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DUPLEX™ Technology Evaluation and Cost Comparison to SCR

for

ClearSign

ClearSign Combustion Corporation

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Introduction

ClearSign Combustion Corporation has developed a new technology for reducing NOx emissions from fired heaters and boilers, called DUPLEX™ Technology. This new combustion technology has the potential for widespread use by refiners and other users as environmental agencies continue to decrease allowable NOx emissions from combustion sources. The technology has been installed in once-through-steam-generators, process heaters, and flares in the western US and has demonstrated low NOx emissions in stable, safe operation with firing rates ranging from 6 to 60 MMBTU/HR.

Norton Engineering Consultants (NEC) was hired by ClearSign to independently review the DUPLEX technology, discuss the operation with early adopters, and to compare the performance, safety, reliability, and operability with another proven NOx reduction technology, Selective Catalytic Reduction (SCR). As part of this comparison, NEC has generated cost estimates for DUPLEX technology and SCR installations for two "typical" refinery process heaters.

DUPLEX Process Overview

DUPLEX technology involves the installation of a porous ceramic surface on which combustion is sustained, downstream of standard gas burners in a fired heater or boiler. The combustion occurs inside the pores of this tile, resulting in substantially reduced flame height and improved radiation. With the premixing of air, fuel, and entrained flue gas prior to combustion at the DUPLEX surface, occurs in the tile, the combustion occurs at lower temperatures and with reduced reaction time compared to traditional burners, thereby reducing thermal NOx formation.

As the combustion is contained within the porous ceramic surface, operation of a heater utilizing DUPLEX technology is expected to minimize tube damage due to flame impingement and to increase overall heater efficiency due to the improved radiation properties of the DUPLEX surface when compared to traditional burner flames.

The operation of the DUPLEX system requires that the surface be first heated, most typically with the existing burner. Once the surface has reached operating temperature, the flame is transitioned from the standard burner to the DUPLEX surface, usually by switching fuel from the existing burner nozzles to one or more specially designed DUPLEX nozzles. The DUPLEX nozzle is designed to introduce fuel in such a way that a flame cannot form upstream of the DUPLEX surface. Fuel from the DUPLEX nozzle entrains air from the burner as well as some flue gas, and then ignites on the hot DUPLEX surface, where combustion is sustained.

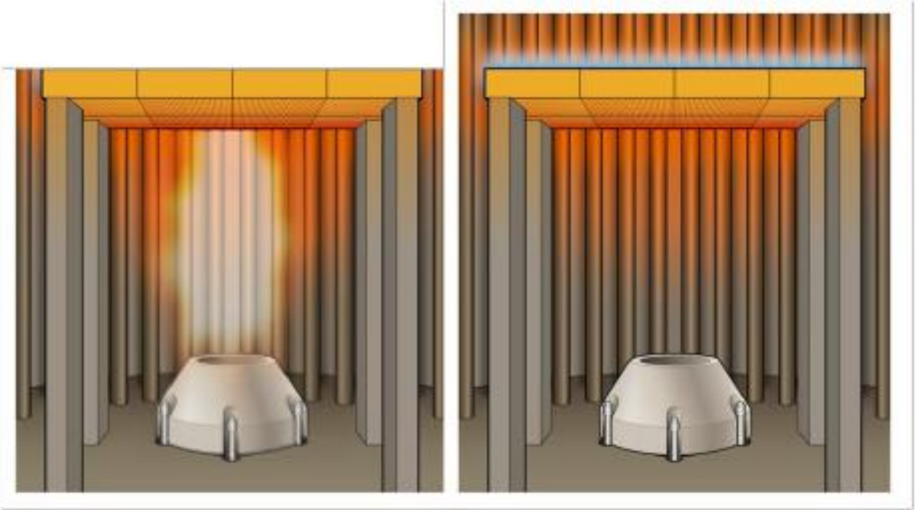

Figure 1: Conventional burner heating up DUPLEX tile, and flame transitioned from burner to DUPLEX surface

Control of the DUPLEX system is substantially similar to control of a standard burner, with firing rate controlled by changing the fuel gas rate to the heater. Some additional monitoring and enhancements to the heater safety instrumented system (SIS) are recommended in order to ensure safe operation of the system. The safety issues are discussed later in this paper.

Field installations of the DUPLEX system have demonstrated safe, reliable performance with NOx levels below 5 ppm at up to 62.5 MMBTU/HR. Initial operation of DUPLEX technology at a small refinery heater demonstrated NOx emissions between 2.5 ppm and 4.5 ppm, averaging 3.7 ppm.

