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Data-Driven Urban Gas Pipeline Integrity Detection and Evaluation Technology System

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Abstract: At present, PE pipelines are widely used in urban gas pipeline networks. As pipeline safety is of great importance to the gas supply, this paper focuses on the safety and reliability of PE pipes during service. First of all, this paper analyzes the aging factors of PE materials and the failure forms and mechanisms of PE pipes. Second, the performance testing methods of PE pipelines are summarized, including pipeline pressure tests, pipeline condition inspections, welded joint inspections, mechanical performance tests, and physical performance tests. In addition, life prediction methods for PE pipelines are introduced and analyzed. The methods and applicability of tensile experiments and DSC experiments based on thermal oxygen aging are both analyzed, and the corresponding experiments are also carried out. On the basis of the above research, the technical system of the integrity detection and evaluation of urban gas pipelines is finally established. The system includes the integrity detection method of urban gas pipelines and the applicability evaluation and determination of retest cycles, which can provide a reference for the safe operation of urban gas pipeline networks.

Keywords: polyethylene pipe; pipeline failure; life predication; integrity detection

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1. Introduction

In recent years, the development of new materials, especially polymer materials, has contributed to the production of PE pipes. There are many advantages of PE pipes over traditional metal pipes in practical applications, such as corrosion resistance, high toughness, excellent flexibility, good scratch resistance, long service life, and so on [1]. Due to the enormous advantages and good applicability of PE materials, PE pipes have been widely used in gas, municipal, and nuclear power engineering, as well as other production and living fields, especially in urban gas pipelines. At the beginning of the 21st century, PE pipelines were used in 99% of the natural gas transmission system in North America [2], and they are also widely accepted in China.

1.1. Influencing Factors of PE Pipe Aging

Although PE pipe has many advantages, its aging problem has always affected the safety and lifespan of pipelines. During the PE aging process, the degradation of PE is delayed due to the presence of antioxidants, and it does not occur until the antioxidant is consumed [3].

The influencing factors of PE pipeline aging can be divided into internal and external factors. Internal factors include crystallinity, density, molecular weight distribution, molecular branching chains, and the introduction of metal ion impurities during processing.

These factors are inherent characteristics of PE materials which fundamentally determine their anti-aging abilities. The external factors of the aging of PE materials come from the application environment, such as light, heat, oxygen, water, pH value, and microbial activity [4].

In terms of physical and chemical properties, the aging of PE materials can be divided into four categories: thermal-oxidative aging, photo-oxidative aging, stress cracking, and other aging.

During the aging of PE materials, the microstructure of the pipeline can be changed and the mechanical properties of the pipeline can also be reduced [5]. When a PE pipeline is used for gas transportation, it is exposed to heat, oxygen, water, and corrosive substances during operation. Therefore, the aging forms in this process are mainly thermal oxidation aging and stress cracking [4].

1.2. Failure Forms and Mechanisms of PE Pipelines

As shown in Figure 1, there are three failure stages for PE pipelines, including toughness failure, quasi-brittle failure, and brittle failure [6].

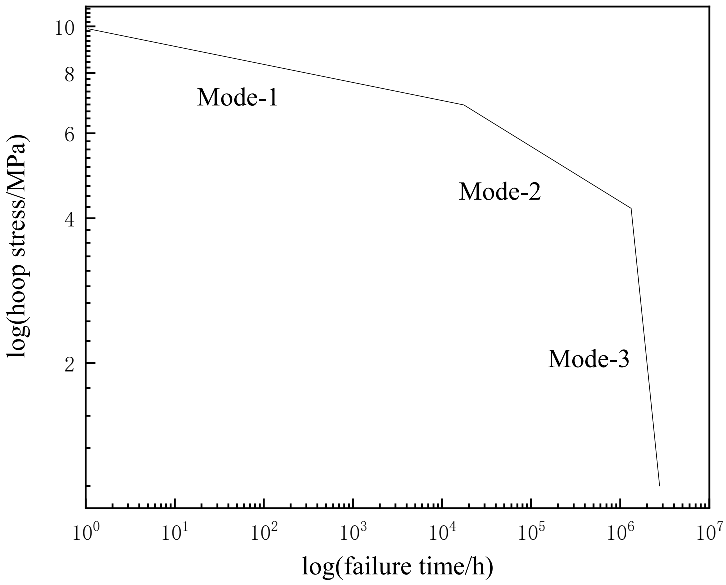

Figure 1. Schematic diagram of failure behaviors of PE pipes [7].

