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Microbiologically Influenced Corrosion in a Gas Storage Well

Noelle Easter C. Co, Ryan D. Milligan, Ming Gao,
Rudolf H. Hausler, Ravi M. Krishnamurthy
Blade Energy Partners
16285 Park Ten PI Suite 600
Houston, TX, 77084
USA

Elizabeth Summer
Ecolyse
11142 Hopes Creek Road
College Station, TX, 77845
USA

ABSTRACT

The failure of a J55 steel grade 178 mm (7 in.) production casing in gas storage well was investigated using a multi-disciplinary approach. The rupture of the production casing was due to the metal loss by corrosion with striated longitudinal grooving. Since the morphology of the striated grooves could not solely be used to establish a microbiologically influenced corrosion (MIC) mechanism, the combined metallurgical, chemical, and biological analyses were used. Scale samples were collected during casing extraction for composition and biological analyses. Corrosion features and corrosion deposits were characterized using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and Raman spectroscopy. Detailed examination of tunnel type corrosion features was done using a combination of focused ion beam (FIB) for *in situ* micro-sectioning and/or micro-metal removal, SEM, and EDS analyses. Most probable number (MPN), quantitative polymerase chain reaction (qPCR), and microbiome population analysis by 16S, archaeal, and 18S amplicon sequence analysis were used to identify the microbes abundantly present in the failed well. A broad study involving other wells in the field lead to the conclusion that at some stage in the period of over 60 years of the life of this well, the activities of the methanogenic archaea caused the observed localized corrosion leading to the production casing rupture.

Key words: MIC, J55 steel, methanogen, archaea, outer diameter casing corrosion, alkaliphile, haloalkaliphile, gas storage, casing, casing failure

INTRODUCTION

A gas storage well was originally drilled as an oil well in 1954; it was then converted into a gas storage well in 1973¹. Gas injection and withdrawal occurred through the 73 mm (2 7/8 in.) tubing and the 178 mm (7 in.) production casing, while the 298 mm (11 3/4 in.) casing was used as a surface casing to protect groundwater (see Figure 1). To ensure the integrity of the well for safe operation, pressure measurements were obtained regularly, the temperature was logged annually, and the noise logs were captured occasionally. There was no indication of integrity issues until the well started leaking in the last quarter of 2015. The production casing axially ruptured and circumferentially parted, resulting in a natural gas blowout for 111 days. The well was controlled in early 2016 and permanently plugged in 2018.

