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Investigating Oxygen Ingress in the Oil and Gas Industry

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ABSTRACT

In this review, events leading to ingress of O_2 in various upstream oil and gas systems are investigated. By analyzing reported instances in the literature, factors leading to oxygen infiltration are elucidated. Pipeline maintenance, equipment failures, system design and construction, accidental introductions, chemical injections, and improper protocols are explored and further analyzed to gain a broad understanding of oxygen ingress pathways. The findings of this study raise awareness of O_2 as a contributing factor in the corrosion mechanisms involved in these systems, coupled with preservation of asset integrity.

Keywords: O_2 ingress, Oil and gas systems, Literature review

INTRODUCTION

Hydrocarbon deposits in geologic reservoirs formed millions of years ago from remains of organic matter buried under layers of sediments. Any O_2 initially present long ago reacted with other compounds leading to its removal as the oil and gas formed; leading to an O_2-free state. The hydrocarbon contents of these reservoirs being oxygen free, the extraction and transportation infrastructure of the oil and gas industry is also falsely assumed to be void of any O_2. This false assumption has also prevented thorough mechanistic investigations of the corrosion consequences of O_2 in these oil and gas systems. Throughout literature and by anecdotal accounts, sources of O_2 ingress have been identified. This paper discusses possible causes of oxygen ingress, as well as mitigation strategies.

OXYGEN INGRESS MECHANISMS

Ingress of O_2 can occur in oil and gas production and transmission systems via numerous pathways. Causes include ingress at the source, fluid injections, maintenance routines, leakage, pumps, or design shortcomings. A comprehensive list of these pathways is listed in Figure 1, each leading to O_2 ingress that could exacerbate corrosion risks for the oil and gas infrastructure; risk generally decreases from left to right across the figure.

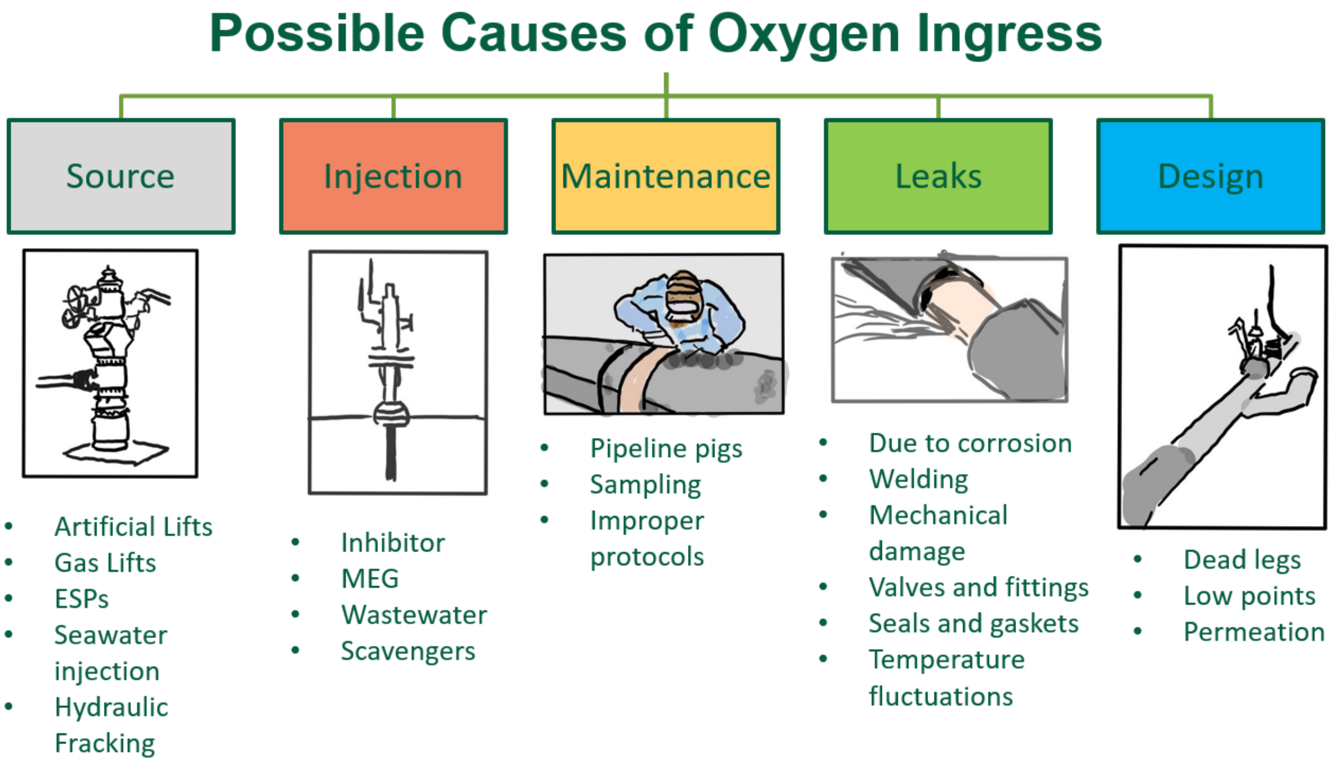

Figure 1. Possible causes of O_2 ingress

Artificial Lift

In the early production stage of an oil well, reservoir pressure provides enough force to flow fluids to the surface. However, as wells age the fluid ceases to flow as reservoir pressure decreases. Hence, artificial lift is employed to draw more fluid out of the well and prevent an otherwise premature death of the well. Artificial lift provides the required force for the well to continue to produce and are thus categorized based on the mechanisms they use for this energy transfer. Figure 2 shows different types of artificial lift that are commonly employed for oil wells[1]. Three of the four shown are susceptible to corrosion by O_2 ingress, each is briefly reviewed below.

