

Hydrogen Embrittlement Failure of Nickel Alloy UNS N07716-140 Tubing Retrievable Safety Valve Component Installed in a Sour Production Gas Well

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ABSTRACT

A failure in a Precipitation Hardened (PH) Nickel alloy component used as part of a Tubing Retrievable Safety Valve (TRSV) assembly occurred in an offshore gas well. The partial pressures of H₂S and CO₂ at the TRSV were estimated to be 333 and 534 psia, respectively. The well also produced 0.1 lb/MMSCF of elemental sulfur. The failed component was manufactured using grade UNS N07716 PH Nickel alloy heat treated to 140 ksi (965 MPa) Specified Minimum Yield Strength (SMYS) and 43 HRC max hardness in compliance to NACE MR0175/ISO 15156-3 standard.¹ The well was completed and had been in production for approximately five years with no major issues before it was shut-in to service wellhead equipment. A few months after shut-in of the well for service, a rapid increase in the tubing-casing annulus (TCA) pressure was observed which resulted in the need to workover the downhole completion. During workover operations, the TRSV was found to have parted at a major body component of the TRSV assembly, resulting in only the upper portion of the Top Sub being initially retrieved. Fishing operations later successfully retrieved the remainder of the TRSV. Failure analysis of the component indicated brittle fracture due to Hydrogen Embrittlement (HE) as the cause of the failure. The failure initiated at a high stress location in a box thread of the component and propagated through the component's cross-section resulting in complete separation of the component into two portions. This paper provides the details of the environment conditions, analysis of the failed component, including metallurgical and engineering analysis, and results of HE testing conducted as part of analysis.

Key words: Precipitation Hardened Nickel Alloy, UNS N07716, Hydrogen Embrittlement (HE), Hydrogen Assisted Cracking (HAC), Hydrogen Induced Stress Cracking (HISC), Tubing Retrievable Safety Valve, H₂S, NACE MR0175/ISO 15156.

INTRODUCTION

A 9-5/8 inch (244.8 mm) Tubing Retrievable Safety Valve (TRSV), which is a type of Sub Surface Safety Valve (SSSV) governed by API Specification 14A, was found to have failed when retrieved during workover operations in a gas production well in June 2019.² This TRSV was installed in the well in November 2013 and was in production service from 2015 until November 2018 when the well was shut in for maintenance of surface equipment. In March 2019, with the well still shut in for maintenance, a rapid increase in the tubing-casing annulus (TCA) pressure was observed. The increase in TCA pressure

resulted in the need to workover the well to retrieve and replace the completion. During workover operations in June 2019, the TRSV was found to have parted at the Top Sub, a body component located at the upper end of the TRSV. This resulted in only the Top End Sub and the box thread from the upper portion of the Top Sub being initially retrieved. Fishing operations later successfully retrieved the remainder of the TRSV including the balance of the Top Sub. The raw material used for the Top Sub component was UNS N07716-140K bar stock with an OD of 12.5 inches (318 mm). The bar stock material had been melted via EF + AOD + VAR route, hot worked (forging ratio of 6.3) and heat treated to 140K via solution annealing and aging process.

The well conditions in which the TRSV was deployed are shown in Table 1 below. The well was primarily producing dry gas containing H₂S and CO₂ along with some elemental sulfur. Very little water was being produced, so the equipment was mainly subject to condensed water especially during conditions such as shut-in. During production the temperature at the TRSV was up to 262°F (128°C), but analysis indicated that during long term shut-in periods exceeding one month, the temperature could drop to 91 °F (31°C). Additionally, during this period with the well head shut in, the TRSV was subject to a pressure differential with pressure inside the TRSV (tubing ID) greater than that outside the TRSV (TCA). The TRSV was located within a 14-inch (355.6 mm) OD API 5CT T95 type grade casing.³ The nominal ID of the T95 casing was 12.400 inches (315 mm) with a drift ID of 12.213 inches (310.2 mm). It is to be noted that the maximum OD of the TRSV UNS N07716-140K Top Sub was 12.125 inches (308 mm), so the T95 (low alloy steel) casing was in very close proximity or likely in contact with UNS N07716-140K Top Sub. The completion tubing was 9-5/8 inches (244.8 mm) UNS N06255 (Alloy 2550) with 110 ksi SMYS. The completion brine in the annulus between TRSV and casing was 13.0 ppg CaBr₂.

