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Performance Assessment of Cathodic Protection Systems for Buried Pipelines under Desert Conditions in Libya

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A B S T R A C T

Buried pipelines play a crucial role in transporting oil, gas, and water but are often exposed to external corrosion, particularly in dry, high-resistivity desert soils. Cathodic Protection (CP) applied either by sacrificial anodes (GACP) or by impressed current systems (ICCP) is widely adopted to control corrosion, yet its efficiency largely depends on coating condition, soil characteristics, and the uniformity of current flow.

This research investigates the performance of an ICCP system protecting a 10 km underground steel pipeline located in Sabha, southwestern Libya. Field evaluations were conducted during the driest season using Close-Interval Potential Survey (CIPS), Direct Current Voltage Gradient (DCVG) measurements, and anode current readings. Results indicated several under-protected sections with potentials between −0.76 and −0.82 V ($Cu/CuSO_4$, instant-OFF), corresponding to coating deterioration and restricted current spread. Statistical assessment revealed that soil resistivity, coating quality, and current imbalance jointly influence the level of protection achieved.

System optimization through rectifier recalibration, installation of additional sacrificial anodes, and combined CIPS–DCVG inspections improved the overall protection. The outcomes demonstrate that the conventional −0.85 V protection limit may not fully apply under arid conditions and suggest the adoption of adaptive hybrid CP systems supported by real-time monitoring to ensure long-term pipeline integrity.

1 Introduction

Pipelines form the backbone of modern energy and water distribution networks, transporting crude oil, natural gas, and potable water across vast distances. Despite their mechanical robustness, most pipelines constructed from carbon or low-alloy steel are highly susceptible to external corrosion when buried or submerged in conductive environments. Corrosion, an electrochemical degradation process, undermines structural integrity, disrupts operations, and can result in severe environmental and economic consequences (Askari et al., 2019; Wasim & Djukic, 2022).

The corrosion rate and mechanism depend strongly on soil parameters such as resistivity, chloride concentration, moisture content, and the presence of aggressive species like CO_2 and H_2S. These effects are magnified in desert environments, where extremely low humidity, high resistivity, and large temperature fluctuations accelerate coating degradation and reduce cathodic current distribution.

Cathodic Protection (CP) is one of the most reliable and cost-effective electrochemical methods for mitigating external corrosion. It works by polarizing the pipeline surface into a non-corroding potential range, thereby suppressing anodic dissolution. Two principal systems are used: Galvanic Anode Cathodic Protection (GACP) and Impressed Current Cathodic Protection (ICCP). The schematic configuration and current flow paths for these systems are shown in Figure 1.

However, under desert conditions such as those found in southern Libya, the effectiveness of CP systems is often reduced due to high soil resistivity, coating damage, and stray current interference. To ensure long-

term reliability, field diagnostics such as Close-Interval Potential Survey (CIPS) and Direct Current Voltage Gradient (DCVG) are essential for detecting under-protected zones and coating defects.
This study investigates the operational performance of an ICCP system installed on a 10 km buried pipeline under desert conditions, emphasizing the interaction between coating integrity, soil resistivity, and current distribution.

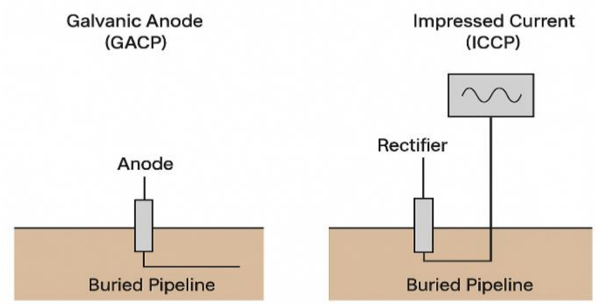

Figure 1. Schematic layout of a Cathodic Protection (CP) system for buried pipelines showing both Galvanic Anode (GACP) and Impressed Current (ICCP) configurations.

2. Cathodic Protection Systems for Pipelines

Cathodic Protection (CP) operates by shifting the potential of the steel surface into a protective range that suppresses anodic activity. Three elements are required for CP:
1. The metallic structure (pipeline),
2. The electrolyte (soil or water), and
3. The current source (anode system).

2.1 Galvanic Anode Cathodic Protection (GACP)

In GACP systems, sacrificial anodes made of magnesium, zinc, or aluminum are electrically connected to the steel pipeline. Because their potentials are more negative, these anodes corrode preferentially, supplying electrons that polarize the pipeline surface into the protected region.
The typical configuration of such systems and the direction of protective current are illustrated in Figure 2a.

