Ethylene is currently produced more than any other petrochemical in
the world. Current ethylene production occurs mainly through the
thermal cracking of various hydrocarbon streams in the presence
of steam. The process of pyrolysis, or steam cracking, is shown in
Figure 1. The heat transfer in the radiant section of the thermal cracking
furnace is critical. The furnace run length, tube life and efficiency are
dependent upon the distribution of the heat transfer produced by the
burners. Therefore, good burner performance is critical to ensure
proper heat transfer occurs throughout the radiant section.

Cracking furnaces present both burner design and operating
challenges in comparison to typical process heaters. These
challenges are attributed to higher radiant box temperatures
as well as the critical need to produce a defined heat flux
circulation throughout the furnace’s radiant section. Over the
past five years, the primary driving force for developing ‘next
generation’ burner technology was to produce lower NOx
emissions. In recent years, various burner suppliers have
explored unproven combustion technology in an attempt
to reduce NOx emissions in cracking furnaces. Unproven
technology can be unreliable and sacrifice safety, heat flux,
flame geometry, and overall efficiency of the unit.

**Burner technology overview**

Historically, most thermal cracking furnaces were fired with
premix radiant wall burners. Premix burners are well known
for their short, compact flame, which can produce uniform
heat flux throughout the radiant section as shown in Figure 2.
The low NOx premix burner incorporates staged fuel
combustion and combustion product recirculation to reduce
the level of NOx generated. Figure 3 provides illustrations of
the venturi inlet, a typical burner assembly and the burner
tip detail. The gas spud with the primary fuel orifices is
shown at the inlet of the venturi. A portion of the fuel, called
primary fuel, discharges into the inlet of the venturi inducing the primary air. If the quantity of primary air is insufficient for combustion, additional air is drawn into the furnace through the secondary air door shown in the second illustration in Figure 3. Although premix burners were the most common design fired in cracking furnaces for many years, there can be significant cost issues associated with the use of these burners. Installation costs can be high due to the large number of burners that must be installed. In addition, premix burners are designed to mix the air and fuel prior to combustion, increasing the possibility of thermal fouling of the burner and resulting in increased maintenance to ensure proper operation of the burners. Typical cracking furnace installations may have pipe scale or green oil present in the fuel gas system which can commonly plug the fuel gas ports causing the burner flames to ‘flashback’ or burn within the burner assembly instead of the furnace. Premix wall fired burner technology is limited in its ability to lower NOx emissions. The primary mechanism for reducing NOx emissions from premix burner designs is to decrease the amount of primary fuel gas directed to the primary combustion zone and increase the amount of secondary fuel gas. Responding to increasingly stringent environmental regulations for NOx reduction, some burner manufacturers have supplied premix radiant wall burner designs with a very large volume of the fuel gas used in the secondary stage combustion zone, which is intended to provide reduced NOx emissions. Caution should be displayed as too much staging of the fuel gas (i.e. in excess of 35 - 40%) can result in flame impingement on the tubes, poor heat flux profile throughout the radiant section and overall lost efficiency in the radiant section.

Due to the nature of the operational problems that can occur with premix burners, as well as the limited NOx reduction that can be achieved, the industry is moving towards 100% floor fired burners (hearth burners) and floor fired burners in combination with side wall burners (balcony burners). See Figure 4 for the various cracking furnace burner arrangements. To maintain a similar wall temperature profile when hearth burners are used, a flat flame burner has been provided instead of the premix radiant wall burners.

In 2004, the Calidus Ultra Blue (CUBL) next generation burner technology was developed. This technology was developed to meet the needs throughout the cracking furnace industry to achieve next generation NOx levels with flat flame technology. The rectangular discharge opening of the burner tile that sits against the furnace wall provides the ‘flat’ flame shape. A small portion of the fuel is mixed with the air stream and is burned with high excess air to cool the flame prior to exiting the tile. The remainder of the fuel is injected nearly vertically from a set of fuel gas risers located near the burner tile face which is parallel to the furnace wall. The high velocity fuel entrains and mixes with combustion products before the fuel begins burning near the top of the burner tile. The delayed mixing of the combined fuel/combustion product with the air permits more heat transfer to occur during the combustion process, which provides a lower flame temperature. The entrained combustion product mass provides an additional heat sink which lowers the flame temperature. The resulting low temperature combustion and delayed mixing of the secondary fuel with the burner air stream results in significantly lower NOx levels when compared to traditional burner designs.

