Research on evaluation and inspection of pressure relief valve

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Abstract. As a pressure relief device of pressure-bearing equipment, pressure relief valve (PRV) should be inspected once a year according to the regulations, which increasingly contradicts the long-term operation of petrochemical units. In recent years, risk-based inspection (RBI) has been widely used in inspection and maintenance of petrochemical equipment. According to the RBI results and Inspection records of PRVs in various refining enterprises, the problems encountered during the prolonging the inspection cycle of PRV are summarized, which provide reasonable basis for prolonging the inspection cycle of PRV. RBI technology is applied to 5810 PRVs in an enterprise, so that nearly 80% of the PRVs achieve the purpose of delayed inspection. In addition, suggestions for improvement measures are provided for common problems encountered during the use and inspection of PRVs.

1. Introduction
As a pressure relief device of pressure-bearing equipment, PRV is widely used in boilers, pressure vessels, pressure pipelines and so on. It is the last protection for safe operation of pressure-bearing equipment. Structure of conventional PRV is shown in Figure 1. Regular inspection is an important means to ensure the effective operation of the PRV. It is stipulated in the Safety Technical Supervision Regulations for PRV and the Supervision Regulations on Safety Technology for Stationary Pressure Vessel that the PRV should be inspected at least once a year [1-4]. In recent years, the contradiction between the PRV’s Inspect-once-a-year and the long cycle operation of the refinery plant has become increasingly prominent. Under the premise of ensuring the safe operation of the plant, it is an urgent problem for every refining and chemical enterprise to reduce the burden of PRV inspection and prolong the inspection cycle.

The inspection cycle of PRVs can be extended to 3-5 years, when they meet the relevant requirements in the Supervision Regulations on Safety Technology for Stationary Pressure Vessel. But in fact, these requirements are quite strict and the PRV managers usually lack relevant professional knowledge, which makes it difficult to implement. In recent years, Risk Based Inspection (RBI) of pressure equipment system has been widely used in various oil refining and chemical plants, which has optimized the Inspection resources, shortened the Inspection time, saved the maintenance cost and ensured the long-term operation of the plant [5-6]. RBI technology is also gradually introduced...
to the PRV inspection. In GB/T 26610 and API581, the RBI analysis method and the criterion to determine the risk level of PRV are given, which provides the method basis for the delay inspection of PRV.[1-4].

Figure 1. Conventional PRV

Figure 2. Process flow of PRV

Entrusted by a refining and chemical enterprise, the RBI technology was applied to 5,810 PRVs in 88 units of the whole plant. The evaluation covers almost all common refining and chemical units, including crude oil unit, catalytic cracking unit, hydrocracking unit, hydorefining unit, ethylene cracking unit, EO/EG unit, etc.

2. Difficulties in PRV inspection

At present, the PRV inspection is conducted once a year according to the regulations. The usual process flow of PRV is shown in figure 2. Based on the inspection history and service condition of 5810 PRVs, the difficulties faced in the inspection are summarized as follows:

a) When the PRV service in the corrosive medium environment, the front and rear hand valves are prone to internal leakage after a long time of service, resulting in the failure of the PRV to meet the detach conditions. According to statistics, 18 PRVs were found to have internal leakage hand valves during the last inspection and detach.

b) Some PRVs do not have front and rear hand valves, which can not meet the detach conditions. Of the 5810 PRVs evaluated, 1262 have no hand valve at the inlet, and can not be removed during service.

c) Some internal leakage PRVs, which working media contains H₂S or other toxic composition, have high remove risk. In addition, the outlet of some PRVs are connected to low pressure gas, high pressure gas or other discharge system with complex composition and H₂S in most cases, which also has great detach risk.

d) Some PRVs are designed together with the equipment. They cannot be teared down and inspected
during operation, but can only be inspected during maintenance when the whole unit shutdown, such as the PRV on the pipe reactor of polypropylene unit.

e) Some PRVs installed on the top of the tower which have good service environment and no corrosion medium. The removal cost of the PRV is much higher than the cost of inspection, which brings a great burden to the enterprise.

