

Resid Hydrotreater Unit Heat Exchanger Failure

Summary

A facility experienced a major fire in its Resid Hydrotreater Unit (RHU) which caused millions of dollars in property damage. One employee sustained a minor injury during the emergency unit shutdown and there were no fatalities.

The RHU incident investigation determined that an 8-inch diameter carbon steel elbow inadvertently installed in a high-pressure, high-temperature hydrogen line ruptured after operating for only 3 months. The escaping hydrogen gas from the ruptured elbow quickly ignited.

This incident occurred after a maintenance contractor accidentally switched a carbon steel elbow with an alloy steel elbow during a scheduled heat exchanger overhaul. The alloy steel elbow was resistant to high temperature hydrogen attack (HTHA) but the carbon elbow was not. Metallurgical analyses of the failed elbow concluded that the HTHA severely weakened the carbon steel elbow.

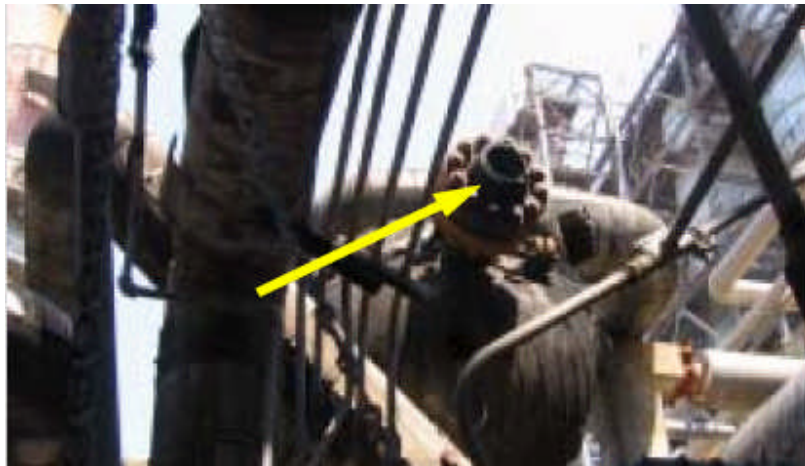


Figure 1. Carbon steel RHU heat exchanger outlet pipe (arrow) ruptured after operating only 3 months in high temperature hydrogen service.

Background

Residual material from the crude oil processing unit is processed in the RHU to remove nitrogen, sulfur and metals. Hydrogen is pressurized to about 3,000 psi, and then pre-heated in the RHU heat exchangers (Figure 2) to about 600 °F.

