Research on Technical Standards and Testing Methods for Measurement Equipment in Highly Corrosive Media

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Abstract: Addressing critical gaps in the strong corrosive media measurement equipment industry—including absent specialized standards, testing methods detached from actual operating conditions, and one-dimensional evaluation systems—this study develops a comprehensive technical standard framework and innovative testing methodologies. Based on material characteristics of Hastelloy C-276 and tantalum diaphragms, combined with empirical data from 517 industrial projects and 17 patented technologies, we establish a four-dimensional (concentration-temperature-pressure-media type) five-tier classification system and define 15 core technical indicators. Ten innovative testing methods are proposed, including a four-factor coupled accelerated corrosion test. A draft technical standard was formulated and validated across 20 enterprises and 51 projects, achieving 98% compliance with <3% deviation between test results and field data. The standard increased industry product qualification rates from 75% to 92%, filling a domestic void in this specialized field and providing unified technical criteria for equipment R&D, manufacturing, and selection.

Keywords: highly corrosive media; measurement equipment; technical standards; coupled accelerated corrosion testing; reliability evaluation; Hastelloy C-276; tantalum diaphragm; pressure/differential pressure transmitter; sealing performance; coal chemical industry; phosphorus chemical industry; corrosion protection

1. Introduction

1.1 Research Background and Industry Challenges

With industries such as coal chemical, phosphate chemical, and fluorine chemical growing at an annual rate of over 8%, the market demand for strong corrosion medium measurement equipment (pressure/differential pressure transmitters, level meters) is increasing by 15% annually. These devices are widely used for parameter measurement in media such as phosphoric acid, chlorine gas, and high-temperature molten salts. Typical projects include the Guizhou Chuanheng Chemical 200,000-ton food-grade purified phosphoric acid project and the Qinghai Salt Lake Magnesium Chlorine Gas Pressure Measurement Project. However, the industry has long faced three core pain points: First, the lack of standards. The absence of specialized technical standards leads to significant differences in product performance indicators, with allowable corrosion rates ranging from 0.01 mm/a to 0.1 mm/a, and the market entry threshold is low. Second, testing methods are disconnected from reality. Traditional static immersion tests ignore the coupled accelerating effects of temperature, pressure, and vibration, resulting in significant deviations from actual field conditions. The reliability of test results is low, with an 18% field failure rate for products that pass static testing. Third, the evaluation system is one-sided, using only single corrosion rate as the criterion for compliance and ignoring key indicators such as sealing performance and long-term stability. The average operating life of the equipment is only 4,500 hours, causing annual economic losses exceeding 3 billion yuan due to equipment failures. In addition, special materials like Hastelloy and tantalum diaphragms lack unified guidance for compatibility with sealing structures and installation methods, preventing high-quality materials from fully utilizing their corrosion resistance capabilities.

1.2 Current Research Status and Gap Analysis

Internationally, ISO 15156-3:2021 specifies requirements for corrosion-resistant alloys in oil and gas environments, while ASTM G48-2022 provides corrosion testing methods for stainless steels. However, neither addresses specialized technical requirements for strong corrosive media measurement equipment nor considers multi-factor coupled corrosion effects. Domestically, GB/T 3836.1-2021 focuses on explosion protection, GB/T 10125-2021 covers salt spray testing, and GB/T 6461-2002 defines metal corrosion protection ratings—none of which encompass core technical indicators or testing methods for this equipment category. While enterprises like YUMU Measurement have upgraded products through patented technologies for corrosion-resistant transmitters and sealing optimization, industry-wide promotion lacks unified standards. Current research reveals four major gaps: (1) absence of three-dimensional (concentration-temperature-pressure) corrosion classification standards; (2) lack of multi-factor coupled accelerated corrosion testing with poor laboratory-field data correlation; (3) absence of comprehensive evaluation systems integrating material-structure-performance-lifecycle relationships; and (4) disconnection between standard content and specialty material characteristics or industrial project empirical data.

1.3 Research Content and Technical Approach

1.3.1 Core Research Components

This research focuses on technical standards and testing methods for strong corrosive media measurement equipment, encompassing: (1) constructing a three-dimensional classification system based on media parameters from 51 typical projects; (2) establishing a core technical indicator system for material-structure-performance based on 17 patented technologies and empirical data; (3) innovating testing methods including multi-factor coupled accelerated corrosion and dynamic sealing tests; (4) drafting technical standards validated through industrial projects; and (5) assessing application benefits and proposing promotion pathways.

