Reliability Analysis of Oil and Gas Pipelines Based on Step-Down-Stress Testing in Corrosive Environments

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Reliability analysis provides a basis for the anticorrosion design and maintenance strategy of pipelines. This paper introduces a calculation method for corroded pipeline life reliability by step-down-stress testing (SDST) and Weibull distribution. SDST is used to obtain the corrosion rate of N80 steel under the action of an H2S and CO2 environment at four different temperatures. The Arrhenius model is used to establish the conversion model of failure time and then obtain quasi-samples with parameters. The quasi-samples are used to estimate the parameters of the Weibull distribution, and finally, we can obtain the reliability function of the corroded pipeline. The life reliability curve shows that the pipeline life decreases with the increase of temperature, and when the operation temperature is 363 K, the average life is 10.09 years, which is far less than the designed life. The life reliability of the pipeline decreases with increasing time, when the service life of a pipe with 90% reliability is approximately 7.4 years, and with 50% reliability, it will increase to approximately 10.2 years. With increasing temperature, the average life of the pipeline declines, and at the same temperature, the higher the reliability is, the lower the average life of the pipeline, which provides a reference for the rational use and maintenance decisions of N80 steel pipes. The life reliability of a pipeline for which the operating time is shorter has a smaller temperature effect than that the operating time is longer. This proves that the effect of temperature on life reliability accumulates. This paper strives to provide a scientific basis for the safety management of oil and gas pipelines.

1. Introduction

The reliability of oil and gas pipelines has been a key focus of petroleum engineering. For pipelines laid in different regions, corrosion is more inevitable under the influence of complex terrain, soil environments, pipeline structures, and conveying media [1]. Corrosion will lead to the pipeline failure, the leakage of oil and gas, and safety accidents at the worst [2–4]. For example, in 2000, the natural gas pipeline of EPNG (El Paso Natural Gas Company) in Carlsbad, New Mexico, broke and caused an explosion and fire. The accident investigation report of the NTSB (National Transportation Safety Board) showed that the accident was caused by serious internal corrosion, which made the pipe wall thin, the pipe wall therefore could not bear the internal pressure and burst. At present, most of the corrosion forms of pipelines are CO2 corrosion and H2S corrosion, both of which often exist in crude oil and natural gas at the same time and will cause damage, perforation and leakage of pipelines. It will not only cause serious harm to the public and pollute the environment but also cause great economic loss to the enterprise. In the LittleGreek oil field (in the United States), due to the lack of CO2 and H2S corrosion protection measures, the oil field pipelines were perforated within 5 months after they were put into production. Therefore, CO2 corrosion and H2S corrosion will not only cause a serious waste of steel resources, shorten the service life of pipelines, and increase the cost of pipeline maintenance but also seriously threaten the safe exploitation of oil and gas resources. In order to ensure the safe operation and timely maintenance for in-service pipelines, it is necessary to study the reliability of pipelines subjected to CO2 and H2S corrosion.

The reliability calculation methods have been applied in the safety management of oil and gas pipelines since the 1960s, and many scholars have carried out research
Regarding pipeline reliability calculation methods. Based on a large amount of historical data and various documents, Bush [5] obtained the reliability data of pressure pipes in an intuitive statistical way and found that the failure probability of large-scale pressure pipes was approximately $10^{-4}$ to $10^{-6}$ times a year, large-scale pipes means the nominal diameter of the pipeline is more than 200 mm (8 in) and otherwise the pipes are small-scale. And further analysis showed that the reliability of large-scale pipes was higher than that of small-scale pipes [6]. Alhammed [7–9] assumed that the corrosion process of carbon steel pipelines follows the power function and examined the residual wall thickness of pipes as a parameter to establish the stress calculation model. This study then used the first-order second-moment method (FOSM) to calculate the life reliability of the pipe. Sadiq [10] used the Monte Carlo method to calculate the corrosion failure reliability of a gray cast iron pipeline, fitted the probability distribution function of time to pipeline failure, and analyzed the sensitivity of the corresponding parameters. Davis [11] studied the reliability of pipelines with randomly distributed cracks and analyzed the failure of pipelines caused by the growth of initial cracks under a static load. Lee [12] studied the influence of defect geometry size on pipeline failure probability.

In general, there are two main forms of research methods for pipeline reliability: one is based on the statistical analysis of historical data or engineering experience to calculate the reliability; the other is to analyze the reliability based on indirect models, and the indirect models are to calculate the pipeline reliability results by analyzing the probability distribution law of influencing factors, these influence factors are usually the high-risk characteristics of pipelines. The material properties, loads, and geometric dimension parameters of the pipelines are all influencing factors for the reliability, and the reliability calculation models also have some variables that affect the final reliability analysis results. However, many of these influencing factors and variables are limited by the detection environment, detection methods, cost, and other external conditions, which make it difficult to obtain accurate values of those influencing factors. The inaccurate values of influencing factors and variables lead to the inaccuracy of the final reliability for the pipelines. Therefore, to make a meaningful analysis of the reliability of the pipelines, the influence of the uncertainty of the influencing factors and variables must be considered, and the uncertainty analysis are usually based on probability and statistics theories.