These factors mentioned above should be taken into account in the evaluation of the relief valve and in determining the inspection cycle.

3. The introduction of RBI method on PRV

The traditional inspection purpose is mainly to ensure the safety of PRVs. The inspection cycle of PRV is generally only 1 year, and can be extended to 3 ~ 5 years in some cases. Contrast to the traditional test methods and overhaul plan, the RBI methodology consider the economy factors, the safety factors and the potential failure risk of PRVs. Through quantitative assessment of the three main parameters (failure probability, failure consequences, the failure risk which is combination of failure probability and consequences), it can be more reasonable to determine the inspection plan of the PRVs [7-8]. The work flow of RBI methodology for PRV is shown in figure 3.

![Figure 3. RBI methodology for PRV](image)

3.1. Determination of failure possibility

According to the operation performance and failure case statistics of the PRV in service in petrochemical enterprises, the failure of the PRV involves many complicated factors. In evaluating the failure possibility of PRV, the failure of spring, operating conditions of PRV, service history and management level are mainly considered. The failure possibility of PRV spring is obtained by sorting out and analyzing the failure statistics of different types of PRV in large petrochemical enterprises. The operating conditions of the PRV include operating pressure, operating temperature, the corrosiveness of the operating medium, the viscosity of the operating medium, the cleanliness of the operating medium and the type of the PRV. The service history includes operation history and inspection history. The classification of management level factors is based on the method of API581 scoring each management index. 1-5 represent five levels of failure probability from low to high.

3.2. Determination of failure consequence

In terms of failure consequence, the characteristics of operating medium, discharge capacity, discharge rate and other parameters shall be mainly considered, and the consequence shall be
determined by the damage area around the pressure vessel or pressure pipeline. A-E represent five levels of failure consequence from low to high \(^{9-10}\). Numerical Values Associated with Probability and Area-Based Consequence Categories is shown in Table 1.

**Table 1.** Numerical Values Associated with Probability and Area-Based Consequence Categories

| Possibility Category | Consequence Category |
|----------------------|----------------------|
| Category range       | Category range(m²)   |
| 1  0.00000<P≤0.00001 | A  CA≤9.29            |
| 2  0.00001<P≤0.00010 | B  9.29<CA≤92.9m²     |
| 3  0.00010<P≤0.00100 | C  92.9<CA≤279m²      |
| 4  0.00100<P≤0.01000 | D  279<CA≤929m²       |
| 5  0.01000<P≤1.00000 | E  CA>929             |

3.3. Determination of failure risk

According to the definition of risk, risk is composed of failure probability and failure consequence. The risk level of PRV can be represented by risk matrix as shown in Table 2. Finally, according to the evaluation results, when the risk of PRV meets the acceptable level, the inspection interval can be extended appropriately.

**Table 2.** Risk Matrix

|   | A             | B             | C             | D             | E             |
|---|---------------|---------------|---------------|---------------|---------------|
| 5 | Medium High   | Medium High   | Medium High   | High          | High          |
| 4 | Medium        | Medium        | Medium High   | Medium High   | High          |
| 3 | Low           | Low           | Medium        | Medium High   | High          |
| 2 | Low           | Low           | Medium        | Medium        | Medium High   |
| 1 | Low           | Low           | Medium        | Medium        | Medium        |

3.4. Risk acceptance criteria

Risk acceptance criteria of PRV are affected by the management level of the user, the status of the PRV itself and the laws and regulations. In the case of this paper, the risk is acceptable if the risk is less than medium and the possibility is less than 4.

4. Failure and problems of PRV during inspection

As the overpressure protection device of pressure-bearing equipment, safety valve must meet the requirements of accurate opening, stable discharge, timely closing and reliable sealing in use. During the use of PRV, media temperature, pressure and physical properties will affect the performance of PRV, even leading to the failure of the PRV.

The inspection reports and service history of 5810 PRVs have been carefully consulted, some failures have been found in service, and some failures can only be found in the detach and verification of PRV. The statistics of problems encountered in the last detach and verification of PRV are shown in Table 3.

