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A POSSIBLE SOLUTION FOR THE U.S. NAVY'S ADDICTION TO PETROLEUM: A BUSINESS CASE ANALYSIS FOR TRANSITIONING THE U.S. NAVY FROM PETROLEUM TO SYNTHETIC FUEL RESOURCES

by

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March 2007

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Considering the variable cost of petroleum, it is fiscally prudent for the Department of the Navy (DON) to consider alternative energy sources for propulsion. The cost of petroleum fuels for the DON have increased fifty-five percent from 2004 to 2005 and the increase is equivalent to the annual cost of over seven thousand personnel or three littoral combat ships. For the near-term and mid-term futures (five to thirty years), these alternative energy sources must be compatible with current power systems. The Chief of Naval Operations Strategic Studies Group XXV (SSG) proposed a Navy Synthetic Fuels Program (NSFP) which recommended embarking on a public-private venture to make synthetic fuels to satisfy the U.S. Navy's needs. This thesis examines one aspect of SSG's NSFP by specifically investigating the construction and operating costs of a coal to liquid synthetic fuel plant using domestic coal resources.

The purpose of this study is to show the conditions where domestic coal to liquid (CTL) fuel production facility investment is financially practical, as well as those where it is financially impractical. This analysis develops cost estimates, provides business case analysis and reviews global estimates for developing a coal to liquid synthetic fuel production facility. It identifies and qualifies risks and sensitivities. It also examines various projected coal and crude oil markets and how each case influences the decision to pursue a synthetic fuel program. It concludes with a decision matrix comparing the pursuit of a synthetic fuel program with maintaining the status quo of the use of fuel from petroleum.

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A POSSIBLE SOLUTION FOR THE U.S. NAVY'S ADDICTION TO PETROLEUM: A BUSINESS CASE ANALYSIS FOR TRANSITIONING THE U.S. NAVY FROM PETROLEUM TO SYNTHETIC FUEL RESOURCES

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LIST OF ABBREVIATIONS AND ACRONYMS

AEO2006	Annual Energy Outlook 2006
AEO2007	Annual Energy Outlook 2007
ASU	Air Separation Unit
bbl	barrel
BOP	Balance of Plant
bpd	barrels per day
BTL	Biomass to Liquid
Btu	British Thermal Unit
CAPEX	Capital Expense
CDF	Cumulative Distribution Function
CER	Cost Estimating Relation
CTL	Coal to Liquid
CWT	Changing World Technologies
DCF	Discounted Cash Flow
DCL	Direct Coal Liquefaction
DESC	Defense Energy Support Center
DoD	Department of Defense
DOE	Department of Energy
DON	Department of the Navy
DPA	Defense Production Act
DTL	Direct Thermal Liquefaction
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
FSU	Former Soviet Union
FT	Fischer-Tropsch
FY	Fiscal Year
GHG	Green House Gases
GDP	Gross Domestic Product
GS	Gasification System
GTL	Gas to Liquid
IPD	Implicit Price Deflator
IRR	Internal Rate of Return

LA	Liquids Area
LCC	Life Cycle Cost
MC	Monte Carlo
MSW	Municipal Solid Waste
MTG	Methanol to Gasoline
NCEP	National Commission on Energy Policy
NRAC	Naval Research Advisory Committee
NSFP	Naval Synthetic Fuels Program
OPEC	Organization of the Petroleum Exporting Countries
OPEX	Operating Expense
OTH	Other (as noted in the WBS)
PB	Power Block
PPI	Producer Price Index
ppm	Parts Per Million
PRB	Powder River Basin
RA	Refining Area
ROI	Return on Investment
SAFE	Securing American Future Energy
SH	Solids Handling
SNG	Synthetic Natural Gas
SSEB	Southern States Energy Board
synfuel	synthetic fuel
syngas	synthetic gas
SVO	Straight Vegetable Oil
SSG	Strategic Studies Group
TCP	Thermal Conversion Process
USDA	U.S. Department of Agriculture
WBS	Work Breakdown Structure
WBSE	Work Breakdown Structure Element
WGS	Water Gas Shift

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EXECUTIVE SUMMARY

The purpose of this study is to show the conditions where domestic coal to liquid (CTL) fuel production facility investment is financially practical, as well as those where it is financially impractical. This report is based on examining capital and operating costs of synthetic fuel plants as proposed by public and private organizations. It is a comprehensive approach that provides insight into the magnitude and variability of the costs of building and operating synthetic fuel plants, thereby permitting conclusions to be drawn about the economics and cost benefit balance of such plants.

The American economy, including the military, needs oil to keep the mechanisms of society turning. The Navy and the Department of Defense must have continued access to fuels to power ships, aircraft and vehicles to provide for the nation's defense. Due to increasing demand, decreasing discovery and supply source instability, there will come a time when access to petroleum from the ground is limited or it has become intolerably expensive.

