Vacuum Unit Fired Heater Coking - Avoid Unscheduled Shutdowns

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Several refiners are targeting crude unit run lengths of 6-8 years to maximize profits through increased on-stream factor and lower maintenance costs. Moderate to rapid fired heater coking causes unscheduled shutdowns. Coke forms because the oil in the tubes is no longer thermally stable at the operating conditions. Oil temperature and oil residence time control the rate of coking for a given feedstock. Oil temperature alone is not a good predictor of coke formation rate. Crude oil feedstock stability varies, but it cannot be controlled. However, temperature and oil residence time can be controlled through heater design and operation. Fundamental design principles influence coke formation rates and correct design parameters must be used to build a more reliable heater or understand why an existing heater is coking so it can be fixed. For many refiners, the vacuum heater performance will determine crude unit run-length. Two case histories will highlight some of the problems that cause rapid coking.

Heater Run-length: Operating Severity

Meeting 6-8 year run-length and product yield targets requires very low coking rates. Coke forms an insulating layer inside the tube, which increases the outside tube metal temperature (TMT). Once the maximum TMTs (Figure 1) are reached, the coke must be removed. This requires a shutdown, otherwise, tube life is reduced or tube failure can occur. Minimizing oil residence time and oil film temperature are the keys to meeting run-length.

Minimizing oil residence time at high film temperature is essential to limit coke formation. Very high oil film and bulk temperatures can be maintained at an acceptable coke formation rate if the oil residence time is kept low. Conversely, if residence time is high, then the oil temperature must be kept low. High oil residence time heaters must operate at low outlet temperature and low HVGO product cutpoints. Radiant section residence time varies from less than 10 to over 90 seconds depending on heater design and operation.

Oil film temperature, not the bulk oil temperature, should be maintained as low as possible. The bulk oil temperature measurement may be 790°F, while the peak film temperature is 950°F. Peak, or maximum, oil film temperature occurs on the inside wall of the tube. This temperature is dependent on peak heat flux and oil mass velocity. Peak heat flux occurs on the 15-20% of the tube outside surface area facing the burner flame. Burner fuel combustion rate depends on flame length and flame stability; (Photo 1) therefore, measured peak heat fluxes vary from the heater floor to the radiant section outlet (Figure 2). The lower the peak heat flux, the lower the peak oil film temperature for the same bulk oil temperature. Oil mass velocity depends on feed rate and radiant tube size. Increasing the oil mass velocity will lower the peak film temperature for a fixed heat flux and bulk oil temperature.

Radiant section heat flux rate is defined as the quantity of heat absorbed by a given outside surface area of the tube (Equation #1).