Table 1
Well Conditions

Well Type:	Gas Production
Max BHP:	9898 psi (682 bar)
Max WHP:	8250 psi (569 bar)
BHT Range:	270 - 285°F (132 - 141°C)
WHT Range during Production:	210 - 250°F (99 - 121°C)
Max TRSV Temperature during Production:	262°F (128°C)
Min TRSV Temperature during shut-in:	91°F (31°C)
Max PH ₂ S @ TRSV:	333 psi (23 bar)
Max PCO ₂ @ TRSV:	534 psi (37 bar)
Elemental sulfur:	0.1 lb/MMSCF
Condensed Water pH (Calculated):	3.2 - 3.5

FAILURE ANALYSIS

After retrieval, the TRSV was examined to understand the possible cause of failure. The TRSV had failed at the box thread on the upper end of the Top Sub separating that component into two pieces. One, a smaller section consisting of the box thread which remained connected to the Top End Sub. The second, a larger section consisting of the rest of the Top Sub still connected to the balance of the TRSV assembly.

Figure 1 shows a general photograph of the received upper section of the failed TRSV. This included the upper portion of the Top Sub and the Top End Sub. Figure 2 shows a photograph of the upper Top Sub fracture surface. For tracking purposes, hour clock positions were assigned to the fractured Top Sub as indicated in Figure 2. Any reference to clock position hereafter will be according to this marking.

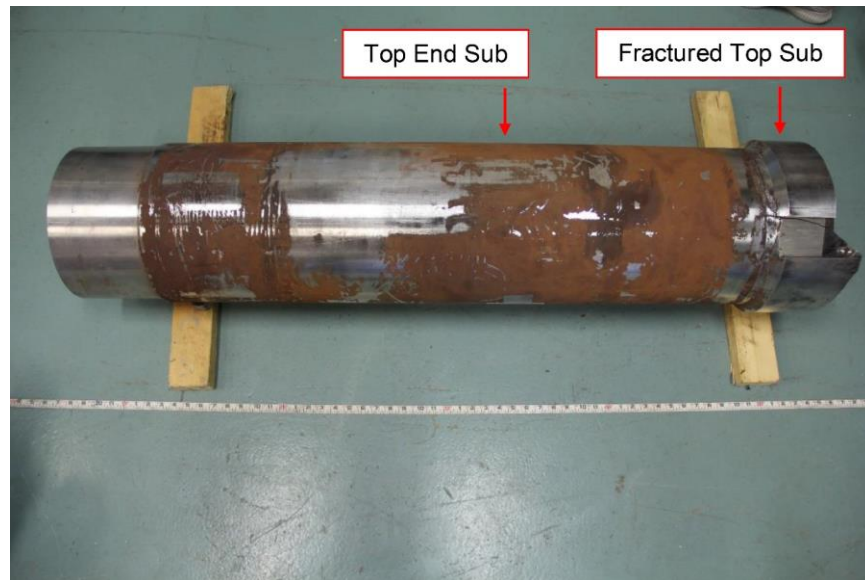


Figure 1: General as-received photograph of the failed TRSSV sample.

