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## **Case Study on the Downhole Materials Selection and Sour Service Qualification for a High Pressure, High Temperature Gas Field**

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### **ABSTRACT**

Materials selection for oil and gas fields is challenged by the dual requirements of ensuring well integrity and affordability. This can be a demanding task for any field, but is particularly problematic for reservoirs with relatively high temperature, pressure and produced water salinity. Over the last decade, there have been advances in the assessment of environment aggressiveness (including pH and the quantity of H<sub>2</sub>S present) and from continued assurance of material performance (gained from multiple qualifications, routine validations and deep technical relationships with one or more mills).

The materials selection for a mildly sour, multi-well gas field is presented, demonstrating how non-ideal gas behaviors were used in the well environment predictions to permit selection of a more economic casing grade. The environmental modelling and extensive ambient and high-pressure sour service validation testing is described with testing approaches optimized to increase confidence in the results. Additional work is presented in defining H<sub>2</sub>S limits for the selected completion materials, demonstrating that both the casing and completion are robust to excursion events. Recommendations are made for materials selection assessments in mildly sour wells, emphasizing that as conservatism is removed from the modelling approach, additional testing is required in qualification and validation.

**Key words:** Fugacity, Environmental Prediction, Sour Service, P110, Domain Diagrams.

## INTRODUCTION

In 2015 in the early stages of an onshore gas project, three production zones were of interest Reservoir A, Reservoir B and Reservoir C. The shallowest of the formations, Reservoir A, is at approximately 4400m and contains no H<sub>2</sub>S. One of the deeper formations, Reservoir B, contains H<sub>2</sub>S up to a design value of 20ppmv in the parts of the field of interest. The final formation, Reservoir C, contains no H<sub>2</sub>S. Hydraulic fracturing is used to increase the productivity and extend the life of each well. At first, the chemical mixture used for fracturing resulted in reactions that created small quantities of H<sub>2</sub>S. This has since been remediated and the chemical additions modified to eliminate this reaction.

To facilitate a common well design and to allow flexibility for recompletion in any of the reservoirs, a common production casing materials selection was required. Thus, all well production casing strings were designed to tolerate 20ppmv H<sub>2</sub>S as a secondary barrier either in gas-contaminated packer fluid (in the event of minor A-annulus communications) or from direct exposure to production fluids (in the event of major A-annulus communications).

Advances in understanding, modelling and testing capability are enabling better assessment of the severity of H<sub>2</sub>S-containing fluids in wells. ISO<sup>i</sup> 15156 / ANSI<sup>ii</sup> NACE<sup>iii</sup> MR0175<sup>1</sup> focuses on the use of partial pressure of H<sub>2</sub>S ( $p_{H_2S}$ ) for the assessment of resistance to sulfide stress cracking (SSC) and other H<sub>2</sub>S-related cracking mechanisms. Under high pressure conditions (such as present in typical gas wells), use of  $p_{H_2S}$  can lead to over conservatism in a cracking assessment. Material selection focuses on H<sub>2</sub>S in the gas phase as a practical convenience, in that H<sub>2</sub>S in the gas is easier to measure, monitor and calculate for typical upstream projects and assets. However, it is the H<sub>2</sub>S dissolved in the aqueous phase, that is more directly associated with the cracking probability and at high pressures H<sub>2</sub>S fugacity is a more accurate measure for gas-aqueous phase equilibrium calculations<sup>2</sup>.

In addition to selection of a material for operation within its listed environmental limits (including for H<sub>2</sub>S), ISO 15156 / ANSI/NACE MR0175 also permits qualification by testing for application in extended limits. The testing approaches rely traditionally upon NACE TM0177<sup>3</sup>, NACE TM0296<sup>4</sup>, NACE TM0198<sup>5</sup> and NACE TM0316<sup>6</sup> methods with total pressures typically no greater than the sum of the field gaseous partial pressures of H<sub>2</sub>S, CO<sub>2</sub> and steam. Indeed, most testing is conducted at only 1 bar total pressure.

Whilst moving to a fugacity ( $f_{H_2S}$ ) approach as a direct substitute to  $p_{H_2S}$  is attractive, there are many barriers to such a move, including:

- Added complexity in increasing the thoroughness of an environmental assessment, including conservative prediction of pH and  $f_{H_2S}$ .
- Uncertainty in the overall conservativeness of materials selection for sour service: in substituting  $f_{H_2S}$  for  $p_{H_2S}$  is some vital conservatism lost that is required to counter a lack of conservatism elsewhere, for example uncertainties in:
  - Field measurement of H<sub>2</sub>S;
  - Reservoir souring predictions (for oil wells with water injection);
  - Service loading.
- Lack of testing capability and procedures to directly reproduce the service environment, to validate the more thorough approach.

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The present paper gives an example in the application of a thorough environmental assessment to the selection of API<sup>iv</sup> 5CT grade P110 production casing for a gas field, including the use of  $fH_2S$  in cracking assessments. It details the prediction, comprehensive validation and selection philosophy that was adopted to address each of the barriers above. The wells are in service and the production casing secondary barrier has functioned as intended.

## SELECTION PHILOSOPHY AND VALIDATION

From the outset, a conservative approach was adopted to both demonstrate fitness-for-purpose and to validate the more comprehensive environmental severity assessment for more general qualification. The actions described below are in addition to conventional good practice material selection procedures.