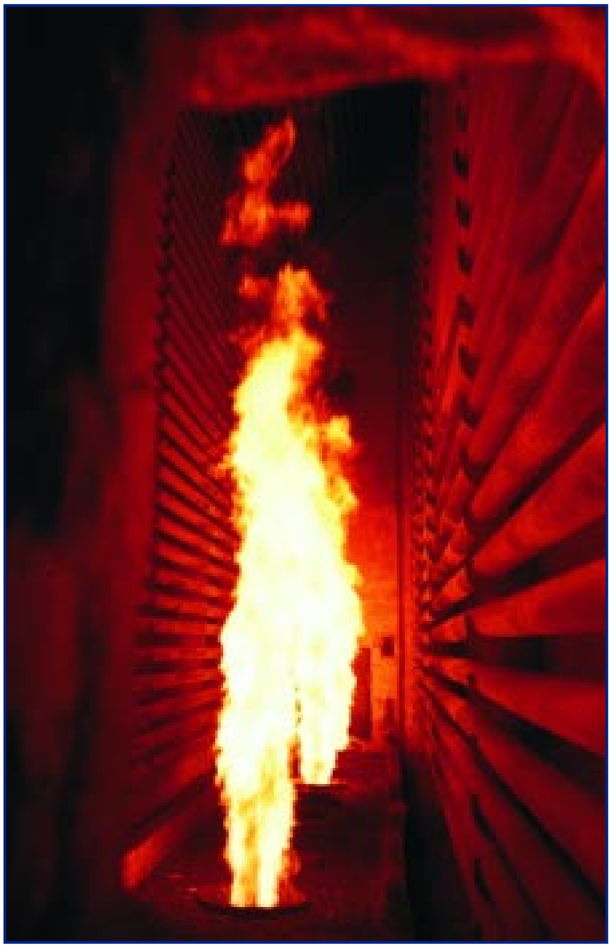

Photo 1 *Burner Flame Stability*

Equation # 1
Heat Flux = Quantity of heat absorbed/Outside tube area
= Btu/hr-ft^2

Mass velocity (flux rate) is the mass of oil flowing through the heater tube cross-sectional area (Equation #2)

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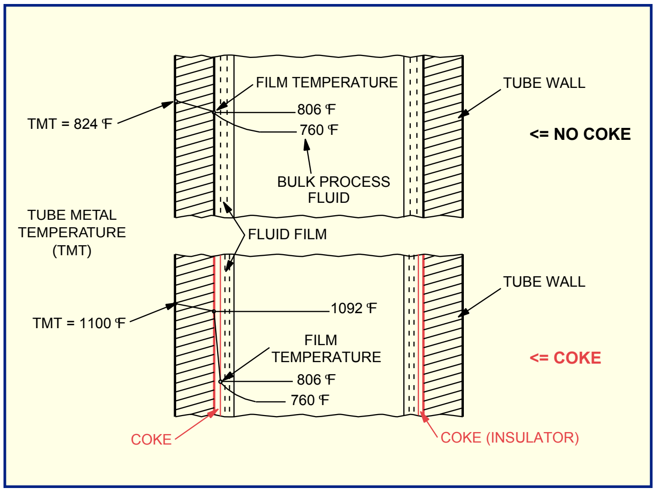

Figure 1 *Tube Metal Temperature (TMT)*

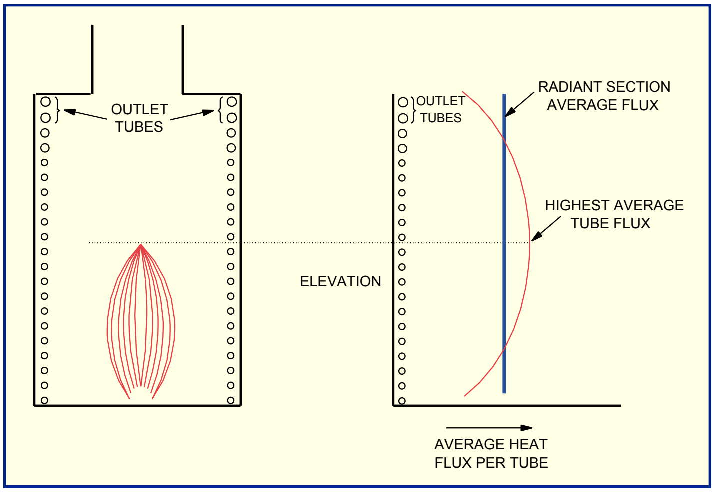

Figure 2 *Heat Flux Variation with Elevation*

Equation # 2

Mass Flux Rate = Mass rate of oil/Inside Cross-sectional area of heater tube
= lb/sec-ft^2

Dry and Wet Vacuum Units

Vacuum units are designed either dry or with steam (wet or damp). Wet or damp systems use steam in the heater coils, while dry units do not inject steam. Dry versus wet design is a controversial issue, with the arguments for dry design focusing on lower capital and operating costs versus wet designs that can achieve higher product yield and better heater reliability. Dry vacuum units are less costly to build and they have lower operating costs. Generally, dry vacuum units operate at relatively low HVGO product yields (lower TBP cutpoints) or they have short heater run-lengths. *A dry vacuum heater can be designed for high HVGO cutpoints on light crude oil. However, it is not possible to achieve long run-length and a high cutpoint when processing heavy crude oil.* Dry heaters must be designed carefully; otherwise, they will coke or they must be operated at low HVGO cutpoint. Product yield and heater reliability are important factors because of their impact on profitability.