① Toughness failure: when the PE pipeline is under high internal pressure, the toughness failure can occur in a short time, which is characterized by large-scale plastic deformation;

② Quasi-brittle failure: the failure form changes from ductile failure to quasi-brittle failure when the load is lower. Quasi-brittle failure always occurs at the defect. Due to the concentration of the defect stress, the initiation and expansion of the crack are accelerated, eventually leading to pipe failure;

③ Brittle failure: when a PE pipeline is in service for a long time, it can go through this stage. A large number of cracks can be formed because of the serious aging of materials. Therefore, small stresses in the pipeline can result in brittle failure.

Yielding leads to most of the PE pipeline failure, and the yield mechanism can be divided into two types: shear yielding and crazing phenomenon.

Shear yielding is the shear deformation of a material due to molecular slippage during deformation.

Under higher pressure, the stress of PE pipes reaches or exceeds the yield stress of PE materials, shear yielding of the PE pipe is generated, and ductility failure occurs. Although the stress of PE pipes under the action of high pressure may not reach the yield stress of the material under real circumstances, the pipe wall is thinned due to the creep effect, which can result in an increase in the yield stress and the generation of ductile failure. Therefore, the toughness life of PE pipes depends on the stress and the creep rate of the material [7].

The crazing phenomenon is associated with slow crack growth. When a PE pipeline with defects is subjected to external force, stress concentration will occur at the defect. If the concentrated stress exceeds the yield stress, silver streaks will appear in the PE pipeline. As time goes on, creep fracture can be witnessed in the craze fibers and cracks are generated. At the new crack tip, new crazes are formed [8]. This process occurs repeatedly, that is, slow crack propagation.

1.3. Test Methods for PE Pipeline Performance

The traditional test methods for PE are performed to investigate mechanical properties, appearance and color, density and quality, thermal properties, thermodynamic analysis, etc. The most common evaluation indicators of mechanical properties mainly include tensile strength, elongation at break, elastic modulus, and impact strength. In the new test methods, microstructure morphology, thermal properties, chemical structure, viscoelasticity, and crystal structure can be analyzed.

In practical engineering applications, pressure tests and direct evaluation methods can be used to assess PE pipes. Pipeline condition inspections, welded joint inspections, mechanical property tests, and physical property tests are direct evaluation methods for PE pipelines. The inspection of pipeline conditions focuses on the surface condition and thickness of the pipeline. The inspection of welded joints mainly includes ultrasonic phased array inspections of electrofusion or hot-melt welded joints. The mechanical property test is performed to obtain the hydrostatic strength of the pipeline, elongation at break, and resistance to slow crack growth, and the physical property test is performed to investigate thermal stability.

1.4. Life Prediction Methods of PE Pipeline

At present, there are many methods for predicting the lifespan of PE pipes according to different principles. Various methods of predicting the life of PE pipes are summarized and analyzed [9–19], as shown in Table 1.

(1) Prediction method of PE pipe life based on the thermo-oxidative aging tensile experiment

Tensile experiments are the most common method for the mechanical characterization of materials and are widely used in material research because of their simple operation and low cost.

In tensile experiments, PE pipes are aged at different temperatures and pressures, and both the aging time and tensile values of the material are obtained. Finally, the service life of the PE pipe is predicted by the Arrhenius formula using their tensile values [9].

(2) Prediction method of PE pipe life based on the thermo-oxidative aging DSC experiment

Oxidation induction time (OIT) is an important parameter for qualitatively evaluating the chemical stability of PE pipes, which can be obtained with the help of DSC experiments [20]. Similar to the tensile values, the OIT values of PE pipes under different experimental conditions are used to predict the service life of PE pipes using the Arrhenius formula [9].

Table 1. Comparison of life prediction methods for PE pipes.

