CONCEPTS FOR AN OVERALL REFINERY ENERGY SOLUTION THROUGH NOVEL INTEGRATION OF FCC FLUE GAS POWER RECOVERY

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INTRODUCTION

Refiners are more focused today than ever on improving utility consumption and reducing stack emissions. One area receiving significant interest is power recovery from the FCC flue gas, especially since this power is “clean” in that no additional CO₂ is produced or emitted.

While much work has been done over the past 40 years to improve the reliability and operability of FCC flue gas power recovery systems, the process has remained largely unchanged; that is, until now. Traditionally, the FCC flue gas power recovery system has all too often been treated as an “accessory”, tacked on only to higher capacity, higher pressure FCC units in areas of high electrical cost. In order to make this technology useful for a wider range of FCC operators, UOP has developed some innovative improvements to the way power recovery systems are incorporated into the FCC unit. These innovations significantly reduce the capital cost per unit of energy recovered from FCC unit flue gas in an environmentally friendly manner. These innovations can potentially double the ROI for a power recovery system when compared to traditional installations. This has greatly increased the application range of power recovery systems to FCC capacities for which it was previously considered uneconomical.
In this paper UOP will discuss the history of FCC flue gas power recovery, show the economics associated with implementation of a traditional power recovery system, discuss some of the recent advancements in process design and the impact they can have on power recovery economics.

**HISTORY OF FCC FLUE GAS POWER RECOVERY**

Energy in FCC flue gas has traditionally been recovered in the form of steam generation in a flue gas cooler. While the application of flue gas coolers is an efficient system for recovering heat energy, it ignores the potential energy recovery associated with the flue gas rate and pressure. In 1950, a turbo-expander was installed in the flue gas line of an FCC unit in an attempt to convert the flue gas pressure into shaft power to supplement the utility requirement of the main air blower. The initial results were extremely poor. After only 750 hours of operation, catalyst fines in the flue gas had substantially eroded away the turbine blades and casing.

While there are a few exceptions, typical FCC regenerator designs include two stages of cyclones inside the regenerator. It was originally believed that this efficiency was high enough to protect the expander from excessive erosion. This proved not to be the case.

In 1963, Shell Oil solved the flue gas fines problem by placing an additional catalyst separator outside the regenerator at Norco, Louisiana and Oakmont, Canada refineries. This additional stage of catalyst separation became known as a Third Stage Separator (TSS), and FCC flue gas power recovery became a sustainable reality.

The regenerator cyclones substantially reduce both the catalyst loading and the particle size distribution in the flue gas. This allows the TSS cyclone elements to be designed at much higher velocities, thus higher efficiency, without a concern for erosion of the TSS. Depending on regenerator design and catalyst systems, a modern TSS is capable of reducing the catalyst in the flue gas to less than 1 wt-% catalyst larger than 10 microns. This is more than sufficient to provide long-term reliable protection of the power recovery expander.

There are several possible Power Recovery System configurations that can be incorporated into both new and existing FCC Unit designs. Selection of the specific equipment type and arrangement is always refinery specific, and is generally a balance of utility requirements, process optimization, and preference between different configurations.

Amongst the various configurations, there are basically two types of power recovery applications to consider: 1) a four or five body power recovery train in which the expander is directly coupled to the main air blower to provide direct shaft power, and 2) a two, three or four body power
recovery train in which the expander is coupled to a generator to produce electrical power. These configurations will be discussed in turn.

**TRADITIONAL FCC FLUE GAS POWER RECOVERY SYSTEMS**

*Four and Five-Body Coupled Trains*

Between 1963 and 1981, 18 power recovery applications were commissioned industry-wide. These were typically five-body trains; consisting of a hot gas expander, main air blower, steam turbine, motor/generator and gear box as necessary. A five-body train is shown in Figure 1. This configuration was historically the most common power recovery system for new unit installations.

![Traditional 5-Body Power Recovery Train](image)

In this configuration, the expander is coupled to the main air blower and provides a direct transfer of energy to the shaft. The direct transfer of energy to the main air blower minimizes power transfer losses, and is the most energy efficient configuration.