Furthermore, the studies of pipeline reliability indirect models are mostly based on the random probability function of parameters and loads and to determine the reliability by calculating the residual strength or the residual life of the corroded pipeline. Based on ASME B31G, DNV-RP-F101, API-579, PCORRC, SHELL-92, and other criteria, Velazquez [13] combined the pipeline failure data provided by the International Pipeline Research Council (PRCI) and used the Monte Carlo method to analyze the reliability of pipelines. Because the analysis method was based on various criteria, the key was to take the residual strength as a variable to calculate reliability, which also provided the original guidance for a large number of subsequent reliability analysis studies. Nahal [14] investigated the effects of residual strength on the irregular zones of pipeline corrosion and computed the failure probability and reliability index of various corroded areas. Nahal [15] also used residual strength coupled with the probabilistic model to find the limit-state function and calculated the structure reliability index of pitting corrosion in pipelines. Timashev [16] used the Markov process to describe the pipeline degradation-simultaneous growth of corrosion and reduction of residual strength, proposing a method for assessing the reliability of defective pipelines.

It was concluded that the residual strength is related to the study of the allowed corrosion depth or the maximum defect size of the pipeline under a certain operating pressure [17]. The residual life is mainly related to the study of the corrosion situation; it is used to predict the residual life of pipeline and provide a reference for determining the inspection cycle and maintenance strategy [18]. The studies on residual strength are more mature; some evaluation criteria such as ASME B31G [19, 20], DNV-RP-F101 [21], and API [22] are widely used, and there also many methods, such as finite-element analysis and elastic-plastic mechanics theory, which could be used in these studies [23, 24]. However, the aforementioned studies provide some references for the reliability calculation of pipeline, and certain effect has been achieved, but a large number of data in the methods are from simulation, or based on empirical formula, the accuracy of reliability calculation results is low and weak applicability. Compared with residual strength, there are few studies on residual life because the corrosion factors are complex and changeable and the mathematical model of life is hard to set up; thus, the life rules are not easily discovered.

For pipeline in corrosive environment, the most direct variable influencing the reliability is corrosion information, and the change of residual strength is indirect, that is, the pipeline strength changed because of corrosion process. Thus, it is more reasonable to calculate pipeline reliability by analyzing the residual life based on the change of corrosion information.

Therefore, at present, the production technology and material components of pipelines have been changed, more and more high-strength steel is used in pipelines. However, due to different steel grades, the reliability empirical calculation methods derived from experimental data and the data recorded for analyzing pipeline reliability in the past are not suitable for analyzing the pipeline in operation now. And it leads to inaccuracies in the reliability analysis for pipelines. To calculate the reliability of corroded pipeline life accurately, ensure timely maintenance or replacement of pipeline and safe transportation of oil and gas. In this paper, we studied the reliability of pipelines corroded by CO$_2$ and H$_2$S. This method is intended to obtain corrosion data based on SDST, assuming the failure time of the corroded pipelines will follow the Weibull distribution and combining the accelerated factor and Arrhenius function to build the conversion model for corrosion failure time. The quasi-sample had been obtained by the conversion model, which estimated the parameter values of the Weibull distribution.
Then, the reliability function for the pipeline was established. SDST can greatly improve the efficiency of testing, and more suitable for obtaining the data of long-life pipeline. The Weibull distribution has strong applicability for small sample testing data. By the reliability analysis of pipeline steel at different temperatures, it provides a reference for the pipeline corrosion prevention and maintenance work.

This paper is organized as follows: Section 2 introduces the accelerated degradation process, including the failure degradation process, the step-down stress testing, the accelerated model, and the accelerated factor. Section 3 describes the Weibull distribution of pipeline life and gives a method for parameter estimation. Section 4 provides an example to validate the reliability calculation method and Section 5 discusses and analyses the calculated results. Finally, Section 6 provides the conclusion and policy implications of this paper.

2. Accelerated Degradation Process

2.1. Failure Degradation Process. For most industrial equipment, the failure rate is a function of time and the failure curve, usually called the bathtub curve [25]. The bathtub curve shows the change in reliability in the whole life cycle of the product from putting it into operation to scrapping. It is generally known that the shape of the curve is high at both ends and low in the middle, and therefore, the change in the failure rate can be divided into three stages with the increase in service time, that is, infant mortality, random failures, and wear out.

For pipelines, the failure rate caused by corrosion is mainly in the third stage of their operation life, and the degradation data in this stage are of analytical significance. Pipelines are long-life and high-cost equipment; the designed service life values are generally 15 to 25 years, and the construction cost per kilometer is $1.5 to $4 million [26]. Moreover, through insufficient attention, the historical data (especially related to safety and reliability) regarding pipelines are often lacking in various countries. Thus, it is not easy to obtain a large amount of degradation data for the equipment with short-life and low-cost. The degradation data need to be obtained through experiments. In general, the conventional experiment is carried in a simulated pipeline operation environment, but the experimental time and cost will not allow the whole experiment process to last the whole pipeline life. Therefore, due to the limitation of experiment time and cost, most degradation data are obtained in the former two stages of operation life. According to the degradation rule of the failure rate, the degradation data are not suitable for reliability analysis [27]. Therefore, in order to solve this problem, it is necessary to use accelerated degradation models to analyze the reliability, which includes accelerated testing and degradation models.