This thesis examines the economics of CTL synthetic fuels plants. One of the primary assumptions used in this analysis is the Department of the Navy (or Department of Defense) will be involved with CTL plants through an arrangement that isolates the price of synthetic fuel produced from the world petroleum market. This arrangement can be structured in numerous ways, but one example may include a guaranteed off-take agreement with a private synthetic fuel company to purchase 100 percent of fuel produced at a minimum retail selling price (the minimum retail selling price is the price required to cover capital costs, operating costs and a reasonable profit for the contracted company). Exact off-take agreement arrangements or contract specifics are not mentioned further in this analysis and are only again addressed in a section discussing areas for further research.

The methodology used in this analysis initiated with data collection and developed work breakdown structures (WBS) for capital expenses (CAPEX) and annual

operating expenses (OPEX). Next, cost estimating relations (CERs) were developed through Monte Carlo simulation and regression analysis.

The cost estimating relations are summarized as follows:

CAPEX	**OPEX**
$y_{CAPEX} = CAPEX \ (2006\$M)$	$y_{OPEX} = OPEX \ (2006\$M/YR)$
$x = Plant\ Capacity\ (bpd)$	$x = Plant\ Capacity\ (bpd)$
MONTE CARLO CER	*MONTE CARLO CER*
$y_{MC\ CAPEX} = 0.0772x - 2.6929$	$y_{MC\ OPEX} = 0.0091x - 0.4044$
REGRESSION CER	*REGRESSION CER*
$y_{REG\ CAPEX} = 0.5040x^{0.8326}$	$y_{REG\ OPEX} = 0.01256x^{1.0014}$
$\alpha = 0.05$	$\alpha = 0.05$
$R^2 = 94.8\%\ \ Adj\ R^2 = 94.6\%$	$R^2 = 87.2\%\ \ Adj\ R^2 = 86.1\%$
$P\ value_{COEF} = 2.6\ x\ 10^{-14}$	$P\ value_{COEF} = 1.1\ x\ 10^{-6}$

The Monte Carlo results are linear, while the regression results are a power function. Both results show a clear increase in costs with increasing plant capacity, while the regression shows benefits for economy of scale with increasing plant capacity.

The Monte Carlo CERs were compared to the regression CERs. For CAPEX, Monte Carlo CER lies completely inside the regression CER, plus or minus two standard deviations, and the medians are almost overlapping. This result means the two relations give very similar results and could be used as mutually validating estimating approaches within the range of the data.

For OPEX, the Monte Carlo CER overlaps a large portion of the lower range of the regression CER (plus or minus two standard deviations from the regression CER median). For values greater than 20,000 barrels of daily plant capacity, the median Monte Carlo CER consistently estimates less than the median of the regression CER. This result means the regression CER will estimate higher costs, and if a conservative estimate (i.e., an estimate which will give a higher cost) is desired, the regression CER should be utilized.

The operating expenses are estimated on a cost per year basis and to find an estimated total life cycle cost (LCC) of a plant with life N years, the following equation would be used: $LCC = CAPEX + N * OPEX$. Even with multiplying $N * OPEX$, the overall life cycle cost is dominated by CAPEX. If overall life cycle costs want to be reduced, effort and research need to be invested in reducing the CAPEX costs of CTL plants. A list of sample CAPEX and OPEX estimates using the above CERs for various plant capacities can be found in Table 1.

Plant Capacity (bpd)	**CAPEX (2006$M)**	**OPEX (2006$M/YR)**
Monte Carlo CERs		
20,000	$1,541	$182
40,000	$3,085	$364
60,000	$4,629	$546
80,000	$6,173	$728
100,000	$7,717	$910
Regression CERs		
20,000	$1,921	$255
40,000	$3,421	$510
60,000	$4,794	$765
80,000	$6,092	$1,021
100,000	$7,336	$1,276

Table 1 Sample CAPEX and OPEX Estimates for Various Plant Capacities

Next, return on investment (ROI) analysis was developed. This analysis related the estimated minimum retail selling price to various internal rates of return. First, the number of years a plant had to operate (also known as plant life) was examined, and the minimum retail selling price was plotted against various internal rates of return for various plant lives. The following conclusions were found:

- The minimum retail selling price is an increasing function of the internal rates of return. That is, the higher internal rates of return that is required, the higher the minimum retail selling price.
- The minimum retail selling price is a decreasing and convex function of the plant life. That is, longer plant life requires lower minimum retail selling price.

- While the minimum retail selling price is a decreasing function of the plant life, it is decreasing at a decreasing rate. In particular, it shows diminishing returns when calculating plant lives beyond 20 years.

The second part of the ROI analysis consisted of comparing minimum retail selling price and internal rate of return (IRR) for the Monte Carlo CER and the regression CER. First, regression model showed the benefits of economy of scale. Specifically, under the same IRR, a plant with a higher capacity could sell the product produced at a lower price than a plant with a lower capacity. Also, the Monte Carlo simulation model demonstrated a minimum retail selling price between the regression model plant capacity of 30,000 barrels per day and 100,000 barrels per day, further reinforcing the similarity between the Monte Carlo model and the regression model. Additionally, the analysis showed that with fuel prices remaining above 60 dollars per barrel, an IRR of 10 percent can be successfully achieved.