Qualification of the manufacturing route was undertaken in conformance with Annex B of ISO 15156 / ANSI NACE MR0175 Part 2. This was undertaken using dual approaches:

- Qualification to the field partial pressure of  $H_2S$ , using ambient pressure testing. This is a more conventional approach and is in line with the partial pressure concepts of ISO 15156 / ANSI NACE MR0175.
- Qualification to the field partial pressure of  $H_2S$ , using full field pressure testing (in effect qualification using the field fugacity of  $H_2S$ ). This is also in conformance with the partial pressure concepts of ISO 15156 / ANSI NACE MR0175 (which does not define a total pressure for fitness-for-purpose tests).

Both approaches are in full conformance with ISO 15156 / NACE MR0175 Part 2, but are complementary in providing a robust qualification. A range of  $H_2S$  partial pressures, well beyond the field  $pH_2S$ , were investigated to establish:

- the performance limit of the production casing (as manufactured using the defined manufacturing route);
- the correlation between high total pressure  $fH_2S$  performance vs ambient pressure  $pH_2S$  performance.

High pressure testing in more representative field conditions is novel and the procedures and methods are not fully established. To improve confidence in the results, testing was undertaken at two independent facilities, building on the expertise sets of both laboratories. The intent was not to create duplicate testing facilities, but to have two subtly different experimental set-ups that could better validate one another.

Modelling of the field condition is highly dependent on the capability of the modelling tools and any errors in the coding. In order to decrease exposure to coding errors and software method two completely independent software tools were used. In addition, although not detailed here, extensive sensitivity studies were performed to investigate different equations of state, reviewing primary and secondary outputs against their strengths, weaknesses and validated ranges.

Although not detailed in this present paper, work was also conducted to verify the conservatism of a relevant entry in ISO 15156 / ANSI NACE MR0175 Part 2 Table A.3, which suggests that API 5CT grade P110 is not susceptible to SSC at temperatures greater than 80°C (176°F). This gave confidence in applying this criterion for acceptance of sections of the casing for which the geothermal temperature (and minimum temperature in the potential presence of  $H_2S$ ) exceeded 80°C (176°F). Other validations were also performed, to provide supporting data for calculations regarding in-situ pH, corrosion rate in static environments (for example, non-flow wet sections of the production casing below the packer), and corrosion rates in flowing environments (for example, corrosion prior to shut-in following major communications). It is emphasized that the UNS S41426 production tubing selection, manufacture,

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connections, make-up and testing are all good practice and that communications are considered a low probability. The thoroughness of these assessments is to provide assurance for the low probability worst-case scenario and to demonstrate robust secondary barrier behavior.

Focus in this paper is placed on pH levels of 4,7 above, representative of formation water, minor A annulus communications, and condensed water saturated with iron (due to CO<sub>2</sub> corrosion). Exposure of the production casing to condensed water that is neither mixed with formation water (buffered), nor quickly iron-saturated is unlikely.

## DETAILS OF THE WELLS

### Service Environment

Essential parameters defining the wells are given in Table 1. These parameters are largely taken from wells producing from Reservoir B, but include some taken from other reservoirs to provide for a single conservative assessment.

**Table 1 – Well Environmental Parameters (approximate).**

| Pressures and Temp                         | Units         | Value   |
|--------------------------------------------|---------------|---------|
| Shut in well head pressure (SIWHP)         | bara          | 510     |
| Flowing well head pressure (FWHP)          |               | 70      |
| Reservoir Pressure                         |               | 620     |
| Shut in well head temperature (SIWHT)      | °C            | 35      |
| Flowing well head temperature (FWHT)       |               | 100     |
| Reservoir temperature                      |               | 160     |
| Depth at which minimum temperature is 80°C | m             | 1 400   |
| Formation Water Chemistry                  | Units         | Value   |
| Sodium                                     | mg/l          | 54 000  |
| Potassium                                  |               | 3 280   |
| Magnesium                                  |               | 70      |
| Calcium                                    |               | 7 000   |
| Iron                                       |               | 15      |
| Strontium                                  |               | 0       |
| Barium                                     |               | 510     |
| Chloride                                   |               | 99 000  |
| Sulphate                                   |               | 0       |
| Bicarbonate                                |               | 330     |
| Organic Acids                              |               | 98.5    |
| Hydrocarbon Mixed Pseudo-Chemistry         | Units         | Value   |
| N <sub>2</sub>                             | Mole fraction | 0,028   |
| C1                                         |               | 0,780   |
| C2                                         |               | 0,080   |
| C3                                         |               | 0,028   |
| i-C4                                       |               | 0,009   |
| n-C4                                       |               | 0,010   |
| i-C5                                       |               | 0,006   |
| n-C5                                       |               | 0,005   |
| C6-8                                       |               | 0,028   |
| C9-13                                      |               | 0,015   |
| C14-19                                     |               | 0,003   |
| C20+                                       |               | 0,001   |
| H <sub>2</sub> S, design (in reservoir)    | Units         | Value   |
| H <sub>2</sub> S in gas phase              | ppmv          | 0 to 20 |
| CO <sub>2</sub> in gas phase               | mol%          | 1       |