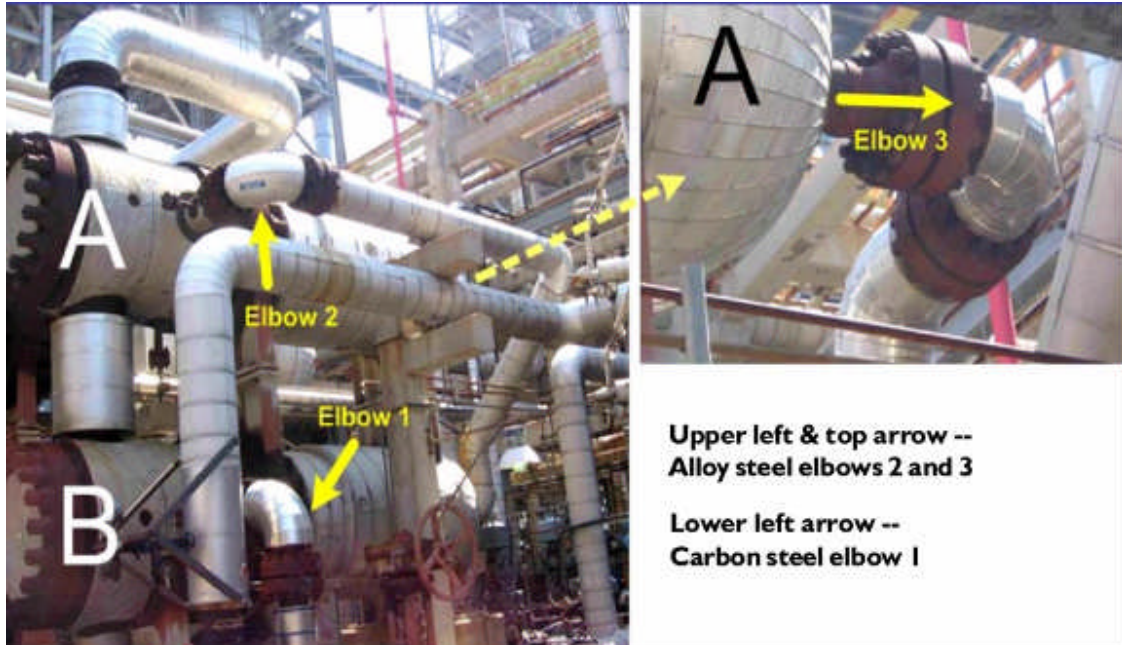


Figure 2. Dimensionally identical piping elbows on RHU heat exchangers A and B.

The preheated hydrogen next passes through a furnace to increase the hydrogen temperature, and then is injected into the reactor feedstock. Hydrogen combines with nitrogen compounds and sulfur within the feedstock in the presence of the catalyst inside the RHU reactors to form hydrogen sulfide and ammonia. Light hydrocarbon, such as gasoline, is then processed in downstream refinery units.

Description

On a given day, the referenced RHU hydrogen gas heat exchanger process pipe ruptured. The venting hydrogen gas ignited and a large fireball erupted in the unit. One employee sustained a minor injury while assisting with the RHU emergency shutdown. The RHU sustained major damage from the hydrogen-fed fire that burned for two hours. There were no offsite impacts but, as a precaution the facility ordered a shelter in place for nearby residents until the fire was contained.

Onsite personnel examined the extensively damaged unit and determined that an 8 inch diameter pipe elbow on an RHU heat exchanger hydrogen gas outlet pipe ruptured (Fig. 3). The investigation team recovered the elbow segments that remained attached to the pipe and three pieces found in the debris.



Figure 3. Ruptured 8-inch pipe elbow on heat exchanger A outlet

INCIDENT ANALYSIS

HTHA Failure Mechanism

Carbon steel in hydrogen service at temperatures above about 450 °F and pressures above 100 psia is susceptible to HTHA. At these operating conditions, atomic and molecular hydrogen permeates the steel and reacts with dissolved carbons or carbides to form methane gas. The loss of carbon in the steel, or 'decarburization,' significantly degrades the steel's mechanical properties, including tensile strength and ductility. The methane gas creates high localized stresses, which combine with the normal piping system stresses to create voids and fissures in the steel, which ultimately causes the pipe to rupture.

Experiments and operating plant data show that HTHA is typically avoided by using low alloy steels containing 1.25-3.0 percent chrome, as the chrome combines with carbon to form chromium carbide, which is resistant to reacting with hydrogen.

Failed Elbow Metallurgical Analysis

The elbow segments recovered from the damaged unit were examined to identify the steel and the failure mechanisms. Chemical analysis and microscopic examination determined that the elbow was made from carbon steel. Microscopic examination also showed that the segments were severely decarburized and had deep fissures on the inside surface (Fig. 4). The decarburized steel and severe fissuring confirmed that HTHA caused the catastrophic elbow failure.