Method	Method Principle	Application Standard	Test Content	Life Prediction Method	Advantages and Disadvantages
Prediction method of PE pipe life based on thermo-oxidative aging tensile experiment	Tensile tests of specimens treated with different thermo-oxidative aging conditions are carried out. The tensile strength of specimens under service conditions is extrapolated using the Arrhenius method.	ISO/TR9272, GB/T20028	The tensile strength of samples under different thermal-oxidative aging conditions	Arrhenius method	The required experimental conditions are simple and closer to real working conditions. The life prediction results are more accurate, but the test reproducibility is poor.
Prediction method of PE pipe life based on thermo-oxidative aging DSC experiment	The DSC test of the samples treated with different thermo-oxidative aging conditions is carried out. The anti-oxidation time of the samples under service conditions is extrapolated using the Arrhenius method.	ISO/TR10837, ASTM D3895-2019	The antioxidation time of samples under different thermal-oxidative aging conditions	Arrhenius method	The required experimental conditions are simple and closer to real working conditions. The life prediction results are more accurate, but test reproducibility is poor.
Prediction method of PE pipe life based on hydrostatic experiment	The failure time is obtained through long-term hydrostatic tests under different conditions. The data are extrapolated to the operating temperature and stress to calculate the service life.	GB/T6111-2003, ISO4437-87	The failure time of the sample under different hydrostatic pressures	Standard extrapolation	This is currently the standard method for long-term strength performance and life prediction of thermoplastic polymer materials. However, the forecast period is too long.
Prediction method of PE pipe life based on creep experiment	The creep tests of the pipe are performed under different conditions. The actual strain greater than the yield strain is taken as the failure criterion. The actual life of the pipe is obtained through the standard extrapolation regression.	none	The creep strain at different pressures	Standard extrapolation	When the yield strain is taken as the failure criterion, the prediction results tend to be conservative.
Prediction method of PE pipe life based on damp-heat aging experiment	Treat the samples under different damp and heat aging conditions. The data are obtained by un-notched impact strength experiment. The service life of PE pipes is predicted using the Arrhenius formula.	GB/T2000-2003	The un-notched impact strength values of samples under different damp heat aging conditions	Arrhenius method	The required experimental conditions are simple and closer to real working conditions. The life prediction results are more accurate. However, the test reproducibility is relatively poor. Life expectancy predictions tend to be conservative.
Prediction method of PE pipe life based on cyclic loading experiment	Record the failure cycle through the cyclic loading test of CRB specimens under different stress ratios. The failure time under static load is extrapolated using linear elastic fracture mechanics, that is, the service life.	ISO/TR10837	The number of cycles for the specimen to fracture under different stress ratios	Linear elastic fracture mechanics	The experimental conditions are simple. The reproducibility is good. The experimental results are highly reliable. However, the predicted fatigue life is more conservative than the experimental fatigue life.

(3) Prediction method of PE pipe life based on the hydrostatic experiment

The long-term hydrostatic test is an important method for calculating the long-term service life of plastic pipes. In the experiment, the pipe sample filled with water or other media is placed in an external medium at a certain temperature. Then, the failure time of the pipe under different operating pressures is recorded and processed to obtain the long-term hydrostatic strength as well as the allowable stress of the PE pipe [10].

(4) Prediction method of PE pipe life based on the creep experiment

PE is a viscoelastic material and has an obvious strain rate effect. The diameter and wall thickness of PE pipes change due to creep, which leads to a corresponding change in hoop stress. The yield failure criterion can be formulated by analyzing the change trend of hoop stress and yield stress. The creep data are obtained through the creep experiment on PE pipes. The standard extrapolation method is used to obtain the ductile failure life of PE pipes [11].

(5) Prediction method of PE pipe life based on the damp-heat aging experiment

The artificial damp-heat aging experiment method is a commonly used method for predicting the life of PE pipes. Polymer materials have time–temperature equivalence. Therefore, the performance change of polymer materials at normal temperatures or low temperatures is often inferred by observing the performance change of polymer materials at high temperatures. Based on this principle, the artificial damp-heat aging experiment has become an effective method to predict and evaluate the life of polymer materials [14].

Through the un-notched impact strength experiment, the un-notched impact strength values under different experimental conditions can be obtained and used to predict the service life of PE pipes using the Arrhenius formula.

