Corrosion Risks Assessment Management of Natural Gas Pipelines Based on TPI Management Mode

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Abstract. In order to clarify the goals of corrosion management of natural gas pipelines, achieve key, orderly, visual and dynamic management of indicators at all levels and get rid of trivial management, the TPI management was used to manage the corrosion block index of natural gas pipelines. Firstly, clarify the management objectives of the corrosion block of natural gas pipelines, and achieve the activity decomposition of the management objectives. Secondly, through the independent-coupling analysis of the risk and the Gray evaluation theory, it proposes the Gray consequence grade equation and the Gray risk matrix, which determines the TPI indicators, and develops an economic rating system. The results of the study indicate that the pipeline is in a critical stage and require the implementation of the targeted management. In addition, the risk value of the outer wall corrosion is the highest in the target activity, and the TPI indicators of the entire TPI system of the Nature Gas pipelines corrosion are as follows: the integrity of the outer protective layer, outer coating thickness, soil pH, soil salinity, soil sulphur, residual stress, sudden stress, design stress, SCC sensitivity, material mechanical strength, material corrosion resistance, inner coating thickness, protection potential, pigging quality, H2S content and CO2 content. And it establishes an economic evaluation model according to the TPI system.

1. Introduction
The safety and reliability of natural gas pipelines is the key to ensuring oil and gas transportation. According to relevant investigations, the highest proportion of the pipeline damage is corrosion, which accounts for 56%, and the Third-party damage is the second reason, which is 30%[2]. Pipeline corrosion will directly lead to the thinning of the pipe wall area and reduction of the pressure bearing capacity, and it is extremely prone to problems such as deformation, cracking and perforation[3]. It also seriously reduces the service life of pipelines, causing huge economic losses. Therefore, It’s necessary to analysis the basic events comprehensively and establish the key management indicators of pipeline corrosion[4-5]. Now, The China's Enterprise Management are most depend on the file management method, lacking of communication and clear goal and ignoring process management, only focusing on the management of results, which result the low efficiency, frequent accidents and low benefits. In response to this situation, South Korea and Japan are widely promoting TPI management[1], which uses "Top-Down" and "Emphasis" as the basic idea.

The China's Enterprise Management of the pipeline corrosion is mainly based on risk assessment, which focus on the risk and results of entire pipelines, This method does not pay enough attention to the monitoring indicators that could cause pipeline corrosion, and fail to achieve orderly, hierarchical
and visual management of indicators, which leads to the vagueness and low efficiency of the management. Once the accident occurs, it will cause a high risk and huge economic loss[6-9].

Pang et al[3] used multi-level evaluation theory to establish the weights of pipeline corrosion indicators; Wang et al[9] adopted the improved five-scale hierarchy theory and determined the pipeline corrosion indicators weights successfully; Liu et al[10] used multi-level fuzzy evaluation theory to study the related indicators weights. However, these methods have not established the key and hierarchical management of the corrosion indicators, which has caused certain ambiguity and difficulty in the management of risk indicators of pipeline corrosion.

According to above methods, this article adopts the risk theory in a further step and introduces the TPI management ideas. Firstly, through accident tree analysis, it decomposes pipeline corrosion area into active units and establishes a corrosion evaluation management model[12]; Secondly, through using the independent-coupling analysis of risk evaluation and the equation of the Gray consequence level, the Gray consequence level of each indicator and the TPI indicators were determined[12-16]. Finally, It establishes the Gray risk matrix to express the TPI indicators, which can realize the targeted, dynamic, and visual monitoring and maximum economic benefits through periodic evaluation[17-18].

2. The TPI management system

2.1. The meaning of TPI management
TPI, proposed by Peter Drucker, is the meaning of “Total productivity innovation”, that is, the productivity has been greatly improved, through the continuous innovation activities, to pushes all activities in one direction (Figure 1). He emphasized that only decompose goals can achieve effective management. TPI management mainly uses “Top-Down” and “Emphasis” as the basic idea, which link the activities of various departments with business objectives and clarify the contribution rate to the objectives.

Figure 1. TPI management means.

