UNEXPECTED MECHANISM OF CRUDE OIL HEATER CONVECTION SECTION FAILURES

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Abstract

Over the last decade several unexpected failures of crude furnace convection sections have been reported. Usual integrity threat evaluation of such furnaces predict failure of the radiant section due to high temperature phenomena. A survey of recent horizontal convection bank failures in the global refining industry revealed a number of commonalities which show the impact of changing crude feed stocks, elevated service conditions coupled with a lack of adaptation of existing equipment. The failures of two such convection banks were unexpectedly found to be due to metal dusting. Initial analysis compared with similar such ruptures were misidentified as sulfidic attack at temperatures in the 270-350 C range. Closer assessment of the coils by direct infrared measurement and shielded thermocouples showed trended skins temperatures above 650 C and the high probability of metal dusting. Metallography of the bulged and cracked coils showed that while the A106 Grade B pipe materials were subject to normal overheating characteristics, the actual failure mechanism was interstitial coke formation, or *metal dusting*. The relevance for extended use of petrochemical heaters in general is discussed.

Keywords: Convection furnace, Crude feed stock

1.0 Introduction

Over the past decade numerous examples of unexpected crude distillation furnace upsets have been reported by NACE (TEG 251 committee of the National Association of Corrosion Engineers) involving deposition reactions or coking ultimately leading to rupture. Normal design criteria for crude oil and hydrocarbon condensate charge furnaces in the refining industry provide for service lifetimes between 30-40 years (API 2001) despite the design life afforded by ASME division VIII section 1 of only 100,000 hours. Traditionally failures in direct-fired heaters have involved problems in the radiant section where the heat flux is at a maximum and deterioration mechanisms such as naphthenic acid corrosion (Nugent & Dobis, 1998, Tebbal et al., 2004) or sulfidic attack (American Petroleum Institute API 571 2003) are now well known. Such threats to heater integrity are treated by simple changes in operation, for example elimination of flame impingement or in extraordinary cases by a suitable change in furnace tube alloy. In recent years however several refiners (Takreer-Abu Dhabi, Miro-Germany, Qatar Petroleum etc.) have reported heater ruptures in the *convection banks* of these same furnaces without any prior associated damage reported in the *radiant* section. Considering that the design of these furnaces has not always facilitated the rapid inspection and repair of these defects, the parent companies have incurred considerable lost production. These losses were exacerbated by the time taken to identify the degradation mechanism prior to adopting any repair strategy.

Moreover the main focus of inspection teams has been on the heater radiant sections with the assumption that convection banks degrade at a slower more predictable rate. These more recent failures are indicative that other less *well understood* degradation mechanisms exist in the background which also have the potential to halt production. The present article considers two separate but similar convection section heater failures and draws attention to the associated high temperature degradation aspects of metal dusting and creep which have been somewhat neglected in crude distillation threat analysis.

2.0 Crude furnace failures

Normal crude furnaces require blended oil from the tank farm to be preheated in a series of shell and tube exchangers, washed in a desalter to eliminate geological debris prior to entering the lower temperature convection bank at circa 250 C. In the convection bank the warm crude oil passing through the coils is heated by hot flue gas at 850-900 C coming from the heater radiant section.

Two almost identical crude furnaces located in South Africa and Australia respectively suffered similar failures in their respective shock tubes (the first rows of tubes in the convection sections subject to the hottest flue gas). The failures both occurred in ASTM A106 Grade B seamless carbon steel pipe, and in both cases the crude units were processing sweet crude of low naphthenic acid content (0.3 Total acid number - TAN) and low total sulphur content. In the immediate years preceding the failures both refineries had begun to process lighter crudes, both with occasional introduction of light gas condensates. Despite this light blend in both cases the theoretical vaporization in the convection bank was zero indicating that the tubes were fully liquid filled and hence deemed adequately cool. The principle observations of the failures are described below:

2.1 Visual observations

Initial observation of both convection sections showed clearly that the failure mechanism was temperature related in that the upper-most, hottest, coils were leaking crude oil into the convection bank space and igniting spontaneously despite the low stoichiometric availability of oxygen (normally 2-3%). In both heaters the coils had occasional bulges sometimes accompanied by a surface-breaking defect (figure 1). Both bulge and defect were exclusively located in the 12 o'clock position indicating local overheating and creep on the uppermost side in the direction towards the oncoming flow of hot flue gas stream. In refinery "A" the crown of one bulged tube was perforated by a 3 mm diameter hole through which the crude oil leaked. In refinery "B" the furnace coils experienced a generalized bulging throughout the uppermost shock tubes and in two cases the bulges had cracked releasing crude oil into the flue gas stream where it combusted. In refinery "B" insufficient oxygen was present to enable complete combustion and a mound of half burnt residue covered the respective pipes (figure 2).