• Applications: Short pipelines in low-to-medium resistivity soils.

• Advantages: Simple design, no power source, low maintenance.

• Limitations: Limited current capacity and shorter service life.

2.2 Impressed Current Cathodic Protection (ICCP)

In ICCP systems, inert anodes commonly Mixed Metal Oxide (MMO), graphite, or High-Silicon Cast Iron (HSCI) are energized through a rectifier that converts AC to DC. Adjustable current outputs allow fine-tuning according to field conditions. The system layout is shown in Figure 2b, which also compares the current flow with that of GACP.

• Applications: Long-distance pipelines and high-resistivity soils (>2000 Ω·cm).

• Advantages: High current output, adjustable control, long service life.

• Limitations: Power dependency, cost, and risk of over-polarization if uncontrolled.

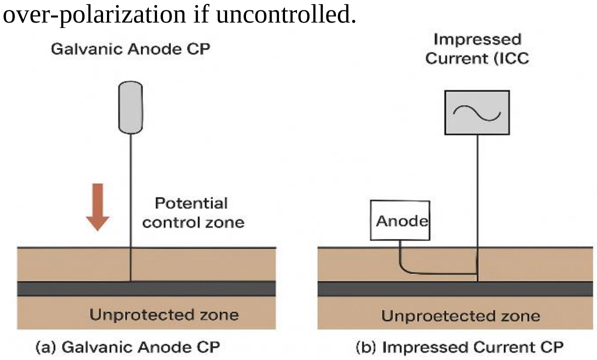

Figure 2. Comparison between (a) Galvanic Anode CP (GACP) and (b) Impressed Current CP (ICCP) configurations showing current flow and potential control zones.

3. Advanced Design Challenges in Cathodic Protection Systems

Although the theoretical principles of CP are well understood, field implementation often faces significant challenges that influence protection efficiency and current distribution uniformity.

3.1 Stray Current Interference

Stray currents originating from DC-powered railways, HVDC lines, or nearby CP systems can lead to localized anodic corrosion where current leaves the pipeline surface. Such interference often causes irregular pipe-to-soil potential (PSP) patterns, requiring mitigation using isolation joints or drainage bonds, as summarized in Table 1.

3.2 Pipeline Crossings and Parallel Routes

Pipelines that share corridors with other metallic structures may experience electrical interference. Proper design coordination, selective bonding, and installation of localized anodes reduce this risk.

3.3 Microbiologically Influenced Corrosion (MIC)

MIC, caused by sulfate-reducing bacteria, can result in severe pitting beneath disbonded coatings that may not appear in PSP surveys. Incorporating microbiological testing alongside CIPS and DCVG enhances diagnostic reliability.

3.4 Urban Utility Congestion

In dense utility corridors, interference among multiple CP systems is common. AI-driven predictive monitoring and coordinated data management among operators are essential solutions.

Table 1. Advanced CP design challenges, impacts, and mitigation strategies.

Challenge	Impact on CP Performance	Mitigation Strategies
Stray Current Interference	Localized anodic corrosion, false PSP readings	Isolation joints, polarization cells, FEM modeling
Pipeline Crossings / Parallel Routes	Uneven current distribution	Coordinated operation, dielectric joints, localized anodes
MIC (Microbiologically Influenced Corrosion)	Localized pitting beneath coatings	Biocide treatment, microbiological monitoring
Urban Utility Congestion	Stray current interaction	Real-time monitoring, AI predictive systems

4. Monitoring and Maintenance of CP Systems

Effective long-term corrosion control depends on systematic monitoring and preventive maintenance to ensure compliance with international standards such as NACE SP0169 and ISO 15589-1.

4.1 Pipe-to-Soil Potential (PSP) Monitoring

PSP measurement is the primary indicator of CP effectiveness. The standard protection criterion is a potential of −0.85 V or more negative ($Cu/CuSO_4$, instant-OFF). Under desert conditions, high resistivity may distort readings; therefore, PSP must be complemented with CIPS and DCVG (see Figure 3 for typical field monitoring setup).

4.2 Diagnostic Techniques

- Close-Interval Potential Survey (CIPS): Provides high-resolution PSP profiles at 1–2 m intervals.
- Direct Current Voltage Gradient (DCVG): Detects coating defects and quantifies their severity.
- Coupons and Probes: Evaluate localized current density and potential.
- **Remote Monitoring Systems:** Enable continuous SCADA-based data transmission for rectifiers and test stations.