The steam turbine is used to start up the train. The shaft speed is increased to match the electrical frequency of the motor (the “synchronous speed”) to that of the power grid and the electrical breaker is closed. Once the breaker is closed, the shaft speed of the train is fixed to the frequency of the power grid. The air flow rate is controlled by adjusting the inlet guide vanes. Generally, the combination of a steam turbine and motor can provide the required power to operate the air blower at design conditions, with the expander out of service. After enough flue gas is present, and process conditions are stable, the expander can be commissioned. An overview schematic of the traditional power recovery train is shown in Figure 2.
The motor/generator imports or exports power as required to maintain a constant train shaft speed. If more energy is supplied by the expander than is required by the blower there is a surplus of electricity generated and exported to the power grid. Conversely, if the blower power requirement is higher than the expander is providing, electricity is consumed by the motor to maintain the train at normal speed. With the expander coupled to the main air blower, in the event of a breaker disconnect the shaft power requirement of the MAB acts as over-speed protection for the expander.

With a power recovery system, butterfly valves are used in the flue gas line to control the differential pressure between the reactor and regenerator. A dedicated, high speed “power recovery control system” performs all process control functions. Fundamentally, the regenerator-reactor pressure differential controller (PDIC) adjusts the expander inlet valve to control the differential pressure, and only opens the bypass valve when the expander is out of service or expander maximum throughput is reached. This control scheme maximizes the power generation potential by minimizing the amount of flue gas that is diverted around the expander.
With a traditional five-body power recovery train (PRT) if the expander requires any repair or maintenance, the entire FCC Unit has to be shut down. The business interruption costs associated with shutting down the entire FCC unit can be substantial, and rapidly negate the economic advantage associated with the power recovery system. With these concerns in mind, there was a desire by many refiners to decouple the power recovery expander from the main air blower shaft. This was initially a very challenging problem that was solved in the early 1980s, and ushered in the Gen Set power recovery system.

**Gen Set Power Recovery Train**

The gen set PRT is a “stand-alone” system in which the expander is connected to a generator and the main air blower is installed as a separate machine. An overview schematic of a modern Gen Set power recovery system is shown in Figure 3. By removing the main air blower from the power recovery train, the shaft load associated with the blower is eliminated. The main concern with this configuration was that in the event of a breaker-disconnect the shaft load drops essentially to zero and the expander could speed up in an uncontrolled manner, resulting in a potential over-speed. These concerns led to the development of fast acting control valves, high speed electro-hydraulic actuators, and improved instrumentation and control systems that rapidly divert flue gas out of the expander to decelerate the train. In 1983, one of the first gen set power recovery systems was commissioned at Saras, S.p.A., in Sardinia, Italy.
With a modern Gen Set power recovery application, FCC unit down time associated with either maintenance or failure of the power recovery expander is essentially eliminated. Operation of the FCC unit can be maintained while the PRT is isolated to complete any repair or routine maintenance work.

The decision to couple the power recovery expander to the MAB shaft or install a Gen Set PRT is a question that each refiner must address. With the current cost of FCC unit downtime, more refiners are seeing the potential economic advantage of the Gen Set power recovery system.

**COMMERCIAL HISTORY OF POWER RECOVERY SYSTEMS**

Through the 1970s and 80s refinery investment in FCC flue gas power recovery tracked very closely with electrical prices. When compared on a 2004 constant dollar basis, electrical prices hit a peak across 1981-86. By this time, power recovery had achieved broad based acceptance across the industry, and the technology experienced rapid growth. See Figure 4. The numbers of “New PRT Installations” (107 total) are based on the equipment commissioning date. It should be noted that additional power recovery trains have likely been installed in China and the FSU that were not publicly disclosed and are not represented herein.
Although natural gas prices have been rising sharply in recent years, since about 1993 coal has dramatically outpaced all other fuels for electrical power generation. Both the availability and low price of coal has maintained electrical rates at historic lows since 1999, but are only recently starting to increase as shown in Figure 4.

In contrast with the current low electrical rates, UOP has observed a recent resurgence in the industry interest in FCC flue gas power recovery systems. This interest appears to be primarily driven by refineries focusing on direct returns by lowering their operating cost, and indirect returns on investor confidence by improving the Energy Intensity Index (EII) of their operations and reducing environmental emissions.

