Underground Bacteria Generates H₂S and Trips Control Panels

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Summary
Instrument equipment shelters (IESs) are important control buildings within operating plants, housing the critical instrumentation and control system (ICS) panels that are essential for plant operations. At one such IES building in one of the plants operated by Abu Dhabi Gas Industries Limited (GASCO), frequent tripping of ICS panels was encountered, without pre-alarm indication, leading to plant upsets and posing risk to the safe operations of the plant. Occasionally, the odor of hydrogen sulfide (H₂S) was observed. This paper addresses the measures undertaken to identify the source of generation and diffusion of corrosive agents into the IES and remedial measures to eliminate this chronic problem.

Ingress of corrosive agents through air inlets/doors was eliminated as a cause because of the absence of any signs of corrosion in heating, ventilation, and air-conditioning (HVAC) air intakes and because of maintenance of positive air pressure within the building. Extensive investigation and testing of soil indicated the presence of a high concentration of sulfate-reducing bacteria (SRB) in the vicinity of the building. A high groundwater table containing sulfates provided nutrition to the SRB. The bacteria reduced the sulfates present in the groundwater to H₂S. The H₂S, thus generated, diffused into the building through cable entry sleeves, reaching the area beneath the false flooring on which panels were mounted, and subsequently entering the panels. The presence of conducive temperature and humidity facilitated the reaction of H₂S with electronic cards, thereby causing corrosion and tripping of panels. The key remedial measures that were recommended—namely, dewatering the surrounding area and lowering groundwater levels to starve the bacteria, thus rendering it dormant and preventing H₂S generation, and sealing of cable entry sleeves to prevent any external gas ingress into the building—were implemented, resulting in resolution of the issue and maintaining the safety and integrity of plant operations.

Tripping of ICS panels because of H₂S generation by bacteria present in soil is a rare phenomenon, not commonly encountered in oil and gas plants. In areas where the groundwater table is high, the construction of buildings needs to be planned carefully. Geotechnical investigation shall include testing for the presence of organic content, sulfates, and SRB in soil and groundwater, in addition to conventional tests.

Introduction
In one IES at one of the GASCO plants, ICS panels that monitor and control the processes of several important units are located. The building, having approximate dimensions of 42-m length, 9.7-m width, and 5.2-m height, is constructed of reinforced concrete walls and roof, and is designed to be blast resistant. There are four rooms in the building: the control room, which houses the instrumentation panels; the uninterrupted-power-supply (UPS) room, which houses the UPS equipment; the battery room; and the HVAC room. The panels in the equipment room are mounted on raised access flooring (false floor), having space for cables running underneath. The plan view of the building is shown in Fig. 1.

The panels in this building tripped frequently, leading to unplanned plant outages, and thereby posing a risk to overall plant operations and integrity. It was observed that tripping of panels was mainly caused by failure of the electronic cards in the panels. Multiple cards had to be replaced, depending on the failure, and the rate of replacement was once in an approximately 1-month interval. Visual inspection of the cards did not indicate any defect. Site survey observations indicated a mild odor of H₂S prevalent in the vicinity of the building and in areas under the false floor, discoloration of soil surrounding the building, high groundwater levels, and damages to building cable-entry sealants. To investigate the root cause and provide remedial measures, a technical study involving several testing techniques was carried out and the root cause was identified. Remedial measures were proposed to overcome the issue and were implemented at site.

This paper presents the tests carried out during the study, the test results, and the recommended remedial measures and their implementation and effectiveness, which enabled mitigation of the failure of the control panels.

Analysis and Testing
Testing of Electronic Cards. Because the visual inspection of the electronic cards did not indicate any defect, advanced and sophisticated testing techniques were carried out on the components.

X-Ray Photoelectron Spectroscopy (XPS). XPS is a surface-sensitive quantitative spectroscopic technique that measures the elemental composition, chemical state, and electronic state of the elements that exist within a material. XPS spectra are obtained by irradiating a material with a beam of X-rays while simultaneously measuring the kinetic energy and number of electrons that escape from the material being analyzed. XPS is a surface-chemical analysis technique that can be used to analyze the surface chemistry of a material in its as-received state or after some treatment. XPS is also known as electron spectroscopy for chemical analysis. Data were recorded from samples measuring approximately 700×300 μm, using monochromatic Al Kα X-rays in “hybrid” mode.

