IMPACTS OF CONDITION ASSESSMENT ON ENERGY USE: SELECTED APPLICATIONS IN CHEMICALS PROCESSING AND PETROLEUM REFINING

SUMMARY REPORT

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THE ROLE OF CONDITION ASSESSMENT IN PLANT OPERATIONS

Condition assessment refers to inspection of equipment for conditions such as corrosion, fatigue, metal wear, wall loss, cracking, and degradation of material linings, coatings, and claddings. Effective methods for condition assessment of process equipment are critical to the efficient, safe operation of chemical and petroleum refining plants. The processes at the core of these industries are typically operated at high temperatures and pressures, and in many cases are comprised of very corrosive environments. Inspection of equipment operating under these severe conditions is required to prevent catastrophic failures and to optimize maintenance practices and productivity.

Processes operating under severe conditions can in most situations also be characterized as energy-intensive. Over 5 quadrillion Btu are consumed every year in chemicals and petroleum refining for process heating and cooling, and a large portion of that energy is input to processes operating under severe conditions. Technologies that effectively assess equipment conditions can reduce energy use associated with maintenance, can ensure equipment is operated at maximum energy efficiency, and help to optimize product yields.

Conventional condition assessment methods are frequently invasive and often require process shutdowns. In some situations, shutdowns are performed more frequently than necessary because current inspection technology cannot adequately assess the condition of equipment or accurately identify conditions that could lead to failures. In most cases, inspection technology is not capable of predicting or identifying conditions that may be contributing to decreased efficiency and poor product yields. Inadequate inspection technology results in excessive maintenance costs, higher energy consumption, and greater potential for unplanned equipment failure.

New condition assessment technologies that are non-intrusive and provide real time data could move inspection processes away from "shutdown" mode. Ideally, new inspection methods would permit an understanding of the mechanical, physical and chemical conditions of equipment and materials of construction, without disturbing process flow or necessitating a shutdown. Optimal methods would be able to flag potentially damaging conditions, or predict conditions that are contributing to reduced efficiency and yields.

The potential impacts of improved condition assessment technologies are lower production costs, enhanced plant safety, fewer emissions to land, water, and air, and reduced energy use. Considering the billions of dollars spent dealing with corrosion, fouling, and other equipment degradation issues in the chemical and petrochemical industries every year, the ultimate economic benefits could be significant.

Energy use is another area where potential impacts could be substantial. The objective of this study is to examine the potential for reducing energy use in two energy-intensive process applications through improved condition assessment technology. The first is the ethylene cracking furnace, which is used in both the chemical and petroleum refining industries to produce ethylene, propylene, and various other products from naptha and ethane. The study also looks at crude preheat trains, which are used to preheat crude oil before downstream refining into products.

Ethylene Furnace Operations

Background

Ethylene is produced by the pyrolysis of hydrocarbon feedstock (naptha, gas oil, or ethane) with steam in a cracking furnace at temperatures ranging from 1400-1600^{o}F. An estimated 1.7 quadrillion Btu[1] is consumed annually in the production of ethylene [EI 2000]; roughly half of that energy is used in the pyrolysis furnace. Production of ethylene is split roughly in half between the chemicals and petroleum refining industries.

Thermal cracking of hydrocarbons is always accompanied by the formation of coke. As the ethylene furnace is operated, coke deposits steadily on the inside walls of the furnace tubes. Coke is a thermal insulator, and thus prevents efficient heat transfer from the furnace firebox to the gas that is reacting inside the tubes. To compensate, the temperature must be raised in the furnace, resulting in higher energy costs. Operating at hotter temperatures also leads to more rapid deposition of coke. Eventually, the buildup of coke becomes so severe that either the tube wall temperature is at a maximum or maximum pressure is reached, and the furnace must be shutdown to remove the coke. In addition, increasing coke deposition reduces the coil diameter and raises the pressure drop across the coil, necessitating an increase in furnace inlet pressure. Both aspects have a detrimental effect on energy use and the yield of ethylene.