2.2. Decomposition of TPI target layer
In order to achieve a comprehensive goal, the goals between the various departments should be specific, and set lower-level goals so that when the goals are broken down, the goals between the departments could be aligned in one direction. In addition, when the goal is decomposed, it is necessary to repeatedly decomposed until it is concrete.

According to the situation and the accident tree theory, establish a corresponding department system for goal management (Figure 3). After each specific goal is set, the comprehensive goal will be set by a certain stage, sequence and discussion, and it is necessary to make a list of all accidents goals that the staff could see clearly (Figure 2).

Figure 2. Decomposition of goals tree. Figure 3. Target management department.
2.3. **TPI productivity system**  
After the enterprise achieves the management objectives, it also needs to further achieve strategic objectives and economic benefits. Through establishing an economic evaluation system based on TPI system, achieves economic evaluation (Figure 4).

![Figure 4. TPI productivity system.](image)

3. **Improvement technology of Target activity**  
Firstly, a new evaluation theory method is established through independent-coupling analysis of risks and grey theory. Then, it determines the comprehensive and secondary targets through target activity decomposition. Finally, this method is used to achieve the risk assessment of target activities and enterprise management, advancing with the times (Figure 5).

![Figure 5. TPI technical management system.](image)

3.1. **Frequency improvement technology of target activity**

3.1.1 **Frequency grade evaluation based on AHP.**  
AHP is one of the important methods to calculate the index weight of each layer. This method is simple and flexible. As a tool for evaluation, decision, and planning, it has been widely used in major fields. This article simplifies the 10/10 ~ 18/2 scaling method based on the 5-scale method, as shown in Table 1, to generate the judgment matrix of the pipeline corrosion model, which not only overcomes the boundary judgment ambiguity, but also satisfies consistency testing and make it easy for experts to compare the importance of indicators.

| Scale | Meaning |
|-------|---------|
| 5/5   | The importance of factor i and j is almost equal. |
| 7/3   | Factor i is more important than j |
| 9/1   | The importance of the Factor i is extremely higher than j |

Table 1. Principles of assignment by scaling method.
6/4, 8/2 Intermediate values of above adjacent judgments
Reciprocal The ration between factors \( i \) and \( j \) is denoted as \( a_{ij} \), otherwise, denoted as \( 1/a_{ij} \)

### 3.1.2 Normalization of target activity frequency.
The experts scored the importance, the interval is 0~1, of the pipeline corrosion index frequency based on personal experience, to establish a judgment matrix that satisfies: \( A \cdot W = \lambda_{\text{max}} \cdot W \) and the \( \lambda_{\text{max}} \) is the largest eigenvalue of matrix \( A \); \( W \) is the normalized eigenvectors of \( \lambda_{\text{max}} \), the \( W_i \) is the normalized weight value of \( W \).

### 3.1.3 Frequency grading of target activities.
The weight value determined by the eigenvector only reflects each indicator importance in terms of frequency, and indirectly reflects the occurrence probability of corrosion indicators in each region. In order to divide the weight value into the range of 0~1 and show in the risk matrix, without changing the importance of each indicator, it is necessary to linearize the index weight value, that is, the highest value will be expanded to 1, and the others will be expanded by the same multiple (Table 2).

| Risk weight (%) | Possibility of occurrence | Frequency level |
|-----------------|---------------------------|-----------------|
| 0~10            | Almost impossible         | 1               |
| 10~30           | Low possibility            | 2               |
| 30~50           | possible                  | 3               |
| 50~70           | High possibility           | 4               |
| 70~100          | Higher possibility         | 5               |

### 3.2 Independent-Coupling Technology of Risk and the Grey Theory
It innovatively proposals a grey consequence grade formula through the independent-coupling analysis of risk and grey assessment theory, and determines the grey consequence grade of each basic index of the pipeline corrosion target unit. the specific steps are as follows:

1. The analytic hierarchy process determines the frequency grade of corrosion index under each area.
2. The \( K \)th expert scores the \( j \)th basic index of the \( i \)th corrosion target unit in turn as \( d_{ijk} \).
3. Select \( e = (4,3,2,1) \) as the four-level Gray category risk value, and then use very serious, serious, general, and slight to describe the situation. Finally, Establish the Gray evaluation function.