Heater Coking

Process side and/or fired side problems can cause high rates of coking. Average radiant section heat flux, total firing rate, and oil outlet temperature are often used to characterize heater severity. While these parameters are useful and can help, they may not be accurate predictors of coking rate.

Monitoring Coking Rate

The rate of coke formation cannot be measured directly; however, it can be inferred. A common method uses infrared scans to determine TMTs, which help identify “hot spots” and areas prone to coking. “Hot spots” indicate high heat flux and/or coke. Once enough coke is deposited to form “hot spots”, it’s often too late to take corrective action and heater firing must be reduced. Oil cracking produces coke and gas. Vacuum ejector system off-gas flow rate is a good measure of the rate of cracking and it should be used to infer coking.

Peak Film Temperature

Peak film temperature should be minimized to achieve long heater run lengths. Film temperature depends on heat flux and oil mass flux. Radiant section inlet tube mass flux rates of 450 lb/sec-ft^2 should be used for design. Lower oil mass velocities will increase the peak film temperature. Fire-side design parameters, including radiant section outside surface area, total heater firing, and convection section duty, impact radiant section heat flux and oil film temperature. Heat flux is also affected by burner type (conventional or low NO_x), number of burners, proper air/fuel mixing, high fuel gas pressure at the burners, air distribution to individual burners, burner and tube layout, and burner interaction. The radiant section outlet tube should be located at the top or bottom of the heater to avoid a high heat flux zone, thereby, reducing film temperature. Outlet tubes exiting the middle of the heater will be exposed to higher temperature flue gas and higher heat flux.

Oil Residence Time

Dry heater oil residence time depends on feed rate and tube size. The smaller the tube sizes for a fixed radiant section outside tube surface area, the lower the oil residence time. Radiant sections use between two to five tube sizes from the inlet to the outlet due to oil vaporization. Oil film temperature increases when the tube size expands because the oil mass velocity decreases. If the tube size is increased before the oil begins to vaporize in a dry heater, both oil residence time and oil film temperature increase. High residence time and high oil film temperature cause coking.

Wet vacuum units inject steam into the radiant section tubes to lower oil residence time. This increases pressure drop through the heater. Steam should be injected upstream of the tube where high coking rates are expected. For instance, if the shock tubes are coking, injecting all the steam downstream at the crossover will not stop the coking. Some heaters are designed with 5” shock tubes and 4” radiant section tubes. The 5” tube oil residence time and peak film temperature are high because mass velocity is low; therefore it cokes. Identifying proper steam injection location requires tube-by-tube analysis using an accurate fired heater model that takes into consideration heat flux variation.

Often, two coil steam injection locations are required to minimize the oil residence time while meeting the overall pressure drop limitations. In one case, the primary injection location used 75% of the total steam in the 4th tube row from the bottom of the convection section. This minimized oil residence time to the secondary injection location while lowering pressure drop. The secondary injection location was the 4th tube back from the outlet tube where coking potential was very high. Two injection locations lower overall residence time in all the coils and reduce residence time in the hottest tubes without the higher pressure drop resulting from a single injection point.

