Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
MAR. 2026 VOL.5, NO.1

Innovative Sealing Structure Design for JUN-E51 Single-Flange Transmitter Under Highly Corrosive Operating Conditions

Ying Zhang[1]

[1] Yuuki Measurement Technology (Shanghai) Co., Ltd., Shanghai 201108, China

Correspondence: Ying Zhang, Yuuki Measurement Technology (Shanghai) Co., Ltd., Shanghai 201108, China.

doi:10.63593/IST.2788-7030.2026.03.006

Abstract

Addressing the bottlenecks of premature aging, high leakage rates, and short service life in conventional sealing structures of single-flange transmitters under highly corrosive conditions, this study investigates the JUN-E51 single-flange remote pressure transmitter from Yuzuki Measurement Technology (Shanghai) Co., Ltd., focusing on innovative sealing structure design and performance optimization. Leveraging data from 517 industrial project implementations, an integrated sealing solution incorporating dual-sealing architecture, pressure relief channels, and gradient material matching is proposed. Finite element simulation was employed to optimize the contact pressure distribution across sealing surfaces. A synergistic protection system consisting of PTFE-reinforced graphite gaskets and modified fluororubber O-rings was selected. Accelerated testing in a high-temperature, high-pressure corrosive environment for 8,000 hours demonstrated that the innovative structure achieved a leakage rate below 5×10^{-8} Pa·m³/s, representing a 92% reduction in corrosive medium permeability compared to conventional designs. Deployment of 16 units in Guizhou Chuanheng Chemical's 200,000-ton/year phosphoric acid project extended equipment maintenance intervals from 6 months to 24 months, with failure rates reduced to zero. The related technology has been granted patent authorization, providing a comprehensive paradigm for improving sealing reliability of industrial measurement equipment under highly corrosive conditions.

Keywords: highly corrosive operating conditions, JUN-E51 single-flange transmitter, sealing structure innovation, dual-sealing design, corrosion protection, engineering validation, PTFE-reinforced graphite gasket, modified fluororubber O-ring, electroless Ni-P alloy plating, sealing failure mechanism, phosphoric chemical industry conditions, leakage rate control

1. Introduction

1.1 Research Background and Engineering Requirements

1.1.1 Current State of Corrosive Operating Conditions in Industry

Highly corrosive media are extensively present in core sectors of the national economy, including phosphoric chemical, coal chemical, and petrochemical industries. Typical operating parameters exhibit multi-dimensional severity: temperature ranges spanning 40~120°C, pressure ranges of 0.5~2.5 MPa, and media types encompassing 85% concentrated phosphoric acid, high Cl^- solutions of 3,800 mg/L (Chinese Mechanical Engineering Society, 2020), hydrogen fluoride, and other highly corrosive substances. Such media possess strong oxidizing properties and high permeability, causing continuous damage to sealing systems of industrial measurement equipment and becoming a critical bottleneck restricting production continuity. Industry statistics indicate that the domestic phosphoric chemical industry—represented by key production areas in Guizhou and Sichuan—incurs over 500 million RMB in unplanned production losses annually due to sealing failures, with average maintenance costs per transmitter increasing by 20,000~30,000 RMB/year, severely impacting enterprise economic benefits and safe production.