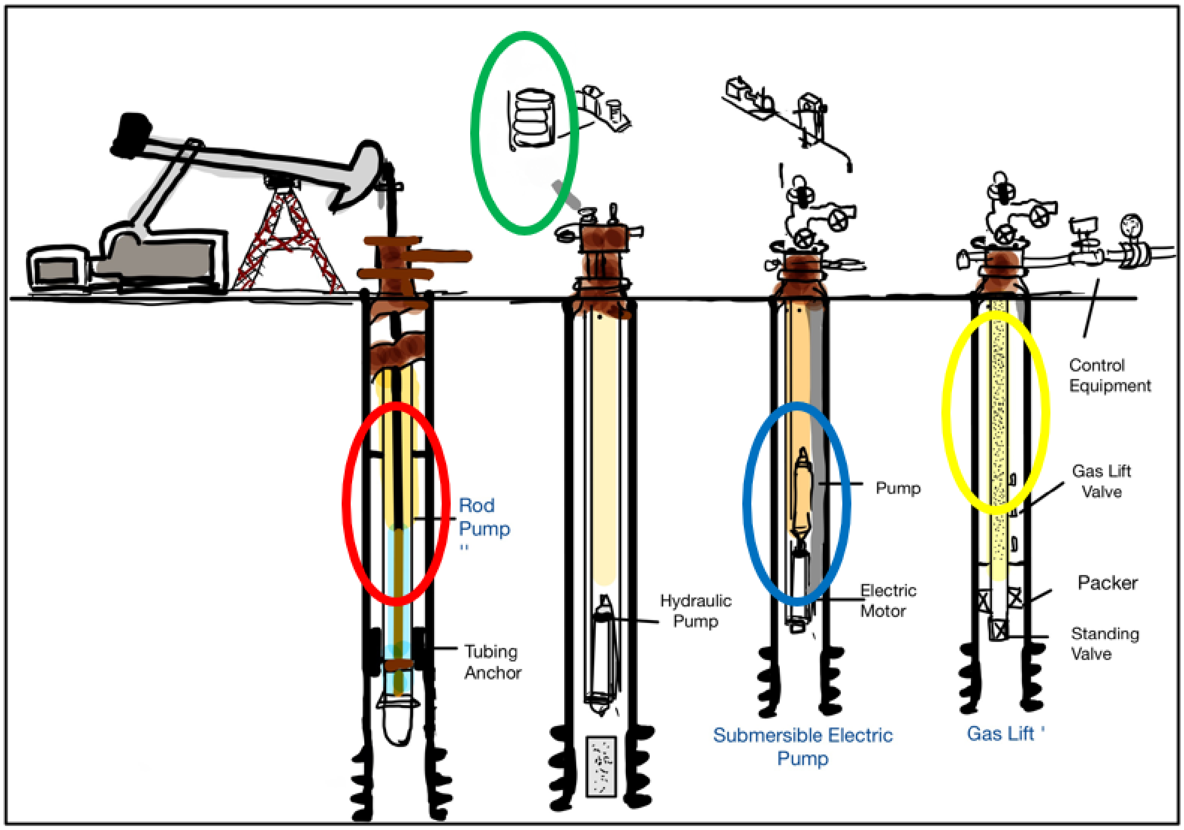

Figure 2. Schematic representation of Artificial Lift Systems

Rod Pumps: A surface power source consisting of a motor transfering energy through a beam and a crank arm that connects to the downhole pump assembly. Through this transfer, energy is converted into the vertical motion of the fluid. The sucker rod is connected with an internal threaded coupling and is generally located in the area marked by the red circle in Figure 2[2]. O_2-enhanced corrosion is mainly reported on the sucker rod coupling[3]. Heavy localized corrosion has been reported in the presence of H_2S.

Hydraulic Pumps: A downhole “hydraulic pump” can be a reciprocating piston pump or a jet pump[4,5]. Hydraulic pumps use a high velocity high pressure fluid (oil or water) that is pumped into the well head and which mixes with well fluids entraining them to the surface[6]. The hydraulic fluid that drives the pump is usually returned up the casing-tubing annulus with oil, water, and gas production[7]. Because of this, the injected fluid needs to be O_2-free. Maintaining such an O_2-free environment can be very expensive so some pumping sites may neglect such precautions. Such a scenario could cause oxygen contamination of the produced fluid which in turn can potentially cause O_2 accelerated corrosion.

Electrical Submersible Pump (ESP): Electrical submersible pumps (ESPs) consist of a submerged motor and a centrifugal pump which are connected to a surface control mechanism and a transformer. ESPs are required to meet high temperature and pressure thresholds, as high voltages and currents are drawn to pump the fluid through a deep-well[8]. Thus, their method of assembly and quality are critical for the ESP to withstand extreme conditions and avoid contaminants. The seal section between the motor and intake serves as a barrier between the motor and well fluids. Because electricity is used as the power to drive the pump, there is no continuous source of O_2 in this case which would be added to the produced fluids.

Gas Lift: In gas-lift wells, gas is injected through the well annulus and into the well tubing at a downhole location. The gas mixes with the fluid in the tubing, decreasing its density[9]. This causes the fluid to rise through the well at even a relatively low bottom-hole pressure. Gas-lift employing the use of air as a lifting medium for oil can face severe problems, not only due to the explosive mixture of air and hydrocarbon but also due to the corrosiveness of O_2[10]. Use of an inert or natural gas avoids explosive risk and mitigates corrosion due to O_2. Produced natural gas can be repurposed for the purpose of gas lifts and should be kept O_2 free to prevent corrosivity as well as risk of explosion. If precautions for maintaining an O_2-free injection gas are neglected, contamination of the produced fluid could readily occur.

Seawater Injection

In offshore oil fields, seawater is injected to maintain pressure and displace hydrocarbons for enhanced and efficient oil recovery. Up to a million barrels of seawater is injected into such wells to maintain adequate pressure[11]. Having an inert purge to remove all dissolved atmospheric oxygen from the seawater is an expensive operation, and if not performed adequately, leads to an ingress of oxygen in the oil well. Injection of huge volumes of oxygenated seawater can risk contaminating the oil well to an irreversible extent.

