Failure in Start-up Heater Tube

Detailed study of incident involving tube rupture at English ammonia plant shows temperature imbalance to be a contributing factor.

J. Mitcalf
Shellstar Ltd.
Ince, England

This is a detailed report of an investigation of a tube failure in an ammonia plant at the Shellstar Ltd. facilities at Ince, England. The ammonia plant is a 1,000 short ton/day unit using natural gas from the North Sea as feedstock. At the time of the incident, the plant had been in fairly normal operation for some months after a major turnaround in early 1973.

At about 8:00 p.m. on Sunday, December 9, 1973, during start-up of the syn loop, with the start-up heater in commission, there was a violent explosion. It was almost immediately identified as a tube rupture in the start-up heater because the loop de-pressured through the rupture and was ignited by the burners, flames issuing from the stack and from the burner registers at the bottom.

The loop was isolated and the fire allowed to burn itself out, nitrogen purge being applied when the pressure had dropped to a low level. The fire subsided in 10-15 minutes. Although a number of fire trucks were available, they were only used for some small subsidiary fires. There were no casualties.

On the morning of the day of the explosion there had been a trip of the syn gas compressor due to an instrument malfunction. The syn loop was being re-started after a number of incidents during the day, including a fire on the top joint of the converter exchanger. The start-up heater was put in commission at around 5:00 p.m. The explosion occurred at 8:00 p.m., when the heater had been in operation 3 hr.

The heater is an upshot, oil-fired, all-radiant, 2-parallel vertical coil, furnace with 4 burners. The tubes are in 2 parallel sets of hairpins comprising 24 tubes each, 4-in. N.B., Schedule 120, and 30 ft. long, made of 5% Cr, ½% Mo steel to ASTM A.335-P5 Specification.

Normal control of the heater firing was by varying the number of burners used and varying the fuel flow to the burners. The safety systems comprised a process gas low flow trip, process gas high outlet temperature trip and a flue gas high temperature trip. On the firing side there was a steam/oil differential pressure trip, a fuel oil low pressure trip and a manual trip.

Extensive damage found

Preliminary inspection showed that the outlet tube of the south coil had ruptured longitudinally, about 10 ft. from the furnace floor, i.e. about 30% up the vertical tube. The length of the rupture was 11 in. It is shown in Figure 1. As can be seen in Figure 2, extensive damage was done to the remainder of the heater tubes.

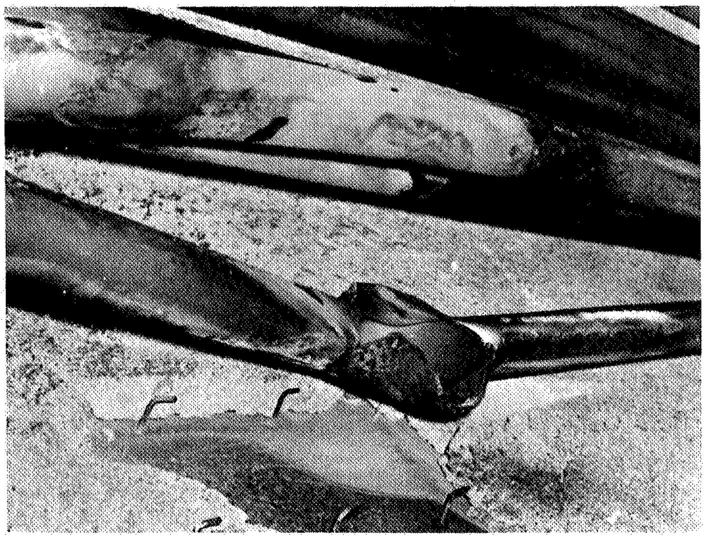

Figure 1. Ruptured tube, showing scouring of the refractory from the furnace wall.

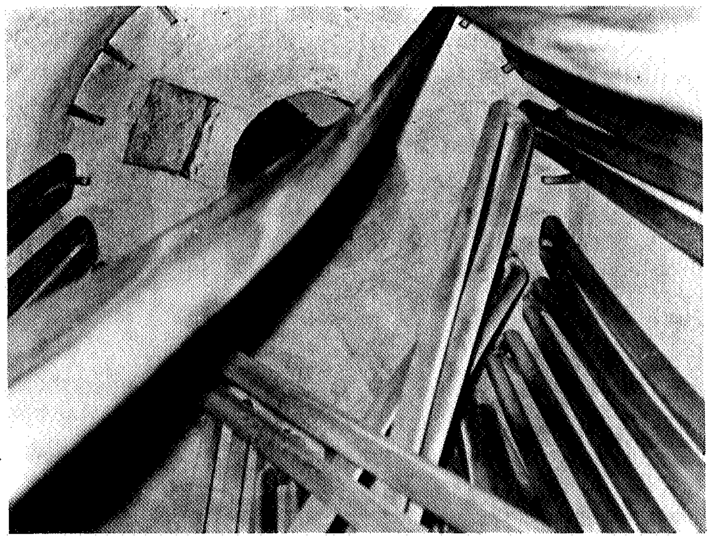

Figure 2. General internal view of the heater, showing piping dislodged from its hangers.