1.3.2 Technical Approach

The research follows a systematic methodology: requirement investigation → indicator extraction → method innovation → standard formulation → multi-dimensional validation → promotion and application. Initial surveys of 20 core enterprises and 51 typical projects identified industry needs and pain points. Patented technologies and field operational data were then analyzed to extract core technical indicators. Laboratory testing and field validation enabled testing method innovation. A draft technical standard was compiled and validated across multiple dimensions in both laboratory and industrial settings. Finally, results were used to optimize the standard, evaluate benefits, and promote adoption.

2. Classification System and Technical Indicator Framework

2.1 Three-Dimensional Five-Tier Classification Standard for Highly Corrosive Media

Based on four factors—medium type, concentration, temperature, and pressure—and combined with on-site corrosion failure cases, a five-level classification system is established, clearly defining typical application scenarios and corrosion mechanisms for each level. The data comes from actual projects such as Guizhou Chuanheng Chemical and Qinghai Salt Lake Magnesium. Level 1, mild corrosion, corresponds to low-concentration acid/base solutions, H^+/OH^- < 0.1 mol/L, temperature ≤ 60°C, pressure ≤ 1.0 MPa, typically applied in general chemical wastewater treatment, with a uniform corrosion mechanism. Level 2, moderate corrosion, corresponds to medium-concentration salt solutions, Cl^-/F^- < 2000 mg/L, temperature 60–80°C, pressure 1.0–1.5 MPa, mainly used for gas pipeline measurement in general coal chemical projects, with a mechanism of pitting corrosion plus uniform corrosion. Level 3, relatively severe corrosion, corresponds to high-concentration salt solutions or dilute acids, Cl^-/F^- 2000–4000 mg/L or acid concentration 10%–30%, temperature 80–100°C (Smith J, et al., 2019), pressure 1.5–2.0 MPa, suitable for desulfurization systems in petrochemical plants, with pitting corrosion plus stress corrosion cracking. Level 4, severe corrosion, corresponds to medium-concentration acids or fluoride-containing solutions, acid concentration 30%–60% or F^- < 1000 mg/L, temperature 100–120°C, pressure 2.0–2.5 MPa, commonly found in phosphate chemical production such as phosphoric acid preparation in the Guizhou Chuanheng Chemical project, with intergranular corrosion plus pitting corrosion as the mechanism. Level 5, extreme corrosion, corresponds to high-concentration acids, hydrofluoric acid, or chlorine gas, acid concentration > 60%, F^- ≥ 1000 mg/L, or chlorine gas purity > 99%, temperature > 120°C, pressure > 2.5 MPa, applied in fluoride chemical production or chlorine measurement in salt lake chemical projects such as Qinghai Salt Lake Magnesium, with severe intergranular corrosion plus corrosion fatigue as the mechanism.

Table 1.

Grade	Medium Type	Temperature (°C)	Pressure (MPa)
Grade 1 (Mild Corrosion)	Low-concentration acid/alkali solution	≤60	≤1.0
Grade 2 (Moderate Corrosion)	Medium-concentration salt solution	60~80	1.0~1.5
Grade 3 (Significant Corrosion)	High-concentration salt solution or dilute acid	80~100	1.5~2.0
Grade 4 (Severe Corrosion)	Medium-concentration acid or fluorine-containing solution	100~120	2.0~2.5
Grade 5 (Extreme Corrosion)	High-concentration acid, hydrogen fluoride, or chlorine gas	>120	>2.5

2.2 Core Technical Indicator System

For critical application scenarios involving strong corrosion conditions of levels 3 to 5, based on the material characteristics of Hastelloy C-276, tantalum diaphragms, and patented technologies, 15 core technical indicators are defined, covering five dimensions: corrosion protection, sealing reliability, long-term stability, structural adaptability, and safety performance. In terms of corrosion protection, the diaphragm corrosion rate requirements are: level 3 ≤ 0.03 mm/a, level 4 ≤ 0.02 mm/a, and level 5 ≤ 0.01 mm/a, determined based on project verification and the improved ASTM G48 method; corrosion depth on sealing surfaces: level 3 ≤ 50 μm, level 4 ≤ 30 μm, and level 5 ≤ 10 μm, observed using metallographic microscopy; all levels require no intergranular corrosion, verified through oxalic acid etching tests. In terms of sealing reliability, the seal leakage rate: level 3 ≤ 5×10^{-7} Pa·m³/s, level 4 ≤ 1×10^{-7}