2.2. Accelerated Degradation Model

2.2.1. Accelerated Testing. Accelerated testing was proposed by the Rome Air Development Center [28]. It is a method based on reasonable engineering and statistical assumptions, using the statistical model related to the physical failure law to convert the reliability information in the accelerated environment beyond the normal stress level and obtaining the numerical estimation of the reliability characteristics for a specimen under the rated stress level. Tal [29] demonstrated in his research that accelerated stress testing could be used to shorten the test time. Turner [30] put forward a quantitative accelerated life test that delivered accurate reliability data and addressed the limitations imposed by conventional reliability tests. Krasich [31] proposed carrying out reliability verification based on the accelerated life test and focused on the expression of reliability under various environmental stresses. Krasich [32] also proposed the sequential test scheme of exponential life based on the accelerated test under multiple environmental stresses.

Accelerated testing applies stress beyond the normal level to the pipelines to obtain degradation data. Compared with degradation data obtained by normal stress, these degradation data are more relevant to the later period of operation life, so they are more suitable for the reliability analysis of pipelines.

2.2.2. Degradation Models. For the degradation model, the degradation path model was commonly used in the early stage. There are two ways to build the degradation path model. One is to obtain the degradation path model based on the failure mechanism of the product, that is, to obtain the model by the physical reaction process and the chemical reaction process that lead to the product failure [33, 34]. Lu and Meeker [35] used the paired fatigue failure model to establish the degradation path model and predict the product life. However, more studies on the degradation path model are based on experience regression by statistical analysis of degradation data. Then, regression curve fitting is used to generate the degradation path of products. Cui [36] studied reliability assessment research on metal oxide semiconductor field effect transistors based on degradation data.

In the later stage, the degradation model based on degradation distribution and the stochastic process was developed by studying the random distribution characteristics of the degradation. Yang and Xue [37] used normal distribution to describe the distribution characteristics of degradation and then used the least square method to estimate the parameters. Zuo and Jiang [38] and Huang and Dietrich [39] used Weibull distribution to describe the distribution law of the degradation, but different methods were used to estimate the parameters. Sun [40] put forward the Gauss–Poisson joint distribution to describe the degradation distribution characteristics of the capacitor when studying the degradation failure of the metal film pulse capacitor. Jayaram [41] established a reliability model based on the degradation exponential distribution. In addition to the models described earlier, there are other degradation models in relevant research and applications: a degradation model based on Poisson shock [42] and a degradation model based on the continuous time Markov model [43, 44]. This paper uses Weibull distribution to describe the failure process of pipelines, and Section 3 describes the details.
2.2.3. Time Conversion Process. There is assumed to be a sequence of decreasing stresses $S_k, S_{k-1}, \ldots, S_1$ in SDST, where $S_k > S_{k-1} > \ldots > S_1$. SDST is the testing in which the stress applies different stresses in different time periods, and the stress is stepped down gradually. For high-reliability and long-life equipment, the shape parameter of the Weibull distribution is $m > 1$. Zhang [45] has proved that the efficiency of SDST is higher than that of step-up-stress testing (SUST) when $m > 1$, so this paper uses SDST to obtain the degradation data of pipelines. Because the pipeline is a long-life equipment, it is impossible for SDST to continue until the pipeline has completely failed. Thus, in order to reduce the test time, censoring testing must be carried out. The censoring data contain incomplete failure information. However, combined with the statistical analysis of life distribution, the obtained life information is still reliable. In this paper, the failure data are obtained based on type-1 censoring testing, that is, the life test that stops at a specified time. The data under different stresses are shown as follows:

$$S_k: t_{k1}, t_{k2}, \ldots, t_{kr_k},$$

$$S_{k-1}: t_{(k-1)1}, t_{(k-1)2}, \ldots, t_{(k-1)r_{k-1}},$$

$$S_1: t_{11}, t_{12}, \ldots, t_{1r_1},$$

(1)

where $r_k$ is the sampling number. Compared with the full sample testing, censoring testing will reduce the test time and ensure life reliability.

The failure time data under these stresses are not the full data, except for the highest stress, because the failure times caused by each stress do not include the cumulative failure time before it. This means that the stress effects caused by a former stress are not included. Therefore, the testing needs to obtain the cumulative failure time by the data conversion between the stresses. A simple example of the conversion process is shown in Figure 1, assuming that there are three different stresses in SDST, where $S_1 > S_2 > S_3$, and the acting time of each stress is $t_1, t_2,$ and $t_3$, respectively. The testing starts from $S_3$, down to $S_2$ after $t_3$, then down to $S_1$ after $t_2$, and stops at the end of $t_1$. The complete failure time of the whole testing process is not only the accumulation of $t_1, t_2,$ and $t_3$ but also should include the conversion time where $S_1$ and $S_2$ acted on $S_3$, which is $(t_{31} + t_{21} - t_3 - t_2)$. Thus, the total testing time is the sum of $t_{31}, t_{21},$ and $t_1$.