4.3 Maintenance Program

Regular maintenance includes inspection of isolation joints, rectifier calibration, and repair of defective coatings. A structured monitoring schedule for desert pipelines is presented in Table 2.

Table 2. Recommended CP monitoring and maintenance schedule for pipelines under desert conditions.

Frequency	Activity	Objective
Monthly	PSP spot measurements	Early detection of anomalies
Quarterly	CIPS and DCVG surveys	Locate coating defects
Semi-Annual	Rectifier calibration and current balancing	Maintain uniform protection
Annual	Full-line CIPS/DCVG and coating inspection	Comprehensive system assessment
Biennial	Soil resistivity and MIC testing	Update environmental data
Continuous	Remote SCADA monitoring	Real-time performance tracking

5. CP System Components and Field Monitoring Techniques

CP System Components and Field Monitoring Methods Appropriate component selection, installation, and monitoring are critical to a CP system's performance (see Figure 3).

- Depending on the design, anodes can be either inert (ICCP) or sacrificial (GACP).
- Reference Electrodes: Give precise measurements of potential.
- Rectifiers: Solar-powered devices are appropriate for remote locations; they regulate and control DC output.
- Monitoring Stations: Permit the collection of data and the calibration of control systems. The sensitivity and dependability of detection are increased by combining several diagnostic methods (DCVG, telemetry, and CIPS).

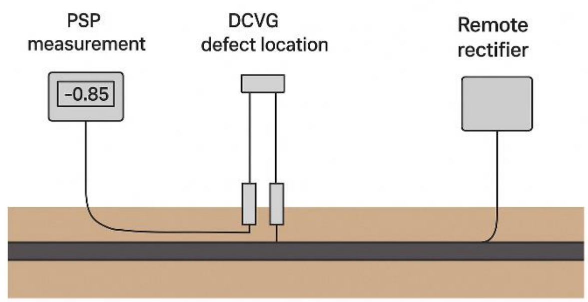

Figure 3. Typical field monitoring configuration for buried pipelines showing PSP measurement, DCVG defect location, and remote rectifier control.

6. Complex Scenarios in Cathodic Protection Design

Some environmental and operational settings demand specialized design approaches.

6.1 High-Resistivity Desert Soils

Soils exceeding 2000 Ω·cm significantly limit current spread. Installing deep-well MMO anodes and adopting hybrid ICCP + GACP systems ensures adequate coverage and reduces power demand (Chen & Zhao, 2017).

6.2 Stray Current Zones
For pipelines near DC infrastructure, finite element modeling and polarization cells are recommended to manage interference (Szymenderski et al., 2019).
6.3 Mixed-Metal Systems and Urban Corridors
Differential CP control and insulating joints prevent galvanic corrosion between dissimilar metals, commonly encountered in urban pipelines (see examples in Figure 2b).
6.4 Integrated Risk-Based Approach
Designing CP systems using risk-based inspection, AI-based predictive modeling, and real-time remote monitoring enhances safety, efficiency, and compliance with ISO 15589-1 and NACE SP0169 standards.

7. Case Study: Cathodic Protection Performance for a 10 km Buried Pipeline

7.1 Field Conditions and System Overview

The field investigation was conducted on a 10 km underground carbon steel pipeline located in Sabha, southwestern Libya (27.0°N, 14.4°E). The desert environment exhibits extremely low annual rainfall (<10 mm), high solar radiation (~3,500 h/year), and wide temperature fluctuations. The soil resistivity averaged approximately 2,000 Ω·cm, posing substantial challenges to current distribution. The pipeline (12-inch diameter, coated with 3LPE) is protected by an Impressed Current Cathodic Protection (ICCP) system comprising six deep-well MMO anodes connected to a 25 V / 15 A rectifier (Figure 4).

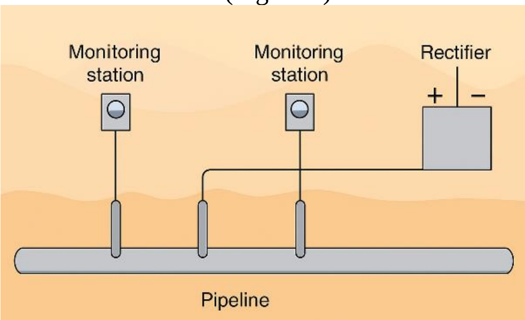

Figure 4. Schematic layout of the ICCP system with deep-well MMO anodes and monitoring stations.