Figure 1: Macro-aspect of crack in bulged convection section pipe (Refinery "B")

Figure 2: Burst convection section (shock tube) pipe in 12 o'clock position with burnt residue covering the rupture

2.2 General indications of overheating

In both refineries the locally bulged pipes were examined metallographically and the normal expected ferrite-pearlite microstructure was substantially modified. Whereas in the normal as-received state A 106 Gr.B seamless pipe has a relatively moderate carbon content (table 1) the usual distribution of cementite was absent indicating spheroidizing in some cases or indeed complete graphitization (figure 3). Further evidence for severe overheating was provided by the thick layer of external oxide formed in bother heaters (figure 4). Microhardness testing on both refineries showed the expected reduction to values around 120 HV at the 12 o'clock position while 160 HV was bound at the 6 o'clock position associated with the "normal" microstructure. In some cases in refinery "A" some recrystallisation was visible at the prior austenitic grain boundaries indicating short term temperature above 723 C. These microstructures combined with the swelling and bulged geometry are clear indications of tertiary creep and expected failure within 1000-5000 hours.

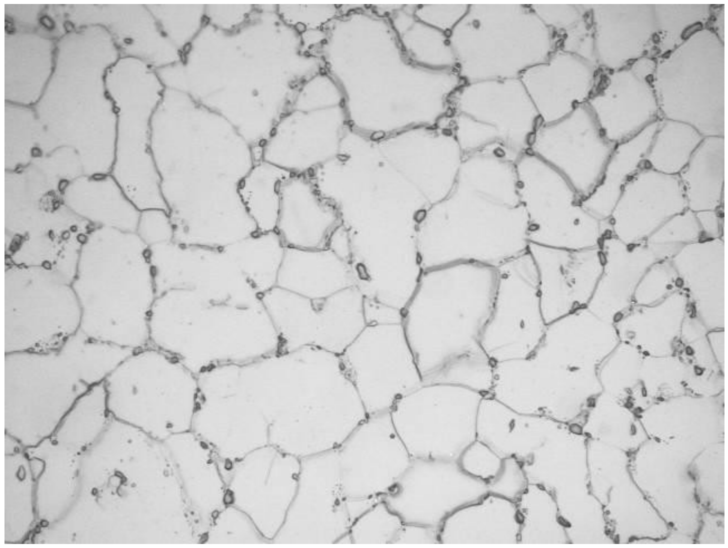

Figure 3: Complete graphitization from normal ferrite-pearlite structure due to local overheating in 12 o'clock position

Figure 4: Thick oxide scale on outside of pipes of both refinery convection sections indicating overheating.

Table 1: Composition of seamless carbon steel pipe compared to standard

Element	Composition of furnace pipe	Composition of ASTM 106 Gr.B
Carbon	0.22	0.3
Manganese	0.88	0.29-1.06
Sulphur	0.007	0.035 max
Phosphorus	0.01	0.035 max
Silicon	0.21	0.1 min
Chromium	0.02	0.04 max
Molybdenum	<0.01	0.15 max
Nickel	0.02	0.4 max
Copper	0.03	0.4 max
Aluminium	0.019	NS
Vanadium	<0.005	0.08 max
Niobium	<0.005	NS
Boron	<0.0005	NS
Titanium	<0.0005	NS
Copper	0.03	0.4 max
Aluminium	0.019	NS
Vanadium	<0.005	0.08 max

Identification of the source of the high temperatures for pipes which are normally considered to be internally cooled by the passage of warm (250 C) crude was associated with the general deposition in both refineries of a coke layer on the inner crown of the pipes. In the case of refinery "A" this coke layer reached 4 mm thick while in refinery "B" the maximum observed was 15 mm thick (figure 5). The refining industry at large has for several years used the general rule that for every 1 mm of coke build up the furnace skin temperature increases by 50 C above that of the outlet temperature. Hence for an expected 300 C crude outlet the refineries "A" and "B" had theoretical skin temperatures of 550 C and 1050 C.