2.3. Accelerated Model and Accelerated Factor

2.3.1. Accelerated Model. The accelerated model is derived from the physical principle related to the failure mechanism, which expresses the relationship between the equipment life and the stress. Generally, the mathematical expression of the accelerated model is known but the model parameters are unknown. Therefore, the main aim of the accelerated life test is to calculate the parameters through the experimental data. Meanwhile, the failure mechanism of equipment under different stresses is the same, so the accelerated model under different stresses can be expressed as follows:

$$\ln \theta = \sum_{i=0}^{n} a_i \varphi_i(S),$$

(2)

where $\theta$ is the life characteristics, $\varphi_i(\cdot)$ is the function with stress, and $a_i$ is the coefficient. When $i = 1$ and $\varphi_i(S) = 1/S$, equation (3) is the Arrhenius model. The commonly used accelerated models include the Arrhenius model, inverse power law model, Eyring model, and so on.

2.3.2. Accelerated Factor. The accelerated factor is used to express the conversion rule of failure information and reflect the equipment lifetime under different stresses [46, 47]. Assuming that $t_i$ and $t_j$ are the action time acted on by stresses $S_i$ and $S_j$, respectively, if the cumulative failure probability of $S_i$ is the same as $S_j$, the accelerated factor is defined as follows:

$$r_{ij} = \frac{t_j}{t_i},$$

(4)

where $r_{ij}$ is the accelerated factor.

It has been assumed that the life of the pipeline follows Weibull distribution. Combined with the accelerated function $\ln t = a_0 + a_1 \varphi_1(S)$, let $\ln t_1 = a_0 + a_1 \varphi_1(S_1), \ln t_j = a_0 + a_1 \varphi_1(S_j)$. The $t_i$ and $t_j$ are

$$t_i = \exp[a_0 + a_1 \varphi_1(S_1)], t_j = \exp[a_0 + a_1 \varphi_1(S_j)]$$

(5)

$t_i/t_j$ is expressed as $t_i/t_j = \exp[(a_0 + a_1 \varphi_1(S_1))/\exp(a_0 + a_1 \varphi_1(S_j))] = \exp[a_1 (\varphi_1(S_1) - \varphi_1(S_j))]$.

And the conversion formula is as follows:

$$t_i = \exp[b (\varphi_1(S_1) - \varphi_1((S_1)))]t_j,$$

(6)

with

$$b = a_1.$$

(7)
where $b$ is the ratio of the coefficients; $a_0$ and $a_1$ are the coefficients of the accelerated function; and $S_i$ and $S_j$ are stresses.

Equation (3) shows that the conversion formula is determined by parameter $b$ and the function $\varphi_i(S)$. If $H(i) = \varphi_1(S_i) - \varphi_1(S_j)$, then Equation (3) becomes

$$t_j = \exp[bH(i)]t_i.$$  (8)

The pipeline failure time each stress acts on is converted to the lowest stress by Equation (4), and the full failure time data are obtained as follows:

$$t_{k1}, t_{k2}, \ldots, t_{kr_k}, \exp[bH(k)]t_{kr_k} + \exp[bH(k-1)]t_{kr_{k-1}}, \exp[bH(k)]t_{kr_{k-1}}, \ldots,
\exp[bH(k)]t_{kr_{k-r_k+1}}, \ldots, \sum_{r=2}^{k} \exp[bH(i)]t_{ir_{r_k}} + \exp[bH(1)]t_{ir_{1_k}},$$

$$\sum_{r=2}^{k} \exp[bH(i)]t_{ir_{r_k}} + \exp[bH(1)]t_{ir_{1_k}}, \ldots,$$

$$\sum_{r=2}^{k} \exp[bH(i)]t_{ir_{r_k}} + \exp[bH(1)]t_{ir_{1_k}}.$$  (9)

The full failure data are also called quasi-samples because they contain the unknown parameter $b$.

3. Distribution of Pipeline Life

3.1. Weibull Distribution of Pipe Life. Weibull distribution is widely used in the data processing of various life reliability experiments. It was introduced by the Swedish physicist Wallodi Weibull in 1939. In a paper published in 1951 [48], he used Weibull distribution to analyze a large amount of failure data, including the yield limit of steel and the fatigue life of st-37 steel. He pointed out that the advantages of Weibull distribution lie in its applicability to small samples and its strong adaptability to various types of test data while establishing the important position of Weibull distribution in the statistical analysis of test samples.