Some burner vendors are experimenting with delaying the mixing to the point that there is no longer a well-defined flame in an effort to both reduce NOx emissions and produce more uniform heat flux to the pyrolysis tubes. This technology has been labelled ‘flameless’ combustion. In theory, because this type of combustion decreases the maximum flame temperature, it could minimise the occurrence of high flux regions and resulting hot spots on the tube surface even though combustion may be occurring on the surface of the process tubes. The difficulty with this approach is the inability, because of flow currents in the furnace, to control the location where combustion occurs resulting in reduced efficiency and possible safety issues at lower furnace operating temperatures.
is a photograph of an installation of CUBL technology in operation.

The CUBL technology utilises the design principles of traditional nozzle mix burner technology that has been used in cracking furnaces in excess of 30 years. This technology is being operated in excess of 10 cracking furnaces throughout the world and has proven to be a viable solution for meeting the operating needs of the ethylene producers.

When selecting burner technology for cracking furnace installations, there are four criteria that must be evaluated to ensure the cracking furnace operational needs are met. The CUBL technology is specifically designed to achieve these four dominant criteria that are critical for cracking furnace operations. These criteria are: safety, reliable heat flux distribution in the radiant section, achieving NOx emissions of less than 80 mg/Nm³ and a reduction in the potential for flame rollover. Flame rollover is the most common form of poor quality flames in this service.

Safety

With increasingly stringent environmental regulations, the industry is exploring "combustion solutions" that are exceeding the traditional limits of safety. In order to be technically acceptable, burner performance should be safe and reliable over the full operating range of the cracking furnace. During startup of the furnace, the burners are subjected to a relatively low temperature environment where the radiant section is well below the auto-ignition temperature of the burner fuel gas. For maximum safety, the burner must be stable over the full operating range, regardless of the furnace radiant section temperature. The burner should be stable without the need of pilots and/or special startup lances. Startup lances are special gas guns that are installed in the burner and operated only at startup and other low firing conditions to ensure the burner does not extinguish. Burner designs requiring startup lances increase the operational complexity of the burners by adding an additional step to the startup procedure. This additional step results in an increased probability for operator error that can place personnel and equipment at unnecessary risk.

In addition to burner instability that can occur during startup conditions, instability can occur while firing the burner at low fire conditions during the furnace de coke process. Over a period of operation, cracking furnaces form coke inside of the process tubes that restrict the process flow. As routine operation, the furnace will cycle through a process known as decocking. The decocking process requires a much lower operating temperature in the radiant section in comparison to
normal operation of the furnace. To achieve the low radiant box temperature, burners must be turned off to reduce the fire box temperature or the burners must be designed to operate at a reduced firing rate which is often referred to as ‘tumdown’. Tumdown is the minimum firing rate the burner can achieve while producing a stable flame. If a burner is designed to fire a maximum heat release of 10 million Btu/hr and can achieve a stable flame down to 2 million Btu/hr, the burners tumdown rating is 5:1 (tumdown = maximum heat release/minimum heat release). In recent years, the trend in the industry is to operate burners with the ability to achieve high tumdown firing rates to avoid the need to turn off burners. Many burner designs have limited tumdown capabilities and as a result the burners can experience instability because of the low fire box temperatures during decocking. As a result, operators are required to turn off burners during the decocking cycle. Typical tumdown for next generation burners is 5:1. The CUBL technology can achieve safe and reliable operation in excess of 10:1 tumdown. The ability of a burner to achieve a tumdown in excess of 10:1 ensures that the burner is capable of maintaining a stable flame beyond the minimum fuel gas pressure limits the plant’s fuel gas system is capable of operating within. A high tumdown ratio provides the plant operations personnel more flexibility when operating the unit as well as provides increased safety in case of operator error.

Radiant section heat flux
The heat flux in a thermal cracking furnace is important. All coils cracking a given feedstock should be maintained at the same temperature, and the temperature of individual coils should increase gradually from inlet to outlet. The burner firing pattern contributes to the coil temperature distribution and affects heater run time between decocking operations. Burners must be designed and adjusted to give a radiant section temperature profile so the tube metal temperature of the radiant coils will increase smoothly and gradually from the inlet to the outlet. Non-uniform heating of the coils leads to hot spots on the tubes, excessive coke formation, high fuel consumption, and high maintenance costs.

Thermal cracking furnace designers have developed ‘desired’ heat flux profiles for the radiant section of the furnaces as shown in Figure 6. The original profiles were developed from data collected in a specific test furnace. Field experience indicated that if these profiles could be achieved in the specific test furnace then satisfactory operation would occur in the actual thermal cracking furnace.

The heat flux at any elevation in the furnace is a function of the gas/flame temperature and radiating surface temperatures. Achieving the desired flux profile was not difficult when the furnaces operated with 100% radiant wall burners. The trend of using fewer burners adds complexity to designing burners that provide the desired flux profile while meeting stack emission levels. Usually, the elimination of wall burners is accomplished by removing several lower rows of burners and then installing hearth burners. The hearth burners have a much higher heat release and are responsible for ‘uniform’ heating of the heater wall from the floor to the level of the top row of radiant wall burners that have been removed. This requires the hearth burners to have very specific flame dimensions in order to achieve satisfactory operations.