Static Secondary Ion Mass Spectrometry (SSIMS). SSIMS, or static SIMS, is a technique for chemical analysis that includes elemental composition and chemical structure of the uppermost atomic or molecular layer of a solid, which may be a metal, semiconductor, or plastic with insignificant disturbance to its composition and structure. It is one of the two principal modes of operation of SIMS, which is the mass spectrometry of ionized particles emitted by a solid (or sometimes liquid) surface upon bombardment by energetic primary particles. Quadrupole, magnetic sector, and time-of-flight (TOF) are the three mass spectrometers used in SIMS. In this case, the test instrument contained a TOF mass...
Positive- and negative-ion spectra were recorded from samples having analysis areas of approximately 200×200 µm.

Soil and Groundwater Investigation. Tests for SRB in Soil. Discoloration of soil observed during site survey necessitated further sampling and testing of soil to check for the presence of SRB. Six boreholes were drilled around the building, and soil samples were collected from each borehole. Further sampling and testing were carried out in accordance with the method described in NACE TM0194-2004 (2004) Tripli cate tests were performed in small (containing 5 mg) and large (containing 10 to 25 mg) samples of the soil material extracted from the boreholes. The samples were placed in a bacterial-growth medium and incubated for 14 days.

Tests for Sulfide Content in Soil. Determination of sulfide content in soil was carried out by liberating the sulfides in the form of H₂S from soil samples by use of hydrochloric acid (50% concentration) as reagent, and passing the gas through sodium hydroxide. The trapped sulfide was quantified by titration against silver nitrate solution and potential measurement using a silver/silver sulfide ion-selective electrode.

Water Analysis. Water samples were subjected to standard ionic analyses in accordance with API RP 45 (1998).

Air-Property Measurements. H₂S Content in Air. H₂S concentration in air was measured with a Drager pump in conjunction with Drager H₂S-detection tubes. This is based on discoloration of a pre-calibrated chemical-impregnated gas-detector tube on pumping a metered volume of air through it.

Temperature and Humidity Measurements. The indoor and outdoor environmental temperature and humidity measurements were carried out by use of a standard thermohygrometer with an external probe.

HVAC-System Tests. Installation of Corrosion Coupons. Corrosion coupons were installed at the building HVAC air intakes to measure any potential source of corrosive agents in the air used for ventilation.

Filter-Media Chemical Analysis. A sample of filter media from the HVAC inlet filters was taken for chemical analysis to detect the presence of any corrosive agents.

Test Results and Assessment

Test Results. XPS Test. The main elements detected were carbon and oxygen along with low levels of sodium (Na), zinc, copper (Cu), nickel, tin, nitrogen, chlorine (Cl), sulfur (S), silicon (Si), and gold (Au). Au was the most abundant metal. Si was present at silicate/silicone material. Cl was present as chloride. Two forms of S were detected, including an oxidized sulfite form along with one or more sulfide species. The percentage of sulfides was in the range of 50 to 55%, with the remaining being in the form of sulfates (Table 1).

SSIMS. The SSIMS test on electronic cards resulted in detection of a wide range of elemental species on the surfaces. Positive ions in the spectra were dominated by Na⁺ and potassium (K⁺), with various forms of Cu ions. The negative spectra were dominated by inorganic species including CN, Cl⁻, NCO⁻, and oxidized S and phosphorus species. Samples from the edge region of the electronic card (Fig. 2) showed greater relative intensity because of the presence of hydrocarbon species.
SRB, H₂S, and Sulfide Measurement in Soil. Bulk soil samples from the six locations in the field were collected. In the laboratory, from each of the six bulk samples, three small samples and three large samples were collected. Out of six sample locations, the presence of SRB was strongly positive in one, moderately positive in four, and had low population density in another. This indicates that the presence of SRB is high in certain locations, and is localized. The presence of sulfides in soil was high (121.8 mg/kg) in areas having high SRB concentration and low to nil in areas having low SRB levels. Correspondingly, in the boreholes having high levels of SRB, high concentrations of H₂S (160 ppm) were also measured (Table 2). In areas having low SRB levels, H₂S was not detected.