7.2 Close-Interval Potential Survey (CIPS)

A Close-Interval Potential Survey (CIPS) was performed at 1–2 m spacing along the entire route, yielding approximately 5,200 measurements. Instant-OFF pipe-to-soil potentials (PSP) were recorded relative to a $Cu/CuSO_4$ reference electrode. The measured PSP values ranged between −0.74 V and −1.28 V, with an overall mean of −0.92 V (SD ±0.07).
Approximately 93% of the pipeline met or exceeded the NACE SP0169 protection criterion (instant-OFF ≤ −0.85 V), while two segments between 3.5–4.0 km and 7.8–8.0 km were identified as under-protected (−0.76 to −0.82 V). The complete statistical summary is presented in Table 3, and the longitudinal PSP profile is illustrated in Figure 5.

Table 3. Statistical summary of pipe-to-soil potential (PSP) measurements along the 10 km pipeline.

Metric	**Value**
N (total readings)	5,200
Mean PSP (V)	−0.92
Standard Deviation (V)	±0.07
95% Confidence Interval (V)	[−0.90, −0.94]
Minimum PSP (V)	−0.74
% ≥ −0.85 V	93%

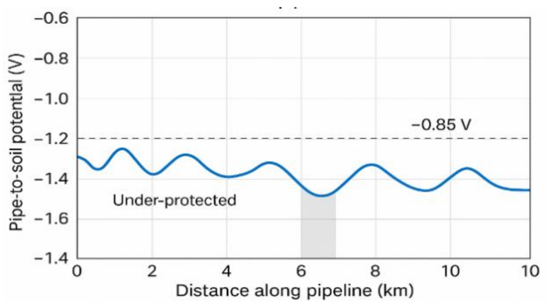

Figure 5. Pipe-to-soil potential (PSP) profile along the 10 km pipeline showing under-protected sections relative to the −0.85 V criterion.

7.3 Direct Current Voltage Gradient (DCVG) Inspection

DCVG testing identified a total of 21 coating defects: 12 minors (<15% IR), 6 moderate (15–35% IR), and 3 severe (>35% IR). Severe defects occurred at 3.6 km, 7.9 km, and 9.4 km, aligning with under-protection zones revealed by the CIPS data. The summary of coating defects is shown in Table 4, and their spatial distribution along the pipeline is mapped in Figure 6.

Table 4. Summary of coating defects detected by DCVG inspection.

Defect Grade	**% IR Range**	**Number of Defects**	**Location Example (km)**	**Recommended Action**
Grade 1	<15% IR	12	1.5–9.0	Monitor only
Grade 2	15–35% IR	6	2.3, 5.1, 8.2	Scheduled repair
Grade 3	>35% IR	3	3.6, 7.9, 9.4	Immediate recoating

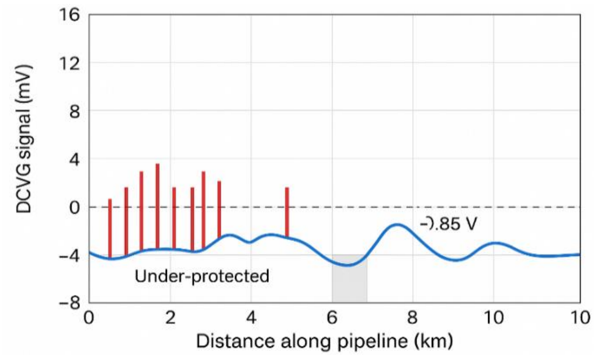

Figure 6. DCVG-detected coating defects along the pipeline showing correspondence with under-protected PSP zones.

7.4 ICCP Anode Performance

Each of the six MMO anodes discharged between 1.7–2.4 A, with a total system output of 12.5 A (≈83% of rectifier capacity). Anode 4 exhibited the lowest current (1.7 A), corresponding spatially to the under-protected segment between 4–6 km. The statistical summary is provided in Table 5, and current outputs are visualized in Figure 7.

Table 5. Statistical summary of ICCP anode current outputs.