1.1.2 Product Positioning and Limitations of Existing Structures

The JUN-E51 single-flange remote pressure transmitter, a core product series of YUUKI Keiki Kogyo Co., Ltd. (Japan), is manufactured, technically adapted, and marketed domestically by Yuzuki Measurement Technology (Shanghai) Co., Ltd. With advantages of high measurement accuracy and convenient installation, it has been deployed at scale in 517 industrial scenarios, including Guizhou Chuanheng Chemical's 200,000-ton/year phosphoric acid project and Xinjiang Xingyue Chemical's coal chemical project. However, conventional single-gasket + single O-ring sealing structures exhibit three critical defects under highly corrosive conditions, as identified through statistical analysis of over 300 field failure datasets: (1) Sealing surface corrosion failure: Traditional 316L stainless steel sealing surfaces in 3,800 mg/L Cl^- solution exhibit a pitting rate of 0.08 mm/a, with surface roughness increasing from Ra 0.8 μm to Ra 3.2 μm after 1,000 operating hours, causing a 40% increase in contact pressure distribution non-uniformity and forming local pressure dead zones that trigger leakage; (2) Gasket performance degradation: Conventional flexible graphite gaskets in 85% phosphoric acid at 100°C show compression rebound rates decreasing from 90% to 45% after 1,000 hours, porosity surging from 5% to 22%, and medium permeability increasing 15-fold, resulting in complete loss of sealing effectiveness; (3) O-ring swelling and aging: Standard fluororubber exhibits 8% swelling in high-temperature corrosive media, while nitrile rubber swelling reaches 35%, with elastic recovery rates dropping below 60%, rendering them incapable of maintaining sealing surface preloading pressure.

1.2 State-of-the-Art and Technical Gaps

1.2.1 Current Industry Technology Development

Internationally, YUUKI's original factory employs a fluororubber + flexible graphite combination sealing solution that can control leakage rates to 1×10^{-7} $Pa\cdot m^3/s$, but service life is limited to only 6,000 hours under 120°C highly corrosive conditions, failing to meet domestic chemical enterprises' requirements for long-cycle operation. Rosemount (USA) has introduced a metal spiral-wound gasket sealing solution, which offers superior corrosion resistance but demands stringent installation torque control within ±5 N·m, exhibiting poor compatibility with domestic chemical enterprise site conditions and susceptibility to sealing failure due to improper installation. Domestic research has primarily focused on optimizing single sealing materials, such as patented ceramic gasket solutions that significantly improve corrosion resistance but suffer from insufficient toughness (fracture toughness only 3.2 $MPa\cdot m^{1/2}$), making them prone to cracking under industrial vibration loads. Other studies have attempted single-material polytetrafluoroethylene (PTFE) sealing, but issues including low-temperature brittleness and high-temperature creep remain unresolved, failing to establish a collaborative optimization system integrating structural design, material selection, and operating condition adaptation. Leveraging 17 related patents, Yuzuki Measurement Technology (Shanghai) Co., Ltd. has accumulated extensive engineering practical experience in sealing for corrosive environments, but previously lacked systematic failure mechanism analysis and multi-condition optimization validation, preventing technical achievements from forming a standardized promotion system.

1.2.2 Core Technical Gaps

Comprehensive analysis of domestic/international research and enterprise engineering practice reveals three core technical gaps in single-flange transmitter sealing technology under highly corrosive conditions: First, no coupled failure model correlating corrosive medium concentration-temperature-pressure-sealing performance has been established, with insufficient research on the synergistic protection mechanism of gaskets and O-rings, making precise structural design guidance impossible; Second, traditional structures ignore the impact of corrosion product accumulation on sealing performance, lacking active pressure relief and self-cleaning design, where medium penetration easily triggers cascading failures; Third, the compatibility between sealing surface treatment processes and corrosive operating conditions is inadequate, with no standardized surface strengthening scheme, resulting in excessive sealing surface corrosion rates.

1.3 Research Content and Technical Approach

1.3.1 Core Research Content

This research targets the objective of improving JUN-E51 transmitter sealing reliability, focusing on four key aspects: (1) Systematic analysis of sealing system failure mechanisms under highly corrosive conditions, including electrochemical corrosion of sealing surfaces, gasket porosity evolution, and O-ring swelling aging patterns, to establish a coupled failure model; (2) Innovative design of dual-sealing + pressure relief channel architecture based on corporate patented technology to achieve multiple protection and active pressure relief functions; (3) Conducting gradient material adaptation studies to identify optimal material combinations and process parameters for primary gaskets, secondary O-rings, and sealing surfaces; (4) Validating the reliability and practicality of the innovative structure through laboratory accelerated testing and engineering demonstration at Guizhou Chuanheng Chemical.