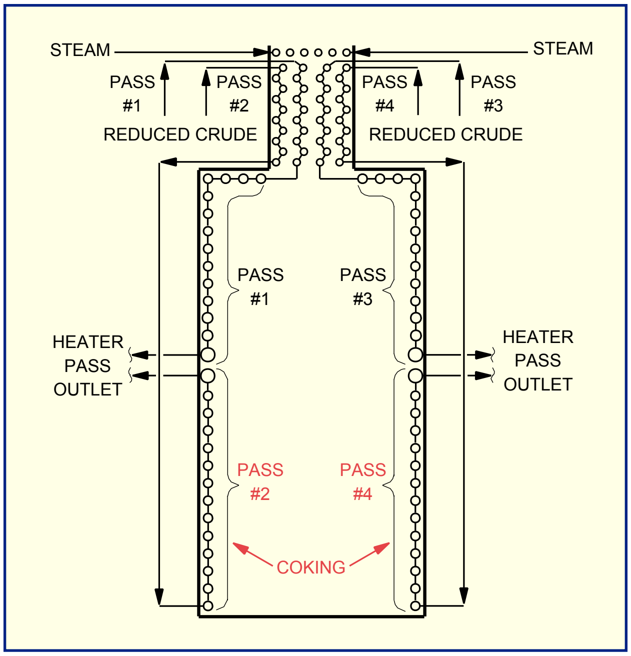

Figure 3 *Heater Tube Layout: Four Passes*

Process-Side Problem: Dry Box Heater

A dry heater had run-lengths of 18 months. The end-fired box heater was designed with 4 tube passes; two up-flow passes located in the bottom and two down-flow passes in the top (Figure 3). Coke was forming in the lower tube heater passes, which caused "hot spots". When TMTs reached 1250°F, the heater was steam/air decoked. All four 10" outlet tubes exited from the center of the radiant section. The heater design caused very high heat flux between the floor to middle elevation of the radiant section. Burner location, type of burner, number of burners, tube layout with respect to burners, and flame length all affected localized heat flux.

With end-fired heaters, the burners will be located below the bottom pass outlet tubes; therefore, the flue gas temperature is higher in the bottom of the radiant section, which causes very high heat flux on the lower passes. The highest heat flux occurs where the burners' flames from either end wall meet. End-fired heaters have extremely high heat flux at this location. Often, floor fired heaters with ultra low NO_x burners will have the highest flux half way up the radiant section due to burner flame length. Vacuum heater outlet tube diameter is often 10 inch; therefore, tubes exiting the middle will be at least 10 inches closer to the flames than the smaller inlet tubes. Flue gas temperature is hottest near or in the burner flame. Therefore, whether end or floor fired, it is poor design practice to have the outlet tube exit in the middle due to high heat flux (Photo 2). High heat flux causes very high peak film temperatures.

Often, radiant section average heat flux is used to infer heater operating severity. However, the overall radiant section average heat flux does not reflect localized conditions. Localized average heat flux may be only 20% higher than the average, or it may be 50-70% higher. Heater designs affect localized heat flux and the rate of coking. Tube layout, burner locations, and burner performance control localized heat flux. In this example, the average radiant section flux rate was 9,000 Btu/hr-ft^2, which is moderate for a dry vacuum heater operating at 775°F transfer line temperature. Coking rates depend on localized heat flux.

Each pass of a properly designed heater will absorb the same amount of heat. Therefore, each pass will have equal flow rates and equal outlet temperatures. Figure 4 shows the relative oil flow rates and the outlet temperatures. The upper two passes' outlet temperatures are 769°F and the lower two passes are approximately 800°F. The upper two heater passes have low oil flow and low outlet temperatures. The lower two passes have high flow and high outlet temperature. The two upper down-flow passes have skin temperatures between 808°F to 950°F, which indicates low heat flux. The lower two up-flow passes have measured skin temperatures ranging from 850 to 1250°F. High heat flux caused localized high peak film temperatures and coking in the lower two heater passes.

The heater performance was rigorously modeled to determine heat flux rates and oil film temperatures on the individual tubes. The heater model used the plant data, including TMTs, to calculate localized heat flux and oil film temperature. The upper and lower passes have average heat flux rates of 5,000 and 13,000 Btu/hr-ft^2, respectively. The maximum average flux rate for one of the heater tubes on the lower passes is over 16,000 Btu/hr-ft^2. The maximum peak heat flux on the lower tubes is over 28,000 btu/hr-ft^2. This is extremely high for a dry vacuum heater. Heater flow pass balancing raises mass flux and helps reduce oil film temperature. The lower passes had mass flux rates of over 500 lb/sec-ft^2, which helps reduce film temperature. The calculated maximum peak film temperatures in the upper and lower passes are 810°F and 875°F, respectively. The heater performance was affected by burner design and tube layout, which resulted in large heat flux imbalances between the passes. These imbalances impacted the rate of coke formation and the heater run-length, even though the average heat flux was acceptable at 9,000 Btu/hr-ft^2. *Radiant section average heat flux is not a good indicator of coking poten-*