The DUPLEX system can usually be installed during a short duration heater shutdown (less than one week). The main structural frame for the DUPLEX surface can be supported by the heater shell or floor (depending on heater configuration) and the DUPLEX support structure is pre-fabricated to allow for “snap together” construction inside the heater. The DUPLEX surface, which is constructed of modular tiles, rests directly on the support structure without additional hardware. Additional elements for the system, including UV scanners, valves, and DUPLEX nozzle modifications to the existing burner can also be installed during the shutdown window.

The DUPLEX nozzle tips have holes similar in size to typical refinery burners (and larger than the holes in ULNB), and do not require additional filtration or fuel gas coalescing upstream of the heater (as is typically required for ULNB to prevent plugging or coking of the fuel tips). The DUPLEX tile pores are larger than the orifices of typical refinery burners and similar in size to the pores in SCR catalyst modules. With these pore sizes, plugging of the DUPLEX pores is not expected for combustion of typical refinery fuel gas.

Although there is limited operating experience and history with the DUPLEX technology, the system is expected to have high reliability and low ongoing maintenance costs. Damage to some of the tiles from falling refractory/insulation or thermal shock (from wet tiles or cold air from observation doors) is possible, but in most cases this is not expected to cause problems that would require a shutdown for repair. Only a significant tile/support structure failure which could impact the DUPLEX nozzle tips would require an immediate shutdown for repair. Experience with DUPLEX technology in operating heaters and boilers has shown the technology to be reliable, demonstrating no loss of NOx reduction effectiveness even with cracked and damaged tiles (see Figure 2 below). Inspection and replacement of damaged DUPLEX tiles and support system can be performed during regular heater shutdowns associated with unit turnarounds or other maintenance activities.

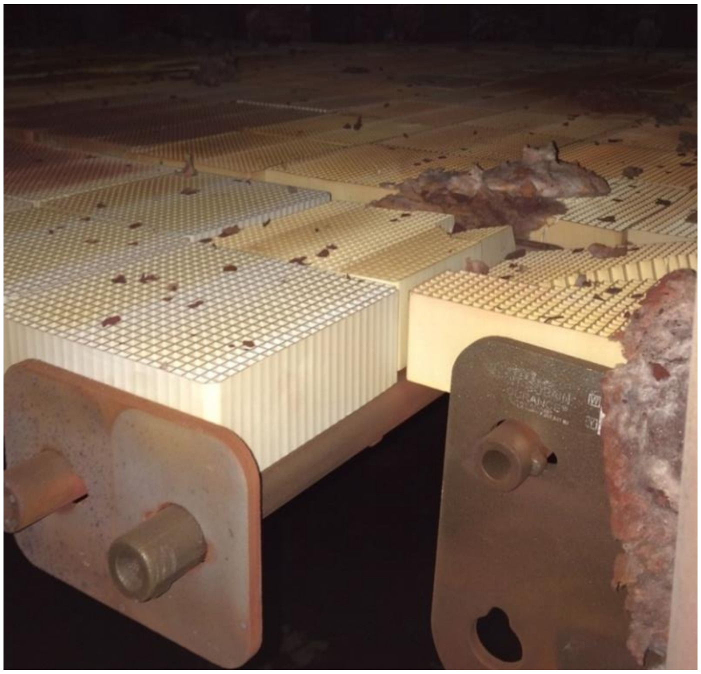

Figure 2: DUPLEX tile in process heater with minor damage to tile

Selective Catalytic Reduction (SCR) Process Overview

Selective Catalytic Reduction (SCR) has been employed as a NOx reduction technique from combustion sources since the 1970s, and SCR systems and catalyst are available from numerous vendors. With this technology, NOx formed during the combustion process is reacted over a catalyst bed with ammonia to form nitrogen and water. The catalyst is typically a porous titanium dioxide carrier material with vanadium, molybdenum, and/or tungsten oxides dispersed throughout. The ammonia (anhydrous or aqueous) is injected upstream of the SCR catalyst bed so that it is well mixed with the flue gas prior to contacting the catalyst.