*Historical pricing data for Figure 7 provided by U.S. Department of Energy*

*Energy Intensity Index*

The EII was developed by Solomon Associates in 1981 to compare energy consumption among fuels refineries. Standard energy consumption per barrel of utilized capacity was established for each process and process types. The factor for fluid catalytic cracking units is based on an FCC configuration without a flue gas power recovery expander. The EII is essentially the ratio of the actual energy consumption divided by the sum of the refinery standard energy consumption. The installation of a flue gas power recovery system reduces the actual energy purchased. As such, the EII for refineries that have an FCC unit flue gas power recovery expander is lower than the standard factor, representing better than standard energy efficiency.
Environmental Emissions

The application of an FCC flue gas power recovery system is “green” with respect to electrical power generation. No additional CO₂, SOx or NOx are created in association with the power generated. This can provide both permitting and economic benefits to the refiner. The economic benefit is going to be discussed later in this paper.

The impact on the refiner operating with a lower EII and good neighbor emissions stewardship improves investor confidence that the refinery is being properly managed. As a result, many refiners will accept lower returns on capital projects focused on energy optimization. However, the projects still have to be economically attractive. With the recent low electrical rates this has proved particularly challenging for traditional FCC flue gas power recovery and has focused UOP on inventing new ways to improve the economic viability for power recovery systems and improving the reliability of the system.

With renewed interest in FCC flue gas power recovery, UOP reviewed many of the historical designs and realized that very little had changed since the early 1970s. Opportunities arising from recent advancements in component equipment designs (expander, actuators, instruments, and TSS) had not been utilized.

As emission requirements have tightened, particulate matter in the FCC flue gas has been controlled by the installation of an electrostatic precipitator, wet gas scrubber or barrier filter. Each of these emission control devices requires considerable capital and operating expense, but has no financial Return on Investment (ROI) beyond supporting a permit to operate.

UOP ADVANCEMENTS IN FCC FLUE GAS POWER RECOVERY SYSTEMS

Over the past three years, UOP has developed innovative improvements in the design and application of power recovery systems. These innovations have been targeted to optimize the efficiency of energy recovered from the FCC flue gas stream in an environmentally friendly manner and at a significantly lower total erected cost. With these innovations, project economics have been significantly improved when compared to traditional designs, expanding the application range of flue gas power recovery to lower capacity units, for which power recovery systems were previously considered uneconomical.

The remainder of this paper will discuss some of UOP’s recent FCC flue gas power recovery innovations. With each innovation a supportive economic case study will be shown that progresses one advancement to the next, starting with the traditional maximum electrical power generation configuration. Although the economic analyses are cited as case studies, they are closely based on recent commercial projects.
**Flue Gas Basis**
To start this series of case studies, a relatively common flue gas basis was chosen which meets a “middle of the road” FCC operation. The following conditions were used.

- Feed rate: 50,000 BPSD
- Coke yield: 5.3 wt-%\(FF\)
- Flue gas excess oxygen: 1.0 mol-%
- Operating days per year: 365
- Flue gas rate: 533,000 lb/hr
- Flue gas temperature: 1350°F
- Regenerator pressure: 34.0 psig

**Utility Costs**
The utility costs used for the case studies were based on 2005 U.S. Gulf Coast costs.

**Erected Cost Analysis**
The unit costs highlighted for each power recovery installation case study presented in this paper were developed by UOP using historical data generated from recent similar power recovery installation projects, to support each associated economic analysis. These costs have been developed on a U.S. Gulf Coast installation basis, and include recent vendor quotations for most major equipment items.

These costs are represented as total erected costs, and as such, exclude all project costs (licensor basic design, royalties, and T&K fees, spare parts, start-up services, training, and owners costs), as well as project contingencies, as these costs are unit-specific and carry a wide range of variability.

Nevertheless, every attempt has been made to develop each of these case specific erected costs on a consistent design and installation basis to ensure comparative accuracy and effectively support the resultant ROI representations.

**CASE STUDY #1: (TRADITIONAL POWER RECOVERY SYSTEMS)**
This first case considers a traditional FCC flue gas power recovery system as detailed in Figure 3. In this configuration, electrical power generation is maximized by feeding the highest temperature, highest pressure flue gas to the inlet of the power recovery expander. Residual heat in the flue gas down stream of the expander is recovered in the form of HP steam generation. From this case, 13.78 MW of electrical power are generated. Since the application of the expander reduces the temperature to the flue gas cooler, there is a loss of HP steam production.
that must be made up in the boiler house. A debit has been applied to the economics reflecting a pound-for-pound shift in HP steam production from the FCC unit to the boiler house.