Photo 2 *Outlet Tubes Exit Middle of Heater*

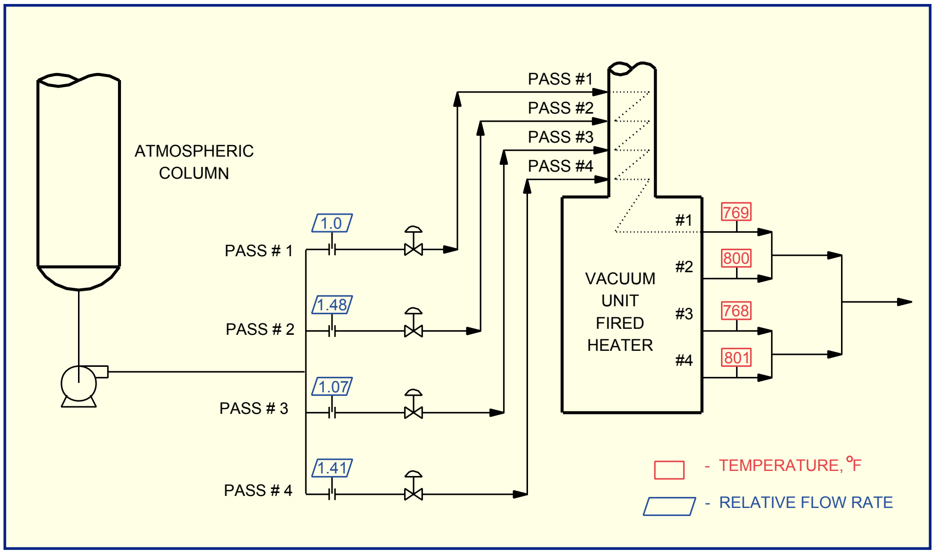

Figure 4 *Pass Heat Flux Variation*

tial on many heaters.

New Heater Design

The most cost-effective solution was to replace the heater. The new heater design used eight passes and small tube sizes to minimize residence time, maximize oil mass flux rate, and minimize peak oil film temperature. A dry design was used because the existing ejector system could not handle steam injection. During the bidding stage, several vendors proposed a four pass design to lower cost. While minimum capital cost is one criterion, vacuum unit product yield and heater reliability impact profitability. Maximizing product yields, up against the coking limit of the heater, optimizes profits.

The heater design will set the HVGO product yield, unit reliability, and heater run-length. Minimizing the rate of coking requires correct tube size, tube layout, and other radiant section design considerations. Oil cracking occurs because the combination of oil residence time and oil film temperature exceeds the oil thermal stability. Dry heaters have high oil residence time when compared to a wet heater. The rate of coke formation is an exponential function of both oil residence time and film temperature. The heater reliability evaluation should ***not*** be based solely on peak oil film temperature. The individual tube oil residence time and peak oil film temperature should be considered when selecting the heater tube design.

Oil residence time, mass flux, and peak film temperature all depend on tube size. Larger tubes have lower oil mass flux, higher oil residence time, and higher oil film temperature. Therefore, larger tubes have a higher tendency to coke.

The oil residence time and peak oil film temperatures of the proposed four pass and eight pass designs were compared. The two heater designs were compared on the basis of equal convection section extended tube surface area and equal radiant section outside tube surface area. The radiant section average flux rate for both designs was approximately 8,500 Btu/hr-ft^2. The vendors stated that the calculated maximum peak oil film temperatures in the outlet tubes are approximately equal for both designs; therefore, the coking tendency in the four and eight pass designs would be identical. Oil residence time was not considered.