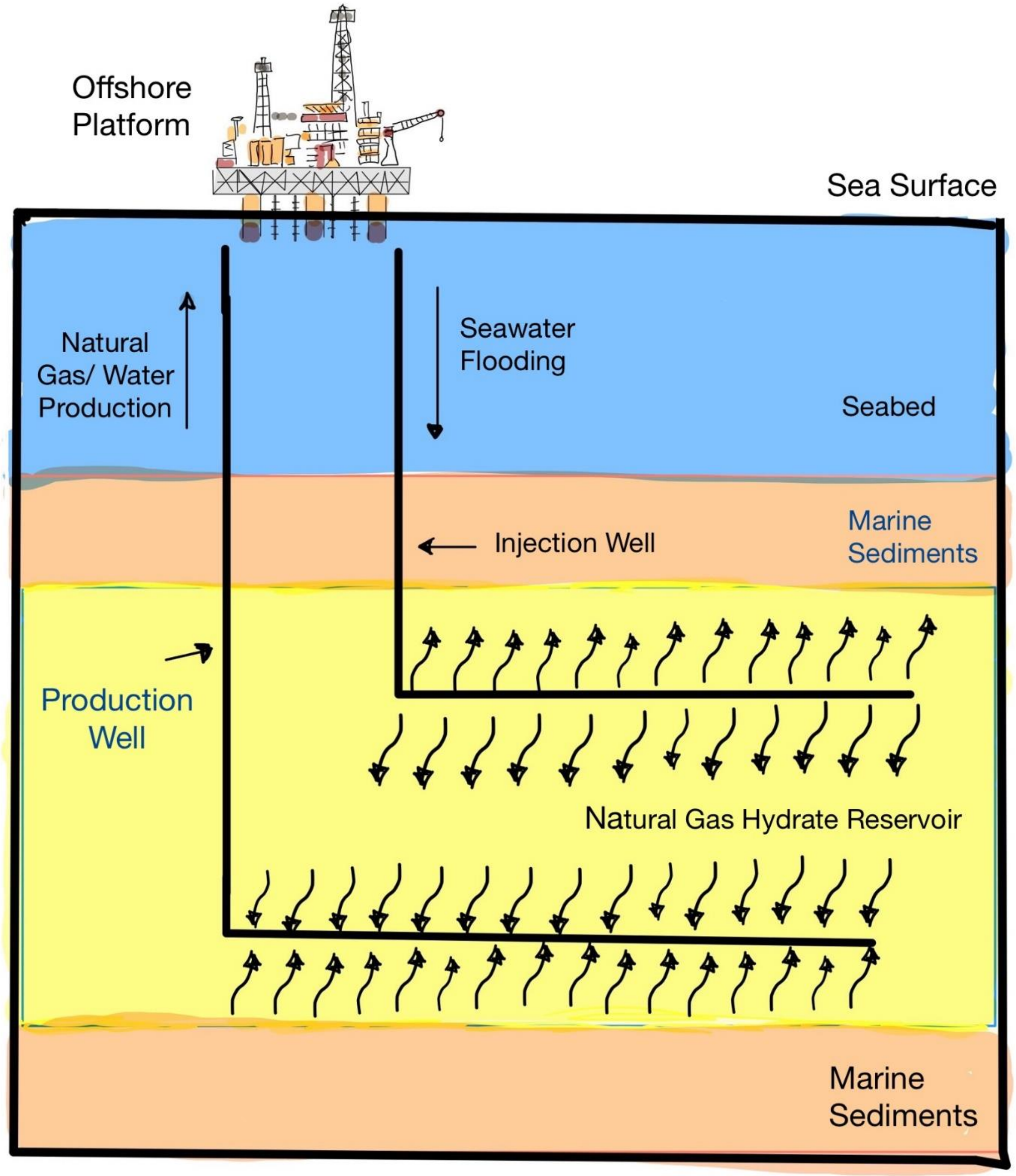

Figure 3. Schematic diagram of seawater injection for offshore wells

Hydraulic Fracking

A majority of the oil shale deposits have very low levels of permeability for oil/gas[12]. Fracturing via injection of fracking fluids creates pathways for the oil to be more accessible to the wellbore. However, if the fracking fluid has not been deoxygenated to suitable standards, it will provide a pathway for oxygen ingress into the well; see Figure 4.