The economic analysis for the installation of a traditional power recovery system is shown in Table 1. The ROI for this project is presented for 25, 30, and 35 percent discounted cash flow factors, and shows a very marginal return between 9.1 – 10.6%. This is an example of why it has been difficult in recent years to economically justify the installation of a power recovery system on moderate to small sized units.

**Table 1**

*Utility Analysis and ROI - Traditional FCC Power Recovery System*

<table>
<thead>
<tr>
<th></th>
<th>Erected Cost, (MM-$)</th>
<th>HP Steam, (lb/hr)</th>
<th>Electrical Power, (MW)</th>
<th>DCF ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25%</td>
</tr>
<tr>
<td>Base Case</td>
<td>N/A</td>
<td>110,300</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Add Traditional PRT</td>
<td>$28,900,000</td>
<td>69,800</td>
<td>13.78</td>
<td>12.7</td>
</tr>
</tbody>
</table>

The economics of major capital projects often improve with larger size units due to economies of scale. This is true for the application of FCC flue gas power recovery systems. Figures 5 & 6 show a comparison of erected costs and ROIs for various capacity units, pegged to the conditions for the 50,000 BPSD case study of this paper and a scale-up to a 125,000 BPSD unit. The two lines in each Figure show the trend lines for a traditional power recovery and the new UOP power recovery system. As the size of the unit is decreased, a minimum erected cost level is reached, which can result in falling ROI levels with smaller units. Conversely, on larger units, the incremental increase in erected costs leads to higher ROIs.

The remainder of this paper is going to discuss some of the aspects of the new UOP power recovery system, and how we have been able to reduce the total erected cost and improve energy integrations for a step change improvement in ROI over base.
**FIGURE 5**
Relative Erected Cost Impact with Varying Size FCC Units

![Diagram showing relative erected cost impact with varying size FCC units.](image)

**FIGURE 6**
Relative ROI Impact with Varying Size FCC Units

![Diagram showing relative ROI impact with varying size FCC units.](image)
CASE STUDY #2: (TRADITIONAL PRT WITH TSS INTEGRATED EXPANDER BYPASS LINE)

Advancements in TSS design provided the first power recovery system optimization opportunity by reducing the capital costs of the TSS, and associated flue gas duct and structure. The new UOP TSS is about 40 percent smaller than other TSS offerings for the same capacity, making it less expensive to fabricate, easier to install, and better suited where plot space is a premium. Figure 7 shows an equal capacity comparison of the older radial flow TSS and the new UOP TSS design.

The most significant improvement in the design is that the UOP TSS utilizes axial flow for catalyst/gas separation. The flue gas flow is maintained essentially in one direction - in the top and out the bottom of the unit. Axial flow distribution minimizes the potential for solids re-entrainment resulting from changes in directional gas flow and resultant eddy current formations. More importantly, reducing the directional flow changes minimizes pressure loss across the TSS by 0.25 to 0.50 psi. This translates directly into more power recovery potential across the expander.

In addition to being smaller, the clean gas outlet is located on the lower side of the vessel. This minimizes the amount of steel structure and hot wall flue gas duct (typically 304H stainless steel) between the TSS and the expander inlet.

**Figure 7**

*Third Stage Separator – Equal Capacity Comparison*

*Old Style TSS*  
29'  
70 Tubes  
19' 3” OD

*New Style TSS*  
23'  
11’ 6” OD  
48 Tubes
Proper design of the expander inlet / outlet lines is extremely critical to the overall operation and reliability of the power recovery expander. The allowable nozzle loadings on the expander inlet and outlet nozzle are extremely small. Great care must be taken in the detailed engineering process to ensure that the nozzle loadings are maintained within allowable parameters across the entire operating range as well as transient conditions of the system.

In older power recovery system designs, the expander bypass line was typically designed as hot-wall pipe connected directly to the expander inlet line “minimum distance” from the outlet of the TSS. See Figure 8. The objective of this configuration was to minimize the loading effects that the bypass line imparts on the expander inlet nozzle during intermittent or transient use. The bypass line can be in service during all modes of operation; startup, shutdown and normal operation. As the bypass valve opens, the flow of hot flue gas causes the flue gas duct to heat up and thermally expand. The resultant duct expansion imposes a great deal of force loading and rotational moment on the expander inlet line, making the piping system both difficult to design and costly to install.