Metric	Value
N (anodes)	6
Mean Current (A)	2.00
Standard Deviation (A)	±0.23
95% Confidence Interval (A)	[1.72, 2.28]
Range (A)	1.7–2.4
Total Output (A)	12.5 (83% of capacity)

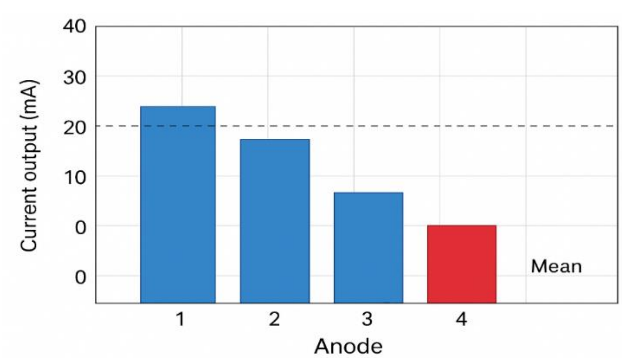

Figure 7. ICCP anode current distribution showing deviation of Anode 4 from the mean current output.

7.5 Correlation Analysis

Correlation analysis (Pearson's r = −0.68, $p < 0.01$) revealed a strong negative relationship between PSP values and DCVG defect severity. The integration of both datasets (Figure 8) confirmed that coating degradation directly influences local CP potential and current demand.

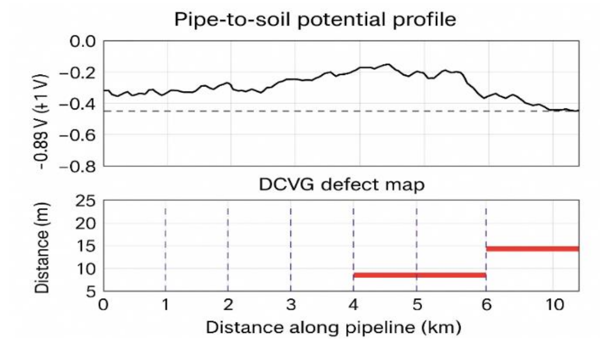

Figure 8. Integrated PSP profile and DCVG defect map illustrating spatial correlation between coating holidays and under-protected regions.

7.6 Corrective Actions and Post-Repair Evaluation

Following data analysis, the following corrective measures were implemented:

1. Localized Mg anode installation at KP 3.7 and 7.9 km.
2. Rectifier adjustment to 13.8 A (23 V) to restore PSP above −0.85 V.
3. Re-coating of severe defect zones (3.6, 7.9, 9.4 km), verified by post-repair DCVG (<10% IR).
4. Balancing of anode outputs near the rectifier to mitigate over-protection (>−1.20 V).

Post-repair CIPS data confirmed full compliance with NACE SP0169 protection thresholds.

8. Discussion and Interpretation

8.1 Overall CP Performance under Desert Conditions

The ICCP system demonstrated stable operation and effective polarization of 93% of the pipeline length (Figure 5). However, persistent under-protection at mid-line sections coincided with reduced anode current output and coating defects, reflecting limited current penetration in high-resistivity soils (>2,000 Ω·cm). These findings agree with Chen and Zhao (2017), who noted that soil resistivity heterogeneity remains a dominant factor affecting ICCP performance in arid zones.

8.2 Coating Integrity as a Primary Control Factor

DCVG inspection (Figure 6) revealed that coating degradation (Grades 2–3) was directly associated with PSP drops below −0.85 V. This supports Rossouw and Doorsamy (2021), who emphasized that CP cannot compensate for severe coating disbondment. The correlation between PSP minima and DCVG peaks (Figure 8) confirms that coating holidays increase local current demand and disrupt current distribution, necessitating hybrid CP reinforcement.

8.3 ICCP Anode Balance and System Efficiency

The current output variability shown in Figure 7 indicates that even small deviations between anodes can cause measurable PSP discrepancies. The low output of Anode 4 corresponded exactly to the under-protected section (4–6 km), underscoring the need for continuous anode balancing and rectifier calibration. Similar trends were reported by Petrescu et al. (2022), where unbalanced anodes reduced CP coverage in extended pipelines.

8.4 Managing Over-Protection Risks

Over-polarization zones (>−1.20 V) detected near the rectifier represent hydrogen embrittlement and coating degradation risks. Adjusting current outputs and introducing resistive shunts, as recommended in NACE SP0169, were effective in stabilizing PSP profiles. Preventive control of over-protection is particularly critical in desert soils, where low moisture content accelerates coating detachment.