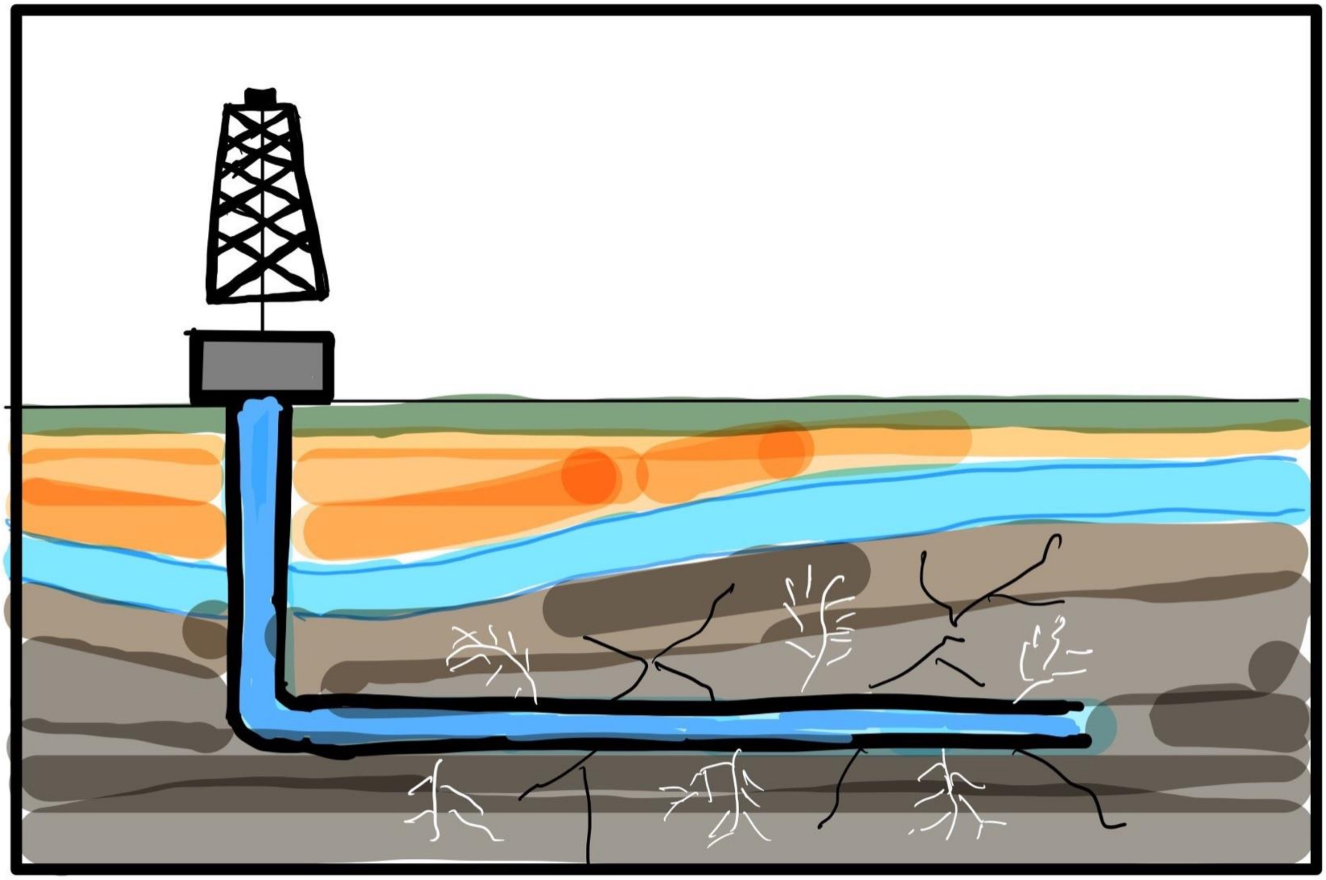

Figure 4. Schematic diagram of hydraulic fracking of shale oil reservoir

Corrosion Inhibitor Injection

Corrosion inhibitors are stored in storage tanks from where they are injected downhole or into pipelines through various fittings, see Figure 5. If proper care is not exercised, the inhibitor in the storage tank itself might get exposed to the atmosphere, causing O_2 to get dissolved into the inhibitor formulation prior to its application. Furthermore, injection of inhibitor through a compromised fitting might be another cause of O_2 ingress in the pipeline[13]. These O_2 levels can vary from ppm to ppb levels and could be consumed at the source of injection itself, thus leading to corrosive attack at the point of injection. However, this is thought to be a lower risk situation as the concentrations of inhibitor applied are in a ppm range. To test this, calculations were made using a pipe flowing with 100% water that is oxygen free and an injected water supply at ambient conditions which would be fully exposed to air as the properties of water are readily available (Figure 6 shows a schematic representation of such injections). Injection amounts are based on a volume/volume basis so total volumetric flow cancels out of the equation. As shown in Figure 7, injection of ppm levels of water containing 8 ppm of O_2 into the pipe flow yields less than 10 ppb of O_2 in the pipeline even up to a 1000ppm(v) injection rate. However, O_2 has been shown to be up to 10 times more soluble in organic compounds than water[14,15], implying that if O_2 is more soluble in the inhibitor chemicals than in water, then ingress of O_2 via inhibitor exposed to atmospheric oxygen would be higher than as calculated in Figure 7. Corrosive effects of this injected O_2 depends on the nature of injection, properties of fluid/flow, and the characteristics of the construction material. Moreover, the O_2 ingress values calculated in Figure 7, are the steady state concentration values of O_2 when the injected chemical and the pipe flow have thoroughly mixed. However, close to the injection site and in the mixing region as seen in Figure 6, the local dissolved O_2 concentrations could reach a value of as high as 8ppm (or even greater depending on solubility) before it gets mixed in with the pipe flow. These high local dissolved O_2 concentrations can possibly accelerate O_2 corrosion.

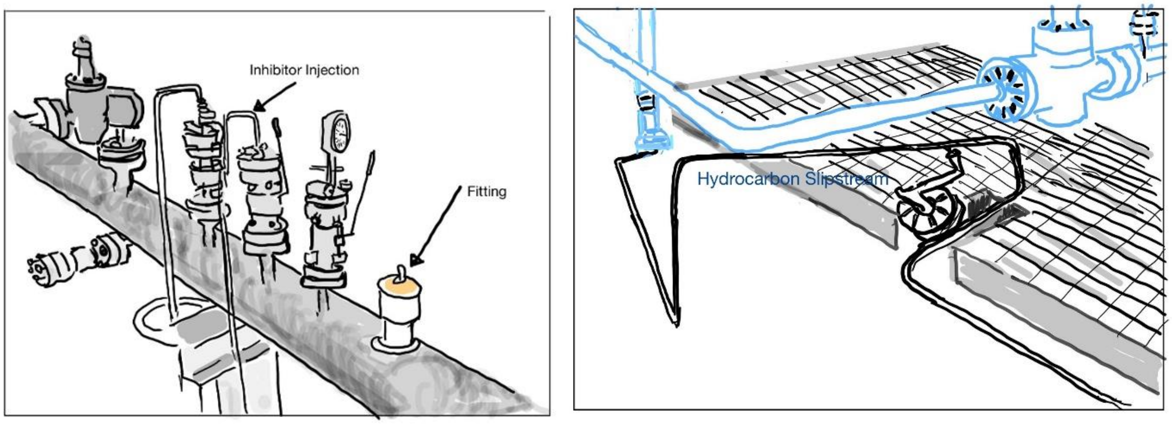

Figure 5. Field images of inhibitor injection (common field schematic for inhibitor injection)

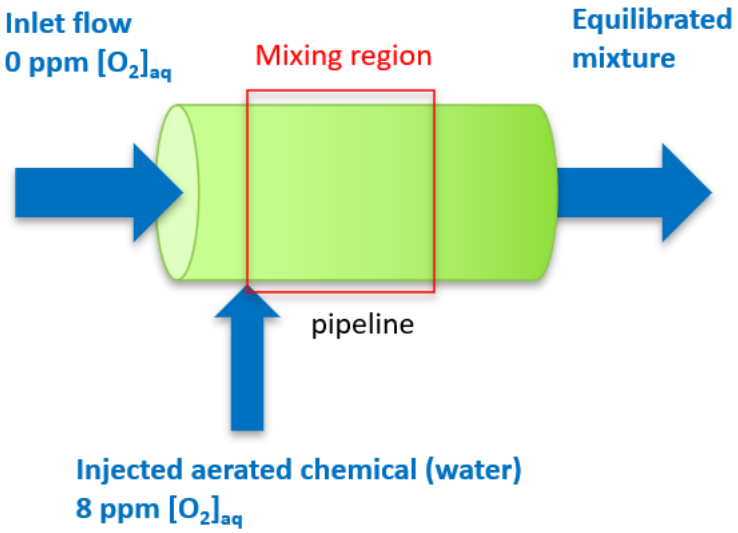

Figure 6. Schematic illustration for injection of an aerated chemical into a pipeline flow

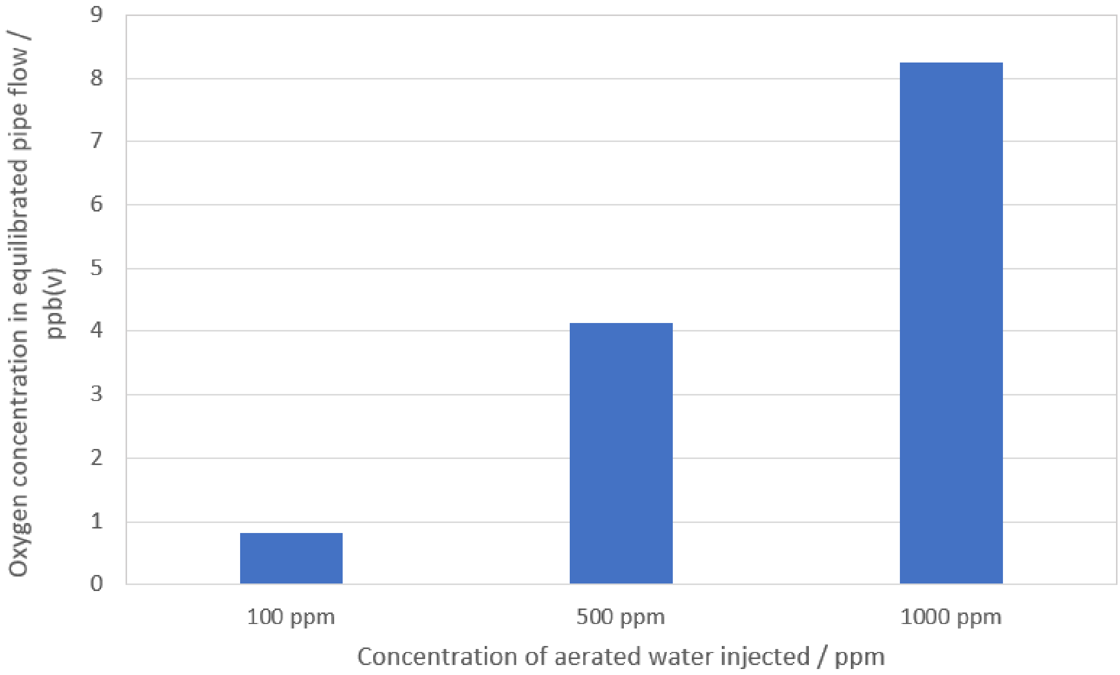

Figure 7. Resultant O_2 concentration in a flowing pipeline after injection of an aerated water at ambient conditions.