\[
e = 1, \quad r_1(d_{ijk}) = \begin{cases} 
\frac{d_{ijk}}{4} & d_{ijk} \in [0,4) \\
1 & d_{ijk} \not\in [0,4) 
\end{cases} \quad e = 2, \quad r_2(d_{ijk}) = \begin{cases} 
\frac{d_{ijk}}{3} & d_{ijk} \in [0,3) \\
6 - \frac{d_{ijk}}{3} & d_{ijk} \in [3,6] \\
0 & d_{ijk} \not\in [0,6] 
\end{cases} \\
\]

\[
e = 3, \quad r_3(d_{ijk}) = \begin{cases} 
\frac{d_{ijk}}{2} & d_{ijk} \in [0,2) \\
4 - \frac{d_{ijk}}{2} & d_{ijk} \in [2,4] \\
0 & d_{ijk} \not\in [0,4] 
\end{cases} \quad e = 4, \quad r_4(d_{ijk}) = \begin{cases} 
1 & d_{ijk} \in [0,1) \\
2 - d_{ijk} & d_{ijk} \in [0,2) \\
0 & d_{ijk} \not\in [0,2] 
\end{cases} 
\]

4. Determine the Gray and comprehensive evaluation coefficient \( x_{ije} \) of the \( e \)th Gray category:

\[
x_{ije} = \sum_{i=1}^{n} r_i(d_{ijk}) \quad x_j = \sum_{e=1}^{4} x_{ije} \quad (1)
\]

5. Determine the \( e \)th Gray evaluation weight of \( W_i \) and the basic indicators weight vector:

\[
t_{ije} = x_{ije} / x_j \quad t = (t_{i1}, t_{i2}, \ldots, t_{ik}) \quad (2)
\]

6. The comprehensive evaluation weight matrix of the basic indicators of \( W_i \):
(7) Calculate the comprehensive risk value of the corrosion unit with \( n \) layers:

If the total unit \( W_i \) of each layer contains \( n \)-level subunits, and the matrix meet associative law of multiplication, the risk value of the total unit is calculated as follows:

\[
B_{i,a} = W_{i,a} \cdot R_{i,a} \cdot e = W_{i,a} \cdot (W_{i,a-1} \cdot (W_{i,a-2} \cdot \cdots (W_{i,1} \cdot (R_{i,1}) \cdots) \cdot e
\]

(4)

\[
B_{i,a} = W_{i,a} \cdot (\prod_{p=1}^{n-1} W_{i,p} \cdot R_{i,p}) \cdot e
\]

(5)

The risk value is generally determined by the probability and the consequences of the accident. In the above formula, it is obviously known that \( W_{i,a} \) is a vector group composed of the frequency, then combining the above formula can determine \( (\prod_{p=1}^{n-1} W_{i,p} \cdot R_{i,p}) \cdot e \) as the vector group composed of the basic index consequence level. Since it is based on Gray evaluation, it can be defined as the Gray consequence level.

(8) Calculate the Gray consequence level of the basic objectives of each corrosion unit:

\[
H_{i,a} = (\prod_{p=1}^{n-1} W_{i,p} \cdot R_{i,p}) \cdot e \quad (n \geq 2)
\]

(6)

\[
H_i = R_{i,1} \cdot e \quad (n=1)
\]

(7)

4. TPI index establishment for a natural gas pipeline corrosion

According to the decomposition of the TPI target layer after determining the total target, the TPI management system is established by expanding the total target combined with the accident tree. In addition, organizing 4 experts, 2 of whom are professors, and 2 are field-experienced experts and combining the risk scoring criteria score the frequency and risk of specific targets to establish a sample matrix. Finally, the TPI index and establish productivity evaluation system is determined.