Decoking is usually accomplished by passing a combination of hot air and steam through the coils and transfer lines to blast the coke off the walls. The unburned coke and gases are then routed for disposal or back to the firebox for additional burnout. Decoking takes place anywhere from 15 to 90 days, depending on the furnace, and contributes to high maintenance costs and lost production. It has been estimated that decoking of ethylene furnaces worldwide costs the industry more than $2 billion every year [Borchardt 2000].

Coke buildup also has the undesirable effect of carburization – the diffusion of carbon into the metal. This makes the furnace tubes and fittings brittle and susceptible to fracture. Carburization requires that furnace tubes and fittings must be replaced every 2 to 7 years, creating another source of high maintenance costs and lost production. Replacement of furnace tubing is estimated to cost ethylene producers another $200 million annually [Borchardt 2000, Shell 2004].

Analysis of Energy Impacts

For this analysis, it is assumed that new condition assessment technologies (tools, sensors, etc.) are applied to ethylene furnaces, with the following improvements:

- Optimization of maintenance schedules, i.e., maximizes operating conditions by decoking the right furnace at the right time;
- Improves ability to cope with unexpected equipment outages and changes in feedstock supply;
- Helps operators coordinate run lengths with operations;
- Allows diagnosis of furnace conditions, and alerts plant operators concerning arising failures; and
- Provides highly accurate estimate of available furnace capacities and changes in heat transfer performance.

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[1] Net energy; considers energy recovered from flue gases, in transfer line exchangers, and primary fractionator.

To conduct the energy savings analysis, a predictive energy, economic and environmental model was employed. This model was adapted from the Threshold Analysis Model developed in the late 1970s and later modified for personal computers in the 1980s [TAM 1985]. The current model consists of a series of linked spreadsheets (MS Excel) and predicts energy savings, reductions in pollutant emissions, and energy cost savings over 25 years. Essential inputs to the model include plant or unit size description and criteria, energy delta between conventional and improved technology, market data, and potential market penetration estimates. The baseline assumptions used in the analysis of the ethylene furnace are shown in Table 1.

Table 1. Baseline Assumptions for the Ethylene Furnace	
Market Size[a]	49 billion lbs of domestic ethylene production, 2002 data.
Market Penetration	80% of U.S. ethylene furnace market impacted by 2025
Market Curve	Relatively rapid penetration (low initial investment, retrofit)
Commercialization	Commercial use in industry by 2006.
Plant Configuration[b]	Plant producing 1 billion lbs of ethylene per year, 8 ethylene furnaces per plant.
Furnace Inputs[c]	Feedstocks 2/3 ethane/propane/butane, 1/3 naptha/raffinate or gas oils; ~2900 Btu/lb energy input to the furnace.
Decoking[d]	\$20k-\$40k cost for each decoking cycle per furnace, mostly for steam and utilities; decoking every 30 days.
Natural Gas[e]	Purchase price for natural gas of \$5 per million Btu.

a *Guide to the Business of Chemistry*, American Chemistry Council, 2003.
b Shell 2004, KES 2003, SKCorp 2003.
c *Energy and Environmental Profile of the Chemical Industry*, Energetics, Inc., Columbia, MD. 2000.
d Shell 2004, KES 2003, SKCorp 2003, ExxonMobil 2003.
e DOE/EIA Natural Gas Report, based on national average for the industrial sector. http://tonto.eia.doe.gov/dnav/ng/hist/n3035us3M.htm

To determine the energy saved by implementing improved condition assessment technology, it was assumed that decoking would be minimized while yield is optimized, resulting in a number of operational changes. The changes in furnace operation that lead to energy savings include:

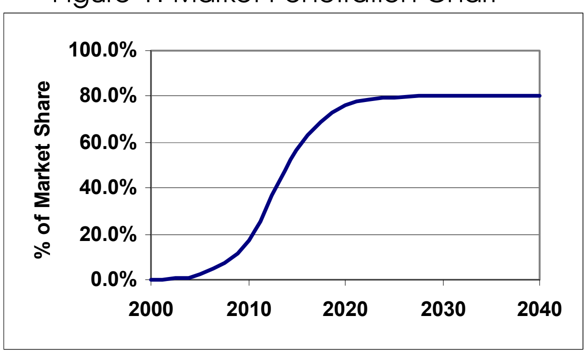
- Increase in furnace run length from 30 days to 45 days.
- Reduction in at decoking overlap (i.e., when two or more furnaces require decoking at the same time), saving two lost days of production.
- Increase in throughput (yield) by 3%.