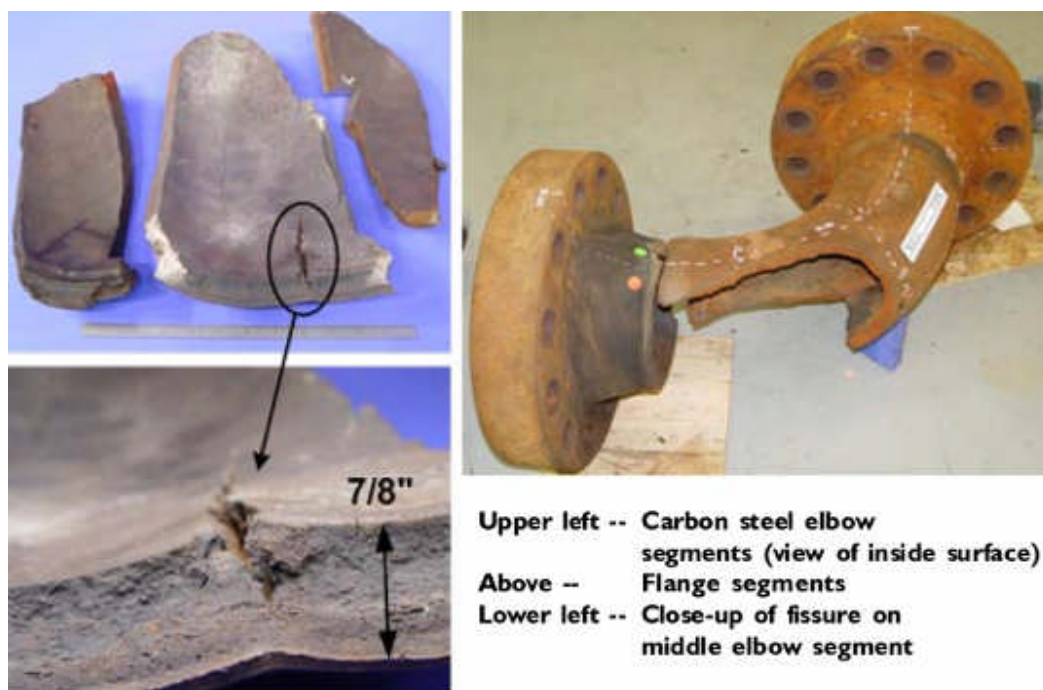


Figure 4. Ruptured 8-inch carbon steel pipe elbow pieces recovered after the fire

Detailed metallurgical examinations and micro-hardness testing quantified the extent of hydrogen damage to estimate the total time the elbow could have been in the high-temperature, high pressure hydrogen service before if failed. The results, compared to existing experimental data and empirical service life predictions, concluded that the elbow failed after being in service for fewer than 3,000 hours.

RHU System Design

Designed in the early 1980's the RHU has three parallel operating systems. Each system contains a heat exchanger assembly that consists of two-series connected heat exchangers to preheat the hydrogen. For high temperature hydrogen gas service piping to resist HTHA, the piping design specification requires 1.25% chrome "low alloy" steel, but for piping in hydrogen service at low temperatures, or those below 450 °F, non-HTHA resistant carbon steel is specified, as using this material minimizes material cost.

Because heat exchanger B inlet piping and components operate at temperatures below 450 °F, they are carbon steel; heat exchanger B outlet and all downstream piping and components (Fig 5) are required to be low alloy steel because they operate at temperatures above 500 °F.