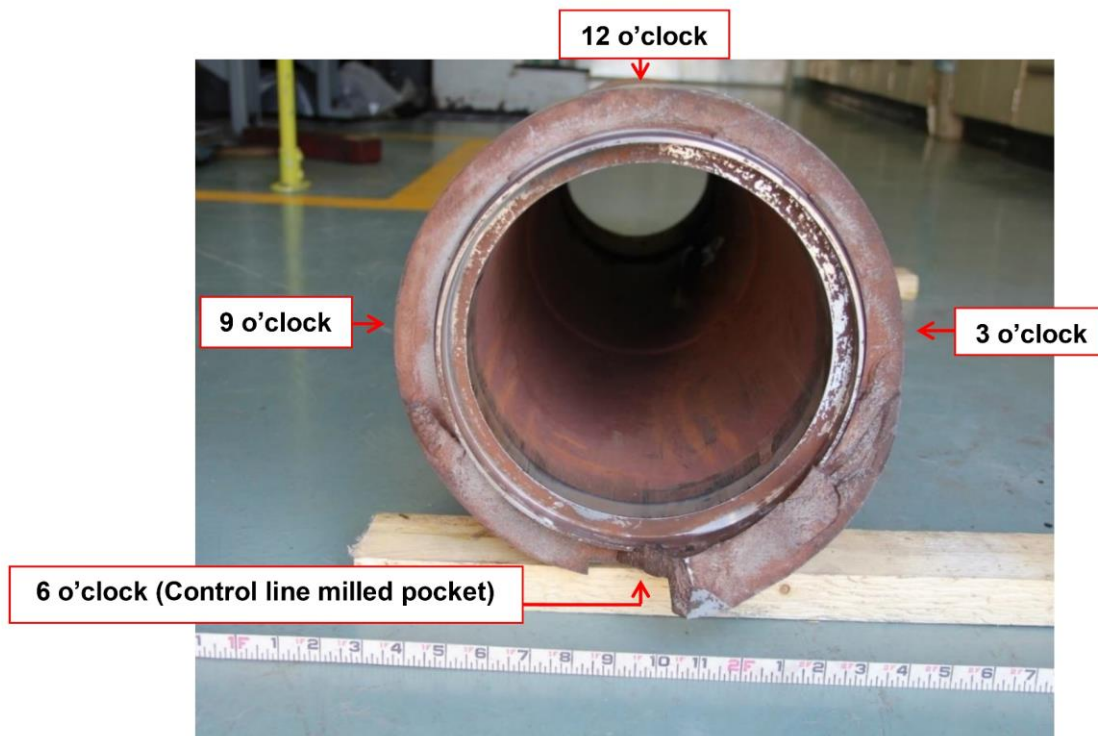


Figure 2: General as-received photograph of the upper Top Sub circumferential fracture.

Visual Examination

Initial visual examination revealed that the Top Sub separated by a fracture mostly transverse to the valve axis (i.e. circumferential) as seen in Figure 2. A longitudinal crack was also observed running along the control line milled pocket (6 o'clock position) as shown in Figure 3. Visual examination also revealed multiple longitudinal secondary cracks on the external side running close to the fracture surface as shown in Figure 4 (3 O'clock position).

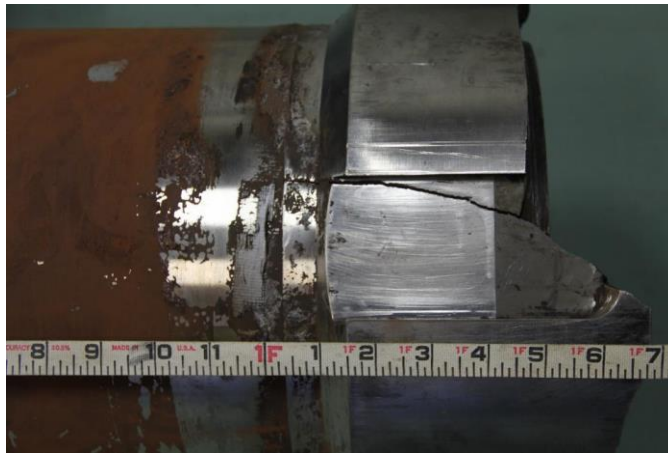


Figure 3: Photograph of the longitudinal crack along the control line milled pocket.



Figure 4: Photograph showing the secondary longitudinal cracks on the OD (arrows).

The circumferential fracture was mostly flat with no visible necking or plastic deformation observed. Two propagation lines running opposite to each other (clockwise and counterclockwise) were observed on the fracture surface that met between the 2 o'clock and 3 o'clock positions, see Figure 5 for illustration.