Weibull distribution is widely used in reliability engineering, especially in the distribution form of the cumulative failure of equipment. It is derived based on the weakest link model. Therefore, the life of equipment that stops operating globally caused by a local failure can be regarded as following Weibull distribution. The fatigue strength, fatigue life, wear life, and corrosion life mostly follow Weibull distribution [49]. Schneider [50] reported work based on the Lieberman–Resnikoff sampling process and proposed a reliability sampling method for Weibull distribution. Yang [51] used the behavior degradation test to develop the no-failure reliability verification test method for Weibull distribution products. Kim [52] established a reliability sampling method based on the accelerated test for Weibull distribution with unknown shape parameters. Chung [53] studied the reliability sampling scheme of Weibull distribution based on step-up-stress accelerated life testing. Therefore, the pipe life distribution caused by corrosion can be expressed using Weibull distribution. This paper uses a two-parameter Weibull distribution to represent the life distribution of a pipeline. The probability density function of Weibull distribution is defined as follows:

$$f(t) = \frac{m}{\eta} \left(\frac{t}{\eta}\right)^{m-1} \exp\left[-\left(\frac{t}{\eta}\right)^m\right].$$  (10)

The cumulative distribution function is defined as follows:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^m\right].$$  (11)

The reliability function is defined as follows:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^m\right].$$  (12)

The average life function is defined as follows:

$$E(t) = \eta \left(1 + \frac{1}{m}\right),$$  (13)

where $\Gamma(1 + 1/m)$ is the Gamma function; $t$ is the pipeline failure time; $m$ is the shape parameter; and $\eta$ is the scale parameter. In the failure analysis of pipelines, the shape parameter is related to the failure mechanism. When $m < 1$, the life distribution of the pipeline belongs to the infant mortality range; when $m = 1$, the life distribution belongs to accidental failures; when $m > 1$, the life distribution belongs to the wear-out period. That is, the life curve of Weibull distribution is consistent with the bathtub curve.

3.2. Parameter Estimation. There is unknown parameter $b$ in the quasi-sample, so the parameters of Weibull distribution cannot be determined by the general calculation methods, for instance, the least square estimation method. However, the maximum likelihood estimation method and the inverse moment estimation method can be used. In this paper, we used the inverse moment estimation method to calculate the parameter value. The specific steps of parameter determination are as follows:

1. For Weibull distribution $W(m, \eta)$, the sample size of failure data is $n$, and the quasi-sample is assumed to increase as follows:

$$t_1(b) < t_2(b) < \ldots < t_n(b).$$  (14)

2. Using the quasi-sample, the BLUE (Best Linear Unbiased Estimator) or GLUE (Good Linear Unbiased Estimation) of $m^{-1}$ can be calculated as follows:

$$\bar{m}^{-1} = \sum_{i=1}^{r} C(n, r, i) \ln t_i(b),$$  (15)

if $r > 25$
\[ \bar{m} = \frac{1}{nk_{r,n}} \sum_{i=1}^{r} \ln t_i(b) - \ln t_2(b), \]  
(16)

where \( C(n, r, i) \) and \( nk_{r,n} \) can be obtained by referring to the reliability test table [54]. \( T_i \) is one of the quasi-samples, and the selection method of \( s \) is as follows:

\[ s = \begin{cases} 
  r, & r \leq 0.9n, \\
  n, & r = n \text{ and } n \leq 15, \\
  n - 1, & r = n \text{ and } 16 \leq n \leq 24, \\
  [0.892n] + 1, & r = n \text{ and } n \geq 25.
\]  
(17)

(3) \( T \) is assumed to be the pipeline life, because \( T \sim W(m, \eta) \), then \( T^m \sim E(1/\theta) \), where \( T \sim W(m, \eta) \) means \( T \) follows Weibull distribution and \( T^m \) follows exponential distribution, \( \theta = \eta^m \).

\[ \begin{align*}
  W'_1 &= nt_1^m (b), \\
  W'_2 &= (n-1) \left[ t_2^m (b) - t_1^m (b) \right], \\
  \quad \ldots \\
  W'_r &= (n-r+1) \left[ t_r^m (b) - t_{r-1}^m (b) \right].
\]  
(18)

Then, \( W'_1, W'_2, \ldots, W'_r \sim E(1/\theta) \), where \( \theta = \eta^m, \eta^m \) is the lifetime parameter under the initial stress.

\[ u_i = \sum_{j=1}^{i} W_j = \sum_{j=1}^{i} t_j^m (b) + (n-i)t_i^m (b). \]  
(19)

The quasi-samples formed by \( u_i \) are as follows:

\[ -\ln \frac{u_1}{u_2}, -\ln \frac{u_2}{u_3}, \ldots, -(r-1)\ln \frac{u_{r-1}}{u_r} \]  
(20)

These samples follow the standard exponential distribution \( E(1) \). As the first origin moment of the standard exponential distribution is equal to 1, the first origin moment of the quasi sample is as follows:

\[ \frac{1}{r-1} \sum_{i=1}^{r-1} (-i \ln \frac{u_i}{u_{i+1}}) = 1. \]  
(21)