Nitrogen oxide emissions
The relatively high combustion temperatures in cracking furnaces lead to the formation of thermal NOx. Older cracking furnaces utilising older burner technology equipment typically produce NOx levels of 100 mg/Nm³ to over 200 mg/Nm³ and potentially even higher. Figure 7 provides a correlation of NOx produced as a function of bridge wall temperature.

Figure 5. Hearth and balcony burners: Top, floor mounted burner. Middle, wall mounted burner. Bottom, wall mounted CUBL burners firing.
Reduced flame temperature and a reduced partial pressure of oxygen available to the flame will reduce the quantity of thermal NOx that is formed in the combustion process. Both of these objectives can be achieved through the use of staged combustion. Staged combustion involves delaying the mixing of the fuel and air and promotes the mixing of combustion products with the fuel/air mixture to provide a reduction in flame temperature and a reduction in the partial pressure of oxygen. The CUBL technology utilises traditional, proven, staged combustion technology while achieving NOx emissions below 80 mg/Nm³.

**Flame rollover**

The combustion product flow patterns in the radiant section of the furnace have a significant impact on the burner performance. The desired flow pattern is illustrated by the photograph in Figure 8. Upward flow occurs along the hot firing wall while there is downward flow (recirculation) adjacent to the lower temperature tubes. With this flow pattern, the burner flames tend to travel vertically up the hot wall, eliminating any contact with the process tubes that could create hot spots and internal tube coking that severely limit runtimes.

The effort to reduce the physical size of the thermal cracking furnace has reduced the furnace volume and increased the heat density or the quantity of heat input per unit volume of the radiant section. The horizontal cross sectional area of the furnace is reduced which promotes the tendency for the hot combustion products that would normally travel upward along the wall to expand out into the furnace causing the downward flow of combustion products along the process tubes to begin lower in the furnace. A number that is sometimes used to quantify the tendency for premature recirculation of the combustion products is the total burner heat liberation divided by the cross sectional area between the furnace wall and the process tubes.

When the length of the furnace is reduced and the furnace capacity is maintained the distance between the burners must be reduced or fewer burners must be used. If the space between the burners is reduced flame overlap (flame interference) can occur. The overlapping of the flames increases the NOx emissions, increases the flame length, and causes the flame between the burners to protrude further into the furnace space between the wall and tubes. If the furnace has a high ratio of heat liberation to cross sectional flow area, which is usually the case when the furnace length is decreased, the ‘premature’ recirculation pattern in the furnace can pull or deflect the ends of the flame toward the process tubes. Any situation in which the flames are deflected toward the process tubes can create hotspots and premature internal coking of the tubes.

Computational fluid dynamics (CFD) has proven to be a useful tool for studying combustion product flow patterns in all types of fired heaters/furnaces. The premature downward circulation of combustion products is illustrated by the results of a recent CFD study for a cracking furnace shown in Figure 8. When this flow pattern occurs, the upper ends of the flames from the hearth burners can be ‘pulled’ horizontally and contact the process tubes. This is sometimes called flame ‘rollover’. Traditional designs utilise blockage in the throat to create a ‘bluff body’, which provides the mechanism for stabilising the flame. These designs require as much as a 50% blockage in the burner throat which, in turn, requires the burner throat to increase in area by as much as 50% to offset the blockage. The larger throat pushes the flame further into the furnace away from the wall, thus increasing the opportunity for the flame to impinge on the process tubes. Calidris’ CUBL technology utilises a stabilisation mechanism that does not require 50% blockage.
in the throat, which greatly reduces the burner size. The reduced burner size allows the burner to fire flat against the wall and avoid being affected by the downward flow of combustion products at the process tube boundary. Through the use of carbon monoxide probing, the CUBL flame has proven to be approximately 40% thinner than previous designs. Figure 9 illustrates the tile projection of traditional burner designs in comparison to the CUBL technology.

Conclusion
While emissions regulations and efforts to reduce capital and maintenance costs for thermal cracking furnaces have introduced new burner design complexities, acceptable burners are available that can meet both the thermal cracking furnace heat transfer requirements and stringent emissions requirements. If furnace designers and burner designers work together using tools such as factory tests in an acceptable test furnace environment and CFD modeling to evaluate the complete burner/furnace system, further improvements are likely to develop. Figure 10 shows a typical test furnace used for verifying burner performance. In addition to normal criteria for acceptable burner performance, items specific to thermal cracking furnaces that should be evaluated are safety, radiant heat flux profile, thermal NOx performance and burner flame geometry.

Figure 10. Calidus test furnace.