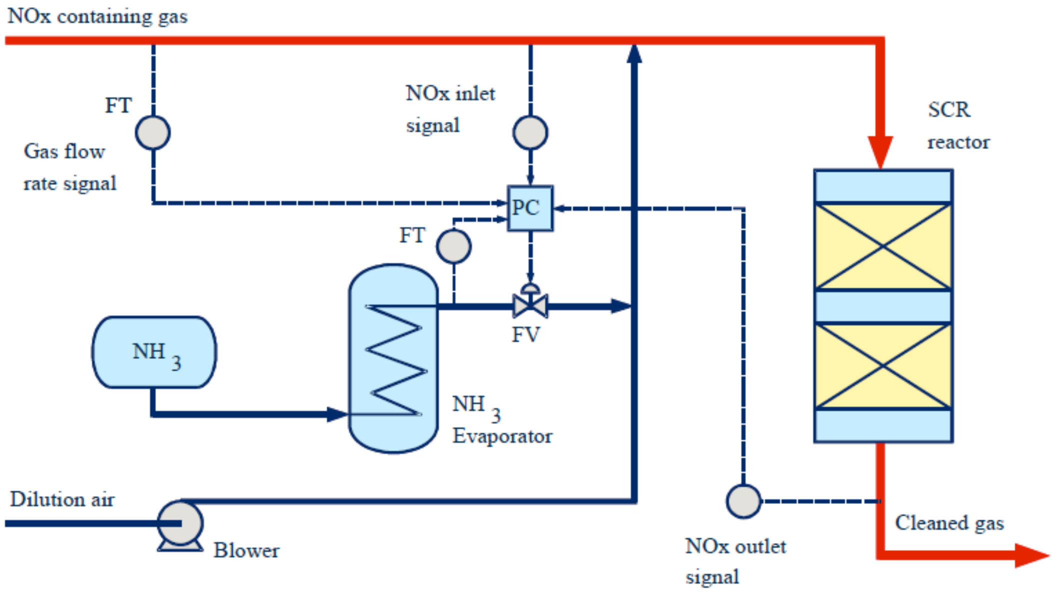

Figure 3: SCR Process Flow Diagram

SCR is most effective when performed in the temperature range of 450°F-800°F, although this temperature window can be extended with increased residence time in the catalyst system. Key to the effectiveness of SCR performance is the distribution of the vaporized ammonia stream into the flue gas stream upstream of the catalyst. If ammonia distribution with flue gas or operating temperature is not optimal, then NOx performance will suffer and increased NH_3 “slip” in the flue gas leaving the SCR will be seen. Even with good NH_3 distribution and catalyst performance, a small amount of NH3 “slip” is expected (up to 5 ppm is typical) from the SCR system. If NH_3 distribution or catalyst performance is non-optimal, then NH_3 “slip” may increase as NH_3 injection is increased to try and reduce NOx emissions – installation of a NH_3 destruction catalyst bed may be installed downstream of the SCR catalyst but will add to the capital and ongoing costs of the SCR system.

SCR performance has been demonstrated at 98% NOx reduction, and with outlet flue gas NOx concentrations under 2 ppm, although reliable operation at such low NOx levels requires additional catalyst beds and excellent ammonia distribution into the flue gas. Units have more typically been designed for and operated at NOx levels under 5 ppm. In fired heaters SCR is sometimes combined with Low NOx Burners (LNB) to achieve maximum NOx reduction.

SCR systems are installed downstream of fired heaters and boilers, and require installation of new ducting from the heater outlet to the new SCR reactor, as well as the installation of the NH_3 storage, transport, and vaporization system required to inject the NH_3 into the flue gas stream. For a natural draft heater, it is expected that a new induced draft (ID) fan will be required at the outlet of the SCR reactor that overcomes the additional pressure drop imposed by the SCR system. Installation of an SCR system can present challenges depending on heater location and available plot space for the reactor, ducting, ammonia vaporization system, and ID fan. In addition to the potential challenges of limited plot space, the electrical infrastructure requirements may also be problematic if existing substations and feeders are at capacity, and capital costs to upgrade this equipment can significantly add to the overall project costs. If plot space is available, then most of the new equipment could be installed prior to a heater shutdown, with tie-in ductwork being done during a heater shutdown in a fairly short timeframe. If limited plot space is available for pre-shutdown work on a new SCR system, then more significant structural modifications to the heater may be required to accommodate the SCR system above heater convection section. These modifications would require additional capital and an extended shutdown for installation.