Water Analysis. Analysis of water indicated water to be brackish, with a pH of 8.02 and low total dissolved solids. However, it may be noted that a high concentration of sulfates (3079 mg/L) was measured (Table 3). Magnesium sulfate dominated the dissolved-salts composition.

Air Properties. Humidity and temperature measurements were recorded at 11 locations inside the shelter. The average humidity level was 44%, and the average temperature was 19°C.

Twelve measurements for humidity and temperature were taken around the perimeter of the shelter. The average humidity was 20%, and the average temperature was 45°C.

Three measurements for humidity and temperature were taken in the building under the false floor. The average humidity was 46%, and the temperature was 20°C.

A minute presence of H₂S (<1 ppm) was detected in the building under the false floor. H₂S was not detected in the building above the false floor.

Tests on the HVAC System. Corrosion coupons installed on HVAC air intakes did not exhibit any signs of corrosion. HVAC inlet filter-media laboratory tests did not indicate the presence of any corrosive elements.

Assessment. On the basis of the site-visit observations and the test results mentioned in the preceding subsections, the following assessments were made.

XPS and SSIMS testing on the electronic cards indicated the presence of sulfides, which caused corrosion of the cards, resulting in tripping of panels. The absence of signs of corrosion on coupons installed in air intakes, the absence of corrosive elements in HVAC-inlet-filter media, and the presence of positive pressure within the building eliminated external atmospheric air as the source of corrosive-agent infusion.

Soil testing indicated the presence of SRB in most of the samples. A high groundwater table containing significant sulfate concentration provided a source of nutrition for the SRB. The SRB, in the presence of organic matter, reduce the sulfates present in the water to H₂S. Hence, it is probable that there is a source of organic matter in the vicinity of the building, which could be a historical waste dump. The reaction is presented by the following equation:

$$\text{SO}_4^{2-} + \text{Organic material} \rightarrow \text{H}_2\text{S} + \text{CO}_2 + \text{H}_2\text{O}. \quad \text{.............. (1)}$$

The level of H₂S in the borehole region was high and localized because H₂S is continuously oxidized in air. This is depicted by the following equation:

$$2\text{H}_2\text{S} + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + 2\text{S} \downarrow. \quad \text{.................................................. (2)}$$

However, in the present case, the rate of generation of H₂S was much higher than the rate of H₂S oxidation because within the soil underground, the presence of oxygen is inadequate for this reaction to occur. Hence, it can be inferred that the H₂S thus generated diffused into the building, under the false-floor region, and through the cable-entry sleeves provided in the building wall. This is corroborated by the site observation wherein the sealants of the cable-entry sleeves were found damaged. This resulted in contamination of air under the false flooring within the building with H₂S, though in very minute quantity.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Sulfide, H₂S (mg/kg)</th>
<th>H₂S (ppm in borehole air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (moist)</td>
<td>Not detected</td>
<td>-</td>
</tr>
<tr>
<td>2 (moist)</td>
<td>121.8*; 31.9**</td>
<td>160</td>
</tr>
<tr>
<td>3 (wet)</td>
<td>8.5</td>
<td>-</td>
</tr>
<tr>
<td>4 (dry)</td>
<td>Not detected</td>
<td>-</td>
</tr>
<tr>
<td>5 (semi-dry)</td>
<td>14.9</td>
<td>-</td>
</tr>
<tr>
<td>6 (semi-dry)</td>
<td>79.8</td>
<td>140</td>
</tr>
</tbody>
</table>

*Black/sandy-brown region, with solid black debris
**Black/sandy-brown region

<table>
<thead>
<tr>
<th>Presence of SRB</th>
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<tbody>
<tr>
<td>Sample Location</td>
</tr>
<tr>
<td>1 (moist)</td>
</tr>
<tr>
<td>2 (moist)</td>
</tr>
<tr>
<td>3 (wet)</td>
</tr>
<tr>
<td>4 (dry)</td>
</tr>
<tr>
<td>5 (semi-dry)</td>
</tr>
<tr>
<td>6 (semi-dry)</td>
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</tbody>
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Table 2—Soil-sample-analysis results.