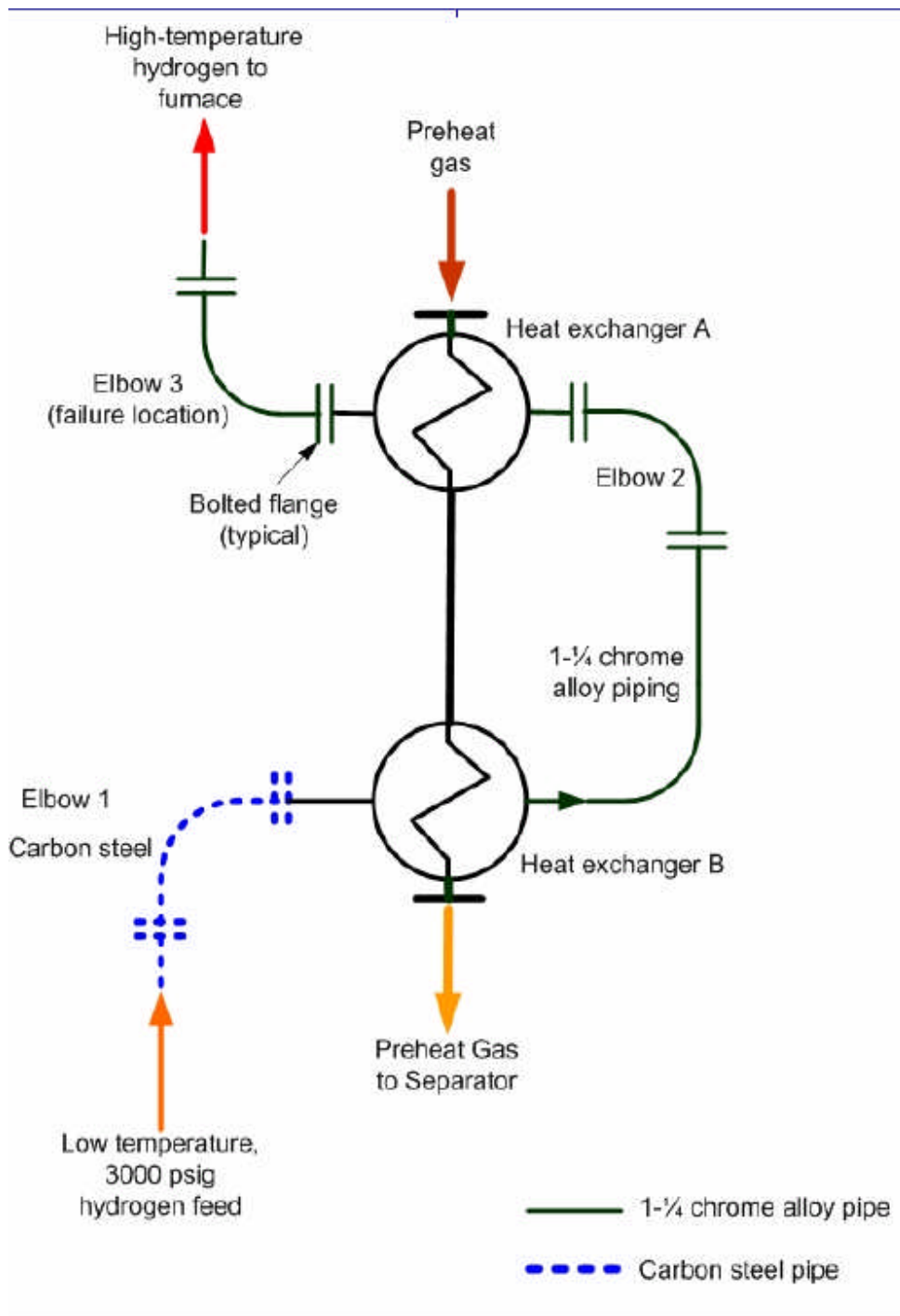


Figure 5. RHU hydrogen heat exchanger piping material requirements

Construction costs may have been saved by making elbows 1, 2, and 3 on each heat exchanger assembly dimensionally identical, as doing so requires fewer pipe assembly fabrication drawings and weld joints in each assembly. Because the elbows are dimensionally identical, the piping contractor had to ensure that the low alloy steel

elbows 2 and 3 were installed in the correct locations where the RHU was built. Had the elbow 1 design dimensions been different, elbow 1 would not have been interchangeable with elbow 2 or 3 (Fig 2).