There is extensive operating history with SCR systems, and in general the systems have exhibited good reliability, especially in relatively clean services such as gas fired heaters and boilers. There are a greater number of components in an SCR system than with DUPLEX technology though, and each of those components requires ongoing preventative maintenance and repair. Rotating equipment (such as the ID fan, NH_3 dilution air fan, and NH_3 pump) will require regular maintenance in order to maintain proper SCR operation. Other elements in the SCR system, such as the ammonia injection grid and the catalyst bed, will require inspection and repair or replacement during scheduled heater/boiler outages. Catalyst life in an SCR system will be dependent on operation and the presence of materials that could plug or poison the catalyst. With relatively clean flue gas as would be expected from a gas fired heater or boiler, catalyst life of 6-10 years is achievable.

DUPLEX Technology Safety Analysis and Recommended Safety Systems

NEC has reviewed the DUPLEX design information and "typical" P&IDs for DUPLEX installations as provided by ClearSign. NEC also visited a DUPLEX installation in California and spoke with engineering and management personnel about their experience with DUPLEX operation. Additionally, NEC interviewed representatives from another California refiner who is considering DUPLEX installation to get feedback on the technology and any safety concerns that they have.

DUPLEX Technology Operation and Safety

As previously described, the DUPLEX technology consists of a porous ceramic tile on which combustion is sustained after that tile has been heated using a conventional burner. The transition from conventional burner operation (Burner Mode) to DUPLEX operation (DUPLEX Mode) is done manually at the direction of the Operator, and DUPLEX flame is confirmed visually by the Operator as each burner is switched from conventional mode to DUPLEX mode. New UV Flame Scanners directed toward the DUPLEX tile are also used to verify that the flame is present on the DUPLEX tile. Once the fuel gas has been fully switched from the conventional burner nozzles to the DUPLEX nozzles and combustion is fully sustained on the DUPLEX tile, the UV Flame Scanners are activated as a trip in the heater Safety Instrumented System (SIS) so that in the event of a loss of flame the fuel supply can be stopped before hydrocarbon can accumulate to a hazardous level in the heater.

In addition to the UV Flame Scanners, NEC recommends the installation of combustible and methane analyzers in the firebox (near the flue gas outlet) and to use these as inputs to the SIS. These analyzers have seen an increase in use in the past few years and many refiners have started to install these as they upgrade their SIS implementation or as they modify the heaters with the installation of Ultra Low NOx Burners (ULNB) or other improvements. These analyzers can either be Tunable Diode Laser (TDL) analyzers or Catalytic Hot Wire Detectors (such as the Ametek WDG-V Analyzer). Analysis of both combustible (or CO for TDL analyzers) and methane are recommended – combustible/CO analyzers are useful in diagnosing combustion issues due to lack of oxygen or poor air/fuel mixing, while methane analysis is useful for confirming a complete firebox purge prior to startup as well as detecting a complete loss of combustion while fuel to the firebox remains in service. These analyzers can provide valuable input to the Operators while making the transition from conventional burner mode to DUPLEX mode, ensuring that the transition is done in a safe and successful manner. They can also provide valuable input during process upsets and ensure that the heater can be safely and quickly shut down if an unsafe accumulation of combustible material were to occur. While TDL analyzers offer excellent response time and measure the average concentration of gasses across the entire heater, they are significantly more expensive than catalytic hot wire detectors.

In addition to flame detection and firebox gas analysis, there are a few additional process parameters that are important to monitor in order to safely monitor and control the DUPLEX operation. Firebox (bridgewall) temperature is an important parameter to monitor – the firebox temperature is used at startup to determine if the DUPLEX tile surface is hot enough for transition from conventional burner mode to DUPLEX mode. The firebox temperature is also monitored during heater operation and used as a means to monitor the safety of the DUPLEX system – in extreme turndown cases the firebox may become too cold to sustain combustion and could result in the accumulation of hydrocarbons in the firebox, creating a deflagration hazard. With proper monitoring of the firebox temperature and corrective action defined for cold firebox temperatures, the system can be transitioned from DUPLEX back to conventional burner mode and the safety of the heater maintained. With additional installed controls (individual automated valves on pilot gas, fuel gas, and DUPLEX gas to each burner, as well as spark ignitors and flame detection for pilots) the transition from DUPLEX to conventional burners could be done automatically in response to cold firebox temperatures.