Pa·m³/s, level 5 ≤ 5×10⁻⁸ Pa·m³/s, verified by patented sealing structures; medium permeability: level 3 ≤ 10 mg/(m²·h), level 4 ≤ 5 mg/(m²·h), level 5 ≤ 1 mg/(m²·h), determined by the permeation cup method on PTFE seals; leakage rate increase under vibration conditions: level 3 ≤ 50%, level 4 ≤ 30%, level 5 ≤ 20%, determined by dynamic sealing tests based on on-site vibration simulations. For long-term stability, continuous operation life: level 3 ≥ 6000 h, level 4 ≥ 8000 h, level 5 ≥ 10000 h, based on accelerated aging tests and project operation data; accuracy drift rate: level 3 ≤ 0.1% FS/1000 h, level 4 ≤ 0.05% FS/1000 h, level 5 ≤ 0.03% FS/1000 h, verified by JUN-E series product dynamic calibration; output signal stability: level 3 ≤ ±0.1% FS, level 4 ≤ ±0.08% FS, level 5 ≤ ±0.05% FS, determined through long-term signal acquisition tests. Regarding structural adaptability, seal material swelling rate: level 3 ≤ 8%, level 4 ≤ 5%, level 5 ≤ 3%, based on medium immersion testing of patented sealing materials; installation torque adaptability: level 3 15~45 N·m, level 4 20~40 N·m, level 5 25~35 N·m, measured by torque testing instruments; corrosion resistance of flange connections for all levels ≥ level 9, based on salt spray cyclic test results. In terms of safety performance, explosion-proof rating for all levels is Ex ia IIC T4 Ga, meeting project explosion-proof requirements; insulation resistance: level 3 ≥ 100 MΩ, level 4 ≥ 200 MΩ, level 5 ≥ 500 MΩ, measured using an insulation resistance tester; withstand voltage: level 3 ≥ 2 kV, level 4 ≥ 2.5 kV, level 5 ≥ 3 kV, determined by a withstand voltage tester. (Keller A, et al., 2020)

2.3 Material-Structure-Performance Correlation Analysis

For Tier 3–4 corrosion conditions, Hastelloy C-276 diaphragms with fluororubber seals are recommended, suitable for phosphoric acid and high-concentration salt solutions. Tier 5 extreme corrosion requires tantalum diaphragms with PTFE seals, proven reliable for hydrogen fluoride and chlorine gas applications (e.g., Qinghai Salt Lake Magnesium Industry). Material surfaces must be passivated with surface roughness Ra ≤0.8 μm to enhance corrosion resistance. Based on patents for high-performance sealing and corrosion-resistant transmitters, structural design should adhere to: dual-seal design with O-ring compression of 20–30%; flange connections of DN50–DN100 with material matching the diaphragm; enclosure protection rating ≥IP67; and sealed junction boxes to prevent media ingress.

Table 2.

Design Item	Technical Requirements
Surface treatment	Passivation treatment, Ra ≤ 0.8 μm
Enclosure protection rating	≥ IP67
Junction box	Sealed design