(6) Prediction method of PE pipe life based on the cyclic loading experiment

The cyclic load notched round bar (CRB) method is based on linear elastic fracture mechanics and was proposed to evaluate PE pipe performance. CRB experiments are carried out under different load ratios in conditions closer to the actual use environment of pipes, which makes the experimental results more reliable. The dynamic curves from the experiments can be used to predict the life of PE pipes with the help of a reasonable extrapolation method [15,16].

The thermal oxygen aging tensile experiment and thermal oxygen aging DSC experiment are compared in this paper.

In the thermal oxygen aging tensile experiment, the tensile strength of polyethylene was tested, reflecting the mechanical properties of PE materials.

In the thermal oxygen aging DSC experiment, the OIT of polyethylene was tested, indicating the chemical stability of PE materials [20]. This method is very simple to operate, and in an in-service pipeline inspection application, only a micro-sampling is required to complete the inspection [21].

Although the service life of PE pipes is 50–100 years [22], PE pipes will be damaged to different degrees because of various factors. Therefore, it is particularly important to predict the life of PE pipelines and carry out integrity inspections and evaluations.

2. Materials and Methods

2.1. Research on Life Prediction Methods Based on Thermo-Oxidative Aging Tensile Experiment

2.1.1. Experimental Materials and Equipment

(1) High-temperature and high-pressure reactor: aging PE materials in high-temperature and high-pressure environments;
(2) Electronic universal testing machine: tensile testing of PE materials;
(3) Experimental material: polyethylene pipe (PE80).

2.1.2. Experimental Procedure

(1) Aging process:

Put the PE pipe into the high-temperature and high-pressure reactor and carry out the aging process at different pressures (0 MPa, 0.6 MPa), at different temperatures (80 °C, 90 °C, 100 °C, 110 °C), and for different aging times (72 h, 160 h, 360 h, 456 h, 520 h);

(2) Preparations of PE test specimens:

Prepare PE test samples according to GB/T 8804 standard. Different sample types are chosen based on wall thickness. Sample Type 1 is shown in Figure 2.

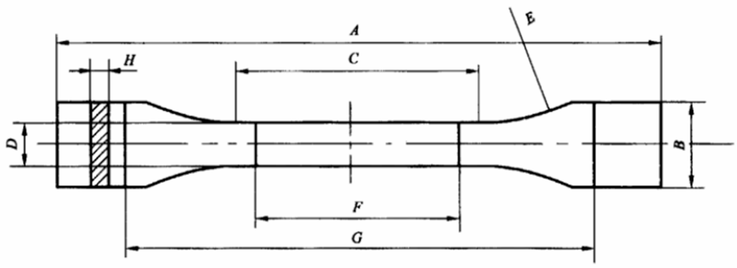

Figure 2. Specimens prepared for tensile tests.

(3) Tensile test:

According to the GB/T 8804 standard, the loading rate of the tensile test is 50 mm/min.

Experiment procedure:

① Turn on the power supply and wait for the electronic universal testing machine to warm up and stabilize before connecting to the computer;

② Fixture installation: select the sample clamp based on the test specifications and install it in the electronic universal test machine;

③ Set the procedure and the operation scheme, and then check whether the experimental instrument is working normally;

④ Install the sample by adjusting the fixture; clamp the sample in the clamp head and put it close to the force sensor, and set the force to zero to eliminate the weight of the sample. Then, clamp the other end of the sample. Run the experiment program;

⑤ After the sample is broken, loosen the clamping fixture and remove the load.

2.2. Research on Life Prediction Method Based on Thermo-Oxidative Aging DSC Experiment

2.2.1. Experimental Materials and Equipment

(1) High-temperature and high-pressure reactor: aging PE materials in high-temperature and high-pressure environment;
(2) TA DSC Q Series Differential Thermal Analyzer: test the oxidation induction time (OIT) of PE materials;
(3) Experimental material: PE pipe (PE80).