Because of this component interchangeability, any heat exchanger piping disassembly / reassembly for maintenance or repair requires the maintenance crew to be careful to install each elbow in the correct location. Because carbon steel and low alloy steel are visually indistinguishable, special test equipment is needed to distinguish the two low alloy steel elbows from the carbon steel elbow. Otherwise, to prevent switching elbow 2 or 3 with incompatible carbon steel elbow 1, the crew must clearly label or mark each elbow before removing them, then confirm that each has been reinstalled in the correct location.

RHU Heat Exchanger Maintenance

The RHU heat exchangers were placed in service in 1984. Scheduled heat exchanger cleaning and inspection were performed in 1989 and 1991. Elbows 1, 2 and 3 were removed from the heat exchangers, set aside, and then reinstalled following the maintenance.

The next heat exchanger maintenance overhaul began in early 2005. The three elbows were removed, stored temporarily, and then reinstalled 39 days later. The maintenance contractor was unaware of the material differences in the elbows and the given company did not require the contractor to implement any special precautions to prevent inadvertently switching the elbows or any post-reassembly testing to confirm the alloy elbows were reinstalled in the correct locations.

Metallurgical analysis after the incident concluded that the carbon steel elbow could withstand the high-temperature, high-pressure service for only a few thousand hours. X-ray fluorescence testing confirmed that an alloy steel elbow was installed in the carbon steel elbow position on the heat exchanger B inlet. Therefore, the investigating organization concluded that carbon steel elbow 1 was inadvertently switched with alloy steel elbow 3 when the maintenance contractor reassembled the piping during the winter 2005 heat exchanger overhaul.

Alloy Piping Material Verification

The given facility has a material verification program, and PMI test equipment that quickly differentiates carbon steel from alloy steel piping components. The companies procedure requires alloy steel components to be verified when they are received in the warehouse and when alloy steel components are shipped from the warehouse for use in new construction. However, it does not require PMI during maintenance, even when there is a risk of inadvertent substitution of the wrong material with alloy piping components.

As this incident demonstrated, merely disassembling and reassembling piping components during maintenance can result in unacceptable system modifications. Lacking post - installation PMI testing, or positive identification of the alloy steel

components before and after installation (e.g., component tagging before disassembly), the maintenance crew's reassembly error went undetected until the pipe failed.

Key Findings

- Piping systems can be designed such that incompatible components cannot be interchanged. All three elbows could have been made from the same low alloy steel material, even though this would have meant additional material expense. Alternatively, elbow 1 could have been dimensionally different from elbow 2 and 3, although this would have meant additional construction costs.
- In early 2005, a carbon steel elbow was installed in the high temperature, high pressure hydrogen line instead of the required 1.25 percent chrome low alloy steel elbow. HTHA caused the carbon steel elbow to rupture after the unit operated for only a few months.
- The given facility's material verification procedure did not require critical piping component PMI testing during equipment maintenance, even though the incompatible components could be inadvertently switched. The test is simple to perform and quickly differentiates between carbon steel and alloy steel.
- The maintenance contractor did not adequately control the disassembly, storage, and reassembly of the piping components to ensure that all the piping components were returned to their original installed locations.
- The maintenance contractor inadvertently switched carbon steel elbow 1 (Figures 2 and 5) with the alloy steel elbow 3 during the RHU heat exchanger overhaul.

LESSONS LEARNED

Human Factors Based Design

Designers should consider the entire process system life cycle, including planned maintenance, to avoid piping configurations that allow critical alloy piping components to be interchanged with non-compatible piping components.

Positive Material Verification Programs

In-situ alloy steel material verification using x-ray fluorescence, or non-destructive material testing, is an accurate, inexpensive, and fast PMI test method. Facility owners, operators, and maintenance contractors should ensure that the verification program requires PMI testing, such as specified in API Recommended Practice 578, or other suitable verification process, for all critical service alloy steel piping components that are removed and reinstalled during maintenance.

At a minimum, piping components and their respective locations should be tagged or marked before removal, and the correct installed location is verified after reinstallation.