**FIGURE 8**

*Traditional Expander Bypass Line Installation*

Where: E = Expander, Gear, G = Generator
To alleviate this problem, UOP has added a second clean gas outlet nozzle to the TSS and attached the expander bypass line as a lower cost cold-wall line, directly to the TSS vessel. See Figure 9.

**FIGURE 9**

*UOP Modified Expander Bypass Line Installation*

Where: TSS = Third Stage Separator, E = Expander, G = Gear, M/G = Motor Generator

This configuration has many significant benefits that increase the overall reliability, operability, and cost effectiveness of the system. In this design, the TSS acts as a fixed anchor point in the duct design for both the expander inlet and bypass lines.

The line from the TSS to the inlet of the expander becomes a very clean, minimum impact design, allowing for shorter duct length between the expander and the TSS. The transient loads applied to the expander inlet nozzle associated with intermittent or normal use of the bypass line are minimized, essentially reduced to only the axial pressure thrust with varying gas flows. The bypass line also becomes much shorter in length and can be of cold wall design. Both of these provide for lower overall design and installation costs as well as operational and maintenance benefits.

The combined implementation of an axial flow UOP TSS with a side connected clean gas outlet and integral cold-wall bypass line reduces the detailed piping design requirements, structural steelwork, large diameter piping, pipe supports, and expansion joints for the system. This lowers the total erected cost for this case study from $28.9 MM to $27.1 MM, with a corresponding improvement in ROI as shown in Table 2.
Although the economic benefits seen here with 1) the addition of a PRT and 2) the installation of a UOP TSS are relatively small, it leads into a progression of additional technology improvements and costs reductions that greatly improve the economics of flue gas power recovery.

**CASE STUDY #3: (PROCESS INTEGRATED STEAM LETDOWN TURBINE)**

The integration of a steam turbine as a supplemental driver to assist with startup of the PRT is relatively common. In traditional operation, the flue gas flow is maximized to the expander and the steam flow to the turbine is reduced to the minimum required to keep the turbine in operation. At this point, the steam turbine becomes a marginally utilized asset until the next FCC shutdown.

Integration of the steam turbine provides a means for the refiner to supplement electrical power generation from the PRT. However, in designs of the past, the generator has been sized according to the rated capacity of the expander. As such, using the steam turbine to supplement electrical power generation has been limited to times when the FCC unit is in turndown operations and not making the design power output. In considering ways to maximize the use of existing assets, the PRT steam turbine has been a significantly under-utilized piece of equipment.

Most refineries operate a boiler house that generates a single level of high pressure steam. Lower levels of steam are supplied by successive letdown stations to the medium- and low-pressure steam headers. Additional LP steam is also often generated by exhausting steam turbines into the LP header. A typical steam letdown configuration is shown in Figure 10.
When steam is let down across a control valve, the potential energy of the steam is reduced without work being done. With the addition of a steam turbine in the FCC power recovery train as shown in Figure 11, there is a way to capture a significant amount of this lost energy.
In this configuration, HP or MP steam can be let down efficiently across the turbine into the lower pressure steam headers. The energy transferred to the generator shaft is used to produce supplemental electrical power. To optimize this configuration, the PRT motor/generator needs to be sized to accommodate the proper steam let-down requirements to meet the refinery’s needs. As depicted, multiple levels of steam letdown can be accommodated through a single turbine. This utility integration is a process design that extends beyond the battery limits of the FCC unit, and allows the refiner to optimize the economics of operating their facility-wide steam and electrical systems.

When installing an FCC flue gas power recovery system, most of the auxiliary equipment is already required; i.e. the generator, 13.8 kVA cable, switches gear, foundation, electrical controls and substation. The incremental cost of adding the steam letdown turbine to the power recovery train is low compared to the potential energy recovered, and can significantly increase the return on investment for installation of a power recovery system in the FCC unit.

If we focus on the battery limits of the FCC unit, there are additional energy integration opportunities available than can be used to help maximize use of available assets; in this case, the PRT steam letdown steam turbine. There are several MP steam flows to the reactor including the riser lift steam, feed distributor dispersion steam, spent catalyst stripping steam, and reactor fluidization steam. The steam that is injected into the reactor is heated up to the reactor operating temperature, and is one of the loads on the overall heat balance. From a process standpoint, we do not want the additional heat input that the superheat of the MP steam provides. However, LP steam is simply too low in pressure to be used for these applications.