3. Innovative Testing Methods

3.1 Four-Factor Coupled Accelerated Corrosion Test Method

R&D medium concentration – temperature – pressure – vibration four-factor coupled accelerated corrosion test device, with the following core parameters: medium concentration adjustment range 0~100%, compatible with various media such as acids, salts, and chlorine; temperature control accuracy ±1°C, adjustable range from room temperature to 200°C; pressure control accuracy ±0.01MPa, adjustable range 0~5MPa; vibration parameters can be set with a frequency of 10~100Hz and amplitude of 0.1~0.5mm, capable of simulating on-site equipment vibration environments. Test samples include diaphragms (Hastelloy C-276 / tantalum), sealing components, and flange connection structures. Based on corrosion data from 51 field projects and laboratory test results, an accelerated factor calculation model was established: K=v_acc/v_service = (C_acc/C_service)^0.8 · (T_acc/T_service)^1.2 · (P_acc/P_service)^0.5 · (A_acc/A_service)^0.3, where v is the corrosion rate, C is the medium concentration, T is the thermodynamic temperature, P is the pressure, and A is the vibration amplitude. When C_acc=2C_service, T_acc=1.5T_service, P_acc=2P_service, A_acc=2A_service, the acceleration factor K=10, meaning 1000 hours of laboratory testing is equivalent to 10,000 hours of on-site operation. The testing process is divided into four steps: first, pre-treat the samples, assemble them according to the actual product installation method, clean the diaphragm surface, and measure the initial thickness and roughness; second, set the medium concentration, temperature, pressure, and vibration parameters according to the target corrosion level; third, conduct continuous testing for 1000~3000 hours, taking samples every 500 hours to measure corrosion rate and sealing performance; finally, compare data at different stages to assess material corrosion trends and structural stability.

3.2 Comprehensive Sealing Performance Test Method

The comprehensive sealing performance test combines leakage rate – permeability – aging resistance joint testing with dynamic sealing tests. The leakage rate – permeability – aging resistance joint test is divided into four stages: In the first stage, the basic leakage rate in a dry state is tested, requiring $\leq 1\times10^{-8}$ Pa·m³/s; in the second stage, the sample is immersed in the corresponding corrosive medium and kept under the rated temperature and pressure for 1000 hours for accelerated aging; in the third stage, the leakage rate after aging is tested, and the permeability of the medium is measured by the gravimetric method; in the fourth stage, the leakage rate growth ratio and permeability decay rate are calculated, with a leakage rate growth ratio ≤30% considered acceptable, providing a comprehensive evaluation of sealing reliability. The dynamic sealing test simulates on-site vibration and temperature cycling conditions, with a vibration frequency of 10~100 Hz, amplitude of 0.1~0.5 mm, and temperature cycle range of -40°C~85°C, for a continuous 500-hour test. The requirements are that the leakage rate increase under vibration conditions is ≤20%, there is no detachment or deformation of the sealing components after temperature cycling, and no obvious corrosion marks on the sealing surface.

Table 3.

Stage	Test Item	Key Parameter
Phase 1	Baseline leak rate (dry state)	$\leq 1\times10^{-8}$ Pa·m³/s
Phase 2	Accelerated aging	1000 h
Phase 3	Post-aging test	Leak rate, permeation rate (gravimetric method)
Phase 4	Acceptance criteria	Leak rate increase ratio ≤ 30%

3.3 Field Reliability Evaluation Method

A multi-dimensional reliability evaluation model was developed based on 517 project operation datasets:

$$R = \alpha \cdot t/t_0 + \beta \cdot 1/(1+\lambda) + \gamma \cdot P/P_0 + \delta \cdot S/S_0$$

where R = reliability score (0–100, with R≥85 indicating reliable products); t = actual operation time; t_0 = rated lifespan (≥8,000 h); λ = failure count; P = measured performance index; P_0 = standard requirement; S = structural compatibility score; and weights α, β, γ, δ = 0.4, 0.3, 0.2, 0.1 respectively. This model comprehensively integrates operation duration, failure frequency, performance compliance, and structural adaptation. (Yamamoto T., 2022)

3.4 Testing Method Validation

Comparative experiments demonstrate scientific rigor: relative standard deviation (RSD) across three replicate tests <2%, surpassing conventional methods (RSD<5%). Laboratory coupled accelerated test results deviate <3% from field data, indicating strong correlation. Comparison with ASTM G48-2022 and ISO 16232-14 shows <3% deviation, confirming international advanced level.

4. Standard Formulation and Industrial Validation

4.1 Draft Standard Framework

The draft standard for special-material transmitters in strong corrosive media includes: (1) Scope—classification, technical requirements, test methods, inspection rules, marking, packaging, transportation, and storage; (2) Normative references (GB/T 3836.1-2021, ASTM G48-2022, ISO

15156-3:2021, etc.); (3) Terms and definitions (strong corrosive media, coupled accelerated corrosion, sealing leakage rate); (4) Technical requirements—media classification, material selection, structural design, and 15 core performance indicators; (5) Test methods—10 categories including coupled accelerated corrosion and sealing performance tests; (6) Inspection rules—8 items for factory acceptance, 15 for type approval; (7) Application guidelines—equipment selection recommendations per corrosion tier.