1.3.2 Technical Approach

This study adopts a closed-loop technical approach of engineering data-driven → theoretical mechanism analysis → structural innovation design → multi-dimensional validation: First, collecting over 300 field failure datasets and operating condition parameters from Yuzuki Measurement Technology (Shanghai) Co., Ltd. to identify critical failure influencing factors; Second, revealing sealing failure mechanisms and establishing coupled models through potentiodynamic polarization tests and material aging experiments; Subsequently, optimizing innovative structural parameters and material combinations using ANSYS Workbench finite element simulation; Finally, completing structural performance validation and engineering implementation through 8,000-hour accelerated testing in a high-temperature, high-pressure corrosive test chamber and field application at Guizhou Chuanheng Chemical.

2. Analysis of Sealing Failure Mechanisms Under Highly Corrosive Conditions

2.1 Sealing Surface Corrosion Failure Mechanism

Focusing on conventional 316L stainless steel sealing surfaces of the JUN-E51 transmitter, potentiodynamic polarization tests were conducted to analyze corrosion behavior under varying Cl^- concentrations. A CS350 electrochemical workstation was employed with electrolyte solutions simulating industrial conditions using NaCl solutions at concentration gradients of 1,000 mg/L, 2,500 mg/L, 3,800 mg/L, and 4,200 mg/L. Test temperature was controlled at 100°C, consistent with typical phosphoric acid production conditions. Results demonstrate significant correlation between sealing surface corrosion behavior and Cl^- concentration: as Cl^- concentration increased from 1,000 mg/L to 4,200 mg/L, corrosion potential continuously decreased from -0.21 V to -0.43 V, and passive film breakdown voltage dropped from 1.2 V to 0.6 V, indicating significantly reduced passive film stability at higher Cl^- concentrations. XRD analysis of corrosion products on failed sealing surfaces revealed primary components of $FeCl_3 \cdot 6H_2O$ and $Cr(OH)_3$ (Chinese Standard, 2012), which are loose, poorly adherent, and prone to spalling, creating pores that increased surface roughness from initial Ra 0.8 μm to Ra 3.2 μm. Contact pressure measurements further revealed that increased surface roughness caused a 40% increase in contact pressure distribution non-uniformity, with local contact pressures falling below medium pressure to form leakage channels—representing a core reason for high leakage rates in conventional structures.

Table 1.

Test parameters	Low concentration condition	High concentration condition
Cl^- concentration	1000 mg/L	4200 mg/L
Corrosion potential	-0.21 V	-0.43 V
Passivation film breakdown voltage	1.2 V	0.6 V
Surface roughness Ra	0.8 μm	3.2 μm
Increase in contact pressure distribution non-uniformity	-	40%

2.2 Failure Mechanisms of Gaskets and O-Rings

Comparative aging tests were conducted on commonly used industrial flexible graphite gaskets, PTFE gaskets, and asbestos-free gaskets under simulated conditions of 85% phosphoric acid medium at 100°C for 1,000 hours. Results indicated that conventional flexible graphite gaskets exhibited the most significant performance degradation, with compression rebound rates decreasing from 90% to 45%, porosity increasing from 5% to 22%, and medium permeability increasing 15-fold. PTFE gaskets maintained compression rebound rates around 70% but suffered from high-temperature creep, reducing sealing surface conformity. Asbestos-free gaskets demonstrated the poorest corrosion resistance, showing obvious swelling and damage after 1,000 hours. The core gasket failure mechanism involves corrosive medium permeation and diffusion through gasket pores, causing chemical degradation, increasing porosity, deteriorating compression rebound performance, and ultimately losing sealing capacity. Three common O-ring materials—nitrile rubber, fluororubber, and silicone rubber—were tested under 85% phosphoric acid at 100°C (Rosemount Inc, 2021). Results showed nitrile rubber exhibited the highest swelling rate at 35%, with complete elasticity loss after 1,000 hours; silicone rubber showed 12% swelling but insufficient temperature resistance, resulting in hardening and brittle fracture; fluororubber demonstrated relatively stable performance with 8% swelling, but hardness decreased from 75 HA to 55 HA at temperatures exceeding 100°C, with elastic recovery rates dropping below 60%. O-ring failure primarily results from corrosive medium penetration causing material swelling, crosslink bond rupture, elastic modulus reduction, and hardness changes, preventing effective sealing gap filling, while medium erosion accelerates O-ring aging and cracking to form leakage channels.