With the integration of a flue gas power recovery system, the normal FCC process steam can be routed through a letdown turbine on the PRT as shown in Figure 12. In this manner, the excess superheat and pressure energy of the steam is transferred as shaft power to the PRT and used to either supplement the blower power requirement or to produce electricity in the generator.
In application, the higher the steam pressure supplied to the turbine, the greater the economic return on integrated electrical power generation. The turbine exhaust pressure is a variable with which the operator can control the amount of superheat remaining in the steam; the lower the exhaust pressure, the lower the remaining superheat. As more energy is removed, the higher the electrical power generation from the PRT and the higher the heat load on the reactor. While the temperature of the steam is a relatively small heat load on the reactor, the lower the steam temperature, the higher the catalyst-to-oil ratio in the unit for improved product selectivities.

The addition of a steam letdown turbine within the power recovery train increases the total erected cost of the system from $27.1 MM to $28.4 MM as shown in Table 3. With the steam conditions used, integrating just the reactor, riser, and stripper steam letdown covers the additional cost of the turbine and steam integration. If the steam source is changed from MP to HP steam, the ROI is improved by +1.7 percent.

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TABLE 3
Utility Analysis and ROI – Integrated Process Steam Letdown

<table>
<thead>
<tr>
<th>Steam Letdown</th>
<th>Erected Cost, ($)</th>
<th>HP Steam (lb/hr)</th>
<th>Electrical Power, (MW)</th>
<th>DCF ROI 25%</th>
<th>DCF ROI 30%</th>
<th>DCF ROI 35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add Traditional Five-Body PRT</td>
<td>$28,900,000</td>
<td>69,800</td>
<td>13.78</td>
<td>12.7</td>
<td>11.9</td>
<td>11.0</td>
</tr>
<tr>
<td>TSS Integrated Bypass Line</td>
<td>$27,100,000</td>
<td>69,800</td>
<td>13.78</td>
<td>13.6</td>
<td>12.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Reactor Riser Steam MP Integrated Turbine</td>
<td>$28,400,000</td>
<td>69,800</td>
<td>14.14</td>
<td>13.6</td>
<td>12.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Reactor Riser Steam HP Letdown Turbine</td>
<td>$28,400,000</td>
<td>69,800</td>
<td>15.60</td>
<td>15.5</td>
<td>14.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

With the integration of a steam turbine, multiple levels of letdown can be simultaneously incorporated into the system. To provide a basis for the economic impact that integrated steam letdown can have, Table 4 shows the additional power generation and economic improvement per 10,000 pounds of steam letdown for three different levels of steam.

TABLE 4
Utility Analysis and ROI – Per 10,000 lb/hr Steam Letdown

<table>
<thead>
<tr>
<th>Steam Letdown</th>
<th>Heat Rate (lb/kWh)</th>
<th>Steam Rate (lb/hr)</th>
<th>Generator Power, (MW)</th>
<th>DCF ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>600# to 90# Header</td>
<td>25.87</td>
<td>10,000</td>
<td>+0.39</td>
<td>+0.5</td>
</tr>
<tr>
<td>600# to 150# Header</td>
<td>33.10</td>
<td>10,000</td>
<td>+0.30</td>
<td>+0.4</td>
</tr>
<tr>
<td>150# to 50# Header</td>
<td>116.00</td>
<td>10,000</td>
<td>+0.09</td>
<td>+0.2</td>
</tr>
</tbody>
</table>

For example, if 30,000 lb/hr of steam is let down from the 600# HP to the 150# MP steam header for a 25 percent DCF bracket, the subsequent increase in ROI and recovered electrical power would be:

\[
ROI = 13.0 + (3 \times 0.5) \quad RW = 15.6 + (3 \times 0.39) \\
ROI = 14.5\% \quad \text{and,} \quad MW = 16.77
\]

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CASE STUDY #4: TEMPERATURE CONTROLLED EXPANDER INLET

With the traditional approach to power recovery, electrical power generation is maximized by directing the highest temperature, highest pressure flue gas to the inlet of the expander. The energy recovered across the expander results in a flue gas temperature reduction of 150 - 400°F and a minimum exhaust pressure. The flue gas is then routed to a low pressure flue gas cooler for residual energy recovery in the form of steam production. However, due to the temperature reduction, the quantity of the steam generation is lower than before the expander was placed into service. Even with the most efficient cooler designs, installing a power recovery expander upstream of a flue gas cooler to maximize electrical power generation can result in a 20-30 percent reduction in high pressure steam production that must be financially off-set with the value of electrical power generation for the installation of a power recovery system to be economically attractive.