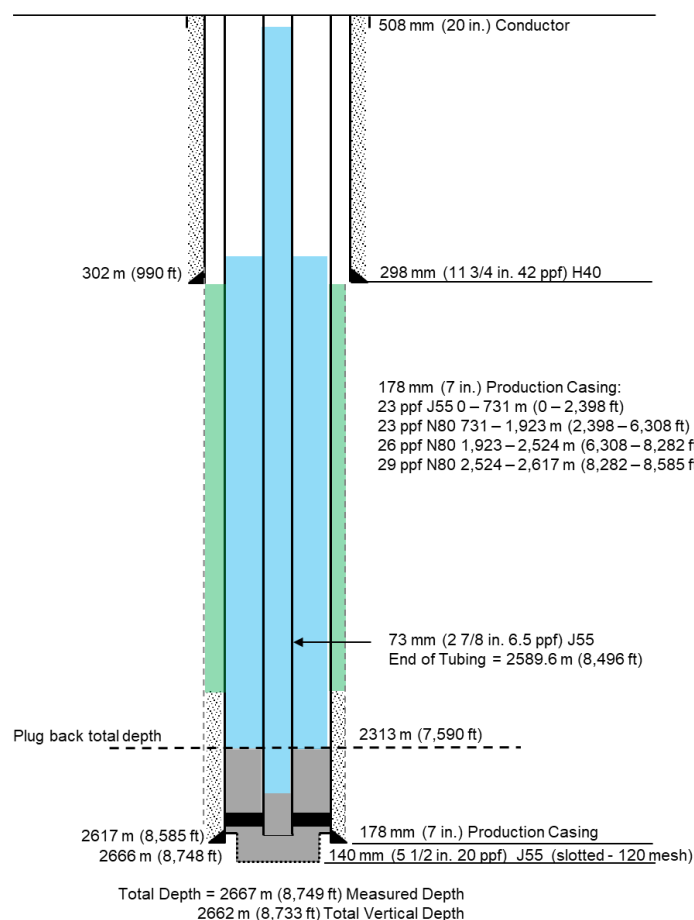


Figure 1: Schematic of SS-25 Well

A root cause analysis for the failure was initiated during the final weeks of the blowout¹. Prior to the extraction of the tubing and the casing, the failure was identified to be a circumferential parting of the 178 mm (7 in.) production casing using wireline deployed casing inspection logs and downhole camera. The failure location was confirmed at a depth of 272 m (892 ft). After removal of the wellhead, the entire length of 73 mm (2 7/8 in.) tubing, and the upper and lower portions of the parted production casing were then extracted for investigation. A total of 312 m (1025 ft) of production casing was recovered. Visual examination of the lower portion of the parted production casing showed that in addition to the circumferential parting, a 52 cm (1.72 ft) long axial rupture had initiated from the 85% wall loss corroded area (9.4 cm x 23.5 cm) on the outer diameter (OD) of the casing. The analysis showed that during the axial rupture, plastic bulging occurred first, along with slow ductile tearing due to internal pressure. When the axial flaw reached the critical size, tearing instability occurred, followed by rapid crack propagation in the axial direction. The axial crack changed direction and finally arrested due to dynamic

energy consumption. As a consequence of the axial rupture, high-pressure gas was released that dramatically decreased the temperature of the adjacent casing. This extremely cold temperature resulted in a brittle failure of the casing circumferentially (see Figure 2).

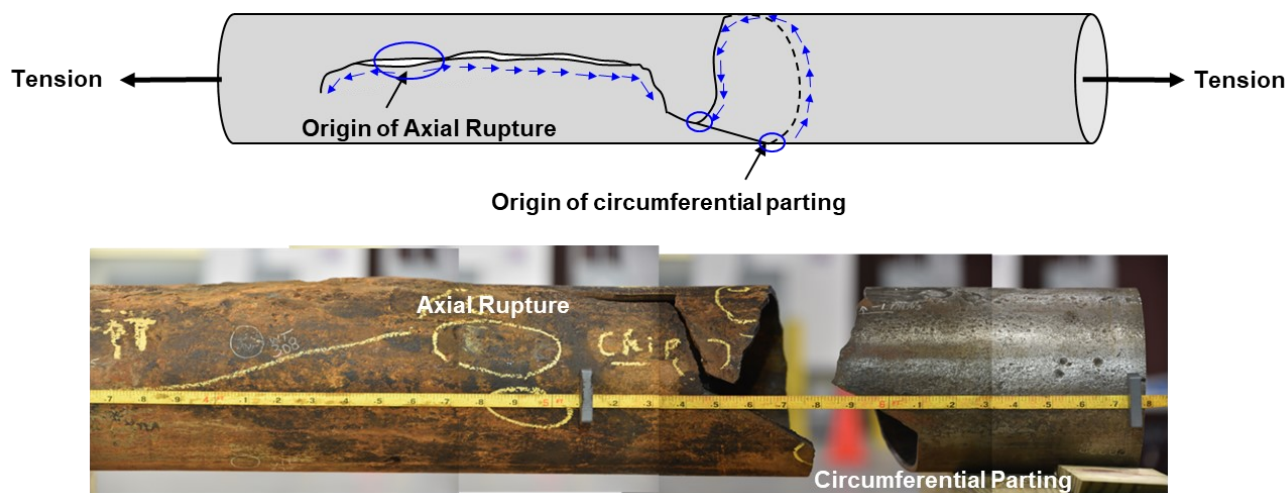


Figure 2: Axial Rupture and Circumferential Parting of 178 mm (7 in.) Casing

Visual examinations and non-destructive evaluation of the wellhead and the entire length of the 73 mm (2 7/8 in.) tubing did not indicate anything that could be related to the production casing failure. For the reason that the cause of the axial rupture and circumferential parting of the production casing initiated from the 85% wall loss by corrosion with striated groove, it is essential to understand the type or mechanism for corrosion. The objective of this paper is to present the multi-disciplinary approach used in the investigation and the findings of the corrosion mechanism assessment of the 178 mm (7 in.) production casing failure, some of which may be attributed to MIC.