The unit energy savings (Btu/lb of ethylene) realized by these operational changes are shown in Table 2. The model was run using the parameters shown in Tables 1 and 2, and yielded estimates of impacts out to 2030. These results are shown in Table 3. The market penetration curve resulting from the model is shown in Figure 1.

Table 2. Energy Savings from Improved Condition Assessment in the Ethylene Furnace	
Source of Savings	**Unit Energy Savings**
Increase in furnace run length	0.188 10^9 ft^3 natural gas/year
Reduction in decoking overlap	0.014 10^9 ft^3 natural gas/year
Increase in throughput (feedstock energy)	0.084 10^{12} Btu per year

Table 3. Energy, Environmental and Economic Impacts for Ethylene Furnace						
Impact By Year	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Units installed	1	11	42	66	79	92
Market penetration	2%	17%	57%	76%	80%	80%
Energy Metrics						
Total primary energy displaced (trillion Btu)	0.371	3.15	12.2	19.2	23.1	26.9
Direct natural gas displaced (bcf)	0.257	2.18	8.46	1.33	16.0	18.6
Feedstock energy displaced (trillion BTU)	0.107	0.905	3.51	5.51	6.64	7.74
Cost						
Energy-cost savings ($MM/yr)	1.54	13.0	50.5	79.2	95.6	111.0
Environmental Metrics						
CO Displaced (Metric Tons)	6.96	59.0	229	359	433	504
Carbon Dioxide emissions displaced (Metric Ton CE)	3810	32300	125000	196000	237000	276000
NOx displaced (Metric Tons)	25.4	216.0	837.0	1310.0	1580.0	1840.0
VOCs displaced (Metric Tons)	0.72	6.10	23.7	37.1	44.8	52.2

Figure 1. Market Penetration Chart



Conclusion

Based on model results, improved condition assessment in ethylene furnaces could save about 3 trillion Btu in 2010 and as much 20 trillion Btu annually by 2020, with about $79 million in avoided energy costs. Displacement of carbon dioxide, based on reduced fuel combustion, would be about 200,000 metric tons of carbon equivalents in 2020.

Some conservative assumptions have been built into this analysis. Natural gas prices were assumed to be steady at $5 per million Btu over the next 30 years, when in reality are expected to be much higher. Furnace energy consumption, which varies between facilities, was selected at the low end of the spectrum. In addition, a conservative market penetration curve was selected, along with a modest ethylene annual growth rate of about 3%.

Crude Preheat Trains

BACKGROUND

Every single barrel of oil processed in U.S. refineries, or about 6 billion barrels of oil annually, passes through crude preheat trains prior to undergoing the first major step of the refining process—distillation. The crude preheat train (CPT) is a series of heat exchangers that take heat from other process streams that require cooling and use the heat to raise the temperature of the crude oil from ambient conditions to 200-280°C. The crude is heated further to 330-370°C in a furnace before entering the distillation column. Nearly 60-70% of the thermal energy required to heat the crude prior to distillation is recovered from produce streams [Panchal 2000].