MEG Injection

Glycols, such as monoethylene glycol (MEG), are frequently used to prevent the formation of gas clathrates, ice-like solids that exist as gas hydrates, in pipelines. During handling, loading or transportation, the glycols can get exposed to air, their injection inevitably leading to ingress of oxygen[16]. A schematic of MEG use and regeneration is shown in Figure 8. The pumps[16,17] used in the regeneration process are also identified to be susceptible to leaks that lead to O_2 being introduced to the production environment. Indeed, this is generally likely for mechanical pumps used in oilfields in various scenarios, where dynamic moving parts are more susceptible to leaks via worn or damaged components.

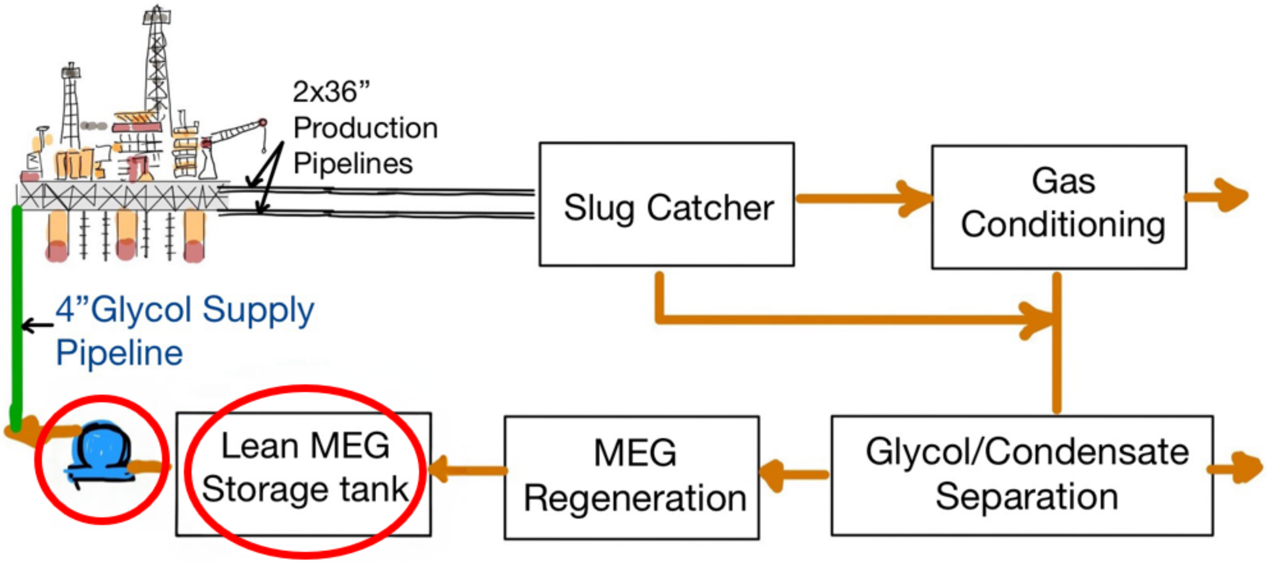

Figure 8. Schematic for use and regeneration of MEG, identifying tank and pump locations associated with oxygen ingress

Wastewater Disposal

Large volumes of wastewater are produced in the oil and gas industry, as depicted in Figure 9. For every barrel of oil recovered, up to 100 barrels of wastewater can be produced[18]. Such large volumes of water must be disposed of or reused. Common methods of reuse include hydraulic fracturing, drilling, and for other purposes outside the oilfield. Wastewater is rarely recycled outside the oilfield because its chemistry is unknown. It is expensive to keep the wastewater deoxygenated while it sits in the storage tanks before disposal. Disposal of such wastewater with some amount of O_2 is commonly carried out through pipelines or via trucks[18]. The oil flow through the pipeline is paused, while the wastewater is pumped in batches through the pipeline. This will cause O_2 ingress into pipelines and associated corrosion phenomena.

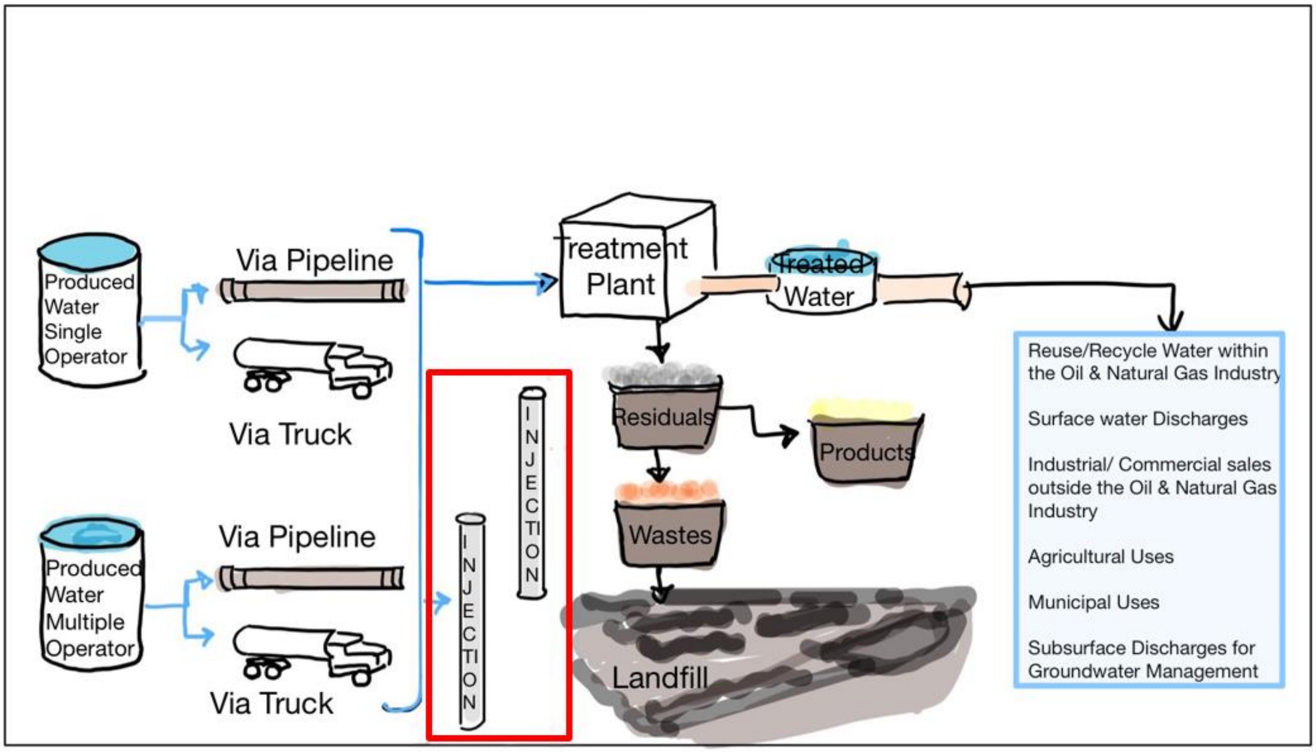

Figure 9. Schematic representation of waste water production and handling associated with oil and gas production