By analyzing the causes of these failures, it is found that the media of the PRV with spring fracture
contain H$_2$S in most case, and the media can directly contact with the spring through the micro leakage of the PRV itself, resulting in the spring stress corrosion cracking and finally fracture. Internal leakage of PRV and internal leakage of hand valves often occur in PRV which work medium is steam or other strong corrosive fluid \cite{[11-12]}. Corrosion is easy to cause sealing failure of hand valve or PRV body in front of PRV, while steam is generally not tightly sealed due to high temperature and unstable pressure. In addition, serious corrosion of valve core and valve seat, damage of gear ring and bearing pair may occur on typical PRV, failure of "O" seal ring and blockage may happen on pilot PRV.

**Table 3** Failure and problems in PRV inspection

| Faults and problems                  | Number of PRVs | Failure rate(%) |
|--------------------------------------|----------------|-----------------|
| Broken spring                        | 24             | 0.43%           |
| Bellows damaged                      | 2              | 0.04%           |
| Internal leakage of PRV              | 16             | 0.28%           |
| Internal leakage of hand valves      | 18             | 0.32%           |
| others                               | 24             | 0.43%           |

5. PRV evaluation process and calculation results

In this assessment, the medium of PRV is diverse, the medium pressure is from low pressure to high pressure, and the temperature is from low temperature to normal temperature to high temperature; the physical properties of medium vary greatly, including corrosive medium, non corrosive medium, self flowing medium and non self flowing medium under ambient temperature; there are impurity medium and clean medium. Therefore, this assessment will effectively analyze the medium in the environment where the PRV exists, and determine the risk of the PRV based on the assessment results. Before the evaluation, the inspection information, temperature, pressure and medium composition of each PRV are collected, and the process personnel of each unit determine whether the medium contains H$_2$S or solid particles, etc. and know whether the PRV has abnormal conditions such as jamming and flutter. The assessment time nodes of PRVs for the project are December 31 2017, 2018, 2019, 2020 and 2021. The results of risk assessment are shown in Figure 4-9.

![Figure 4](image1.png)  
**Figure 4.** Risk distribution in 2017.

![Figure 5](image2.png)  
**Figure 5.** Risk distribution in 2018.
Figure 6. Risk distribution in 2019.

Figure 7. Risk distribution in 2020.

Figure 8. Risk distribution in 2021.

The risk distribution of PRVs in each year is shown in Figure 9. It can be seen from the figure that with the increase of assessment time, the number of high-risk and medium high-risk PRVs increases significantly, and the overall risk increases year by year.

Figure 9. Risk distribution of PRVs in each year
6. Determination of inspection intervals of PRV

Based on risk acceptance criteria confirmed with the client, the following principles for determining the inspection interval of PRVs are established:

a) At the risk assessment time of December 31, 2021, if the calculated risk of PRV is medium risk (including the risk below medium level) and the probability of failure is less than 4, the inspection shall be carried out before December 31, 2021, with an inspection interval of 5 years.

b) In addition to the PRV whose inspection time is determined in a), at the risk assessment time point of December 31, 2020, if the calculated risk of PRV is medium risk (including the risk below medium level) and the failure probability is less than 4, the inspection shall be implemented before December 31, 2020, with an inspection interval of 4 years.

c) In addition to the PRV whose inspection time is determined in a) and b), at the risk assessment time point of December 31, 2019, if the calculated risk of PRV is medium risk (including the risk below medium level) and the probability of failure is less than 4, the inspection shall be implemented before December 31, 2019, with an inspection interval of 3 years.

d) In addition to the PRVs whose inspection time is determined by a), b) and C), at the risk assessment time point of December 31, 2018, if the calculated risk of PRVs is medium risk (including the risk below medium level) and the probability of failure is less than 4, the inspection shall be carried out before December 31, 2018, with an inspection interval of 2 years.

e) In addition to the PRVs whose inspection time is determined in a), b), c) and D), other PRVs shall be calibrated before December 31, 2017, with an inspection interval of one year.