4.1. TPI target system of a natural gas pipeline corrosion

Table 3. TPI target of a natural gas pipeline corrosion.

| Overall goal (Department) | Sub-goals (Department) | Specific goals |
|---------------------------|------------------------|---------------|
| Pipeline corrosion (W) (Headquarters) | External wall corrosion (W1) (Dept1) | Integrity of outer protective layer (X1), thickness of outer coating (X2), soil PH (X3), soil salty (X4), soil sulphur (X5), soil resistivity (X6), biological bacteria (X7), soil porosity (X8), soil stray current (X9) |
| | Inner wall Corrosion (W2) (Dept2) | Inner coating thickness (X19), protection potential (X20), pigging (X21), H2S content (X22), CO2 content (X23), water vapor content (X24), transport flow rate (X25), transport pressure (X26), transport temperature (X27) |
| | Intergranular corrosion (W3) (Dept3) | Residual stress (X10), external stress jump (X11), surrounding salt content (X12), design stress (X13), material sensitivity to SCC (X14), |
| | Material properties (W4) (Dept4) | Material insulation (X15), material mechanical strength (X16), material heat resistance (X17), material corrosion resistance (X18) |
Figure 6. TPI target management system for a natural gas pipeline corrosion.

4.2. Frequency score of a natural gas pipeline corrosion target

\[
W_1 = \begin{bmatrix}
0.7 & 0.8 & 0.7 & 0.8 \\
0.6 & 0.7 & 0.6 & 0.7 \\
0.5 & 0.5 & 0.4 & 0.5 \\
0.5 & 0.5 & 0.6 & 0.4 \\
\end{bmatrix},
W_2 = \begin{bmatrix}
0.5 & 0.4 & 0.5 & 0.4 \\
0.5 & 0.4 & 0.3 & 0.4 \\
0.3 & 0.3 & 0.4 & 0.3 \\
0.2 & 0.3 & 0.2 & 0.2 \\
\end{bmatrix},
W_3 = \begin{bmatrix}
0.3 & 0.4 & 0.3 & 0.2 \\
0.3 & 0.3 & 0.4 & 0.3 \\
\end{bmatrix},
W_4 = \begin{bmatrix}
0.4 & 0.4 & 0.4 & 0.4 \\
0.7 & 0.6 & 0.6 & 0.6 \\
0.3 & 0.3 & 0.4 & 0.4 \\
0.6 & 0.7 & 0.7 & 0.7 \\
\end{bmatrix}
\]

\[
W = \begin{bmatrix}
0.8 & 0.8 & 0.7 & 0.8 \\
0.7 & 0.7 & 0.6 & 0.7 \\
0.5 & 0.4 & 0.5 & 0.4 \\
0.4 & 0.3 & 0.2 & 0.2 \\
0.3 & 0.3 & 0.2 & 0.2 \\
\end{bmatrix}
\]

4.3. Risk score of a natural gas pipeline corrosion target

\[
D_1 = \begin{bmatrix}
4.0 & 3.5 & 3.5 & 4.0 \\
3.5 & 3.5 & 4.0 & 3.5 \\
3.5 & 3.5 & 4.0 & 3.5 \\
3.5 & 3.5 & 3.5 & 3.0 \\
3.5 & 4.0 & 4.0 & 3.5 \\
3.0 & 3.5 & 3.0 & 3.5 \\
3.0 & 3.0 & 3.5 & 3.0 \\
2.5 & 3.0 & 3.0 & 2.5 \\
2.5 & 2.5 & 2.5 & 3.0 \\
\end{bmatrix},
D_2 = \begin{bmatrix}
3.5 & 3.5 & 4.0 & 3.5 \\
3.5 & 3.0 & 3.0 & 3.5 \\
4.0 & 3.5 & 3.5 & 3.5 \\
3.5 & 3.0 & 3.5 & 3.0 \\
2.0 & 2.5 & 2.0 & 2.0 \\
3.0 & 3.5 & 3.0 & 3.0 \\
2.0 & 2.5 & 2.0 & 2.0 \\
3.0 & 3.0 & 3.5 & 2.5 \\
2.5 & 3.0 & 3.0 & 2.5 \\
\end{bmatrix},
D_3 = \begin{bmatrix}
4.0 & 4.0 & 3.5 & 3.5 \\
3.5 & 4.0 & 3.5 & 3.5 \\
3.5 & 3.5 & 3.0 & 3.5 \\
2.0 & 2.5 & 2.0 & 2.0 \\
2.0 & 2.5 & 2.0 & 2.0 \\
3.0 & 3.0 & 3.5 & 3.0 \\
3.0 & 3.0 & 3.5 & 3.0 \\
3.5 & 4.0 & 4.0 & 3.5 \\
2.0 & 2.5 & 2.0 & 2.0 \\
\end{bmatrix},
D_4 = \begin{bmatrix}
2.0 & 1.5 & 2.0 & 2.0 \\
3.0 & 3.5 & 3.0 & 3.5 \\
2.0 & 2.0 & 2.0 & 2.0 \\
3.5 & 4.0 & 4.0 & 3.5 \\
\end{bmatrix}
\]