Examination of the failed tube, i.e. the south outlet, showed that in the region of the rupture there were fissures in the tube bore up to 1.7 mm. in depth; the inner surface of the tube was nitrided to a depth of 0.8 mm. on the flame side and 0.38 mm. on the shadow side. Figure 3 shows some of the damage. It was also noted that the fissures themselves were nitrided to a depth of 0.2 mm.

At a location 20 cm. from the rupture, 5% creep was

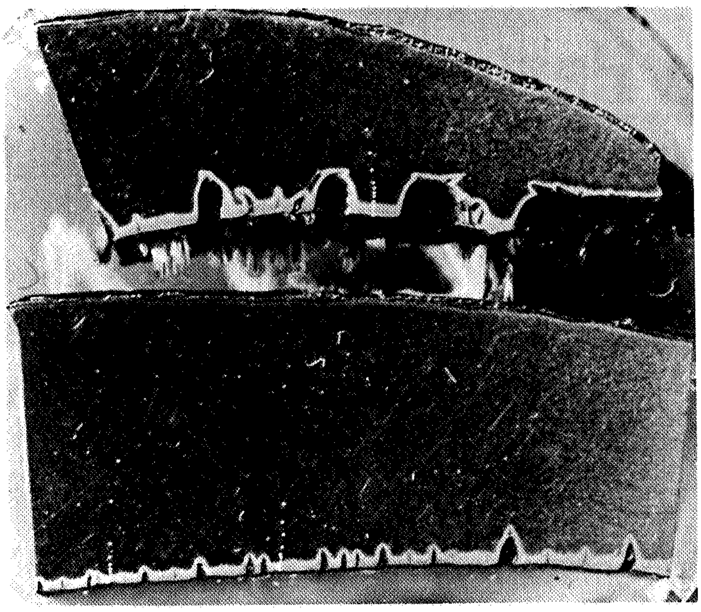

Figure 3. Cross section of rupture on a location halfway its length, south inlet tube.

present, and at this point the tube wall had thinned from 11 mm. to 9 mm., although the tube bore remained circular.

The outlet tube of the north coil was also checked, and at a height of 10 ft. from the heater floor, nitriding to a depth of 0.34 mm. on the flame side and 0.22 mm. on the shadow side was found. There were no surface fissures found on the inner wall, although circumferential creep of 2.5% was measured together with 0.8 mm. local thinning.

From experience of nitriding rates in similar steels gained within the company, it could be concluded that the inner surface of the failed tube had been subjected to a temperature of at least 500°C to produce 0.8 mm. of nitriding in 6,500 hr., the operating life of the heater to the time of the explosion. In the same way, to produce 0.34 mm. depth of nitriding in the north coil outlet, the temperature of the inner surface of the metal would have been at least 430°C.

Design conditions and past operating conditions are given in Table 1. The heater was designed for a gas inlet temperature of 299°C, gas outlet temperature of 427°C at a pressure of up to 3,200 lb./sq.in. gauge, and under these conditions should have had a life of 30,000 hr. In addition there was a corrosion allowance of 1/16 in.

Previous operating performance

During 1971 and 1972 it had been necessary, in order to keep the ammonia plant in operation, to run the start-up heater continuously. The initial reason for this was poor performance of the converter feed/product exchanger. In addition, the plant was short of 1500-lb./sq.in. gauge steam, there being at the time only one source of this range of steam—the reformer gas boiler.

This situation was aggravated by a partial blockage in the bottom of the catalyst bed in the converter, restricting ammonia production and hence heat input to the high-pressure boiler feedwater. Since the start-up heater had been designed for 30,000 hr., the decision was taken to operate in this way until the next major turnaround when the converter catalyst would be changed and a new hot exchanger fitted, among other things.

In all, therefore, the start-up heater had been in operation around 6,500 hr. at the time of failure. Much of this time, some 5,000 hr., had been continuous operation, and it is fairly clear that nitriding of the inner surface, fissuring, and subsequent further nitriding took place during this period. It should be pointed out that nitriding of the tubes was not a consideration when deciding on this mode of operation.

Up to the time of the explosion, the heater had a syn gas flow indicator with a low flow trip. This flow indicator was not, however, pressure or temperature compensated. In addition, there was a process gas high outlet temperature trip. There was also a temperature indicator on the combined process gas outlet—the guiding feature for the operator, and a flue gas temperature indicator, with a trip set at 950°C. As can be seen in Table 1, on December 9, the heater appeared to be operating well within its design and trip conditions.

Furnace tube temperature calculations are shown in Table 2. The expected metal temperatures for gas oil firing were calculated using the following assumptions:

1. Variation in heat flux around the tubes 1.8:1.
2. Variation in heat flux up the furnace 1.65:1.
3. Additional 15°C allowed for non-uniformity of firing around the center line of the heater.
4. No fouling on the inside of the tubes.