2.2.2. Experimental Procedure

(1) Put the PE pipe into a high-temperature and high-pressure reactor and age it at different pressures (0 MPa, 0.6 MPa), at different temperatures (80 °C, 90 °C, 100 °C, 110 °C), and for different times (72 h, 160 h, 360 h, 456 h, 520 h);
(2) Cut the aged PE fines to obtain a sample with an appropriate thickness and with a sample weight of 15.0 ± 0.5 mg;
(3) Place the sample in an aluminum crucible, retrieve an empty aluminum crucible as a reference pan, and put both crucibles in the DSC together;
(4) Increase the DSC at a rate of 20 K/min until the temperature is constant. Adjust the temperature of the sample to 473K ± 0.1K by correcting the heater voltage, and start recording the thermometer (the relationship between temperature difference and time);
(5) When the nitrogen flow (50 cm^3/min) keeps steady for 5 min, oxygen starts to flow at the rate of 50 cm^3/min, and this point should be marked on the thermometer. This process should be completed within 1 min;

(6) The operation does not stop until the oxidative exotherm reaches its maximum value.

3. Results

3.1. Life Prediction Method Based on Thermo-Oxidative Aging Tensile

The smaller the maximum tensile force of PE material, the worse its mechanical properties and the shorter its remaining life. Figures 3 and 4 show the relationship between the aging time and the maximum tension at different aging temperatures.

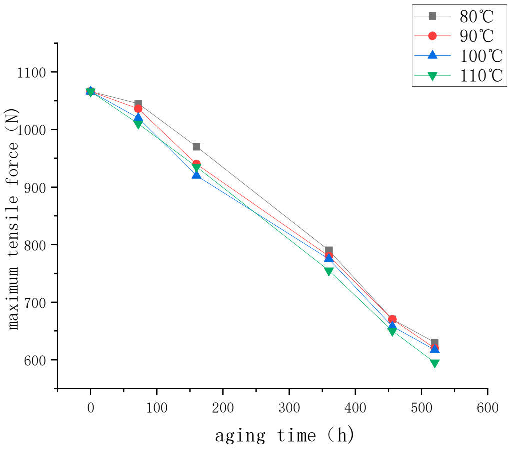

Figure 3. The relationship between the maximum tensile force of the pipe and the aging time (PE80, 0 MPa).

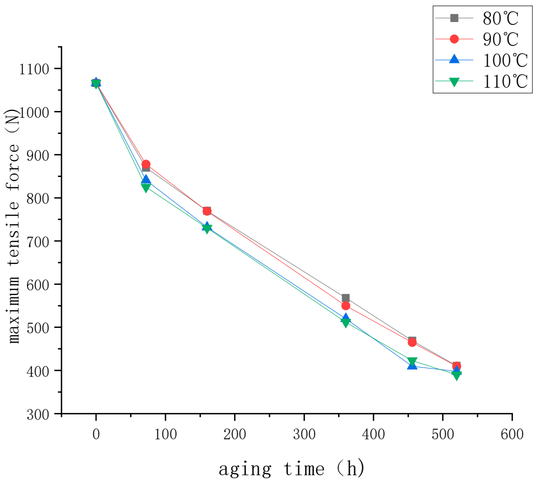

Figure 4. The relationship between the maximum tensile force of the pipe and the aging time (PE80, 0.6 MPa).

At the same temperature and pressure, the maximum tensile force of the PE material decreases significantly with the increases in aging time, which shows that its mechanical property is obviously decreased.

At the same pressure and time, the maximum tensile force of the PE material decreases with the increase in temperature. In the adjacent temperature difference, the value drop may not be significant. However, compared with the experimental results at 80 °C and 110 °C, its value decreased significantly.

Comparing the data in the two tables, the maximum tensile force of the PE material at the same temperature and time decreases significantly with the increase in pressure. After aging for 520 h, the maximum tensile force in Figure 4 dropped below 50% of the original value, whereas in Figure 3 it stayed above 50%.

To sum up, the mechanical property of the PE material will decrease with the increase in temperature, pressure, and aging time. Among them, aging time has the most significant impact.

The principle of life prediction is conducted according to the Arrhenius formula [9].

$$Q = f(q) = A\exp(-Kt). \quad (1)$$

where:

Q—rate constant, the ratio of the performance value F after aging to the performance value F0 before aging;

t—aging time, d;

K—reaction rate constant, d^{-1};

A—material constant.

$$K = Ze^{-E/RT}. \quad (2)$$

where:

T—absolute temperature, K;

E—activation energy, $J\cdot mol^{-1}$;

Z—frequency factor, d^{-1};

R—gas constant, 8.314 $J\cdot K^{-1}\cdot mol^{-1}$.