Scavenger Injection

Scavenger chemicals, such as to eliminate trace concentrations of H_2S, are injected into oil and gas systems to remove contaminants that pose risks to the infrastructure. As discussed for the case of inhibitors previously, if the solubility of O_2 in scavenging chemical is higher than water, injection of scavengers with exposure to atmospheric oxygen could lead to higher amounts of oxygen ingress than as shown in Figure 7. Moreover, the O_2 ingress values calculated in Figure 7 are the steady state concentration values of O_2 when the injected chemical and the pipe flow have thoroughly mixed. However, close to the injection site and in the mixing region as seen in Figure 6, the local dissolved O_2 concentrations could reach a value of as high as 8ppm (or even greater depending on solubility in the scavenging chemical) before it gets mixed in with the pipe flow. These high local dissolved O_2 concentrations can possibly accelerate O_2 corrosion in the localized region. Therefore, if proper care hasn't been administered to deoxygenate such scavengers, oxygen ingress can occur.

Pipeline Pigs

Pigs are mechanical devices used for cleaning of pipelines as well as application of corrosion inhibitors. Pigs are introduced into the mainline of a pipeline through a pig launcher (Figure 10), which requires the operator to follow certain protocols before their introduction. If the operator fails to adhere to proper protocols while operating the pig launcher, O_2 is likely to be introduced into the pipeline.

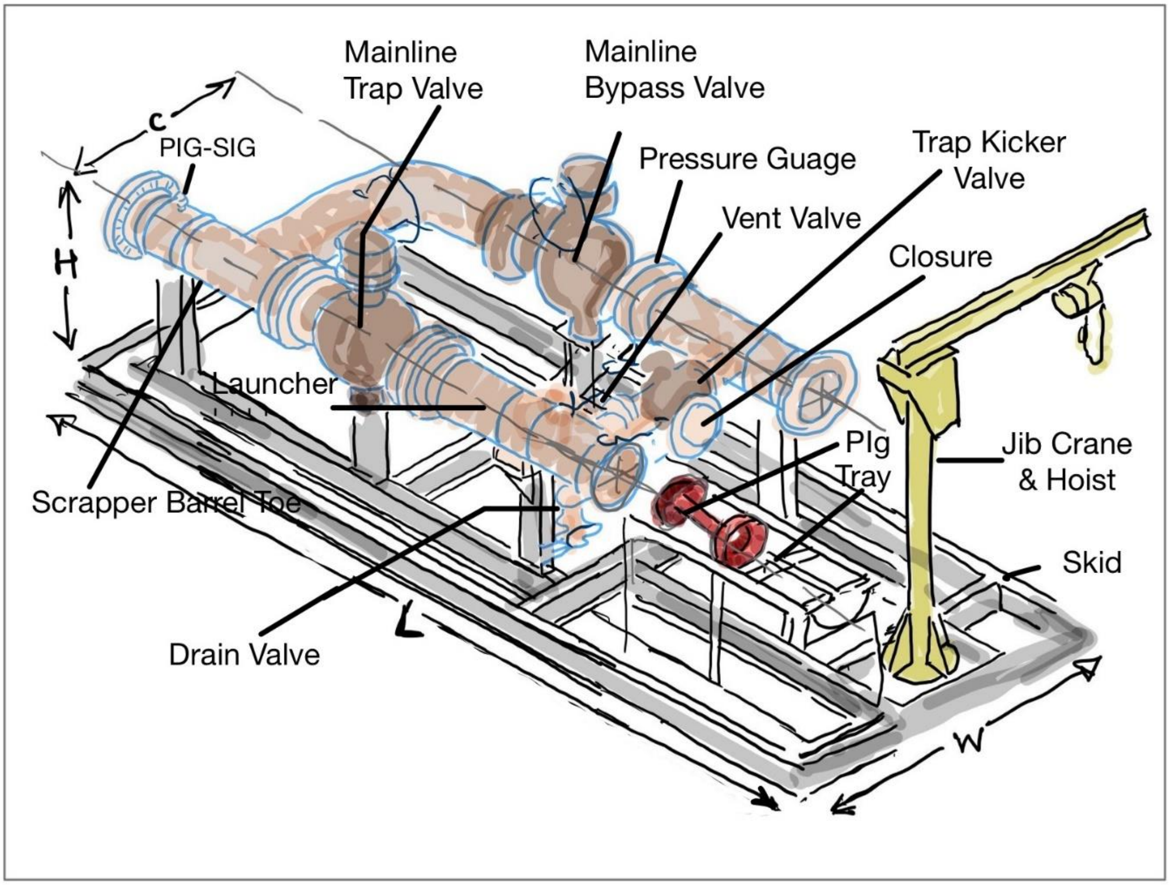

Figure 10. Schematic for Pipe Inspection Gauge (PIG) launcher

Pipeline Sampling

Periodic sample collection from a pipeline is necessary to evaluate oil quality, monitor corrosion risks, and detect impurities. Small volumes are collected from the flowing pipeline, however, if proper care is not exercised, ingress of O_2 could occur. If a pipeline is being depressurized for sample collection, air could be drawn in leading to O_2 ingress. As seen in Figure 11, sampling points on the pipelines can act as openings between the inside and outside of the pipe[19]. Containers or sampling bottles hooked on to these sampling points via valves can be a cause of oxygen ingress. If any residual O_2 is present in the sampling container, and such a container is hooked onto a sampling point, the contents of container could be transferred to the pipe via the sampling point, risking oxygen ingress. Frequent samplings from a pipeline could lead to a frequent opening and closing of the sampling point, resulting in a higher chance of O_2 ingress.