The values of \( m \) and \( b \) can be calculated by Equations (10) to (16). Because \( W'_1, W'_2, \ldots, W'_r \sim E(1/\theta) \), the samples \( W'_1/\eta^m, W'_2/\eta^m, \ldots, W'_r/\eta^m \) also follow the standard exponential distribution \( E(1) \) according to the inverse moment estimation method [55]; we can obtain the equation:

\[ 1 - \frac{1}{r} \sum_{i=1}^{r-1} \left( \frac{W'_i}{\eta^m} \right) = 1, \]  
(22)

that is, \( \eta_1 \) can be calculated by

\[ \eta_1 = \left[ \frac{1}{r} \sum_{i=1}^{r} t_i^m (b) + (n-r)t_i^m (b) \right]^{1/m}. \]  
(23)

4. A Case Study

4.1. Experimental Preparation. For the corrosion of pipelines caused by \( H_2S \) and \( CO_2 \), this paper conducted SDST under four temperatures, \( T_1 = 333 K \), \( T_2 = 343 K \), \( T_3 = 353 K \), and \( T_4 = 363 K \). The steel model of the pipeline was N80, for which the thickness was 12.7 mm. The chemical compositions of N80 are shown in Table 1. The schematic illustration of the autoclave is shown in Figure 2. The simulated corrosion environment is as follows: Preparation of simulated formation water with \( KCl \), \( NaCl \), \( NaHCO_3 \), \( CaCl_2 \), \( MgCl_2 \), \( Na_2SO_4 \), and distilled water, where the mass concentration of \( Cl^- \) is 50 g/L, the mass concentration of \( Ca^{2+} \) is 18 g/L, the mass concentration of \( Mg^{2+} \) is 2 g/L, the partial pressure of \( CO_2 \) is 1.2 MPa, and the partial pressure of \( H_2S \) is 0.014 MPa.

4.2. Experimental Steps. Before testing, the surface of the specimen was polished step by step with 400# and 600# sandpaper, removing the machining marks. Then, the oil was wiped off the surface, it was dried with cold air and finally weighed. The treated specimens are shown in Figure 3.

The treated specimens were placed in the autoclave, the corrosion medium was added to 3/4 volume of the autoclave and the autoclave was sealed quickly. High-purity \( N_2 \) was added for 12 hours to remove oxygen, the system was heated to the predetermined temperature, and then \( H_2S \) and \( CO_2 \) were added to the predetermined pressure. The flow rate of the medium relative to the steel specimen was set to 1 m/s by adjusting the rotary device, and the whole testing time was 72 hours. At the end of the experiment, the steel specimen was taken out of the autoclave, washed with water to remove the corrosive medium, and then washed with absolute ethyl alcohol to remove the water. Finally, the steel specimen was characterized by the weight-loss method. The corrosion rate of the specimen was calculated according to the weight difference before and after corrosion:

\[ v = C \cdot \frac{W_0 - W}{\rho At}, \]  
(24)

where \( C = 8.76 \times 10^4 \) is the conversion factor based on 365 days. \( W_0 \) is the weight before corrosion, and \( W \) is the weight after corrosion. \( T \) is the corrosion time. \( A \) is the corroded area of the specimen. \( \rho = 7.85 \text{ g/cm}^3 \) is the density of N80 steel.

The experiments were carried out at four temperatures (333 K, 343 K, 353 K, and 363 K), and 35 corrosion rate data points were obtained. As the pipeline is long-life equipment, the number of censored numbers is actually the number of samples, so these 35 corrosion rate data points were taken as the testing data, which are listed in Table 2. The corrosion rate value at a higher temperature is larger than that at a lower temperature on the whole. However, at a lower temperature, there is also a larger corrosion rate value.

According to the ASME B31G standard, when the ratio of the corrosion depth to pipe wall thickness is greater than 0.8, the pipe is considered to have reached complete failure; thus, the maximum corrosion depth of the pipeline is 10.16 mm, and the maximum corrosion time (i.e., failure time) is calculated as follows:

\[ t_i = \frac{10.16}{v_i}, \]  
(25)
where $v_i$ is the corrosion rate. The sample values of failure time are presented in Table 3.

4.3. Reliability Calculation. Arrhenius model is used as the accelerated model. Arrhenius studied the rates of chemical processes in 1880 and thought that the failure of equipment was generally due to physical or chemical processes. Temperature is an important factor for physical and chemical processes; therefore, temperature is the most commonly used stress in accelerated life tests, which is used for accelerating corrosion [56] and destroying insulation [57]. The function of Arrhenius model is as follows:

$$
\eta = Ae^{\frac{E}{kT}},
$$

where $\eta$ is the life scale parameter, $A$ is a constant, $E$ is the activation energy of the failure mechanism, $k$ is the Boltzmann constant, and $T$ is the thermodynamic temperature. Taking the logarithm of both sides of the formula, the linearization of Arrhenius model is performed as follows:
The number of samples is 35; letting $b_1 = \exp \left[-10/128139\right]^a$, $b_2 = \exp \left[-20/124509\right]^a$, and $b_3 = \exp \left[-30/120879\right]^a$, $t_{32}(b)$ could be expressed as follows:

$$t_{32}(b) = 3.1264 + 3.4593 * b_1 + 5.6972 * b_2 + 6.8348 * b_3. \quad (31)$$

Therefore, the parameter values of Weibull distribution are calculated as follows:

$$\begin{aligned}
\hat{m} &= \frac{35k_{35,35}}{\sum_{i=1}^{35} \ln t_i(b) - \ln (b')} \\
\sum_{i=1}^{34} (-i(\ln u_i - \ln u_{i+1})) &= 34\eta_l = \left(\frac{\sum_{i=1}^{35} t_i^m(b)}{35}\right)^{1/m}, \\
\end{aligned} \quad (32)$$

with

$$b' = 3.1264 + 3.4593 * b_1 + 5.6972 * b_2 + 6.8348 * b_3, \quad u_i = \sum_{j=1}^{i} t_j^m(b) + (35 - i)t_i^m(b), \quad (33)$$

where $s = 32$. By referencing the "reliability test table", we can determine that $35k_{35,35} = 50.7308$. Substituting the quasi sample into equations (27) and (28) and building the nonlinear equations for Weibull distribution parameters, the solution results of the equations can be obtained by computation.

By solving the equations, the estimated values of the parameters are $m = 5.832$, $\eta_l = 10.889$, and $b = 1.676$. From equation (22), we determined that the value of constant $a$ is 2.382. Therefore, the curve of the accelerated model is shown in Figure 4, and the accelerated equation for pipelines is as follows:

$$\text{In} \eta_l = 20.382 + \frac{1.676}{T_i} \quad (34)$$

Weibull distribution function of N80 steel is as follows:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta_l}\right)^{5.832}}. \quad (35)$$

The reliability function is as follows:

$$R(t) = \exp\left(-\frac{t}{\text{exp}[2.382 + 1.676/T_i]^{5.832}}\right). \quad (36)$$

where $T_i$ is the thermodynamic temperature. When the pipeline operating temperature is 363 K, the pipeline reliability curve is shown in Figure 5, and the average life is 10.09 years. The reliability of the normal operating pipelines should be more than 90%. Thus, if the operating temperature is 363 K and the protective layer has not been considered, the reliable operation life is 7.40 years. The calculated result is far from the designed service life (20 years); this shows the importance of the protective layer to the pipeline.

Based on the average life formula and reliability formula, the relationship between the life and temperature of pipelines under different reliability values is shown in Figure 6, and the relationship between the reliability and temperature of pipelines under different service life values is shown in Figure 7.
5. Discussion

5.1. Analysis of Reliability for Pipelines. Figure 4 shows that the life characteristics of an N80 steel pipeline decrease with rising temperature, which initially reflects the negative impact of temperature on the pipeline life. The curve of pipeline life reliability is shown in Figure 5. The life reliability of the pipeline decreases with increasing time; the decrease rate first increases and then decreases. This is because the corrosion reaction of H₂S/CO₂ accelerated with the increasing temperature in the early stage. Then, in the late stages, the corrosion is inhibited because the solubility of H₂S/CO₂ in the medium decreases and less-corrosive substances is generated. Meanwhile, the formation mechanisms of the corrosion products are changed. The inner surface of pipeline has formed a product membrane, which does not easily participate in the corrosive chemical reaction. The curve shows that the operating temperature can promote the chemical reaction of H₂S/CO₂ and the steel of the pipeline. Therefore, the pipeline operating in the H₂S/CO₂ environment should use a steel model that has good chemical resistance.

5.2. Analysis of the Relationship between Service Life and Temperature. Figure 6 shows that with increasing temperature, the average life of the pipeline declines. Meanwhile, at the same temperature, the higher the reliability is, the lower the average life of the pipeline. This is because the pipeline with a short average service time is affected by corrosion factors in a short time, so the pipeline could still be highly safe, and the reliability is higher than that for the pipeline with a long average service time. That is, the reliability probability of an N80 steel pipeline with a short service life is higher than that of a pipeline with a long service life. The service life of an N80 steel pipe with 90% reliability demand is approximately 7.4 years and that of an N80 steel pipe with 50% reliability demand will increase to approximately 10.2 years, which provides a reference for the rational use and maintenance decisions for N80 steel pipes.

5.3. Analysis of the Relationship between Pipeline Reliability and Temperature. As seen in Figure 7, the life reliability of the pipeline with a shorter operating time is less affected by temperature than that of a pipeline with a longer operating
time. That is, the reliability of a pipeline with long service time exhibits greater changes with the change in temperature than a pipeline with a short service time. For example, in Figure 7, the reliability difference between 300 K and 400 K is $0.1715 - 0.1691 = 0.0024$ when the pipeline is operated for 12 years and $0.9695 - 0.9693 = 0.0002$ when the pipeline is operated for 6 years. This proves that the effect of temperature on life reliability accumulates.

Compared with the normal stress testing, the testing time of SDST is greatly reduced, and saves a lot of manpower and material resources, and suitable for the acquisition of corrosion data for long service life pipelines. The life
reliability analysis results based on Weibull distribution can be used as a reference for the safety evaluation or maintenance strategy of corroded pipelines.