Table 3—Water-sample-analysis results (anions).

<table>
<thead>
<tr>
<th>Anions</th>
<th>(mg/L)</th>
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<tbody>
<tr>
<td>Chloride</td>
<td>484</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>584</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3079</td>
</tr>
<tr>
<td>Carbonate</td>
<td>0</td>
</tr>
<tr>
<td>Hydroxide</td>
<td>0</td>
</tr>
</tbody>
</table>

$\text{H}_2\text{S}$, being heavier than air, tends to settle in lower spaces, and the area underneath the false floor provided a low-lying area. The ICS panels were mounted on the false floor, with the panel bottoms having provision for cable entry. These cable entries at the panel bottom were not sealed properly because of access limitations. Suction fans were located on the top of the panels, and louvers were provided on the panels at the sides toward the bottom. This system enabled entry of cool air from the room into the panels from the sides and expulsion of hot air from within back into the room from the top of the panels. Because the bottom cable entries were not sealed appropriately, they provided a path for the contaminated air from the bottom to pass into the panels as a result of suction from the fans placed at the top.

In the presence of a conducive environment with appropriate temperature and humidity, there is high affinity for air to form condensation on the Cu surface of the electronic cards located within the panels. According to International Society of Automation (ISA) standard ANSI/ISA-71.04-2013 (2013), Annex B, the presence of $\text{H}_2\text{S}$ concentration as low as 50 ppb creates a harsh (severity level G3) environment, and any presence in concentration $\geq$ 50 ppb will result in a severe (severity level GX) environment for Cu, at less than 50% humidity levels. The severity level G3 (harsh) is identified as an environment in which there is high probability that corrosive attack will occur. The severity level GX (severe) indicates an environment in which only specially designed and packaged equipment would be expected to survive.

In the present case, it can be inferred that $\text{H}_2\text{S}$ present in the air, along with humidity, resulted in sulfidation of the Cu surfaces of the electronic cards. The presence of copper sulfide was observed on the card surface samples. The chemical reaction between the metal surface and $\text{H}_2\text{S}$ was confirmed by the XPS and SSIMS techniques.

In view of the preceding, it can be concluded that the SRB present in soil reacted with sulfates present in groundwater to generate $\text{H}_2\text{S}$. The $\text{H}_2\text{S}$, thus generated, diffused into the building through cable-entry sleeves provided on building walls. The suction fans located at the top of the panels draw the air in, and, hence, this contaminated air from the bottom could ingress into the panel. Prolonged exposure to contaminated air and humidity resulted in surface metal corrosion of electronic cards in the panels. This phenomenon caused the frequent tripping of panels. This is represented in Fig. 3.

**Recommendation of Remedial Measures**

A combination of remedial and control measures was recommended for implementation to address the problem. The measures were classified as primary (which directly address the issue) and secondary (which could provide an additional layer of protection). The recommended primary measures are as follows:

1. Dewatering of groundwater in the vicinity of the building to at least 1 m below the building foundation levels. This measure will keep the soil surrounding the building dry, thereby starving the SRB of its main nutrient. This will render the bacteria inactive, and $\text{H}_2\text{S}$ generation will be mitigated.
2. Replacement of existing cable-entry sealants with thixotropic and temperature-resistant high-grade industrial gas-proof sealant, having high adhesion to semiclean surfaces. This will prevent any ingress of air/gas from outside the building to the indoor environment.
3. Sealing of cable entries at the panel bottom, to the extent practicable because of access restrictions. This will assist in mitigating ingress of air from under the false floor into the panels.
4. Reversing the direction of air flow in the panels. At present, fans at the top of the panels circulate air by suction, thereby resulting in probable ingress of air from under the false floor. If the air flow is reversed, then the possibility of $\text{H}_2\text{S}$, which is heavier than air, entering the panels will be greatly reduced.
5. Reduction of humidity levels in the building to less than 40%. This will provide an unfavorable environment for the reaction of air and the metal surface of panel electronic cards, thereby mitigating corrosion.