EXPERIMENTAL PROCEDURE

Three methods—namely metallurgical, chemical, and biological methods—were used to investigate the distinct corrosion feature that caused the rupture. In addition to analysis of the primary rupture site, the corrosion features on a total of 25 extracted casing joints were examined to determine the distribution of corrosion features in terms of size and number along the 312 m (1025 ft) long casing. Scales and pertinent samples were obtained prior to cleaning and blasting of the extracted joints.

Metallurgical

The OD of the production casing was visually inspected. The distribution of the corrosion damage from 0 to 312 m (0 ft–1025 ft) was obtained via a laser scan. The corrosion morphology of the failed specimen (located at joint 22) was assessed using optical and scanning electron microscopy (SEM). The number of the grooves in a corrosion patch was estimated using an image processing software. Focused ion beam (FIB) was used to cross-section the corrosion deposit, and the tip of the corrosion damage.

Chemical

Energy dispersive spectroscopy (EDS) was used to determine the elements present on the corrosion products. Inductively coupled plasma (ICP) and X-ray fluorescence (XRF) were used to verify the elements present in the scale samples. The collected scales were also analyzed using Raman and X-ray diffraction (XRD) spectroscopy to determine the compounds present in the scale collected from the OD of the casing.

Biological

Samples for biological analyses were collected off of the surface of the casing joints 24 and 25 from the rig floor as the casing was being extracted from the well. Disposable new plastic tools were used to remove material by scraping onto a catch paper, transferred into individual plastic bags, and stored at 4°C prior to analysis. Forty-two samples were collected. Each sample was analyzed independently. The dynamics of the rupture event and the extended activities performed to contain the initial gas leak, precluded direct analysis of the microbe population at the exact site of the rupture feature.

Most Probable Number (MPN). Culture-based analysis: the population of viable, culturable organisms in the samples was evaluated using the MPN approach. Media used were MPB (modified Postgate's Medium B), which detects (grows) sulfate-reducing bacteria (SRB), PRD (phenol red dextrose), which detects acid-producing bacteria (APB) and general heterotrophic bacteria (GHB), IRB (iron-reducing bacteria medium), and NRB (nitrate-reducing bacteria medium). All media salinities were set at 2.5%, and the culturing temperature was set at 30°C. The sample was subjected to a serial 10X dilutions in each of the selective indicators of bacterial culture media. The dilutions were set up in triplicate. The highest dilution for which growth was observed after 28 days was used to calculate the concentration of bacteria in the sample.

qPCR. Bacteria, Archaea, and Eukaryotes were quantified in the samples by qPCR. Total DNA was isolated from the samples using commercially available DNA isolation kits. Primer sets used for qPCR were the 16S primers (515F-GTGCCAGCMGCCGCGGTAA and 806R-GGACTACHVGGGTWTCTAAT)² that detect bacterial and archaeal 16S genes, archaeal primers (Arch517F-GCYTAAAGSRNCCGTAGC and Arch909R TTTCAGYCTTGCGRCCGTAC)³ that detect archaeal 16S genes but not bacterial 16S genes, and Eukaryotic 18S primers (Euk1391F GTACACACCGCCCGTC and EukBR TGATCCTTCTGCAGGTTACCTAC)⁴ that detect Eukaryotic 18S gene and some 16S bacterial genes.

rRNA Gene Amplicon Sequencing. Population profiles were elucidated by 16S and 18S amplicon sequencing analysis, using the same DNA and primer sets as used for qPCR analysis. Sequencing was performed on the Illumina MiSeq platform. Resulting reads were trimmed and subjected to quality control. Sequences were then compared against a ribosomal RNA database, and each sequence was assigned a taxonomic designation. Because most organisms were identified to a taxonomic classification higher than the species level, these clusters are referred to here as "taxa". Identified taxa were assigned ecological, metabolic, taxonomic traits based on the relationship to organisms for which data is available. The resulting data were evaluated to generate microbial population profiles of each sample, including the number of taxa and percent abundance of taxa.

RESULTS

Figure 3 shows the corrosion distribution as a function of depth and circumferential orientation for the casing in the well from joints 1 to 25 (0 to 1025 ft depth) based on the laser scan data. The color map includes information about corrosion depth, the maximum depth, the total feature, and the total corroded area per casing. These parameters are taken as indicators of corrosion severity. The color map in Figure 3 has a distinct zone of severe corrosion, beginning at 213 m (700 ft). High-resolution vertilog (HRVRT) inspection of the inner diameter of 298 mm (11 3/4 in.) surface casing also revealed the presence of corrosion starting at this depth. The 213 m (700 ft) depth corresponds to the level of fluid inside the 298 mm (11 3/4 in.) x 178 mm (7 in.) annulus. A spike in the maximum corrosion depth (dark red region in the color map) was observed at joint 22 near connection 23. This spike was identified as the corrosion associated with the axial rupture.