Oil residence time in the four and eight pass heater is significantly different. For a fixed radiant section outside tube surface area, the smaller the tube size the lower the oil residence time. The four pass design used 5 inch tubes for the radiant inlet and transitioned to 6, 8 and 10 inch tube sizes. The four pass heater total radiant section oil residence time was 94 seconds. The eight pass design used 3.5 inch inlet tubes and transitioned to 5,6,8, 10, and 12 inch (Figure 5). The smaller tubes minimized residence time as the oil vaporized. The eight pass heater total radiant section residence time was 64 seconds. Tube size was selected based on the oil vaporization profile and multiple tube sizes were used on the individual tubes, thereby, maximizing mass flux, while maintaining mixed phase velocity below sonic velocity.

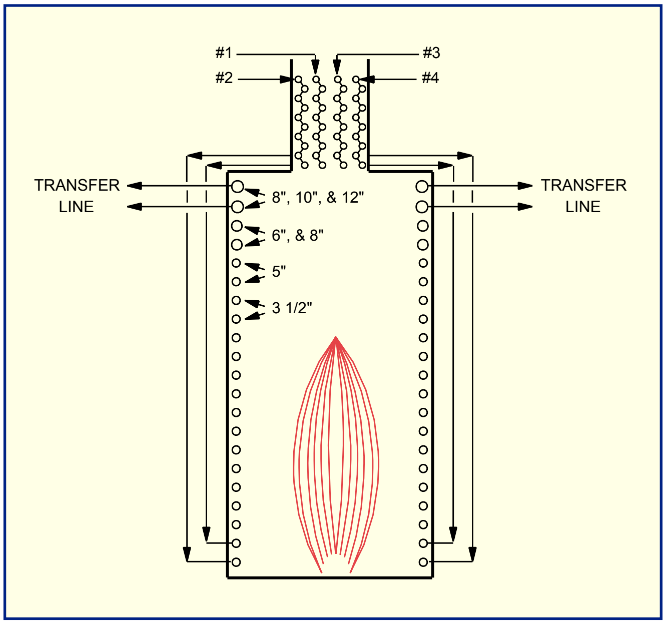

Figure 5 *New Heater Design - One Cell*

Dry heater tube size transition locations must be determined from the oil vaporization profile in the individual heater tubes. An incorrect oil vaporization profile may cause the tube size to be increased sooner than it should. Heater tube layout and transition size locations are important design variables. “Hot spots” often occur several rows from the outlet tubes where tube sizes start to increase.

Increasing tube size raises oil film temperature due to lower oil mass velocity and the oil residence time increases. In a dry heater, coke formation often occurs where the heater tube sizes are increased, not the outlet tubes. The outlet tubes operate at very high velocity; therefore, coke may be formed but it does not lay down in the tube. With the eight pass design, the transition location residence times are much lower than the transition location residence times in the 4 pass design. Also, the last several 3.5” tubes (5” tubes for four pass design) and the first tube transitions have higher heat flux because they are located closer to the burners, which further increases peak oil film temperature. The transition tubes operate at low enough velocity for coke to lay down if it is formed.

Comparing oil residence time in the four and eight pass designs when the peak oil film temperature exceeds 850°F is important. The eight and four pass heater designs have residence times of 6.7 and 21.7 seconds, respectively, when oil is above 850°F. Also, the eight pass design has 15-20°F lower peak film

Photo 3 *Vertical Cylindrical Heater*

temperatures throughout the 3.5” tubes, compared to the four pass design with 5” tubes, due to higher oil mass flux rates. The eight pass design has lower peak film temperature and lower total oil residence time. Therefore, the eight pass heater will be more reliable. The eight pass heater was installed and is operating with higher HVGO product yields than the design.

Fire-Side Problem: Vertical Cylindrical Heater

Fire-side problems cause heater coking. These include poor burner operation, incorrect burner layout, burner design errors, tramp air leakage, and several other factors. In this case, the heater coked due to poor flame stability causing flame impingement on the tubes. Some TMTs were over 1300°F after a thorough decoking. The heater is a high height-to-width (L/D) ratio (greater than 3.0) vertical cylindrical heater. Run-lengths were 12-18 months between decokings. Coil steam injection was used to increase product yields and to control oil residence time in the radiant section at 12-15 seconds. Low residence time heaters can operate at average heat flux rates higher than 12,000 Btu/hr-ft^2 when fire-side performance allows good heat flux distribution.