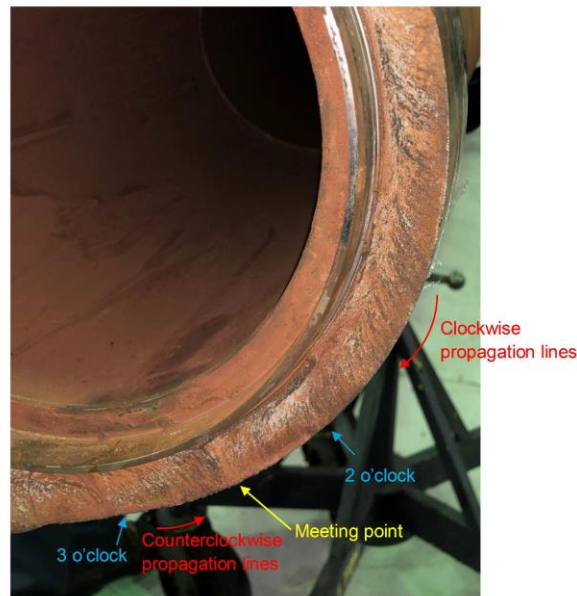


Figure 5: Close up photograph of where the fracture propagation lines meet.

Further examination revealed signs of wear damage with directional patterns which were observed on the Top Sub near the longitudinal crack on the control line milled pocket side (6 o'clock position). Upon further sectioning of the Top Sub, it was revealed that the longitudinal crack shown earlier in Figure 3 was running through the thickness as seen in Figure 6.



Figure 6: Photograph of the longitudinal control line milled pocket crack after sectioning

Dye Penetrant Examination

Dye penetrant testing (PT) was conducted on the external side of the Top Sub around the circumference (OD side). Examination revealed a series of parallel secondary cracks longitudinal to the valve axis and close to the fracture surface as shown in Figure 7 mainly from the 9-3 o'clock positions.



Figure 7: Photographs of the PT examination on the Top Sub external surface.

Further PT (Figure 8) revealed a series of non-surface breaking cracks in the Top Sub mid-wall along with the surface breaking cracks that were initially observed during the external surface PT examination.



Figure 8: NDE evaluation of long section of fracture Transverse Cross-section showing multiple secondary cracks

Stereo-Microscope Examination

The fracture surface of the Top Sub was examined under low magnification stereo-microscope after ultrasonic cleaning. Control line milled pocket (box thread) location was further evaluated at higher magnification after cleaning. The examination showed a very smooth surface with directional wear patterns from the internal surface (ID) toward the external surface (OD) of the upper Top Sub as seen in Figure 9.

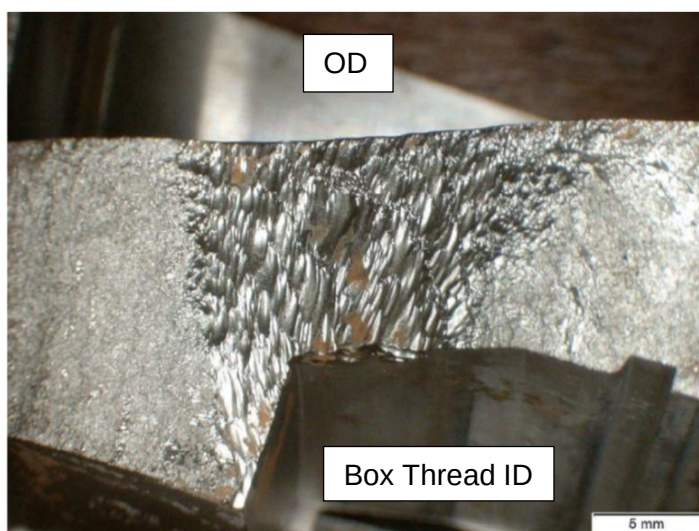


Figure 9: Stereomicroscopy images showing erosion damage pattern from box thread ID to OD

Fractographic Examination

Two samples were cut from the fracture surface, as illustrated in Figure 10, and examined under a Scanning Electron Microscope (SEM). Sample A was cut near the 12 o'clock position based on the stereo-microscopic examination to be representative of the flat fracture area.