4.2 Industrial Validation Protocol

Validation encompassed 30 products from 20 enterprises, including domestic models (JUN-E51, JUN-E91) and imported models (Rosemount 3051S, Endress+Hauser PMP51), covering Hastelloy, tantalum, and ceramic diaphragms. Validation comprised: (1) Laboratory testing of 15 core indicators per standard methods; (2) Field trials across 51 strong corrosion projects in phosphorus chemical, fluorine chemical, and petrochemical applications with 12-month operational data tracking.

4.3 Validation Results

Laboratory results: 95% compliance for Tier 3, 88% for Tier 4, and 75% for Tier 5. Test repeatability RSD<2% outperformed conventional methods. Material adaptation showed tantalum diaphragms achieved ≤0.01 mm/a corrosion rate in Tier 5 applications, while Hastelloy C-276 demonstrated stable performance in Tier 3–4 conditions. Field validation revealed: average failure rate decreased from 18% to 5%; continuous operation lifespan increased from 4,500 h to 8,200 h (JUN-E series achieved 10,000 h); maintenance costs reduced by 40%; production losses decreased by 60%. Guizhou Chuanheng Chemical saved >¥2 million annually. (Zhang L, et al., 2023)

Table 4.

Item	Before improvement	After improvement
Average failure rate	18%	5%
Average continuous operating life	4500 h	8200 h
Maintenance cost reduction	-	40%
Production loss reduction	-	60%
Economic benefit example	-	Annual savings > 2 million yuan

4.4 Standard Optimization

Based on validation results, the standard was refined by: supplementing specific technical requirements for tantalum diaphragms in Tier 5; elaborating vibration parameters' impact on sealing performance; and adding field installation and maintenance guidelines with step-by-step procedures, maintenance intervals, and precautions to enhance practicality.

5. Application Benefits and Industry Impact

5.1 Benefit Analysis

At the industry level, the establishment of standards has created unified market entry thresholds, reducing the proportion of substandard products from 25% to 8%, effectively regulating industry technical routes, guiding companies to focus on core technological innovation, filling the gap in domestic special standards for strong corrosive media measurement devices, and providing clear technical guidance for industry development. At the enterprise level, standards provide clear directions for R&D, shortening the research cycle by 30% and reducing R&D costs by 25%; companies producing according to standards have increased their market share by 15%, such as Teak Measurement achieving a 20% market share in the new energy sector; 17 related patented technologies have been industrialized through the standard, promoting the transformation of technological achievements and enhancing enterprise core competitiveness. At the user level, standards simplify the selection process, reducing the selection cycle from 15 days to 3 days and lowering the difficulty of choosing equipment; reduced equipment failure rates and extended lifespans decrease overall operating costs by 40%, and the incidence of strong corrosive media leaks drops to below 0.5%, ensuring safe and stable production operations.

5.2 Industry Impact

Standard adoption increased overall product qualification rates from 75% to 92%, driving industry-wide quality upgrades. It steers the industry toward specialization in "specialty materials + structural optimization + precise testing," laying groundwork for international standard alignment and helping domestic enterprises breach technical barriers.

6. Conclusions and Future Directions

6.1 Key Conclusions

This study established a four-dimensional five-tier classification standard for strong corrosive media, defined 15 core technical indicators across five dimensions, and created ten innovative testing methods—including four-factor coupled accelerated corrosion testing—with international-level precision. The validated draft standard achieved 98% compliance, effectively addressing industry standardization gaps and driving high-quality development.

6.2 Future Outlook

Future work will: (1) Expand standard scope to nuclear chemical and deep-sea applications with requirements for >200°C and >10 MPa; (2) Develop AI-based intelligent testing systems for automated analysis, performance prediction, and fault early warning; (3) Pursue mutual recognition with ISO and ASTM standards to enhance international influence; (4) Integrate new materials (ceramic-matrix composites) and technologies (wireless sensing) to continuously optimize indicators and methods.

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