Firebox oxygen content is also an important parameter to monitor for DUPLEX operation. While oxygen in heaters with conventional burners is typically monitored for heater efficiency and to ensure that enough oxygen is available for complete combustion, for DUPLEX operation high oxygen content can also become a hazard. At high firebox O_2 levels, the DUPLEX tile can be cooled by the excess air such that combustion cannot be sustained on the tile, which can lead to a hazardous accumulation of hydrocarbon in the firebox. With the importance of maintaining safe oxygen levels for proper DUPLEX operation, ClearSign recommends automated O_2 control on heaters with DUPLEX installed. This control can either be accomplished through automated draft and stack damper control or through automated air register controls to each burner. The choice of the best system for O_2 control will depend on heater design and operation – heaters that are operating significantly below design and have poor damper control of draft and O_2 may require air register control for each burner. Individual air register control actuators can reliability control heater O_2 even with poor stack damper control but this control may be more expensive, especially with heaters that have large numbers of burners. For heaters with a large number of burners, a new air plenum constructed to encase the heater burners with inlet damper air control could be an alternative solution.

One additional benefit from installation of the DUPLEX technology is the reduction of potential flame impingement issues on tubes of refinery heaters, especially older heaters that are being pushed beyond original design. Many older heaters were designed with very tight burner-to-tube clearances (below current API 560 recommendations), and as capacities have been pushed, these heaters suffer from flame impingement issues, accelerated coking, and resultant tube damage. Retrofitting these heaters with ULNB can prove to be problematic as the longer flames seen with ULNB can aggravate flame impingement issues, and create flame coalescing that ultimately limits the NOx reduction that can be achieved. DUPLEX technology, with the flames contained inside the tile and the improved radiation from the DUPLEX surface, can operate safely in units that have experienced issues with flame impingement while delivering NOx control which is markedly superior to that available from ULNBs.

After a thorough assessment of the system design and discussions with current users of the technology, NEC feels that the system can be designed and operated such that safety of the heater and the operating personnel can be maintained. A more detailed review of safety issues based on individual heater design and local safety standards and history is recommended as potential installations are implemented.

DUPLEX Technology SWOT Analysis

SWOT Analysis technique is used by many companies to evaluate their performance and future opportunities. In this type of analysis, the following areas are considered:

- **S** – Strengths – internal company (technology) strengths and advantages
- **W** – Weaknesses – internal company (technology) weaknesses or problems
- **O** – Opportunities – external opportunities driven by market factors, government regulations, etc.
- **T** – Threats – external threats to the organization from competition, market factors, government regulations, etc.

This technique has been used to evaluate the DUPLEX Technology and the use of this technology in the future. Results are outlined below.

Strengths

- Simple technology to install – no moving parts.
- Small footprint - most of the new components are internal to the heater.
- No external ductwork, rotating equipment, or catalyst systems.
- No potential impact on electrical infrastructure (and cost to upgrade infrastructure).
- Imposes minimal additional backpressure on combustion equipment or duct components.
- No chemical reagents required – no handling/safety issues or transportation & logistical issues.
- No ongoing operational costs – no additional electrical load or chemical costs
- Reduced Greenhouse Gas emissions (improved heater efficiency, no electricity usage for ID fan, no transportation of NH_3).
- Technology also provides secondary benefits to heaters with tight geometry or flame impingement issues. Potential to minimize coking issues and tube failures.
- Lower NOx emissions than is currently achievable with ULNB.
- Improved heater efficiency due to improved radiation from DUPLEX tile.
- No emissions of additional pollutants from "slip" (i.e. NH_3 slip emissions from SCR and SNCR).
- No waste streams or byproduct.

Weaknesses

- Limited experience with DUPLEX in an operating heater.
- No long term reliability data is available for the materials of construction in an operating unit.
- Limited experience with operational upsets and ability of technology to maintain safe operation.
- Safety system integration for DUPLEX technology not yet fully defined.

Opportunities

- Tightening NOx emission regulation remains a focus of government agencies (especially in California).
- Operating companies eager for low cost options for NOx reduction.
- Countries such as China are imposing tighter NOx reduction regulations on the power and refining/petrochemical industry.

Threats

- Future NOx restrictions may be lower than that achievable with DUPLEX (under 2 ppm).
- Uncertainty of incoming administration and impact on regulation.
- Competing technology (SCR) is widely demonstrated and has an extensive operating history.

