Quantitative Risk Evaluations of LNG Equipment Applying ASME Risk-Based Maintenance Concepts

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Future regulatory requirements in Japan will mandate that all high-pressure gas production companies impose a maintenance system based on predictive data rather than on equipment inspections. This paper describes a risk-based maintenance (RBM) system to achieve these new regulatory requirements. © 2005 American Institute of Chemical Engineers Process Saf Prog 24: 187–191, 2005

INTRODUCTION

The Ministry of Economy, Trade and Industry (METI) in Japan has revised its policies regulating high-pressure gas equipment. The conventional regulative administrative guidance has been modified to require setting up of autonomous control. Consequently, the maintenance of self-imposed standards that specifically control individual equipment has become an essential issue. The basic articles of the safety law state that significant inspections, based on scientific and technical backgrounds, should be executed on a system of personal (corporate-level, management-level, personnel-level, etc.) responsibility for deteriorative and dilapidated apparatuses and equipment in high-pressure gas plants.

A terminal of Nihonkai LNG Corporation that is an important energy base on the Japan Sea has, fortunately, not experienced any disaster in the past 20 years. However, certain data do predict the deterioration of any equipment, and it is therefore important to draw up an appropriate safety plan that allows for routine and ongoing verification of these deteriorations, to secure a safer plant. Although there are no codes or standards that quantify the deterioration of LNG (liquefied natural gas) equipment, it is possible to apply the risk-based maintenance (RBM) of the American Society of Mechanical Engineers (ASME) [1] and the American Petroleum Institute (API) [2] and focus on the performances properties of the material used for the components to reduce qualitative risks. By applying this method to the low-pressure LNG pump [3] on evaporative-type LNG terminals, it was found that by organizing the repair and data, an appropriate safety plan for equipment could be established without special properties such as metallographic tests or analysis of material properties.

This goal of this presentation is the delivery of a safer terminal and avoidance of public disasters by applying the quantitative risk evaluation method, designed by focusing on the material properties of LNG pumps, to other equipment as well as by applying and using these methods to similar terminals.

STANDARDS OF API AND ASME AND THE QUANTITATIVE RISK EVALUATION METHOD FOR APPARATUSES AND EQUIPMENTS

Based on the risk index, obtained by combining the probability of leaks occurring in the pressured equipment and its extent of influence, the RBM is a rational way to reduce the risk and cost at the same time while carrying out inspections. To calculate the probability of leak occurrence, evaluation modules—such as the progress pace and receptivity of various levels of deterioration that occur to equipment, the ability to evaluate levels of deterioration by nondemolition tests, the condition of the equipment, and the monitoring data—have been prepared. RBM was created by summarizing the 170 major accidents that occurred in the U.S. petroleum and petrochemical industries during the past

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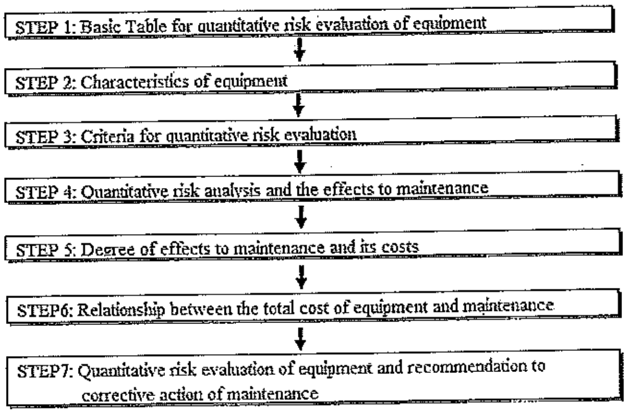

Figure 1. Quantitative risk evaluation method.

30 years from 1961 to 1991. Approximately 40% of the accidents were caused by mechanical strain on various equipment, among which 80% was attributed to damages in the pressurized parts such as the pipes, drums, columns, receptors, tanks, pumps, and cooling units. RBM was introduced to effectively reduce the mechanical damages as the number of occurrences and the cost increased year by year.

RBM was originally used as a probabilistic risk assessment (PRA) to analyze malfunctions in the U.S. nuclear power generation industry, but from the end of the 1980s to the beginning of the 1990s it has been applied to provide economical safety control management as well as to secure the reliability and safety of petroleum and petrochemical plants.