4.4. TPI index of a natural gas pipeline corrosion

The results show that the Gray risk value of overall target is 3.033, which needs pay more attention. the outer wall corrosion risk is 3.324, which is a critical management part. According to the risk acceptance curve, it determines TPI index, which is the key management index, belongs to the red area under the corresponding target system (Figure 7). So, the TPI basic indexes of the outer wall corrosion target are as follows: integrity of outer protective layer, thickness of outer coating, soil PH, salinity and sulfide; which the Gray risks to value is 17.74 / IV, 8.974 / IV, 6.84 / III, 6.66 / III, 6.84 / III orderly. The TPI basic indexes of inner wall corrosion target are as follows: inner coating thickness, protection potential, pigging quality, H2S content, CO2 content; which the Gray risks to value is 10.4/IV, 6.61/III, 8.46/III, 10.51/IV, 6.78/III orderly. The TPI basic indexes of intergranular corrosion target are as follows: residual stress, stress jump, design stress; SCC sensitivity; which the Gray risks to value is 17.74/IV, 13.22/IV, 7.64/III, 7.85/III orderly. The TPI indexes of material property target are
as follows: material mechanical strength, material corrosion resistance; which the Gray risks to value is 11.81/IV, 12.84/IV orderly.

Figure 7. Gray risk matrix.

The irregular changes in target activity frequency and harmful consequences result in changes in evaluation indicators, realizes the indicators dynamic and visual management and provides a good help for accident prevention and effectively realizes the economic benefits of business operations.

4.5. Productivity evaluation of a natural gas pipeline corrosion TPI system

4.5.1 Contribution rate of basic target.
According to the target accident tree distribution under the TPI system, the contribution rate can be evaluated by the structure importance. The solution of structural importance is mainly to simplify the calculation by the minimal cut sets, which can ensure sufficient accuracy without being too cumbersome. After calculating the minimal cut sets, the structural importance can be determined according to the following formula:

\[ I_r = \sum_{i, x_j} \frac{1}{2^{n_j-1}} \]

Kr-the rth minimal cut sets; \( n_j \) - The number of basic events of the minimal cut sets containing \( x_j \).

4.5.2 Productivity economic evaluation system.
According to Figure 4, the productivity economic system of a natural gas pipeline corrosion is established (Figure 8).

Figure 8. A natural gas pipeline corrosion productivity economic evaluation system.
5. Conclusion
In this paper, it is shown that the pipeline is in a critical stage and require the implementation of the targeted management, and the risk value of the outer wall corrosion is the highest in the target activity, and the TPI indicators of the entire TPI system of the Gas pipelines corrosion are as follows: The integrity of the outer protective layer, outer coating thickness, soil pH, soil salinity, soil sulphur, residual stress, sudden stress, design stress, SCC sensitivity, material mechanical strength, material corrosion resistance, inner coating thickness, protection potential, pigging quality, H2S content, and CO2 content.

The innovation of this article is the combination of the TPI management thinking and the general risk theory, and it puts forward the grey consequence grade equation and the Gray matrix to realize the dynamic management of basic indicators, proposes a new evaluation technology about the risk management, achieves independent-coupling analysis of risks and the Gray theory from frequency and the consequences to the whole system separately. The Introduction of TPI indicators and the TPI economic evaluation System help to realize real-time monitoring and dynamic economic forecast and evaluation.

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