In addition to the above principles, referring to the problems of PRVs found in use and inspection of other enterprises, the following problems shall be considered when determining the inspection interval:

(1) For the PRV discharged to the flare, high-pressure gas, low-pressure gas and other systems, due to the backflow of media, the PRV will directly contact with the flare gas containing H\(_2\)S and other media, resulting in potential risks such as spring fracture. In this case, the original inspection interval of PRV which is more than 3 years, should be reduced by 1 year;

(2) The inspection interval of all PRVs with stress corrosion tendency is one year, such as PRVs with working medium containing H\(_2\)S and strong alkali, except for bellows balanced PRVs;

(3) The inspection period of PRV with serious corrosion tendency is generally less than 1 year, such as the PRV on the top of atmospheric and vacuum tower and delayed coking reactor.

(4) For the PRV on the boiler drum, due to long-term operation under high temperature and pressure, the spring is prone to stress relaxation. According to the regulations, online thermal adjustment is usually required, and the inspection interval is not more than 1 year;

(5) For the PRV with solid particles in the medium and blocking tendency, the next inspection interval shall not exceed 3 years, such as heavy oil hydrogen production and coal char hydrogen production water washing section;

(6) If there is any abnormal PRV after inspection, the next inspection date shall be shortened, and it shall be inspected immediately if necessary;

(7) For the pilot PRV, the next inspection period shall not exceed 2 years, considering that the replacement of "O" sealing ring is usually required for 1-2 years;
(8) All PRVs that have been out of service for one year or more shall be reinspected before being put into use;

(9) For other PRVs under special circumstances, the inspection interval can be adjusted appropriately after consultation with the enterprise.

According to the results of risk assessment and the principle of delayed inspection, 3097 sets of PRVs can be extended for the next 5 years, 594 sets of PRVs can be extended for the next 4 years, 547 sets of PRVs can be extended for the next 3 years, 252 sets of PRVs can be extended for the next 2 years and 1 year. The number of PRVs is 1222. 80% of the PRVs achieved the purpose of delayed inspection.

7. Suggestions and Prospects

(1) H₂S is the most common corrosive medium in petrochemical enterprises. The failure of many PRVs is related to H₂S. For the PRV with severe corrosion tendency of such and other media, the user shall upgrade the materials of vulnerable parts such as spring and valve core seat. The corrosion hazard can be effectively reduced by using anti hydrogen cracking material or stainless steel material and changing the ordinary spring type PRV to bellows balanced PRV.

(2) The flare system of oil refining unit and chemical unit shall be designed separately to prevent the "reverse filling" of the medium containing H₂S in the flare system, which may result in the damage of PRV spring and other components.

(3) The assessment of PRV shall be continuous. After this assessment, the annual use and inspection of PRV shall be tracked and counted to verify the assessment results of PRV and adjust the inspection interval of abnormal operation PRV in time.

(4) The use, inspection and evaluation units of PRVs are usually not the same. The users have a better understanding of abnormal opening, jamming and flutter of PRVs; the inspection units have a better understanding of the blockage and internal leakage of PRVs; and the evaluation units have a better understanding of the PRVs of various refining and chemical enterprises, different units and different working conditions. In the past, the information statistics of PRVs were insufficient and each fought its own way. The use, inspection and evaluation units should jointly investigate the use of PRVs and record the use and inspection of PRVs in detail, so as to count the failure mode and probability of domestic PRVs.

(5) The risk acceptance criteria of PRV assessment are determined by the management level of the user, the status of the PRV itself and the laws and regulations. Usually, the risk acceptance criteria is set by the managers. But in China, the RBI method is a newly implied inspection means, the managers do not have the specialized knowledge to determine the risk acceptance criteria. Therefore, the risk acceptance criteria formulated by different enterprises is quite different. It is also a problem that the industry association needs to solve to formulate a reasonable and unified reference principle according to the current situation of domestic PRV inspection.

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