2.3 Coupled Failure Model for Sealing System

Integrating the failure mechanisms of sealing surfaces, gaskets, and O-rings, a coupled failure model for the sealing system was established based on over 300 field failure datasets from Yuzuki Measurement Technology (Shanghai) Co., Ltd.:

$$\lambda = K \cdot C \cdot T/(P \cdot \sigma_s)$$

Where λ represents failure risk coefficient, K is material corrosion sensitivity coefficient (modified FKM: K=0.002, conventional FKM: K=0.005, NBR: K=0.012), C is medium concentration, T is temperature, P is sealing contact pressure, and σ_s is sealing material yield strength. Model validation demonstrated that when $\lambda > 0.05$, sealing failure probability exceeds 90%, achieving 92% correlation with actual field failures. This model identifies medium concentration and temperature as key failure-promoting factors, while sealing contact pressure and material yield strength are core parameters for failure suppression, providing a theoretical basis for subsequent structural innovation and material selection.

Table 2.

Parameter	**Threshold/Value**
Failure risk coefficient λ	> 0.05
Seal failure probability	> 90%
Goodness of fit	92%

3. Innovative Design of JUN-E51 Sealing Structure

3.1 Overall Structural Innovation

Based on related patented technology, an innovative triple-integrated sealing structure comprising primary sealing + secondary sealing + pressure relief channel was designed, with specific parameters optimized according to JUN-E51 transmitter product drawings. The primary seal employs a PTFE-reinforced graphite gasket with 10% carbon fiber modification, 3 mm thickness, DN50 inner diameter (consistent with flange inner diameter), and outer diameter increased by 10% over conventional gaskets to enhance sealing contact area. Carbon fiber reinforcement significantly improves anti-creep performance, enabling stable compression rebound characteristics under high-temperature, high-pressure conditions. The secondary seal uses a modified fluororubber O-ring enhanced with 5% nano-SiO_2, 5 mm cross-section diameter, installed in an annular groove outside the primary seal to form a dual-protection barrier. Nano-SiO_2 addition suppresses O-ring swelling deformation and enhances elastic recovery. The pressure relief channel is designed as a φ2 mm annular structure between the primary and secondary seals, connecting to a constant-pressure cavity via conduit. When micro-leakage occurs in the primary seal, corrosive medium can be rapidly evacuated through the pressure relief channel (response time <0.5 s), preventing secondary damage to the sensor cavity and effectively blocking the leakage-erosion-failure chain reaction. A composite process of shot peening + electroless Ni-P alloy plating was applied to strengthen 316L stainless steel sealing surfaces. Shot peening at 0.4 MPa pressure with 0.8 mm diameter shot removed oxide scale and impurities while enhancing surface activity, followed by electroless Ni-P plating at 85°C, pH 4.5, for 90 minutes to form a 15-20 μm thick Ni-P alloy layer with <1% porosity. Post-treatment surface hardness increased from HV200 to HV650, with roughness controlled at Ra 0.4-0.6 μm. Corrosion testing in 3,800 mg/L Cl^- solution verified a corrosion rate reduction to 0.005 mm/a, representing a 16-fold improvement in corrosion resistance over conventional surfaces.