Crude oil is primarily a mixture of hydrocarbons and heavy organic compounds. As it flows through the heat exchanger, the heavy organics flocculate and deposit on the heat exchanger walls, fouling the surface. The fouling acts as a thermal insulator, reducing the rate of heat transfer from the hot process stream side of the heat exchanger to the cooler crude oil side. When the fouling reaches a limit predetermined by the refinery operators, the heat exchanger is taken offline to be cleaned. In some cases, there are spare heat exchangers that can be rotated into the CPT lineup when one is taken offline for cleaning so that the performance of the CPT is unaffected. However, if more heat exchangers must be taken offline for cleaning than there are replacements, or the heat exchanger to be cleaned is in such a location that there are no spares, the performance of the train is diminished and the downstream furnace must bear a greater heat load.

Heat exchangers in the preheat train foul at different rates, depending on the composition of the crude oil and the operating conditions, making it difficult to develop an optimal cleaning schedule. The cleaning schedules vary from refinery to refinery and depend heavily on the crude composition, but "average" heat exchangers are cleaned every three to five years [ChevronTexaco 2004, Shell 2004]. A poor performing unit would need to be cleaned more often, on the order of every year. Heat exchangers are cleaned using chemicals; this takes eight to ten hours to complete and can cost approximately $10,000 per heat exchanger cleaned, not including the cost of lost operating capacity [ChevronTexaco 2004, Shell 2004]. Condition assessment offers the opportunity to optimize the cleaning schedule for higher heat transfer rates with minimal cleaning.

Heat exchanger tube failure is another issue of concern for the CPT. In a typical refinery, failures occur every three to four years due to material corrosion, resulting in unplanned shutdowns [ChevronTexaco 2004]. Crude oil contains sulfur and chlorine in varying amounts and these compounds can contribute to corrosion of process equipment. Tube design lifetimes are estimated to be on the order of 10 years, but this is based on sulfidation corrosion which is a steady, uniform deterioration of the tube material. The reduction of heat exchanger wall thickness is measurable and failure due to sulfidation can be predicted fairly accurately, enabling operators to replace the tubes before they fail.

Another corrosion mechanism that occurs in the preheat train is pitting, a localized form of corrosion in which cavities or holes are produced in the tube wall. Pitting is considered more dangerous than sulfidation corrosion because it is more difficult to detect, predict, and design against [KTS 2004]. Failure due to pitting can be quick or not at all, making it a critical corrosion mechanism to monitor. Unplanned shutdowns are costly in terms of safety, lost production, and additional energy consumed during shutdown and start up. Lost production time can be valued at $500,000 to $1 million per day [ChevronTexaco 2004].

Analysis of Energy Impacts

For this analysis, it is assumed that new condition assessment technologies (tools, sensors, etc.) are applied to the crude preheat train, with the following improvements:

- Optimization of maintenance schedules, i.e., maximizes operating conditions by cleaning or replacing the right heat exchanger at the right time;
- Provides highly accurate estimate of heat exchanger heat transfer performance; and
- Allows diagnosis and monitoring of heat exchanger conditions, and alerts plant operators concerning impending failures, reducing the frequency of unplanned shutdowns.

The energy savings analysis was conducted employing the same predictive energy, economic, and environmental model used for the ethylene furnace case. The baseline assumptions used in the analysis of the crude preheat train are shown in Table 4.

Table 4. Baseline Assumptions for the Crude Preheat Train	
Market Size[a]	6,017 million barrels of domestic crude oil refining, 2002 data.
Market Penetration	65% of U.S. ethylene furnace market impacted by 2025
Market Curve	Relatively rapid penetration (low initial investment, retrofit)
Commercialization	Commercial use in industry by 2007.
Plant Configuration[b]	Refinery processing 100,000 barrels of crude per day
Fouling Energy Loss: Baseline and Fouling Rate Reduced by 1/2[c]	Baseline: 12,300 Btu per barrel crude; at ½ the fouling rate: 7,365 Btu per barrel crude.
Unplanned Shutdowns[d]	Occur every three to four years and last approximately 7 days; the energy consumed daily by crude distillation is 114,000 Btu/barrel; value of lost production is approximately $500,000 to $1 million per day. The energy consumed in shutdown and start up the preheat train (and the downstream distillation process) is assumed to be approximately twice the amount of energy used daily in crude distillation.

a DOE-EIA 2003.
b Panchal 2000.
c Panchal 2000.
d ChevronTexaco 2004, *Energy and Environmental Profile of the Petroleum Refining Industry*, Energetics, Inc., Columbia, MD. 1999.