① Substitute the maximum tensile force data obtained from the tensile experiment into Formula (1). The Q value is the ratio of the maximum tensile force after aging to the maximum tensile force before aging, and the K value is obtained using the least squares fitting method;

② Substitute the K value into Formula (2) and obtain the K value at room temperature (20 °C) using the least squares fitting method;

③ Substitute the K value obtained by the fitting method and the Q value in the critical state into Formula (1) to obtain the life of the PE pipe at room temperature.

3.2. Life Prediction Method Based on Thermo-Oxidative Aging DSC Experiment

A long OIT of PE materials indicates a strong oxidation resistance and long remaining life [23].

The relationship between the aging time and the oxidation induction time at different temperatures and pressures is shown in Figures 5 and 6.

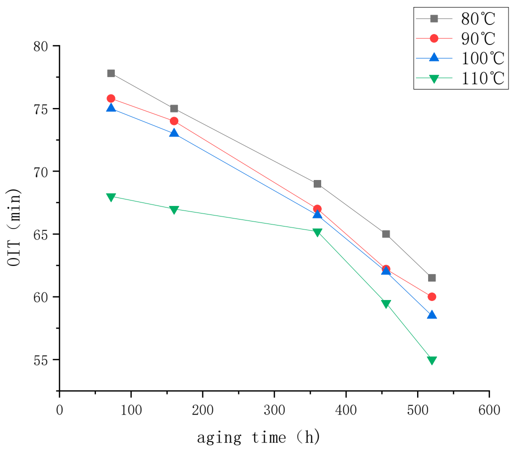

Figure 5. Relationship between the oxidation induction time and the aging time (PE80, 0 MPa).

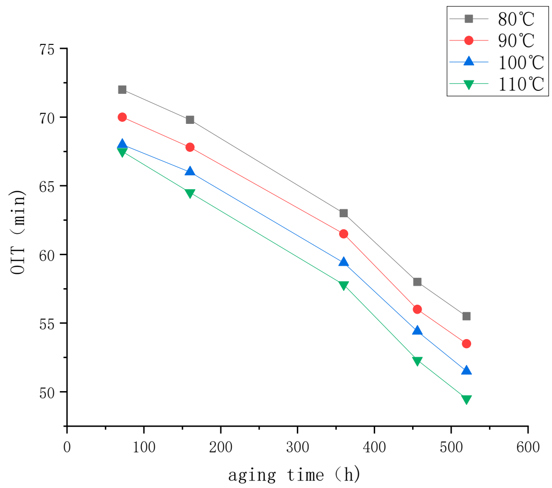

Figure 6. Relationship between the oxidation induction time and the aging time (PE80, 0.6 MPa).

At the same temperature and pressure, the OIT of the PE material decreases significantly with the increase in aging time, which shows that its antioxidant activity decreases significantly.

At the same pressure and time, the OIT of the PE material decreases with the increase in temperature. Compared with the experimental results at 80 °C and 110 °C, the value decreases more significantly.

Comparing the data in the two tables, the OIT of the PE material at the same temperature and time decreases with the increase in pressure.

To sum up, the oxidation resistance of PE material will decrease with the increase in temperature, pressure, and aging time. Among them, aging time has the most significant impact.

The Arrhenius formula is also used in this life prediction method.

① Substitute the OIT data obtained from the DCS experiment into Formula (1). The Q value is the ratio of the OIT value after aging to the OIT before aging, and the K value is obtained by using the least squares fitting method;

② Substitute the K value into Formula (2) and obtain the K value at room temperature (20 °C) using the least squares fitting method;

③ Substitute the K value obtained by the fitting method and the Q value in the critical state into Formula (1) to obtain the life of the PE pipe at room temperature.

4. Discussion

Pipeline integrity evaluation is an important part of pipeline integrity management. Its main purpose is to test the pipeline, clarify the condition of the pipeline, and formulate corresponding plans to reduce pipeline risks. At present, there is still a lack of a systematic integrity evaluation technology system for PE pipes.