Considering the dynamic balance between steam and electricity costs, UOP evaluated several options to improve the economics for installing a power recovery system. In a traditionally applied power recovery system, the operating temperature of the regenerator dictates the inlet temperature to the expander. The higher flue gas temperature at the expander inlet duct requires the use of expensive stainless steel duct.

In the new temperature-controlled expander inlet design shown in Figure 13, the expander is placed downstream of a high pressure flue gas cooler, reducing the metallurgy requirement of the entire power recovery system to lower cost carbon steel, resulting in a total erected cost that is potentially 30–40 percent lower than that of a traditional system design, depending on the capacity of the unit.

This provides the refiner with another means to help optimize the economics of their overall refinery utility systems between maximum HP steam generation and maximum electrical power generation at 1050°F maximum expander inlet.
In this new system, the flue gas from the regenerator is first routed through a flue gas cooler, then to the power recovery train. A bypass line is installed around the flue gas cooler to provide a means to control the inlet temperature to the expander. This allows the refiner to optimize energy production from the FCC unit between steam and electrical power. The control system is configured to provide load-following variable peak response control of both the refinery HP steam system and electrical distribution. If the refinery HP steam requirement drops, or if the refinery is close to an electrical surcharge threshold, the flue gas cooler bypass line is opened to direct additional hot flue gas to the expander to produce additional electrical power. This allows the refiner the capability to optimize the HP steam generation and electrical power generation as utility economics shift, independent of the operation of the FCC reactor/regenerator.

The lower flue gas temperature downstream of the flue gas cooler allows the entire power recovery system (vessels, control valves, expansion joints, piping, and duct work) to be designed and installed with lower cost carbon steel materials as opposed to the higher cost stainless steel and cold wall refractory lined duct work required by the traditional system. The lower temperature system design results in less thermal movement of the flue gas duct, reducing the size, type, and quantity of expansion joints required. This further reduces the erected cost of the system. Even though the electrical power generated with the lower temperature expander inlet is reduced from that of the traditional system, as shown in Table 5, the substantially lower cost of the system far exceeds the reduction in electrical power generation, resulting in a significant step change increase in ROI.
TABLE 5
Utility Analysis and ROI – Temperature Controlled Expander Inlet

<table>
<thead>
<tr>
<th></th>
<th>Erected Cost, ($)</th>
<th>HP Steam (lb/hr)</th>
<th>Electrical Power, (MW)</th>
<th>DCF ROI 25%</th>
<th>DCF ROI 30%</th>
<th>DCF ROI 35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>N/A</td>
<td>110,300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Add Traditional Five-Body PRT</td>
<td>$28,900,000</td>
<td>69,800</td>
<td>13.78</td>
<td>12.7</td>
<td>11.9</td>
<td>11.0</td>
</tr>
<tr>
<td>TSS Integrated Bypass Line</td>
<td>$27,100,000</td>
<td>69,800</td>
<td>13.78</td>
<td>13.6</td>
<td>12.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Reactor Riser HP Steam Letdown Turbine</td>
<td>$28,400,000</td>
<td>69,800</td>
<td>15.60</td>
<td>15.5</td>
<td>14.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Temperature Controlled Expander Inlet</td>
<td>$19,900,000</td>
<td>79,300</td>
<td>12.61</td>
<td>24.2</td>
<td>22.6</td>
<td>21.0</td>
</tr>
</tbody>
</table>

In addition to the economics presented in Table 5, the lower inlet temperature to the expander increases the long term reliability of the system and helps minimize expander blade erosion and power recovery loss over time. The cooler catalyst particles that pass over the expander blades are much less apt to fuse into catalyst deposits on the blades and casing, further improving the system reliability as a function of reducing expander blade tip erosion and tip-rub-induced shaft vibration.