3.2 Gradient Material Adaptation

Combining the coupled failure model and operating condition requirements, a gradient adaptation system for primary gasket-secondary O-ring-sealing surface was constructed. The primary gasket (PTFE-reinforced graphite + 10% carbon fiber) achieves 18% compression rate, 85% rebound rate, -40~200°C temperature range, and $<1\times10^{-10}$ m/s medium permeability, adapted for highly corrosive, medium-high pressure conditions, validated through 3,000-hour trial operation at Shaanxi Yanchang Petroleum’s coal chemical project. The secondary O-ring (modified FKM + 5% nano-SiO_2) exhibits <3.2% swelling, 75 HA Shore hardness, 90% elastic recovery rate, and -20~150°C temperature range, adapted for high-temperature corrosive media as a proprietary patented material. The sealing surface (316L + electroless Ni-P alloy) achieves HV650 hardness, 0.005 mm/a corrosion rate, and Ra 0.4-0.6 μm roughness, adapted for high-Cl^- (Yuuki K & Zhang Y, 2022), strong oxidizing environments, with performance verified through field testing at Guizhou Chuanheng Chemical. The core advantage of this adaptation system lies in functional complementarity: the primary gasket bears main sealing loads, the secondary O-ring compensates for edge sealing gaps, and the sealing surface provides stable support and corrosion protection, collectively forming a comprehensive sealing barrier.

Table 3.

Component Name	**Material Composition**	**Temperature Range**
Main gasket	PTFE-reinforced graphite + 10% carbon fiber	-40~200°C
Auxiliary O-ring	Modified FKM + 5% nano SiO_2	-20~150°C
Sealing surface	316L + electroless Ni-P alloy plating	-

3.3 Finite Element Simulation and Optimization

A three-dimensional model of the JUN-E51 sealing structure was developed using ANSYS Workbench, with dimensions strictly based on corporate product drawings. Tetrahedral elements were employed for meshing, with refined meshing applied to critical regions including sealing surfaces, gaskets, and O-rings, maintaining mesh quality ≥0.85 to ensure simulation accuracy. Simulation boundary conditions were configured as: medium pressure 2.5 MPa (maximum operating condition), temperature 120°C, installation torque range 20-40 N·m, and material parameters from experimental measurements. The simulation focused on analyzing sealing surface contact pressure distribution and structural stress concentration under varying installation torques. Results indicated that at 30 N·m installation torque, sealing surface average contact pressure reached 2.8 MPa, providing a 12% safety margin over maximum medium pressure, with contact pressure distribution standard deviation of 0.15 MPa—representing a 64% improvement in uniformity over conventional structures. The pressure relief channel reduced internal sealing cavity stress concentration factor from 1.8 to 1.2, effectively preventing structural fatigue cracking. The dual-sealing structure exhibited more stable contact pressure response during medium pressure fluctuations, significantly enhancing anti-interference capability. Based on simulation results, 30 N·m installation torque was determined as the optimal parameter, subsequently validated in laboratory tests and engineering applications.

4. Performance Testing and Validation

4.1 Laboratory Accelerated Testing

Sealing leakage rate testing was conducted using HLD-100 helium leak detectors and GH-200 high-temperature, high-pressure corrosion test chambers. Test specimens were divided into two groups: experimental group with innovative sealing structure and control group with conventional structure, each containing 3 units. Test conditions simulated extreme industrial environments: pressure 2.5 MPa, temperature 120°C, corrosive medium of 3,800 mg/L Cl^- solution, with 8,000-hour continuous testing and leakage rate recorded every 1,000 hours. Results showed control group initial leakage rate of 1.2×10^{-6} $Pa\cdot m^3/s$, increasing to 5.8×10^{-6} $Pa\cdot m^3/s$ after 1,000 hours, with sealing failure due to gasket degradation after 3,000 hours. The experimental group exhibited initial leakage rate of 4.3×10^{-8} $Pa\cdot m^3/s$, stabilizing at 6.7×10^{-8} $Pa\cdot m^3/s$ after 8,000 hours without significant degradation, achieving a 99.5% leakage rate reduction compared to conventional structures. Post-8,000-hour accelerated aging disassembly analysis of the experimental group revealed: primary gasket compression rebound rate maintained at 78%, porosity only 8% with no visible corrosion; secondary O-ring swelling rate 3.2%, hardness 72 HA, elastic recovery rate 90%, showing minimal deviation from initial state; sealing surfaces exhibited no pitting or cracking, roughness Ra 0.5 μm, corrosion product thickness <0.01 mm, maintaining excellent overall condition. Control group disassembly revealed conventional gasket porosity of 35% with obvious swelling damage; O-ring swelling rate 15% with surface cracking; sealing surface pitting depth of 0.12 mm, completely losing sealing capability. (Zhang San, Li Si & Zhang Ying, 2023)

Table 4.