So far, PE pipes have been used for a long time in China. With the increase in the service time of PE pipelines, the failure probability of PE pipes in urban gas pipeline networks is also increasing. Although the life expectancy of PE pipelines can reach 50 years or more, in very complex actual service environments and operating conditions in the actual operation process, it is always affected by many factors and greatly reduced.

Aiming at the safety and reliability of PE pipelines, based on the analysis of existing technical and experimental data, a technical system for evaluating the integrity of urban gas PE pipelines is constructed. The framework is shown in Figure 7.

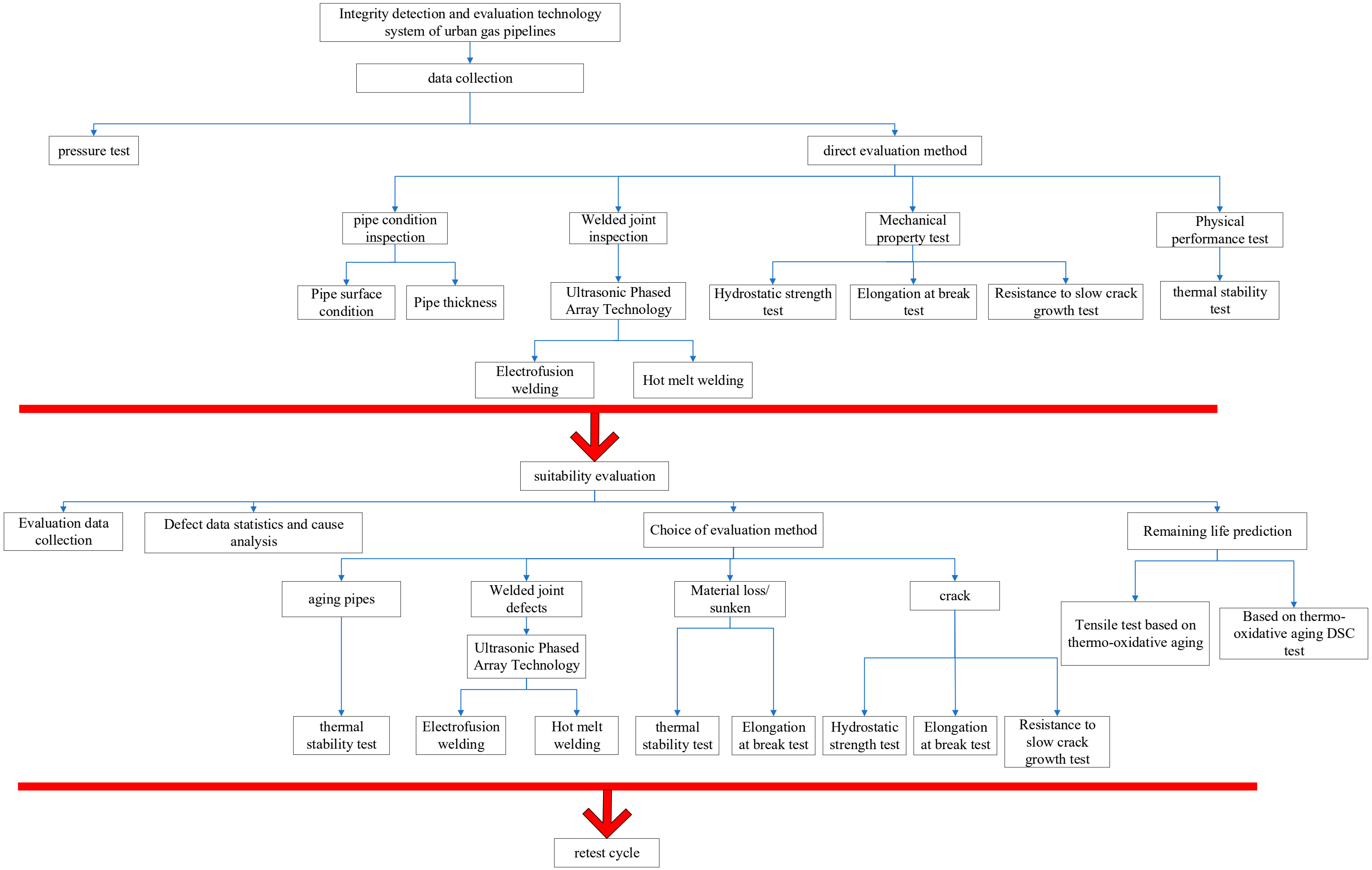

Figure 7. Framework diagram of the technical system for integrity detection and evaluation of urban gas pipelines.