To determine the energy saved by implementing improved condition assessment technology, it was assumed that (1) the fouling rate would be decreased through optimization of the cleaning schedule, and (2) the frequency of unplanned shutdowns due to heat exchanger failure (pitting and/or sulfidation corrosion) would be reduced. The changes in operation of the crude preheat train leading to energy savings include:

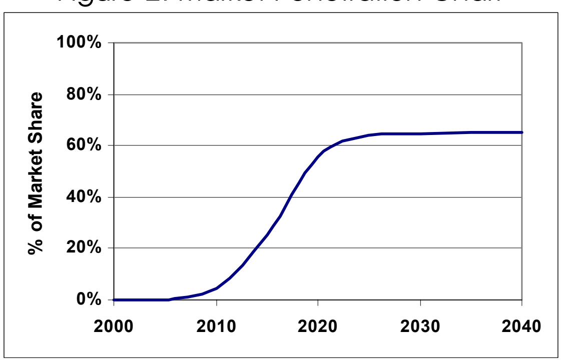
- Optimized cleaning schedule, resulting in a fouling rate that is ½ of the baseline case
- Reduction in the frequency of unplanned shutdowns from once every three years to once every six years, saving energy lost in the shutdown and start up of the preheat train and crude distillation unit.

The unit energy savings (Btu/bbl crude oil) generated by the implementing improved condition assessment technologies are shown in Table 5. The model was run using the parameters in Tables 4 and 5, and yielded estimates of impacts out to 2030. These results are shown in Table 6. The market penetration curve resulting from the model is shown in Figure 2.

Table 5. Energy Savings from Improved Condition Assessment in the Crude Preheat Train	
Source of Savings	**Unit Energy Savings**
Reduced Fouling Rate	0.185 10^9 ft^3 natural gas/year
Reduced Frequency of Unplanned Shutdowns	0.004 10^9 ft^3 natural gas/year

Table 6. Energy, Environmental and Economic Impacts for Crude Preheat Train						
Impact By Year	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Units installed	0	8	47	108	131	140
Market penetration	0%	4%	25%	55%	64%	65%
Energy Metrics						
Total primary energy displaced (trillion Btu)	0.0	1.5	9.2	21.0	25.4	27.2
Direct natural gas displaced (bcf)	0.0	1.5	8.9	20.5	24.7	26.4
Feedstock energy displaced (trillion BTU)	0.0	0.0	0.0	0.0	0.0	0.0
Cost						
Energy-cost savings ($MM/yr)	0.0	4.9	31.7	79.1	102.0	116.0
Non-energy cost savings ($MM/yr)	0.0	3.4	20.7	47.4	57.3	61.3
Environmental Metrics						
CO Displaced (Metric Tons)	0.0	43.2	266	609	737	788
Carbon Dioxide emissions displaced (Metric Ton CE)	0.0	21500	132000	303000	366000	391000
NOx displaced (Metric Tons)	0.0	158	976	2230	2700	2880
VOCs displaced (Metric Tons)	0.0	4.5	27.5	62.9	76.1	81.3

Figure 2. Market Penetration Chart



Conclusion

Based on model results, improved condition assessment in the crude preheat train has the potential to save approximately 1.5 trillion Btu in 2010 and 21 trillion Btu annually by 2020, with about $79 million in avoided energy costs. In 2020, displacement of carbon dioxide due to reduced fuel combustion would be about 303,000 metric tons of carbon equivalents.

This analysis is based on two areas—rate of fouling and frequency of unplanned shutdowns—that can vary widely from refinery to refinery. Assumptions were made for a typical refinery and did not include the balance between maintenance costs and longer runs. A conservative crude oil refining annual growth rate of about 1% was selected, along with a modest market penetration curve.

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