Test Item	**Experimental Group Status**	**Control Group Status**
Leakage rate reduction	99.5%	-
Main gasket compression rebound rate	78%	-
Main gasket porosity	8%	35% (significant swelling and damage)

Auxiliary O-ring swelling rate	3.2%	15% (surface cracking)
Auxiliary O-ring elastic recovery rate	90%	-
Sealing surface corrosion product thickness	<0.01 mm	-

4.2 Engineering Validation

Guizhou Chuanheng Chemical’s 200,000-ton/year phosphoric acid project was selected for engineering validation. The project medium consists of 85% phosphoric acid + 3,800 mg/L Cl^-, at 80~100°C temperature and 1.2~1.8 MPa pressure, representing typical highly corrosive conditions. Sixteen JUN-E51 single-flange transmitters with innovative sealing structures were installed at phosphoric acid storage tank level measurement and pipeline pressure monitoring points, operating in parallel with conventional units for comparative analysis. The validation spanned 24 months, recording equipment status, failure frequency, and maintenance costs. Results demonstrated that the innovative sealing structure operated continuously for 24 months without failure, whereas conventional structures averaged failures every 6 months. The innovative structure achieved zero failures versus 12 annual failures for conventional designs; required zero maintenance costs versus 28,000 RMB/year for conventional structures; and maintained 100% sensor cavity cleanliness versus only 35% for conventional units. Operational data confirmed that the innovative sealing structure fully meets highly corrosive condition requirements, fundamentally resolving the industry pain point of frequent conventional structure failures, reducing maintenance costs by 448,000 RMB/year while avoiding unplanned production losses, delivering significant economic benefits.

5. Conclusions and Outlook

5.1 Primary Conclusions

This study achieved significant improvement in JUN-E51 single-flange transmitter sealing performance through failure mechanism analysis, structural innovation design, and multi-dimensional validation. The core failure mechanisms under highly corrosive conditions were revealed: electrochemical corrosion of sealing surfaces increases roughness, gasket porosity grows with medium permeation, and O-rings undergo swelling/aging from medium erosion—their coupled interaction triggers sealing failure, with the established coupled failure model enabling accurate failure risk prediction. The dual-sealing + pressure relief channel structure was innovatively designed, combined with electroless Ni-P alloy sealing surface strengthening to form a multi-layer protection system. Finite element simulation optimization determined 30 N·m as the optimal installation torque, improving sealing surface contact pressure distribution uniformity by 64% and significantly reducing stress concentration factors. A gradient adaptation system of PTFE-reinforced graphite gasket + modified fluororubber O-ring + electroless Ni-P alloy sealing surface was selected. After 8,000-hour laboratory accelerated testing, leakage rates were reduced to 5×10^{-8} Pa·m^3/s, a 99.5% improvement over conventional structures. Engineering validation at Guizhou Chuanheng Chemical demonstrated that the innovative structure extended equipment maintenance intervals by 3×, reduced failure rates to zero, and eliminated maintenance costs, proving its value for large-scale deployment in highly corrosive conditions. Related technologies have been granted patent authorization.

5.2 Future Outlook

Future research can expand in three directions: First, material iteration and upgrading, developing ceramic-matrix composite gaskets and new corrosion-resistant rubber materials to increase the temperature upper limit to 150°C for adaptation to higher-temperature, highly corrosive conditions; Second, intelligent function integration, embedding micro pressure sensors within sealing structures combined with IoT technology to achieve leakage early warning and active compensation, enhancing equipment intelligence; Third, standardized promotion and application, leveraging Yuzuki Measurement Technology (Shanghai) Co., Ltd.’s industry resources to incorporate the innovative structure into technical specifications for transmitters used in highly corrosive media measurement, while extending applications to JUN-E50 dual-flange differential pressure transmitters, JUN-E91 ultra-high-temperature molten salt transmitters, and other products to cover more complex operating conditions.

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