Figure 5: Extensive internal coking in 12 o'clock position (highest heat flux)

Interestingly in both refineries the microstructures of the 6 o'clock position, being cooled by the liquid crude, remained in a normal ferritic-pearlitic structure with no evidence of decomposition. These observations point clearly to the cooling effect of crude existing at the bottom of the horizontal tubes while the 12 o'clock position was subjected to overheating almost certainly due to gas accumulation at the top which is an inefficient heat convector compared with crude oil. In these circumstances it would be expected that while the crown would be subject to high temperature degradation phenomena, the 6 o'clock position steel would remain intact.

2.3 Specific indications of Metal dusting

In addition to the evidence of creep associated with the macro-bulging another mechanism was present in both refineries. While bulging and microstructural decomposition due to high temperatures was in evidence, the internal 12 o'clock position in both heaters was also characterised by graphite deposition at the grain boundaries forcing the grains apart and causing a general wall loss by flaking off of grain layers (figure 6). In the case of refinery "A" this deposition not only extensively penetrated the boundaries but also took the form of internally grown large graphite nodules which appeared to displace the surrounding steel grains and their physical deformation (figure 7). This mechanism has been tentatively identified as *Metal Dusting*, a process resulting from extremely high local temperatures and a high carbon activity (ac) resulting from thermal cracking of available hydrocarbons. Refinery "A" estimate that the process occurred in the region 560-620 C. In refinery "B" skin temperatures were eventually measured by thermocouple to exceed 650 C for long periods of time without the expected damage by more conventional mechanisms (creep).

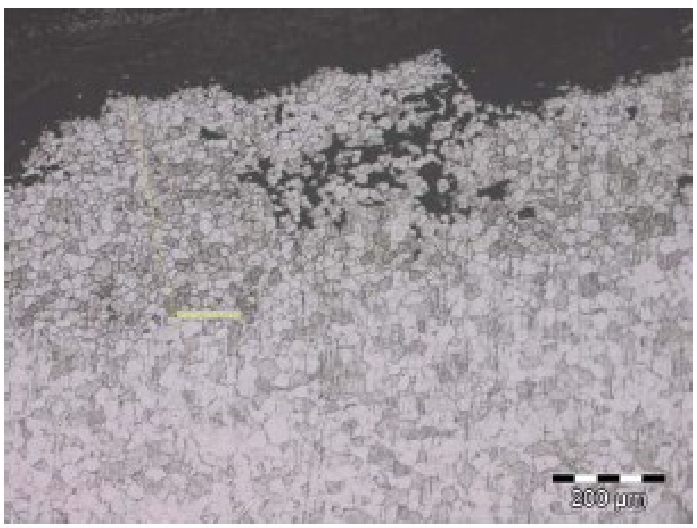

Figure 6: Carburization of internal surface pipes in both refineries

Figure 7: Internal growth of graphite nodules in refinery "A"

2.4 Operational parameters

The principle operational parameters for operations include the flow rate *circa* 3 m/s and *estimated* single phase (no vaporization) hydraulic regime. The skin temperatures were initially estimated in the region of 350-450 C in both refineries however subsequent infra-red and thermocouple measurements indicated this was too low by some 100-150 C. During the same period flue gas temperatures for both refineries increased towards 1000 C in order to compensate for the "normal" loss of thermal transfer afforded by fouling of the preheat train exchangers as the run length progressed. Crude slates for both plants while originating from different parts of the world did tend to lighter API grades where the probability of vaporization would be higher leaving the crown of the pipe without liquid crude direct cooling . In refinery "A" the crude slate included *East Gippsland* (70-80%) / *Bach Ho* while in refinery "B" a mixture of Arab Light / West African crudes such as *Bonny Light* and *Forcados*. In the most recent crude campaigns prior to failure both refineries blended gas condensates such as *Khuff* which rendered the overall crude mix much lighter than usual. In addition to the above parameters some consideration was given for an apparent increase in overall nitrogen content and geological debris (fines) carried over from the desalting operation may have increased the fouling rate in the tubes.