With this in mind, surveys on domestic and international codes, standards, and other similar criteria have been conducted to apply RBM to evaporative-type LNG terminals. However, the reduction of risks linked with cracks and defects, particularly welding defects, was evaluated quantitatively because it was impossible to find a direct method to assess qualitative risks of equipment.

NEW QUANTITATIVE RISK EVALUATION OF EQUIPMENT BASED ON ASSESSMENTS OF MATERIAL PROPERTIES IN COMPONENTS

The flow of the quantitative risk evaluation shown in Figure 1 consists of a workflow from Step 1 to Step 7 where the workflow is completed at each step.

It is a purpose of Step 1 to build a basic quantitative risk evaluation table, which contains the influences and the rate of occurrences applying the RBM risk evaluation matrix as shown in Figure 2, which is the basic table for quantitative risk evaluation for equipment. The horizontal axis depicts the degree of influence of deterioration toward the system, caused by changes in environment and operational conditions. This is because the axis originally showed the impact of damage caused by the equipment. The vertical axis depicts the occurrence rate of deterioration.

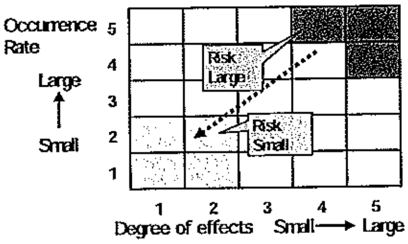

Figure 2. RBM risk evaluation matrix.

Table 1. Degree and contents of influences.

Scale	Description
5	Creep and friction
4	Loading
3	Brittle failure
2	Fatigue
1	Erosion and corrosion

By focusing on the parts that make up the equipment, Step 2 designates the characteristics of the parts by analyzing their material properties. By obtaining information of materials, it is possible to understand their life span with respect to endurance toward temperature, pressure, and cyclic load. The main point is to check the test results and repair records from the beginning of operational use, to cover every sign of deterioration. Through Steps 1 and 2, it is essential to obtain data with respect to tendency of troubles and check every single part of various equipment to analyze current safety situation of plants.

Step 3 includes processes of creating evaluation standard of quantitative risk, using the influences and the rate of occurrences in the basic table (Table 1) that was prepared in Step 1. Moreover this step surveys (1) the mechanisms relating to the occurrence of damages, (2) the technologies to diagnose deterioration, (3) investigation of examples of existing damage, and (4) investigation toward standards, documents, and references related to techniques for evaluation of cracked and fatigued parts.

From this survey, as well as from the fact-finding research done by Davies [4] and Dolan [5] on the causes of damages, it was found that erosion and corrosion possessed the strong relationship with the cause of damages, followed by fatigue, brittle failure, loading, creep, and friction. Tests conducted in similar environments at an LNG terminal showed matching results. Therefore, it can be concluded that erosion and corrosion constitute the strongest trigger for damage, followed by fatigue, brittle failure, loading, creep, and friction.

Table 1 is a summary of these results. Focus was placed on the material properties of stainless steel and aluminum, which is often used in LNG plants, to grasp the status of the occurrence rate of their damage. Although stainless steel is often used as an anticorrosion material, according to the studies by Kitamura and Suzuki [6] corrosion in stainless steel can occur when: (1) the welding process is inadequate, (2) there is no reflux of precipitation in the salt level, and (3) when water enters through the welding between the cold insulator and pipes. In addition, similar results were

Table 2. Damage occurrence rate of stainless steel and aluminum alloy.

Scale	Description
	Stainless Steel
5	Welding seams (cold insulator, indoor), erosion and corrosion, temperature change (normal–low), precipitation of highly dense salt, shutdown, low cycles
4	Welding seams, materials and cold insulators, erosion and corrosion, precipitation of highly dense salt, temperature change (normal-low)
3	Welding seams, materials and cold insulators, erosion, and corrosion
2	Welding seams, materials, and cold insulators
1	Welding seams, and no abnormalities in structural tests
	Aluminum Alloy
5	Number of start-ups and shutdowns are over 4000 times, erosion and corrosion, welding seams, temperature difference (low and normal), low cycle, shock waves (closed check valves), precipitation of dense salt
4	Number of start-ups and shutdowns are over 4000 times, erosion and corrosion, welding seams, temperature difference (low and normal), low cycle
3	Number of start-ups and shutdowns are over 4000 times, erosion and corrosion, welding seams, temperature difference (low and normal)
2	Number of start-ups and shutdowns are over 4000 times, erosion and corrosion, welding seams
1	Number of start-ups and shutdowns are over 4000 times, no abnormalities in structural tests

Table 3. Effects on maintenance.

