–38.

[2] Khan FI, Haddara MR. Risk-based maintenance of ethylene oxide production facilities. Journal of Hazardous Materials A 2004;108:147–59.

[3] Det Norske Veritas (USA). API committee on refinery equipment: Base resource document on risk based inspection. Houston (TX): DNV industry Inc.; 1998.

[4] Kruchten P. The rational unified process: An introduction. 3rd ed. Addison-Wesley; 1999. p. 277–78.

[5] Chang RR. Study for remaining life estimation of localized and high temperature corrosion and inspection strategy for piping of refinery plant. Doctoral dissertation. Yunlin (Taiwan): Institute of Engineering Science & Technology, National Yunlin University of Science and Technology; 2004.

[6] Merrick EA, Leonard CR, Eckhardt P, Baughman H. Risk-based methods optimize maintenance work scope. Oil & Gas Journal 1999;97:47–52.

[7] American Petroleum Institute. API Publication 581. Risk-based inspection base resource documentation. 1st ed. Washington (DC, USA): American Petroleum Institute; 2000.

[8] Tsao CC. Establishing an auditing guide of extension and alternative inspection for pressure vessels. Final audit report. Executive Yuan (Taiwan): Institute of Labor Safety and Health, Council of Labor Affairs; 2002. p. 38–43.

[9] Kim CH, Weston RH, Hodgson A, Lee KH. The complementary use of IDEF and UML modeling approaches. Computers in Industry 2003;50: 35–56.