Cost Estimates

Cost estimates were prepared for both DUPLEX and SCR installations for two different refinery heater cases. These cases are described below:

Case 1

- 100 MMBTU/HR fired duty
- Vertical Cylindrical Heater – 25' diameter
- 8 existing Low NOx burners
- Manual operation of DUPLEX nozzle and standard burner valves

Case 2

- 40 MMBTU/HR fired duty
- Vertical Cylindrical Heater – 16' diameter
- 4 existing Low NOx burners
- Manual operation of DUPLEX nozzle and standard burner valves

Case 3

- 40 MMBTU/HR fired duty
- Vertical Cylindrical heater – 16' diameter
- 4 existing Low NOx burners
- Automated operation of DUPLEX nozzle, standard burner, and pilot gas fuel valves

Modifications to each heater for installation of the DUPLEX technology include:

- New supports and support structure for the DUPLEX surface
- DUPLEX ceramic tiles
- New DUPLEX gas nozzles, risers, and header ring retrofitted to existing burners
- New DUPLEX gas supply piping and valves
- New stack educator for purge of the heater firebox prior to lightoff
- New sealed observation doors to prevent tramp air at burner tile
- New UV Scanners
- New O_2 analyzer
- Programming for existing SIS to accommodate DUPLEX technology and new I/O.

The O_2/Combustible/methane analyzer discussed in the safety analysis is listed as an optional component in the estimates

For Case 1 (100 MMBTU/HR heater), the scope also includes:

- Stack damper actuator for O_2/draft control

For Case 2 (40 MMBTU/HR heater), the scope from Case 1 is modified:

- Stack damper actuator for O_2/draft control is removed and burner air register actuators are installed for O_2 control.

For Case 3 (40 MMBTU/HR heater), the scope is modified from Case 2 as follows:

- Automated burner fuel gas shutoff valves to each burner
- Automated DUPLEX gas shutoff valves for each burner
- Automated pilot gas shutoff valves for each burner
- Automated spark ignitors for each pilot
- Flame detection for pilots (fire rod)

For the installation of SCR at each heater, NEC used cost curves for SCR installation that were developed for previous work done for the South Coast Air Quality Management District (SCAQMD). The curves were developed using quotes for SCR equipment and factored for different sized combustion sources. Included in the SCR costs are:

- Ductwork from heater to SCR reactor
- SCR reactor and catalyst
- Ammonia injection grid
- Ammonia storage, injection, and vaporization equipment
- ID Fan
- Support Steel

The SCR costs assume a moderate installation complexity, and also assume that the SCR installation is for a single heater. In some cases SCR installation can be combined for multiple heaters and this can reduce the cost substantially per heater – but that was not assumed for this analysis. In addition, any significant electrical infrastructure upgrades (substations, feeders, etc.) for the ID fan are not included. Depending on the available capacity of existing electrical substations and feeders, significant upgrades (and capital costs) may be required - as the level of required upgrade would be specific to the installation location, this is left out of the cost estimates for SCR.

Cost estimates for each case and technology considered are presented in the table below:

	Case 1 – 100 MMBT/HR **(**no fuel supply automation)		**Case 2 – 40 MMBTU/HR** (no fuel supply automation)		**Case 3 – 40 MMBTU/HR** (automation for fuel supply)	
	Capital Cost $K	Operating Costs	Capital Cost $K	Operating Costs	Capital Cost $K	Operating Costs
DUPLEX	$1,440	$0	$960	$0	$1,950	$0
SCR	$13,400	$211.4K/year	$11,200	$84.6K/year	$11,200	$84.6K/year

For the DUPLEX technology installation, there is no incremental operating cost associated with the technology. For SCR, incremental operating costs include ammonia and electricity.

The incremental cost for the optional O_2/Combustible/Methane analyzers that provide additional safeguards (as discussed in the safety section of this report) is approximately $187K.

In addition to initial capital and ongoing operational costs, there will be periodic SCR catalyst replacement or DUPLEX tile replacements necessary. Over a 10-year period, the ongoing costs (excluding initial capital) for DUPLEX technology and SCR are shown below.

	Case 1 – 100 MMBT/HR 10 Year ongoing costs	Case 2 – 40 MMBTU/HR 10 Year ongoing Costs	Case 3 – 40 MMBTU/HR 10 year ongoing costs
DUPLEX	$180K	$93.6K	$143K
SCR	$2,192K	$877K	$877K

Included in the 10 year ongoing costs for each technology are:

DUPLEX Technology

- Annual Maintenance Costs for I&E and SIS
- Replacement costs for 50% of tile/support system (as needed).

SCR

- Annual Maintenance Costs for I&E, SIS, and Rotating Equipment
- Replacement costs for catalyst (complete changeout once every 10 years)
- Annualized operating costs (primarily for electricity and ammonia)