High L/D heaters (Photo 3) have a small floor diameter and long vertical tubes. They have higher heat flux variation due the distance from the floor burners to the radiant section outlet. The API 560 heater specification limits L/D for vertical and box heaters to 3.0 and 2.7, respectively. All high L/D heaters using ultra low NO$_x$ burners require good flame stability, otherwise flame impingement occurs.

The low NO$_x$ burner flames and hot rising flue gas entrain a large quantity of cooler recirculated flue gas at the floor of the heater. The burners entrain due to high gas velocity exiting the burner throat and the buoyancy of the hot gas in the burner flame. Ultra-low NO$_x$ burners have much longer flames than conventional burners; therefore, it is easier to disrupt them. Ultra-low NO$_x$ burners use recirculated flue gas, in addition to the fuel/air mixture, to create the longer colder flame. Hence, the flue gas recirculation must be controlled and stable, whereas, shorter flame length conventional burners are less affected by poor flue gas flow patterns. Many revamps from conventional to ultra-low NO$_x$ burners have had problems associated with flame stability and flame impingement. Flame temperature is very hot; when flames hit the tubes they cause very high localized heat flux and extremely high tube metal temperatures. “Hot spots” occurred immediately upon commissioning the unit before coke had time to accumulate. High peak oil film temperatures eventually will produce coke. When operating with extremely high heat flux, a thin layer of coke will quickly raise the TMTs above maximum.

Field data, field observations, and computer modeling were used to identify the problem. Field observations showed very poor flame stability. Burner flame shape will be tightly defined when operating properly. The hot flue gas from the burner should flow upward through the center of the heater without the flames approaching the tubes. However, poor flame stability caused fuel/air combustion in front and behind the heater tubes just above the floor. Measured localized heat flux rates were over 40,000 Btu/hr-ft^2 about 15 feet off the heater floor (Figure 6). Combustion around the tubes caused extremely high heat flux, high oil film temperature, and high rate of coke formation. Stable flame pattern is important in any heater, but it is essential with a high L/D heater using ultra low NO$_x$ burners.

Normal radiant section flue gas flow patterns have hot gas flowing upward above the burners and cold flue gas flowing downward behind and along the tubes. Radiant section tube layout, radiant section-to-convection section transition, burner design, burner circle layout, and several other factors can impact flue gas flow patterns.

Burner inspection through the view ports showed cold flue gas flowing down the middle of the heater, while hot flue gas flowed upward along and behind the heater tubes. Field tests using baking soda also showed flame disruption approximately six feet above the burner floor. The burner flame was being flat-

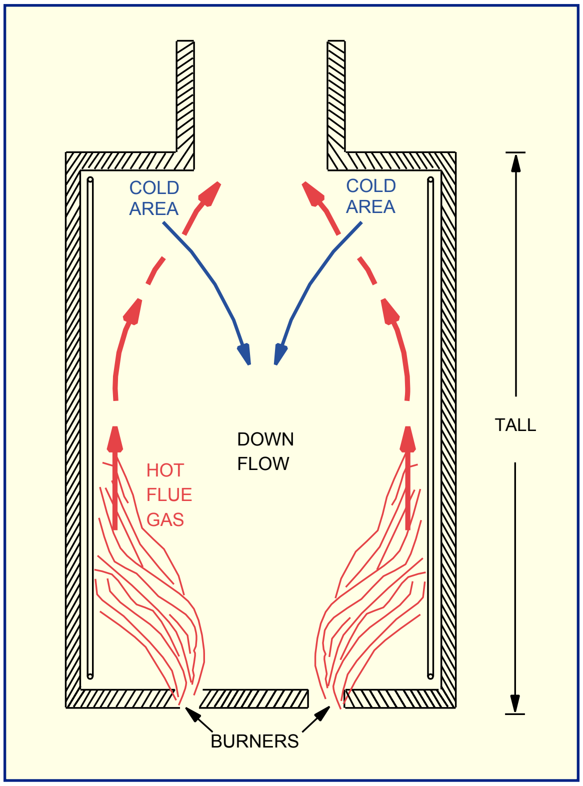

Figure 6 *Poor Flame Stability*

tened by down-flowing flue gas in the center of the burner circle. This pushed the burner flame outward toward the tubes. Combustion was occurring in front of and behind the heater tubes. Proper air/fuel mixing was not taking place; therefore, combustion was delayed. Delayed combustion created the donut shaped "fireball" around and in front of the tubes.