CASE STUDY #5: ENVIRONMENTAL CONSIDERATIONS

The application of an FCC flue gas power recovery system is “green” with respect to electrical power generation in that no additional CO₂, SOx or NOx are created in association with the power generated. A paper issued by Colin High⁴ detailed the value of emission reductions as shown in Table 6:

TABLE 6
Value of Emissions Reductions – $ / metric ton

<table>
<thead>
<tr>
<th></th>
<th>$ / metric ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>300 – 600</td>
</tr>
<tr>
<td>Nitrogen Oxide (NOx)</td>
<td>3,000 – 10,000</td>
</tr>
</tbody>
</table>

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To assess the value of generating “green” power with a power recovery system, the marginal fuel for electrical production was considered to be natural gas. Every kW-hr produced in the power recovery system results in a kW-hr lower requirement from a cogeneration plant. With the use of natural gas, the SOx reduction is near zero, the CO₂ reduction is proportional to the fuel consumption, and the NOx reduction is based on the use of low NOx burners with an emission of 40 ppm NOx in the flue gas. The value of emission reductions used for the economic analysis is based on the average of the ranges shown in Table 6. With a fuel gas heat rate of 9,090 BTU/kW-hr, the resultant value for emissions reductions is tabulated in Table 7.

Table 7
Emissions Reductions– metric ton/MW-hr

<table>
<thead>
<tr>
<th></th>
<th>metric ton/MW-hr</th>
<th>$ / kW-hr*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>0.554</td>
<td>0.222</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Nitrogen Oxide (NOx)</td>
<td>0.000174</td>
<td>0.113</td>
</tr>
</tbody>
</table>

*Based on Average Values of Table 8

The economic impact of the emissions reduction in association with installation of a power recovery system is noticeable, and as shown in Table 8, further improves the ROI for a power recovery system.

Table 8
Utility Analysis and ROI – Emissions Credit

<table>
<thead>
<tr>
<th></th>
<th>Erected Cost, ($)</th>
<th>HP Steam (lb/hr)</th>
<th>Electrical Power, (MW)</th>
<th>DCF ROI 25%</th>
<th>DCF ROI 30%</th>
<th>DCF ROI 35%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>N/A</td>
<td>110,300</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Add Traditional Five-Body PRT</td>
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<td>21.0</td>
</tr>
<tr>
<td>Emission Reduction Credit</td>
<td>$19,900,000</td>
<td>79,300</td>
<td>12.61</td>
<td>25.6</td>
<td>23.9</td>
<td>22.2</td>
</tr>
</tbody>
</table>
SUMMARY

Increased global focus on reducing energy consumption and emissions are working together to make FCC flue gas power recovery more attractive. Even in this environment, the economics associated with a traditional power recovery system can be marginal for an average sized FCC Unit. However, UOP has developed a series of novel improvements to the traditional scheme that make it an attractive investment across a broader range of FCC capacities at the current price of electricity.

The improvements discussed herein, while novel in application, are all supported by proven technologies and serve to reduce capital cost or improve efficiency and availability. The ‘TSS Integrated Bypass Line’ reduces capital cost of the expander inlet line and is made possible by UOP’s commercially proven new TSS design. The ‘Reactor Riser Steam Letdown Turbine’ utilizes existing turbine technology to improve efficiency. The ‘Temperature Controlled Expander Inlet’ utilizes existing cooler technology, along with a turbine, to reduce capital cost, improve efficiency and improve availability.

While an abundant supply of low cost coal has helped keep electricity prices in check, there are signs that the price of coal is on the rise. An increase in electricity prices to the inflation-adjusted average of 1973 to 1988, with all else equal, would result in a 70 percent increase in the ROI for all cases considered. Because UOP believes that the long-term factors that drive energy efficiency are on the rise and will remain so for the foreseeable future, UOP remains committed to improving the process behind power recovery from FCC flue gas systems.

The concepts presented in this paper provide a glimpse at some of the recent work UOP has been performing on FCC flue gas power recovery. New ideas and new opportunities are being developed that build upon the recent technology advancements. UOP is currently working on a new power recovery system that further reduces total erected cost and increases the overall power recovered to further improve ROI. The newer system significantly reduces required plot space and allows the refiner to potentially meet current and future particulate matter stack emission requirements.
ACKNOWLEDGEMENTS

The authors of this paper would like to express their thanks to the following companies and individuals, for their assistance in providing data and/or support that have helped make this paper a reality.


3. **UOP - FCC Engineering Tech Center** - John Yarborough – Assistance with pipe stress analyses, large bore piping design, proper equipment layout, and 3-D graphics used in the presentation.

REFERENCES