The system mainly includes integrity detection methods for urban gas pipelines, applicability evaluations, and retest cycles, which are introduced in detail as follows.

(1) Integrity detection methods for urban gas pipelines

A direct evaluation method for the integrity of urban gas pipelines is preferably adopted, and the pressure test method can also be used. The direct evaluation method is shown in Table 2.

Table 2. Direct evaluation method of PE pipelines.

Test Type		Test Content/Method	Standard Test	Evaluation Results
Pipe condition inspection		Pipe surface condition	-	-
		Pipe wall thickness	GB 15558.1-3; CJ/T 125	
Welded joint inspection	Electrofusion welding Hot melt welding	Ultrasonic phased array technology	GB/T 29461—2012 T/ZJASE 008—2021	
Mechanical property test		Hydrostatic strength test	GB/T6111-2018	GB 15558.1-3
		Elongation at break test	GB/T 8804.3-2003	
		Resistance to slow crack growth test	GB/T 18476-2019	
Thermal stability test		Thermal stability test	GB/T-17391-1998; GB/T 19466.6-2009	

(2) Applicability evaluation

Applicability evaluation is carried out according to the results of the integrity test for urban gas pipelines, which includes data collection, defect data statistics and cause analysis, selection for the evaluation method, residual strength evaluation, remaining life prediction and re-inspection cycle, measurements and suggestions, etc.

(a) The following data for applicability evaluation should be related to pipeline properties, defect parameters, mechanical properties of base metals and welds, load parameters, construction data, operation data, historical data, geographic and environmental information, risk assessment results, etc. The reliability of the collected data needs to be analyzed [24];

(b) Defect data statistics and cause analysis. Statistical analysis of defect data is carried out, and possible causes of defects are analyzed according to the type and distribution law of defects and the corresponding relationship between the defects and pipeline elevation as well as geographical environment [24].

(c) The evaluation method should be selected based on factors such as the defect type, load condition, evaluation objective, and the quality and type of evaluation data [24]. The most commonly used evaluation methods for different defects can be found in Table 3.

Table 3. Selection of defect evaluation methods.

Defect Type		Recommended Test Method/Content	Standard Test	Evaluation Results
Aging		Thermal stability test	GB/T 17391-1998; GB/T 19466.6-2009	GB 15558.1-3
Material loss		Thermal stability test	GB/T 17391-1998; GB/T 19466.6-2009	
		Elongation at break test	GB/T 8804.3-2003	
Cracks		Hydrostatic strength test	GB/T6111-2018	
		Elongation at break test	GB/T 8804.3-2003	
		Resistance to slow crack growth	GB/T 18476-2019	
Welded joint defects	Electrofusion welding Hot melt welding	Ultrasonic phased array technology	GB/T 29461—2012 T/ZJASE 008—2021	

(d) Remaining life prediction for PE pipes

According to the method of life prediction in Table 4, the life of urban gas pipelines can be predicted.

Table 4. Life prediction methods and standards for PE pipes.

Method	Application Standard	Method of Prediction
Life prediction method based on thermo-oxidative aging tensile experiment	ISO/TR9272, GB/T20028	Arrhenius method
Life prediction method based on thermo-oxidative aging DSC experiment	ISO/TR10837, GB/T20028	Arrhenius method

(3) Retest Cycle

The next evaluation cycle of the pipeline is given according to the inspection results and evaluation results.

5. Conclusions

(1) The results of the thermo-oxidative aging tensile experiment show that the mechanical property of PE material will decrease with the increase of temperature, pressure, and aging time. Among them, aging time has the most significant impact.
(2) The results of the thermo-oxidative aging DSC experiment show that the oxidation resistance of PE material will decrease with the increase in temperature, pressure, and aging time. Among them, aging time has the most significant impact.
(3) This paper establishes a technical system for the integrity detection and evaluation of urban gas pipelines. It provides a reasonable reference for the application of PE pipes in engineering practice.

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