Radiant section heat-flux variations always occur due to burner heat release profiles. However, large heat flux variability cannot be tolerated at high average heat flux. Abnormal combustion caused the lower half of the heater to be extremely hot, while the upper half was very cold. TMTs varied from 800°F in the top of the heater to as high as 1300°F in the bottom of the heater. Correcting the flue gas flow patterns was the key to fixing this problem.

Poor flue gas flow patterns were caused by several factors. The heater was designed with a large diameter burner circle. This permitted the cold flue gas to down-flow in the center of the burner circle. This pushed the flames out toward the tubes and caused flame impingement. Several other design errors contributed to the problem. The radiant section tubes were bowed towards the refractory preventing a flow lane for cold flue gas to down-flow behind and around the tubes. The heater floor had a solid Reed Wall between the tubes and the burner circle. This prevented stable flow of recirculated flue gas into the ultra-low NO_X burners. The convection section had a narrow, rectangular inlet on the top of the radiant section. This created cold areas in the top of the radiant section that contributed to flue gas flowing down the center of the heater. The flue gas outlet ducts to the induced draft fan also caused channeling through the convection section, which disrupted flue gas flow. All these factors contributed to the observed flue gas patterns and poor flame stability.

Heater Revamp

Once the heater was revamped and good flame stability was established, the TMTs dropped by 400°F on some of the tubes and coking was eliminated. The radiant section had to be retubed to provide a smooth flow lane for cold flue gas behind the tubes. The burner circle diameter was reduced to allow the hot gas core to flow up the center of the circular heater (Figure 7). A checkered Reed Wall was installed to allow recirculated flue gas to flow smoothly to the ultra-low NO_X burners. Radiant to convection section ducting was added to permit uniform flow of hot flue gas upward and eliminate cold areas. The convection section was replaced to increase convection section duty and reduce radiant section duty. This permitted flue gas ducting changes to reduce channeling. Proper flue gas flow patterns have greatly improved flame stability, which lowered heat flux variations, reduced oil peak film temperature, reduced the TMTs to 850-950°F, and thus eliminated coking.

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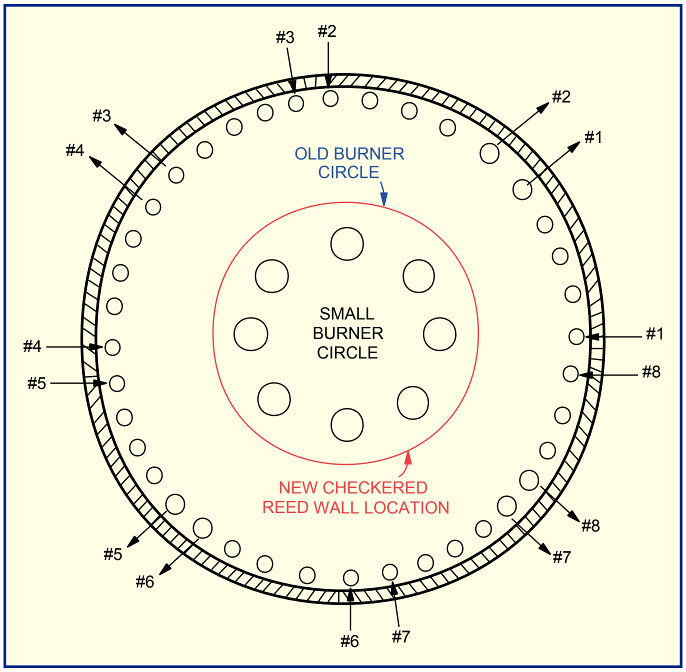

Figure 7 *Burner Circle Modification*

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