Scale	Description
5	Fundamental checks for pressure container repairs (piping damage, cracks in pots, cracks in panel tubes, and so forth)
4	Fundamental checks for entrusion of inner fluid
3	Fundamental checks of valve blocks (edge cutting, air locks, and so forth)
2	Checks during shutdown (shutoff locks, cut off power, repairs on switches, no valve blocks)
1	Checks without shutdown

found in past inspections records and repair results conducted by our company. Aluminum alloy proved to show a prominent decrease in tenacity because intergranular fractures tend to generate in low temperatures. It is reported that the tenacity in the material itself decreased and fractures generated specifically after conducting a Charpy shock test in low temperatures. This is attributed to the transition of slide stress to intergranular fractures, which proves that brittle fracture progresses in the aluminum alloy used in extremely low temperatures [7]. Although these characteristics of aluminum alloy have not been detected in equipment from our safety inspection records, it is necessary to consider their possibility, as suggested in the research reported by Kobayashi *et al.* [7]. Table 2 summarizes the causes of damage and the rate of occurrence for stainless steel and aluminum alloy equipment.

With the status table on material damage of properties compiled in Step 3, Step 4 inspects the effects this will have on maintenance (the vertical axis represents the rate of occurrences; the horizontal axis, the effects on maintenance). It is necessary to find the relationship between maintenance and the damage status of the components because, although the effects in Step 3 may be small, the actual labor on maintenance may be substantial. Table 3 shows the effects on maintenance and is based on the actual applications carried out by our company as the workload.

Table 4. Scale of costs.

Scale	Cost to Maintenance
5	Over 125%
4	100–125%
3	Current status 100% (scheduled checkups)
2	Over 25%–under 99%
1	0–25%

Components that were evaluated as having low occurrences of damages and had only slight effects on maintenance are not included in Step 5.

Step 5 examines the maintenance costs for components that were identified in Step 4. Components that had high occurrences of damage and considerable effects on maintenance should be selected through the process. By retaining the horizontal axis with respect to the effects in maintenance found in Step 4, the vertical axis on the occurrence rate of damages is substituted with the scale of costs. Table 4 shows the breakdown of the scale of costs based on the company's present standard at 100%.

Regarding the components that were found in Step 5

Table 5. Evaluation and corrective actions of damage occurrence rates.

						Evaluation and Corrective Actions of Damage			
						Costs of Individual Equipment		Occurrence Rate of Damage	
Name	No.	Name	Specs	Units	Cost	Regulation	Control	Corrective Data	Specific Method
	12	Impeller	AC4C-T6	3					
	13	Buffer plate	SUS3166	1					
	14	Impeller spacer	BC6	1					
	15	Lock hub	A6061-T6	1					
	16	Balance drum combined	SUS316/ BC6	1					
	19	Wearing	BC6	3					
	34A	Orifice	SUS304	1					

Table 6. Assessment criteria for damage occurrence rates.

Category	Evaluation
Regulations	◎: regulated by law, ○ yes: periodical checks, O: autonomous regulations, —: not necessary
Control	◎: could not monitor or discover from the items on the right, ○ yes: trip, O: alarm, —: patrol
Cost	◎: great damages, ○ yes: damaged, O: little damages, —: none
Corrective data	◎: unavailable, ○ yes: available through research, O: available through experience and documents, —: available

to have considerable costs as well as significant effects on maintenance, Step 6 inspects how much the cost will affect the individual equipment as a whole. By leaving the horizontal axis on the effects on maintenance in Step 5 unchanged, the vertical axis on the scale of costs in Table 4 is substituted with the total costs of equipment. Whereas the scale of costs in Step 5 indicated the construction fees required to exchange components, the total costs of individual equipment define the future costs necessary to maintain them and at the same time this evaluates the occurrence rate of damage shown in Table 5 as well as specific corrective actions. To calculate the cost, it is necessary to use this table. A process is carried out by adding costs of satisfying regulations and of overseeing the equipment to the costs of the construction fees required to exchange components, which are from Step 5. Table 5 is also able to confirm whether regulations, control, costs, and corrective data, as entered in Table 6, can be used to suggest practical specific executable solutions to reduce the occurrence rate of problems/damage. As a result, the solutions can be extremely effective to reduce the occurrence rate and also to reduce individual equipment costs.