6. Conclusion

In this paper, we used SDST and Weibull distribution to analyze the reliability of pipelines in an H₂S/CO₂ environment. The corrosion rate data of corroded pipelines were obtained by SDST under four temperatures (333 K, 343 K, 353 K, and 363 K) and converted into quasi-samples. A two-parameter Weibull distribution was used to represent the life distribution of the pipeline. The quasi-samples were used to estimate the parameters of Weibull distribution, and finally, the reliability function of corroded pipeline was obtained. Based on the reliability function, we can know the life of the pipeline under different temperatures or different reliabilities, which provides a reference for maintenance decisions regarding pipelines. The main conclusions are as follows:

(1) The corrosion rate data for pipelines under different temperatures can be obtained by SDST, and the corrosion rate in the wear-out failure period of the pipeline is obtained under high temperature. As corrosion damage mainly occurs in the wear-out failure period, the corrosion rate data obtained by SDST has high reliability for pipeline analysis, and SDST also saves testing time and cost. The corrosion rate at a higher temperature is larger than that at a lower temperature, on the whole. However, at a lower temperature there is also a larger corrosion rate value.

(2) Weibull distribution can reflect the influence of pipeline corrosion defects on pipeline life. It is suitable to use the Weibull distribution as a model for N80 steel pipeline life distribution. The life reliability decreases gradually with the increase of time and temperature, and the life reliability of the pipeline with a shorter operating time is less affected by temperature than that with a longer operating time. This proves that the effect of temperature on life reliability accumulates.

(3) The experiment results show that the service life of an N80 pipeline cannot reach the designed service life. When the operating temperature is 363 K, the average life is 10.09 years. The reliability of the normal operating pipelines should be more than 90%; thus, if the protective layer has not been considered, the reliable operation life is 7.40 years, which is far from the designed 20 years.

Therefore, to prevent the corrosion damage of oil and gas pipelines caused by CO₂/H₂S, it is necessary to control the transportation conditions and the contents of corrosive media in the transportation of gas as much as possible, optimize the pipeline design, and apply some anticorrosion measures. The transportation conditions mainly include flow rate and pH value. If the flow rate of is too high, the corrosion scales on the inner wall will be destroyed by erosion, while the low flow rate will cause liquid accumulation in the lower part of the pipeline, which is more likely to form CO₂/H₂S aqueous solution and cause localized corrosion. In order to minimize the corrosion rate, the flow rate should be controlled in 3–15 m/s. At high pH value, CO₂/H₂S will react with carbon steel to form a protective layer, but low pH value will accelerate the corrosion process of CO₂/H₂S, and in order to control the corrosion, pH = 6 is a critical value. The contents of corrosive media could be reduced by dehydration technique, desulfurization technique, and deoxidization technique. The pipeline design can be optimized using protective measures. The lining, coating, or painting can be used to form an interlayer between the steel and the corrosive medium to reduce the corrosion process. Meanwhile, for the sudden change of flow state will form strong shear stress and cause damage to the protection layer, the pipeline elbows should be used as little as possible to prevent the sudden change of flow state. The commonly used anticorrosion measures are as follows:

(1) Using the corrosion inhibitors. At present, imidazoline inhibitors have excellent corrosion inhibition performance and good thermal stability for H₂S/CO₂ corrosion.

(2) Using corrosion-resistant alloy steel. Compared with conventional steel, corrosion-resistant alloy steel could depend on its corrosion resistance to H₂S/CO₂ corrosion.

(3) Using electrochemical anticorrosion technology. The main method is cathode protection method.

(4) Using inner coating. The inner coating of the pipeline can not only protect the inner wall but also increase the smoothness of the inner wall of the pipeline and reduce the friction loss. The cost of using inner coating is low and it has effective anticorrosion. The most used inner coatings of the pipeline include inorganic coating and organic coating.

In addition to anticorrosion measures, monitoring methods can also be used to monitor the corrosion influencing parameters and give early warning. The commonly used monitoring methods include corrosion weight-loss method, probe method, and manual measurement method. At present, the new ultrasonic corrosion monitoring technology can measure various common pipeline materials. More accurate corrosion information can be obtained by increasing monitoring sites and monitoring frequency. The pipeline with serious corrosion needs to be repaired or replaced in time to prevent disasters. Therefore, we need to make scientific maintenance plan. The pipeline can be divided into several pipe sections, and the corrosion condition of each section should be judged. For example, based on the number of serious corrosion points or the size of the corrosion area, the engineers can decide the implementation of maintenance and replacement work.

The pipeline maintenance or replacement needs more costs, and the cost must be considered when making maintenance and replacement plans. Therefore, it also needs to study of maintenance strategy optimization methods.
Condition-based maintenance (CBM) method is a good choice, by monitoring pipeline corrosion status founding problems and taking maintenance measures in time, CBM can greatly decrease corrosion hazards, reduce maintenance workload, and save a lot of manpower and cost.

Data Availability

The data used to supporting the study have been included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References


