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Potential hazards from undetected corrosion in complex equipment: A case study of the destructive separation of an offshore heat exchanger

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ABSTRACT

This paper describes hazards from undetected corrosion in complex equipment using findings from a collaborative forensic investigation into the destructive separation of a heat exchanger on an offshore gas storage platform. The heat exchanger had been in service for 24 years. The heat exchanger was a conventional shell-and-tube type with both the tubes and shell being manufactured from titanium. However the bonnet and tube sheet were manufactured from carbon steel. The seawater side of the carbon steel tube sheet had been protected from corrosion by titanium cladding.

The investigation revealed localised corrosion of the carbon steel tube sheet in areas exposed to acidic condensate containing hydrogen sulphide. Corrosion was galvanic in nature and had occurred where, by design; the carbon steel–titanium interface was exposed. The results showed that hydrogen, generated cathodically by the galvanic corrosion, had formed titanium hydride in the interfacial region of the titanium cladding.

The evidence indicated that the separation of the tube bundle and shell from the bonnet was probably initiated when a large area of the cladding bond interface failed suddenly due to hydride formation. The final destructive separation of the tube bundle can be explained by the deformation of the cladding after complete failure of the bonded interface with the tube sheet.

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1. Introduction

1.1. Background

A horizontal shell-and-tube heat exchanger failed on an offshore storage platform. The tube bundle and shell separated completely from the bonnet with considerable force and approximately 10 tonnes of hydrocarbon gas was released [1]. Adjacent equipment on the platform was damaged by the force generated from the separation of the heat exchanger. There

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was further extensive damage in the fire and explosion that ensued when the gas cloud ignited. Personnel on the platform were evacuated successfully and there were only minor injuries.

The Health and Safety Laboratory (HSL) carried out a forensic metallurgical investigation for the Health and Safety Executive (HSE) to determine how the heat exchanger had failed. This investigation was overseen by a collaboration of technical experts from HSL, HSE and the platform operator with industrial experts from two independent organisations. The Offshore Division of the HSE issued a Safety Alert [2] to make the results of the investigation available to other users.

The original function of the heat exchanger was to cool hydrocarbon gas from wells before pumping on-shore. In recent years, however, the heat exchanger had been used on a cyclic basis, cooling gas being pumped off shore into the formations for storage during summer months and cooling gas extracted from the formations during winter months. It was reported that gas pumped for storage was pre-dried before passing through the heat exchanger but gas extracted from the formations contained moisture that was intended to condense in the heat exchanger.

1.2. Design aspects

The heat exchanger was a conventional shell-and-tube bundle design that was manufactured in 1983 for a gas pressure of 100 bar (1450 psig) in the tubes and a shell seawater pressure of 10.3 bar (150 psig). At the time of failure, the gas pressure was 90 bar (1300 psig) and the cooling water pressure was 10 bar (145 psig). The heat exchanger was approximately 9 m long overall with a shell diameter of 1 m and a bundle of 1130 tubes, each 6.5 m long. The tube specification was ¾ in. OD, 16 BWG tubing to ASTM/ASME SM338 Grade 3 titanium. Fig. 1 shows the main components schematically.

The tube bundle and shell were manufactured from titanium. The bonnet and tube sheet were manufactured from carbon steel (CS) but the seawater side of the tube sheet had been clad with 13 mm thick titanium. The cladding had been applied by explosive bonding and every tube-to-cladding joint was circumferentially welded into a recess in the titanium cladding sheet, Fig. 2.

The heat exchanger was designed to use titanium for seawater contact and a combination of titanium and carbon steel for surfaces in contact with the hydrocarbon gas and condensate. The interface between the titanium and carbon steel surfaces on the gas side was inside the holes of the tube sheet. A significant design feature, therefore, was the exposure of the titanium–carbon steel interface to the high pressure gas stream and condensate.

Tube–tube sheet joints are a critical feature of heat exchanger design. A number of joint designs can be used which range from welded joints to tubes that are mechanically expanded into sealing grooves. In the heat exchanger that failed, the tube to cladding sheet joint was an automatic tungsten inert gas (TIG) weld made from inside each tube. The weld was effectively 0.8 mm thick compared with the 1.65 mm wall thickness for the tube so the load bearing area of the weld that was less than that of the tubing. Thus any load or strain transmitted from a tube to the tube sheet would have caused the highest stress levels to occur in the weld metal. A further important feature was that the welds connected each tube to the cladding sheet. Consequently the explosively bonded interface was part of the load path and any load or strain passing between the tube bundle and the steel tube sheet was transmitted across the interface.

The heat exchanger was fitted with sensitive hydrocarbon detection on the water-side to indicate leakage of gas through to the water side. There was also a water-side bursting disc which was estimated by the operator to be capable of withstanding the simultaneous failure of at least two tubes.

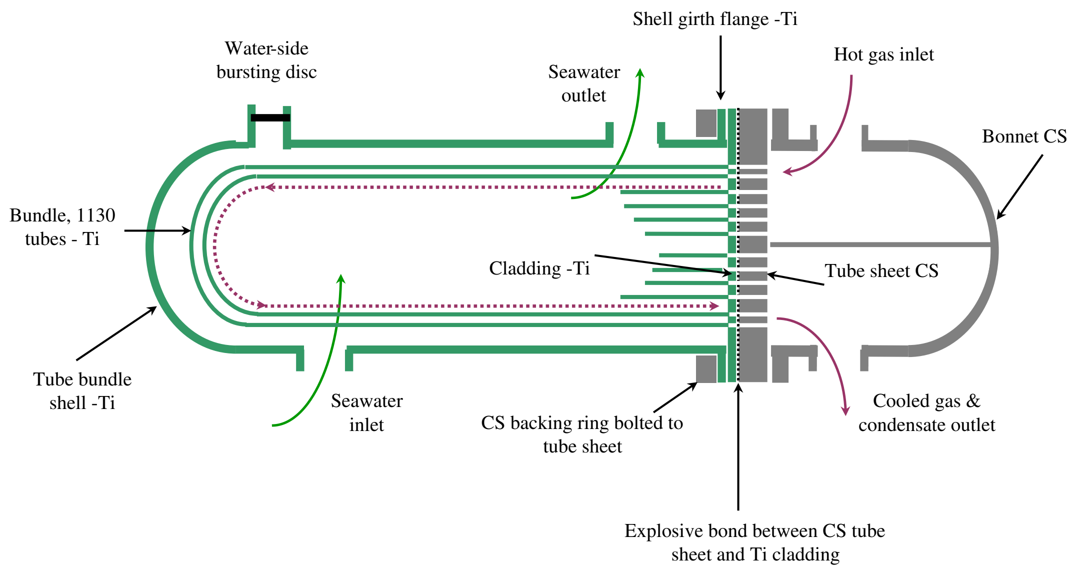

Fig. 1. A diagram showing the key features of the heat exchanger and the seawater and gas flows in normal operation.