3.0 Discussion

The interruption of crude distillation for unexpected phenomena such as metal dusting has very undesirable consequences. Unplanned shutdowns of essential process units tend to have grave consequences for the associated business and indeed crude distillation units are considered by the industry to be well understood and manageable risks since the integrity threats are quantifiable and contained early. In the present case two almost identical refineries in different parts of the world experienced metal dusting in the same location of the crude furnace without prior knowledge of the mechanism. Both refineries had successfully employed carbon steel in this service for several decades without harm and the respective service interruptions were caused grave upset.

In recent years the tendency for both refineries to choose lighter crude/condensate blends over extended run periods appears to have contributed to excessive skin temperatures and a new degradation mechanism, namely metal dusting, which was not previously taken into account on the threat register.

Metal dusting, experienced in the refining and petrochemical industry (Holland & De Bruijn, 1996, Hermse et al., 2007) and in more general processes (Fabiszewski et al, 2000) has been well described in terms of the effect of the more damaging gases (notably CO and H2). In simple crude distillation however the process temperatures are generally lower than those required for metal dusting 450-800 C (Jones and Baumert, 2001) and this satisfactorily explains the low incidence of such failures in this process. It is however unlikely that either free water or hydrogen are carried over into the crude heater and contribute to the observed metal dusting. Nevertheless metal dusting has been reported in three prior cases of crude distillation heater failure under clear conditions of exposure to excessive temperatures (Sadek, 2001, Jones and Baumert 2001, Lant & Tomkings 2001). Certainly corrosion of carbon steel by crude oils at lower temperatures does not involve metal dusting (Tebbal et al., 2004). Muller-Lorenz and Grabke (2000) demonstrated that the involvement of fine Iron (Fe) particles catalysed fibril coke formation substantially accelerated the process above 540 C. This temperature limit is not considered a "normal" condition for convection banks where the process outlet hardly reaches 325 C. While for carbon and low alloys steels the growth of this surface coke has a flaking effect, in the case of the two refineries' heaters the coke lay-down also occurred substantially between grains in one case forming very large nodules occasionally several millimetres in diameter. Possibly this exemplifies a differentiating characteristic in the absence of free hydrogen from that of the morphology of dusting commonly observed in synfuel process streams.

Some consideration is also required for the origin of CO since hydrogen cannot be present. It is clear that CO does not exist in any quantity in the raw crude and normally would be stripped out with all the other permanent gases in a vessel called the *preflash column* directly upstream of the crude furnace. It is hence reasonable to conclude that the CO originates in the exact same location as it is consumed: the shock tubes of the convection section. In these circumstances local overheating due to vaporization of lighter crude blends (gas space) rapidly followed by thermal cracking in the upper crown section of the tubes appears to be the only viable source of CO.

Finally, the two present refinery cases also indicate a general failure to appreciate hitherto secondary degradation phenomena which were previously masked by other more measureable mechanisms (i.e. creep, napthenic acid corrosion). As the energy market diversifies away from traditional heavy API grades to lighter less well known crudes, and experiment with more commercially attractive condensate blends, it must be expected that "new" degradation mechanisms appear leading to process upsets. Possible solutions may involve recirculating residue fractions to prevent local boiling/ overheating or indeed the more traditional but ultimately counter-productive solution to metal dusting of sulphur injection.

4.0 Conclusions

- Two refineries experienced high temperature metal dusting in crude distillation furnaces
- A significant contributing factor was the spiking of the process stream with lighter crude condensates leading to unexpected vaporisation. The vaporization in turn created insufficient cooling contact between liquid and pipe wall in the upper part of the horizontal coils leading to higher skin temperatures.
- Although the expected maximum metal skin temperature was 325 C, the subsequent internal coke lay down contributed to increasing the temperature to the metal dusting range of 450-800 C.
- The metal dusting process could only have been facilitated by the production of CO from thermal cracking of the crude itself.

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