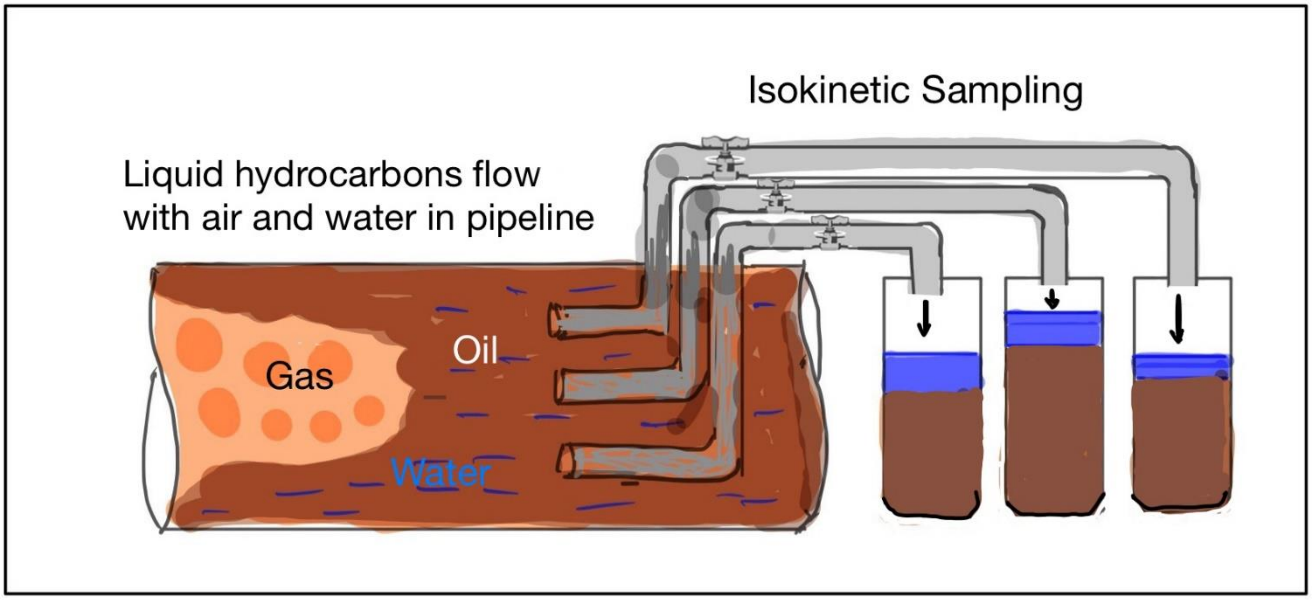

Figure 11. Reproduced schematic illustration of a sampling method for oil and gas pipelines[19]

Improper Protocols

Inadequate training of personnel on proper protocols and dangers can lead to human errors causing O_2 ingress. Inadequate purging of pipelines or tanks would allow residual oxygen to mix with hydrocarbons. Lack of routine inspections and negligent maintenance can result in the development of pathways for the ingress of oxygen. Not monitoring O_2 concentrations can allow them to build up to a critical level, which can be otherwise prevented.

Leaks

Leaks can develop within the oil and gas systems due to a variety of reasons. Corrosion, especially localized corrosion, can eventually degrade equipment integrity causing leaks[20]. Although oil and gas systems operate at high pressure, some backflow from the atmosphere into the high-pressure pipeline via a perforation can be speculated. This, however, needs extensive evaluation to determine the exact flow mechanisms at play. Welding performed with improper care can result in poor or porous welds, this can provide pathways for ingress of O_2[21]. Mechanical damage to the oil and gas infrastructure can lead to cracks, punctures, and localized thinning. These defects can allow O_2 from the atmosphere to contaminate the system. Possible leakage points are also created by malfunctioning valves, fittings, seals and gaskets which can lead to O_2 ingress. Wear and tear over time, delayed inspection and maintenance, improper design selection, poor manufacturing, incompatible parts, and damage to surface installations are some of the reasons that issues with valves, fittings, seals or gaskets may lead to O_2 ingress. Oil and gas systems designed for a particular operating temperature may experience upsets and fluctuations in temperature due to change in seasonal ambient temperature, changes in production rates, changes in process stream temperatures, temporary shutdowns, and cold restarts. This temperature cycling fatigues materials over time, where cooler temperatures can cause contraction of seals, joints, fittings, valves, and gaskets. This may lead to the opening of gaps and thus ingress of O_2.

Design

Poor choices while designing oil and gas infrastructure can leave systems vulnerable to O_2 ingress during operations. Use of components with incorrect specification requirements for oxygen permeability may lead to passage of O_2 through solid components, which can build up to significant amounts over time. Parts and components manufactured out of polymers are pathways for O_2 ingress via diffusion through solid media. Systems designed with sections of pipes that stay stagnant due to changes in flow are called dead legs (See Figure 12) and can experience accelerated corrosion than the flowing section of the pipes due to accumulation of corrosive species in the dead leg. This can introduce O_2 ingress pathways due to potential corrosion failures, leading to a build of O_2 concentration when in stagnant condition. Restarting a dead leg section could mix O_2-rich streams with hydrocarbon streams leading to oxygen ingress. Irregular pipeline geometries with steep rises and falls can lead to pockets of gas or liquid to build up over time. These intermittent collection zones can build up O_2 concentrations over time and eventually dissolve with the flow stream.

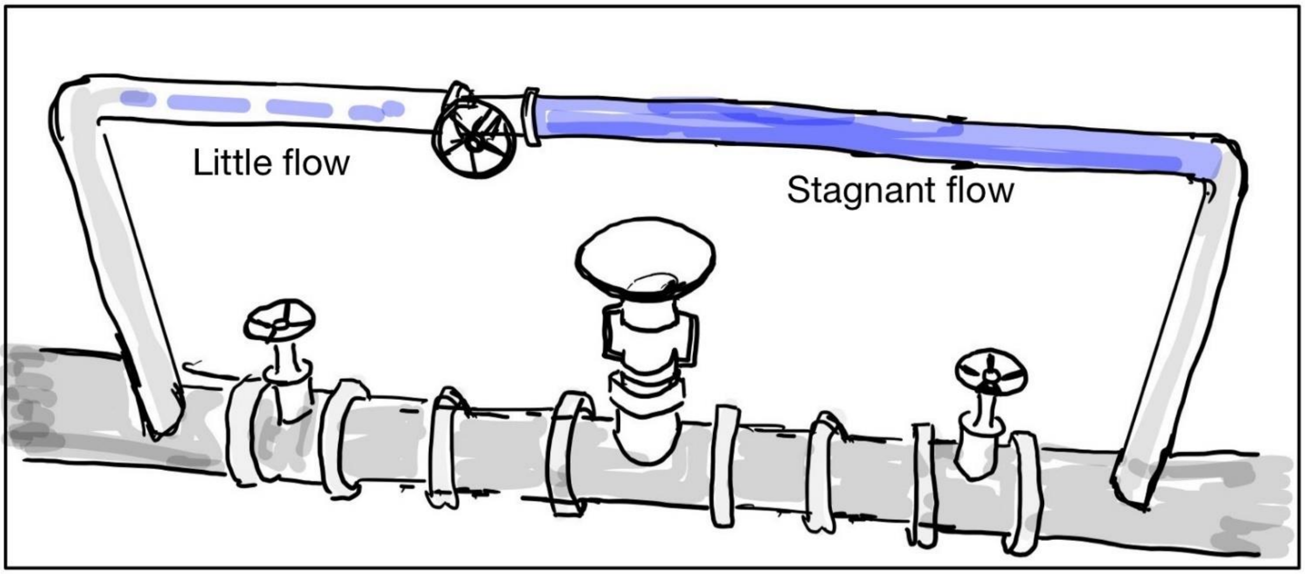

Figure 12. Schematic illustration of a dead leg in oil and gas system

MITIGATION AND PREVENTION STRATEGIES

Mitigating oxygen ingress requires an integrated approach across all the mechanisms discussed in the previous section. A detailed account of all the mitigation and prevention strategies is listed in Table 1.