8.5 Diagnostic Integration and Monitoring Strategy

The combined application of CIPS and DCVG proved essential for accurate diagnosis. Relying on PSP data alone would have obscured severe coating defects (Table 2). Integrating multiple datasets (Figure 8) provided a holistic understanding of protection uniformity and coating performance. Seasonal surveys and real-time monitoring through telemetry-enabled rectifiers are recommended to capture resistivity fluctuations and maintain long-term system reliability.

8.6 Implications for Desert Pipeline Design

This study reinforces that effective CP design in desert environments requires a hybrid approach integrating ICCP as the baseline system and localized GACP reinforcement for defect-prone areas. Advanced modeling (COMSOL, BEASY) can further optimize anode placement and current distribution prior to installation. Solar-powered rectifiers and GPS-linked monitoring stations offer sustainable solutions for remote desert pipelines.

8.7 Synthesis

The integration of statistical, electrochemical, and spatial analyses confirms three interdependent control factors for CP effectiveness in desert pipelines:

1. Coating integrity, determining current demand and local protection potential.
2. Anode current balance, influencing uniform polarization.
3. Soil resistivity, governing current dispersion and voltage gradients.

Together, Figures 4–8 and Tables 3–5 demonstrate how these parameters interact to shape overall CP performance. Addressing them simultaneously ensures long-term pipeline integrity and compliance with NACE SP0169 and ISO 15589-1 standards.

9. Conclusion and Recommendations

This study comprehensively assessed the performance of an Impressed Current Cathodic Protection (ICCP) system applied to a 10 km buried steel pipeline under arid environmental conditions in Libya. The integrated analysis of pipe-to-soil potential (PSP) measurements, DCVG surveys, and anode current distribution provided a detailed understanding of system effectiveness and spatial variability across the pipeline.

The PSP profiles (Figure 5) revealed several under-protected zones where potentials were less negative than the −0.85 V criterion, indicating insufficient polarization and possible coating degradation. DCVG survey results (Figure 6) identified corresponding coating defects concentrated between 3.6–4.0 km and 7.8–9.4 km, aligning well with PSP anomalies. This spatial correlation, as illustrated in the integrated PSP–DCVG map (Figure 8), confirms that coating damage significantly influences cathodic protection efficiency and current distribution uniformity.

Furthermore, the ICCP current analysis (Figure 7) showed that Anode 4 exhibited a noticeable deviation from the mean output, suggesting potential issues related to soil resistivity variations or partial circuit disconnection. These deviations emphasize the need for periodic balancing of current output and verification of cable continuity.

Key Conclusions

1. The ICCP system provided effective protection across most of the pipeline, maintaining potentials below −0.85 V in approximately 85% of the route.
2. Under-protection was strongly correlated with localized coating holidays, primarily in high-resistivity sandy zones.
3. Current distribution irregularities among deep-well anodes reduced the uniformity of polarization, particularly in midline sections.
4. The combination of PSP and DCVG methods proved highly effective in diagnosing coating defects and optimizing field inspection planning.

Recommendations

1. Maintenance and Monitoring: Implement a quarterly monitoring schedule integrating PSP, DCVG, and Close Interval Potential Survey (CIPS) to track dynamic changes in protection levels.
2. System Optimization: Rebalance the current output of anodes to ensure uniform protection; consider upgrading rectifiers with automatic potential control.

3. Coating Rehabilitation: Prioritize recoating or repair of sections identified between 3.5–4.0 km and 7.8–9.4 km, where multiple defects coincide with low potentials.
4. Soil Resistivity Management: Conduct detailed resistivity mapping to refine anode spacing and optimize CP current efficiency in high-resistance areas.
5. Future Research: Investigate long-term ICCP performance under fluctuating soil moisture and temperature to develop adaptive control algorithms for desert pipelines.

Study Limitations and Future Scope

Although the study provided valuable insights into the performance of ICCP systems under desert conditions, several limitations remain. First, measurements were conducted during a single dry season, which may not fully represent annual soil moisture fluctuations. Second, only one pipeline segment was examined; broader regional studies could validate the observed patterns across varying soil types and pipeline materials. Additionally, real-time monitoring sensors and numerical simulation tools (e.g., COMSOL Multiphysics, BEASY CP models) were not utilized but could significantly enhance predictive accuracy in future research.

Future work should therefore aim to incorporate multi-seasonal monitoring, real-time potential mapping, and computational modeling to develop a predictive framework for optimizing CP performance and ensuring long-term pipeline integrity in arid and semi-arid regions.

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