The recommended secondary measures are as follows:

1. Installation of vapor-corrosion-inhibitor units within the panels to inhibit the formation of any corrosive coating on the electronic components.
2. Placement of $\text{H}_2\text{S}$ scavengers near the cable-entry sleeves under the false floor.
3. Sealing of all doors and other openings.
4. Construction of an air-lock chamber at the entry to prevent external-air ingress and to control temperature and humidity.
5. Installation of a flexible membrane liner at the building periphery, underground, to isolate the area and allow filling the region near the building with fresh, uncontaminated soil.

**Implementation of Remedial Measures**

The recommendations from the study provided an exhaustive list of measures to be considered for implementation. Considering the practicality, constraints of working in a brownfield within an operating plant and interfaces with instrumentation and control-panel vendors, and HVAC-system limitations, the following were the measures implemented:

- Dewatering: French drain or weeping tile drain system with perforated pipes and collection chambers discharging into a
Sump pit for final discharge. This system comprises a trench excavated into the ground to a level 1.3 m below the existing building foundation level. The bed surface was prepared with compacted gatch, and 160-mm-diameter polyvinyl chloride machine-perforated pipes were laid on a slope. The pipes were covered with two layers of graded gravel packs, and wrapped with geotextile membrane. The remaining portion of the trench was backfilled with imported dune sand. Four collection pits, constructed of reinforced concrete and having a size of 1.5×1.5 m and varying depths, were built to form the collection network. One collection pit/pumping chamber consisted of two submersible pumps (one working and one standby) for disposal of collected water. Associated level instruments, switches, and local control panels were installed for automatic operation of pumps. The final discharge line was a 6-in. high-density polyethylene pipe, and the disposal location was approximately 1000 m from the gathering pit. The system is depicted in Fig. 4.

- Sealing of building cable-entry sleeves: As recommended, the building cable-entry sleeves were sealed using industrial high-grade ultraviolet- and temperature-resistant sealant. The sealing was carried out for both used and spare sleeves. The method adopted is depicted in Fig. 5.
- Sealing of cable entry at panel bottom: The cable entries at panel bottoms, wherever practically feasible, were also sealed with industrial-grade sealant.

The following measures were not implemented:
- Reversing the air flow: This required significant changes to the panel enclosure design because the reason for the suction fan being located at the top of the panel was so that the hot air inside the panel would rise to the top. Reversing the air flow would require that the air circulation inside the panel be modified. This is a major task because there are panels from multiple vendors with different parameters, including sizing and heat dissipation. Hence, this measure was not implemented.
- Maintaining humidity at less than 40%: The existing HVAC system is currently incapable of reducing the humidity to 40%. The system would require major modifications and refurbishment to achieve this feature. Hence, this measure was not implemented.

It was decided to implement the three primary measures, as described in the preceding, and monitor the performance before considering the secondary measures for implementation.

Performance Evaluation
The remedial measures of sealing the building cable-entry sleeves and the panel-bottom cable entry were executed in the initial phase. As a result, the frequency of tripping of panels reduced significantly; however, it was still higher compared with panels located in other buildings. To eliminate the source of H2S, the dewatering system was installed. After approximately 1 year of performance monitoring, the tripping of panels was reduced dramatically, and is at present comparable with the performance of panels in other buildings.

Other benefits are that plant safety and integrity are maintained, the area around the building is clean and dry, and the dewatering method is sustainable and simpler to implement compared with other available methods, such as air injection to oxidize H2S or biocide injection to treat the bacteria. Additionally, the
implemented measures are cost efficient and long term, requiring minimum maintenance; finally, all measures were implemented in the running plant without any interruption to plant operations. Because the desired performance of the panel cards was achieved after execution of dewatering and cable-entry sealing, the other recommended measures were not implemented.

Conclusions
Tripping of ICS panels because of ingress of H₂S generated from SRB present in the soil is a unique phenomenon, not commonly encountered in oil and gas plants in the region. The necessity to arrive at a solution while working in an operating plant without any plant outage and within the confines of the restricted area available posed several challenges. In areas having a high groundwater table, careful planning of building design and careful construction need to be carried out. Initial site survey and geotechnical investigation must include tests for identification of SRB and other contaminants in the soil. Minor increase in building elevation may be considered in the design, without impacting the required blast resistance.

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References


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