For data sheet conditions, 1,250 LTPD process flow, 270°C inlet and 400°C outlet. Peak metal temperature was calculated at 511°C.

Table 1. Operating conditions of start-up heater

	Design	Typical start-up Condition	Continuous operation June '71 & March '73	At time of explosion Dec. 9, '73
Gas inlet temp.,°C	299	200	187	235
Gas outlet temp.,°C	427	400	398	400
Gas press., lb./sq.in.gauge	3,500	1,800	2,800	2,500
Gas flow, LTPD	1,250	600	600	600
Fuel oil press., Bar	–	8	8	12
Fuel oil flow, LTPD	–	16.0	16.0	19.2
Flue gas outlet temp.,°C	–	750	720	850
Gas composition:				
H_2	65.3			
N_2	21.8			
A	2.5			
NH_3	4.0	*	*	*
CH_4	8.4			
CO	0			
CO_2	0			
Fuel oil calorific value lower H.V., Btu./lb.	18,823	18,100	18,100	18,100

*Approximately as design.

Table 2. Calculation of wall temperatures, stresses, and lifetime

	Design	Typical start-up Condition	Continuous operation June '71 & March '73	At time of explosion Dec. 9, '73
Calculation of wall temperature:				
Heat transferred, K cal./hr.	5.37×10^6	4.03×10^6	4.25×10^6	3.32×10^6 (*1*)
Average heat flux, k cal./hr.sq.m.	40,406	30,323	31,979	24,981
Max. heat flux, k cal./hr.sq.m. (*2*)	120,006	90,059	94,978	74,194
Film coeff. inside (h_2) k cal./hr.sq.m.°C	4,868	2,707	2,707	2,707
$1/h_2$, (hr.sq.m.°C)/k cal.	0.00021	0.00037	0.00037	0.00037
Wall resistance, (hr.sq.m.°C)/k cal.	0.00037	0.00037	0.00037	0.00037
Δt at max. heat flux: film °C	25	33	35	28
wall °C	44	33	35	28
Safety factor, °C	15	15	15	15
Peak metal temp., outside wall, °C	511	481	483	461
Peak mid-wall temp., °C	489	465	466	447
Calculation of stresses and lifetime (according to API R.P. 530):				
Stress, lb./sq.in. (*3*)	17,500	9,000	14,000	10,000
Expected lifetime at peak outside temp., hr.	20,000 (*4*)	100,000	100,000	100,000
Calculated with average temp:				
Stress, lb./sq.in. (*3*)	21,000	10,800	16,800	12,000
Expected lifetime at peak mid-wall temp., hr.	40,000	100,000	100,000	100,000

(*1*) Based on 400°C process gas outlet temperature.
(*2*) Based on inside surface.
(*3*) Taking into account the 1/16-in. corrosion allowance (1.6 mm.).
(*4*) At a pressure of 3,400 lb./sq.in.gauge instead of 3,500 lb./sq.in.gauge this would be 30,000 hr.

For the continuous running conditions, i.e. with a flow of 600 LTPD equally distributed between the coils, the peak metal temperature should be 485°C with a temperature drop across the wall of 35°C. These conditions in themselves would not have caused either the rate of nitriding experienced or creep failure of the tube in less than 100,000 hr.

Skin thermocouples subsequently fitted to the tubes in the region 10 ft. from the bottom confirmed this temperature drop across the tube wall. With a gas temperature at outlet of 400°C, the tube skin temperature was measured as 430°C. However, the nitriding of the south coil indicated that the inside wall of the tube had been subjected to 500°C. By calculation, the inside temperature should have been 485-35 or 450°C. A further explanation was therefore sought.

Using the ASME stress rupture curves for 5% Cr ½% Mo, the design of the heater was checked and found suitable for a life of 30,000 hr. Also, again as shown in Table 2, for the operating conditions during the periods of start-up, continuous operation, and under the conditions just before the explosion, the expected lifetime should have been in excess of 100,000 hr.

Based on the estimated inside wall temperature of the north outlet tube, the expected lifetime would also have been more than 100,000 hr. However, based on the estimated inside wall temperature of the south coil outlet tube, the life would have been about 10,000 hr., i.e. close to the actual life of 6,500 hr. to failure. If the lifetime is again estimated using the average conditions of north and south outlet, it is still more than 100,000 hr.

Conclusion

From the nitriding evidence it is clear that the failed tube had been subjected to 500°C at its internal wall for most or all of its life. At this temperature, together with the stress produced by the operating pressure and the wall thickness after fissuring, creep failure could be expected in the 6,500-hr. life of the tube.

What cannot be explained conclusively is the apparent long-term temperature difference of around 70°C between the south and north tubes. This difference can be accounted for by a difference in flow through each of the coils or a difference in heat flux. It should be said, however, that both during operation and in the subsequent inspection, no evidence was found to support these reasons for temperature imbalance. #

MITCALF, J.