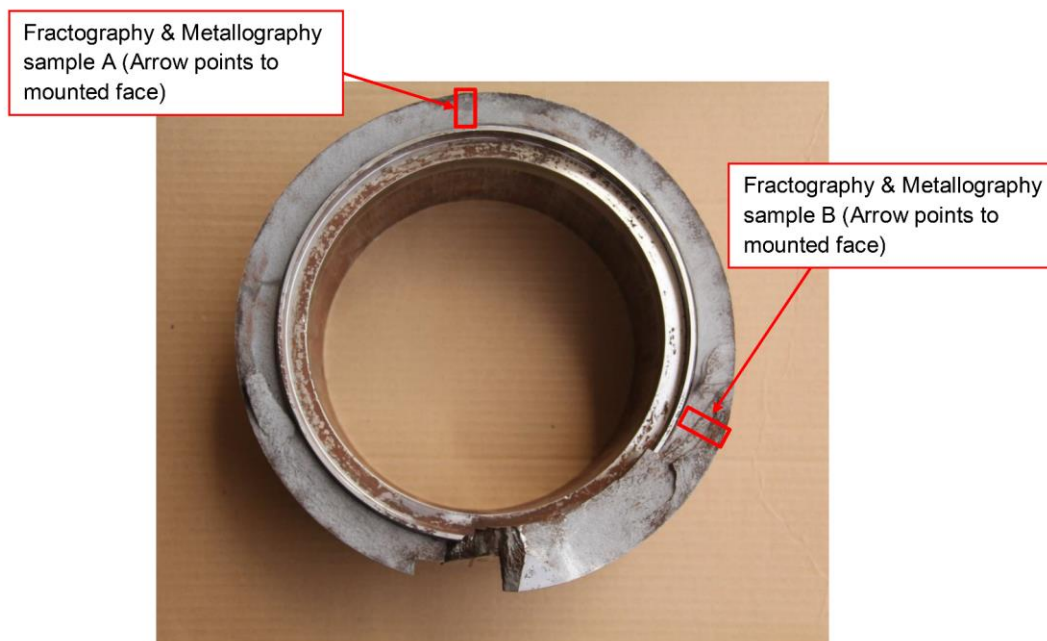


Figure 10: Annotated photograph showing the locations of the extracted samples.

Examination revealed the fracture of sample A to be mainly transgranular. However, the longitudinal cracks (secondary cracking) intersecting this transverse fracture were intergranular. These mixed areas of intergranular and transgranular fracture modes can be seen in Figures 11. Generally, no signs of clear microvoids coalescence were observed at this location.

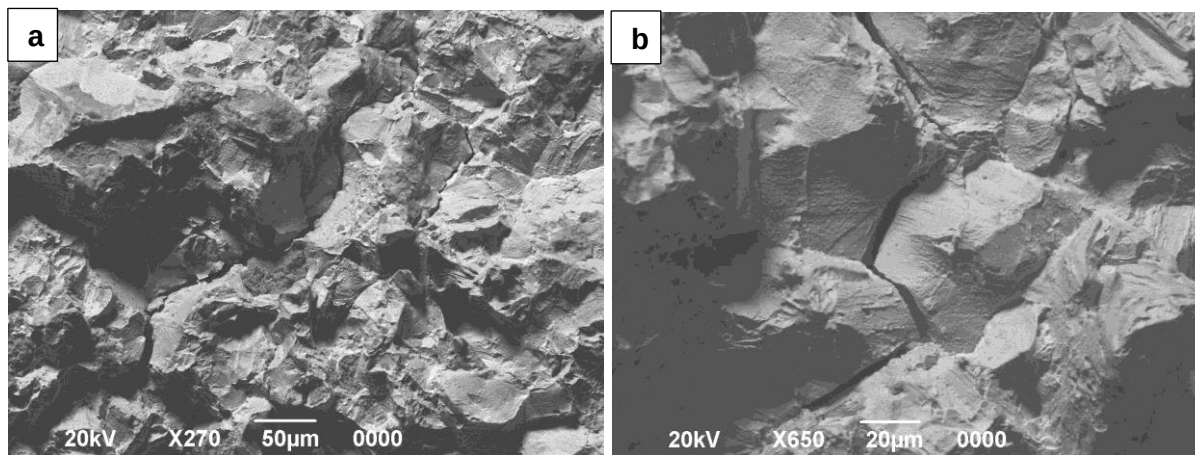


Figure 11: (a) SEM micrograph of the fracture surface sample A (b) Higher magnification image

Sample B was cut between the 3 o'clock and 4 o'clock positions to examine the area at which the flat fracture surface changes direction. The results were similar with mixed areas of intergranular and transgranular fracture modes as can be seen in Figures 12. No signs of microvoids coalescence were observed at this location as well.