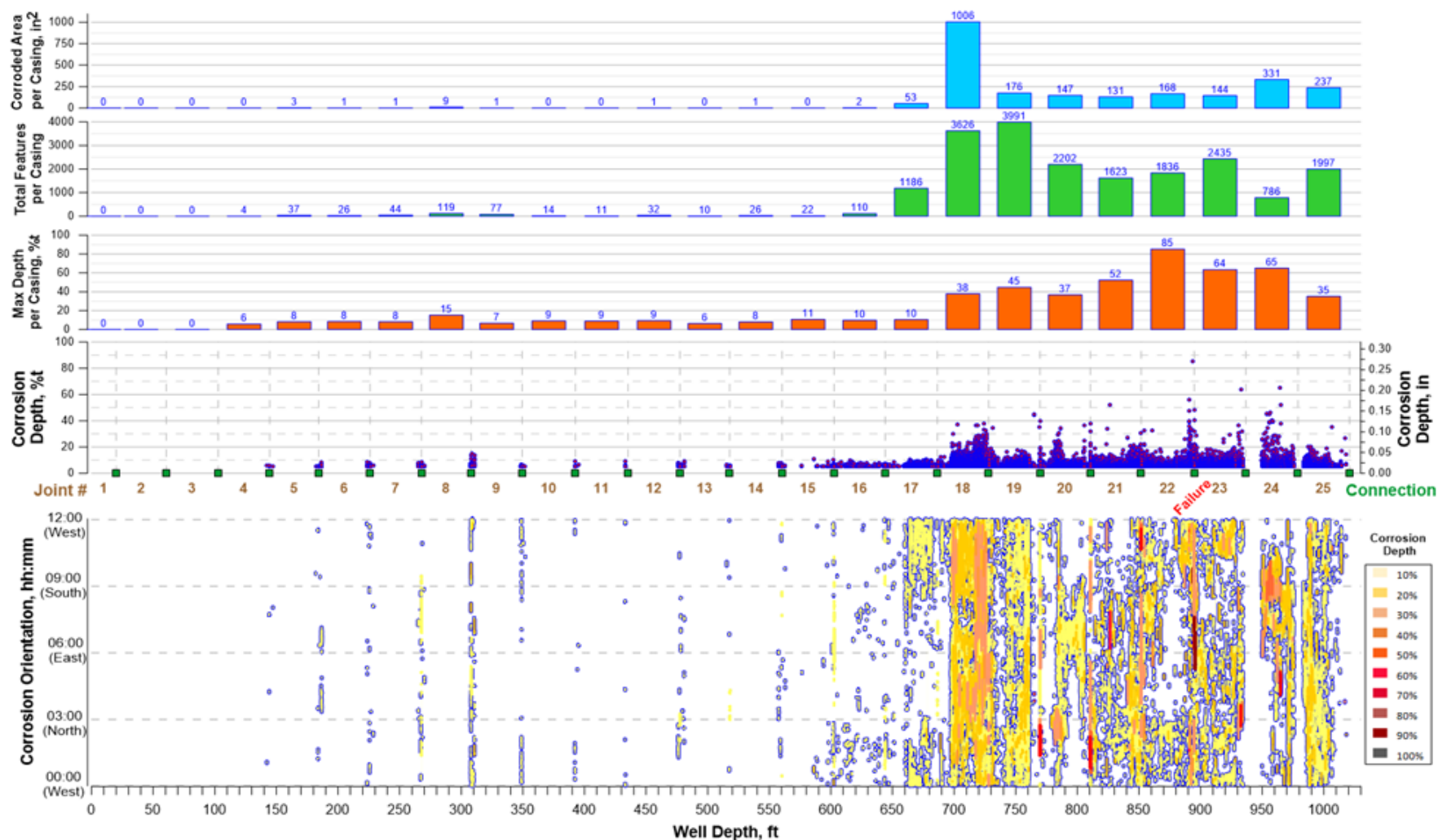


Figure 3: Corrosion distribution based on laser scan data