Step 7 completes the tasks between Step 1 and Step 6 as well as recommends corrective actions for maintenance.

DEVELOPMENT OF LOW-PRESSURE LNG PUMPS FOR QUANTITATIVE RISK EVALUATION INSPECTIONS

A specific example of an inspection procedure for low pressure that develops from the flow is shown in Figure 1. The materials were distinguished by using different colors on the LNG pump layout drawing in Step 2. Records of the past inspections and repairs of each component (visual checks, penetrant test, measurement of size, state of condition, replacement of parts, and so on), and whether abnormalities occurred during the inspections, were entered into the table. Other details about the usage of the components such as fatigue, erosion, friction, and so on were also entered to create a table that covers everything about the usage of the low-pressure pump.

To calculate the occurrence rate of damages for Step 3, 19 reports predicting deterioration of materials were found among our operational reports. These results were cross-checked with the component lists that were complied in Step 2 to calculate the occurrence rate for damages.

1. The inner components of the stainless steel pumps were given low risk because many were not in a state to accumulate salt levels.
2. The inner components of the aluminum pumps were also given low risk, given that ruptures and extensions were minimal because the number of start-ups and shutdowns were not enough to incur repeated fatigue.
3. The inner stainless steel bearings were given high risk because deterioration from past frictions was detected.
4. Pots and pipes were given high risk because accumulation of salt concentration was possible in the welding seams.
5. Nuts and bolts were given high assessments because they are placed in areas where the possibility of salt concentration accumulation is great. Furthermore, they are in an environment where load is applied.

With reference Table 3, Step 4 evaluated how each component affects the maintenance and the results were as follows:

1. The inner components of the low pressure LNG pump were given high risk because the pump must be stopped during maintenance and the inner fluid must be purged. However, it was removed from Step 5 because the damage occurrence rate was low.
2. The maintenance effects on bearings are high, but because they are exchanged during the periodic repairs, the damage occurrence rate was low.
3. Because pots, pipes, nuts, and bolts are pressurized parts, LNG will leak if these parts are damaged. This aspect was given high risk because repairs involve legal procedures and a long-term shutdown can be anticipated.

Step 5 evaluated the costs of repair at the components that were given high risk in Step 4. With reference to Table 4, calculations were carried out on the material and labor costs based on the present costs of periodic checks. As a result, vessels, pipes, nuts, bolts, and bearings were given high risk because they must be replaced when damaged.

To find the appropriate maintenance methods for pots, pipes, nuts, bolts, and bearings, which were given high risks in Step 5, Step 6 evaluates the level of priorities from the perspective of both the damage occurrence rates and the reduction of maintenance costs, with reference to Tables 5 and 6. As a result:

1. By carrying out nondestructive tests during periodical checks to verify the deterioration of materials properties in vessel standpipes, a corrective action plan was devised to simultaneously reduce both maintenance costs and damage occurrence rates.
2. A corrective action plan was devised for bearings by carrying out a cooperative research with the bearing manufacturers to find whether it is possible to replace the materials of construction with those having a longer life.
3. A corrective action plan to reduce damage occurrence rates in nuts and bolts was devised by replacing the parts, depending on the degree of damage, after carrying out tests on the materials.

CONCLUSION

Ten years have passed since this high-pressure gas equipment began operation. Costs for repairs will increase as the equipment deteriorates over time. With the administrative regulations now requiring autonomous control, it has become essential for enterprises that possess high-pressure gas equipment to provide thorough safety control to continue to develop their business as well as to fulfill their social responsibilities.

With this in mind, safety will be secured at plants by applying appropriate maintenance methods that are derived from the RBM methods based on the API and ASME standards, which focus on the material properties of the equipment. To demonstrate the advantages of this method, it will be applied on apparatuses and equipment other than low-pressure LNG pumps from fiscal year 2005. We plan to apply this to equipment other than low-pressure LNG pumps.

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