Table 1. Mitigation and prevention strategies for ingress of oxygen

Artificial lifts/Gas lifts	Maintain tight system integrity with good seals. Any O_2 should be removed from the gases and the hydraulic fluids used in artificial lifts.
Seawater injection	Use seawater from deeper parts of the sea, which have lower levels of dissolved O_2. However, the energy required to pump seawater from deeper parts of the ocean is high and concentration of dissolved oxygen levels may still be above recommended values. Use mechanical demarcation and oxygen scavengers to rid residual O_2 from injected seawater.
Hydraulic Fracking	Use of O_2-free fracking fluid with appropriate inert gas purge.
Injections	Chemical injection systems need to be airtight. Any injection fluid needs to be purged with an inert gas to remove any residual oxygen.
Pipeline Pigs	Having blanket purge gases while launching pigs. Proper sealing to keep pigging equipment sealed from the atmosphere and to avoid any air pockets.
Sampling	Sampling systems need to be purged to rid them of any O_2 contamination. Robust non-intrusive sampling methods can be employed. Minimize the frequency of sampling to minimize O_2 contamination.
Improper protocols	Adherence to robust operational and maintenance procedures. Frequent inspection and maintenance routines.
Leaks	Robust corrosion monitoring, and timely maintenance on damaged sections. Using good welding practices to ensure nonporous welds. Proper selection, installation, and maintenance of parts which are susceptible to leaks.
Dead Legs	Isolating dead ends and unused branches of a pipeline stream.
Permeation	High quality non-permeable polymers.

SUMMARY AND CONCLUSIONS

Procedures, equipment, practices and accidents in the oil and gas industry can risk ingress of O_2 in the otherwise O_2-free infrastructure. Understanding each individual pathway for O_2 ingress is key to mitigate and manage the risk. Robust protocols, controlled processes, regular inspection, materials selection, proper design, and trained personnel are vital to prevent O_2 ingress into the oil and gas systems.

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REFERENCES

1. Chevron Main Pass 313 Optimization Project. *Schlumberger Gas Lift Design and Technology*.; 1999.
2. Guo B, Liu X, Tan X. Sucker Rod Pumping. *Petroleum Production Engineering*. Published online 2017:515-548. doi:10.1016/B978-0-12-809374-0.00016-7
3. Champion X Artificial Lift Norris. *Sucker Rod Failure Analysis*.; 2022.
4. PEH: Hydraulic Pumping in Oil Wells - PetroWiki. https://petrowiki.spe.org/PEH:Hydraulic_Pumping_in_Oil_Wells
5. O'Connor P, America BP, Bucknell J, Corp MSLS, Lalani M, Ltd MSLE. Chapter 14 – Offshore and Subsea Facilities. *Petroleum engineering handbook*. 2007;Volume III:525-564.
6. Peeran SM, Beg N, Sarshar S. Novel Examples of The Use of Surface Jet Pumps (SJPs) To Enhance Production & Processing: Case Studies and Lessons Learned. *SPE Middle East Oil and Gas Show and Conference, MEOS, Proceedings*. 2013;2:887-905. doi:10.2118/164256-MS
7. Hydraulic pumping system design - PetroWiki. https://petrowiki.spe.org/Hydraulic_pumping_system_design
8. Steve Breit, Neil Ferrier. Electric Submersible Pumps in the Oil and Gas Industry | Pumps & Systems. Published 2008. https://www.pumpsandsystems.com/electric-submersible-pumps-oil-and-gas-industry
9. Dev B, Samudrala O, Jifeng W. Comparison of Leakage Characteristics of Viton and Polytetrafluoroethylene Seals in Gas-Lift Valve Applications. *Journal of Energy Resources Technology, Transactions of the ASME*. 2017;139(1). doi:10.1115/1.4034512/385134
10. Prasad DrRG. Role of Artificial Lift Techniques in Oil and Gas Production with Respect to Gas Lift System in Tertiary Recovery. *Int J Res Appl Sci Eng Technol*. 2018;6(1):2106-2114. doi:10.22214/ijraset.2018.1332
11. Bader MSH. Sulfate removal technologies for oil fields seawater injection operations. *J Pet Sci Eng*. 2007;55(1-2):93-110. doi:10.1016/J.PETROL.2006.04.010
12. Hassett K, Mathur A. Benefits of hydraulic fracking. *Oxford Energy Forum*. 2013;91.
13. Ingham B, Ko M, Shaw P, et al. Effects of Oxygen on Scale Formation in CO_2 Corrosion of Steel in Hot Brine: In Situ Synchrotron X-ray Diffraction Study of Anodic Products. *J Electrochem Soc*. 2018;165(11):C756-C761. doi:10.1149/2.0461811jes
14. Golovanov IB, Zhenodarova SM. Quantitative structure-property relationship: XXIII. Solubility of oxygen in organic solvents. *Russ J Gen Chem*. 2005;75(11):1795-1797. doi:10.1007/S11176-005-0512-7/METRICS
15. Dvoranová D, Barbieriková Z, Brezová V. Radical Intermediates in Photoinduced Reactions on TiO2 (An EPR Spin Trapping Study). *Molecules 2014, Vol 19, Pages 17279-17304*. 2014;19(11):17279-17304. doi:10.3390/MOLECULES191117279
16. Kvarekval J, Olsen S, Skjerve S. The effect of O_2 on CO_2 corrosion in pH stabilized gas/condensate pipelines. In: *NACE CORROSION*. NACE; 2005:NACE-05305.
17. Olsen S, Dugstad A, Lunde O. pH-stabilization in the Troll gas-condensate pipelines. In: *CORROSION 99*. OnePetro; 1999.
18. U.S. Environmental Protection Agency. Final Report: Oil and Gas Extraction Wastewater Management | US EPA. EPA-821-S19-001 . Published 2020. Accessed September 27, 2023. https://www.epa.gov/eg/final-report-oil-and-gas-extraction-wastewater-management
19. Saushin I, Goltsman A. Uncertainty of isokinetic sampling of the phase composition of a gas-oil-water mixture at different regimes of a developed horizontal pipe flow. *J Pet Sci Eng*. 2020;195:107901. doi:10.1016/j.petrol.2020.107901

20. Askari M, Aliofkhazraei M, Afroukhteh S. A comprehensive review on internal corrosion and cracking of oil and gas pipelines. *J Nat Gas Sci Eng*. 2019;71:102971. doi:10.1016/j.jngse.2019.102971
21. Mgonja CT. The Consequences of cracks formed on the Oil and Gas Pipelines Weld Joints. *International Journal of Engineering Trends and Technology*. 2017;54(4):223-232. doi:10.14445/22315381/IJETT-V54P232