The above CERs furthered the understanding of estimated capital and operating costs of CTL plants, but the following question still remained: Should the Navy or Defense Department initiate a synthetic fuel program or remain with petroleum based fuel? This question was investigated through extensive use of the EIA AEO2006 energy price projections. The following conclusions were found:

- Jet fuel from petroleum price was highly variable over the evaluation period.
- Synthetic jet fuel pricing remained relatively stable over the evaluation period.
- Jet fuel pricing was very sensitive to price fluctuations, while synthetic fuel was far more stable.
- Synthetic fuel's price insensitivity relative to coal price fluctuation is due to the large CAPEX costs relative to the cost of the feedstock. CAPEX is the dominant factor which drives the minimum retail selling price of synthetic fuel.
- For the landscape of possible projected prices for crude oil and coal, 57 percent of the cases favored synthetic fuel and 43% of the cases favored fuel from petroleum.
- This study's results can be extended from supporting the Navy fuel requirements to supporting the Department of Defense fuel requirements, by assuming the DoD needs six 60,000 barrel per day plants, to supply

120 million barrels per year, compared to the Navy's use of two 60,000 barrel per day plants. This is a conservative statement since lessons will be learned during the construction of the first two plants and can be used to optimize the construction or operation of the third to sixth plants.

This thesis concludes with a discussion of areas for further study.

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I. INTRODUCTION

A. SCOPE AND LIMITATIONS

The purpose of this study is to show the conditions where domestic coal to liquid (CTL) fuel production facility investment is practical, as well as those where it is impractical.

This report recognizes the fact that capital and operating costs of synthetic fuel plants are highly dependent on location, feedstocks, capacity, configuration, design, capitalization structure, permitting and current or proposed legislation. Nonetheless, benefit can be found in examining the wide-range of capital and operating costs proposed by public and private organizations. This comprehensive approach should provide insight into the magnitude and variability of the costs of building and operating synthetic fuel plants, thereby permitting conclusions to be drawn about the economics and cost benefit balance of such plants.

Although various domestic feedstocks are capable of producing fuel, and this report briefly addresses various domestic feedstocks, this analysis specifically focuses on CTL plants. This is due to the fact that the U.S. has great energy reserves in coal, approximately 250 years of supply at current production rates, and the Fischer-Tropsch (FT) process is a proven method of making synthetic fuel.

B. WORLD ENERGY

The world is undeniably tied to oil. It is the lifeblood of modern, industrialized urban existence. It impacts virtually every human endeavor. The impact of oil spans from transportation to medicine, from agriculture to manufacturing or from plastic cups to fighter aircraft. The American economy, including the military, needs oil to keep the mechanisms of society turning. While most people take oil for granted, like the air that they breathe, its absence is immediately noticed. [Copulos 2006]

The following characterize the current global energy environment:

- Total U.S. energy consumption is projected to increase at an average rate of 1.2 percent per year (from 99.7 quadrillion Btu in 2004 to 127.0 quadrillion Btu in 2025). [AEO2006]

- World oil consumption is estimated to increase at a rate of 1.9 percent a year, while the peak world discovery year was 1962 and has consistently dropped since then. [AEO2006] Clearly world oil demand has outpaced discoveries.
- A majority of known oil reserves are located in unstable regions of the world.
- There is limited world oil production capable of surging to meet new demand. The world oil production which is capable of meeting new demand is known as "swing" oil production.
- Domestically, net imports of oil have increased and are continuing to increase.
- The U.S. military is undeniably dependent on liquid hydrocarbons for the next several decades.

These assertions are clarified in the paragraphs below.

1. Consumption is Skyrocketing

To a great extent, developed and developing nations of the world have replaced the production of mechanical power from the power of a man or domesticated animal to energy resources, primarily in the form of oil, coal or natural gas. In a prominent speech by Admiral Hyman G. Rickover to an Annual Scientific Assembly of the Minnesota State Medical Association on 14 May 1957, he stated:

> Today (1957) coal, oil, and natural gas supply 93 percent of the world's energy; water power accounts for only 1 percent; and the labor of men and domestic animals the remaining 6 percent. This is a startling reversal of corresponding figures for 1850 - only a century ago. Then fossil fuels supplied 5 percent of the world's energy, and men and animals 94 percent.

Although Admiral Rickover's words are dated by half a century, they are still relevant in describing the direction in which the world's energy sources has been trending. World energy consumption has been incessantly rising on all fronts, primarily due to developed and developing nations' growing economies and, in the case of developing countries, their populations. The Energy Information Administration (EIA) Annual Energy Outlook 2007 (AEO2007) estimates U.S. energy consumption will increase from 100.2 quadrillion British Thermal Units (Btu) in 2005 to 131.16 quadrillion Btu in 2030, even after accounting for basic increased vehicle efficiencies and assuming slower growth in vehicle miles traveled. This is the basis for the 1.2 percent annual growth rate estimate. Figure 1 shows U.S. energy consumption (in quadrillion Btu) by fuel types from 1980, as well as EIA's projection to 2030.

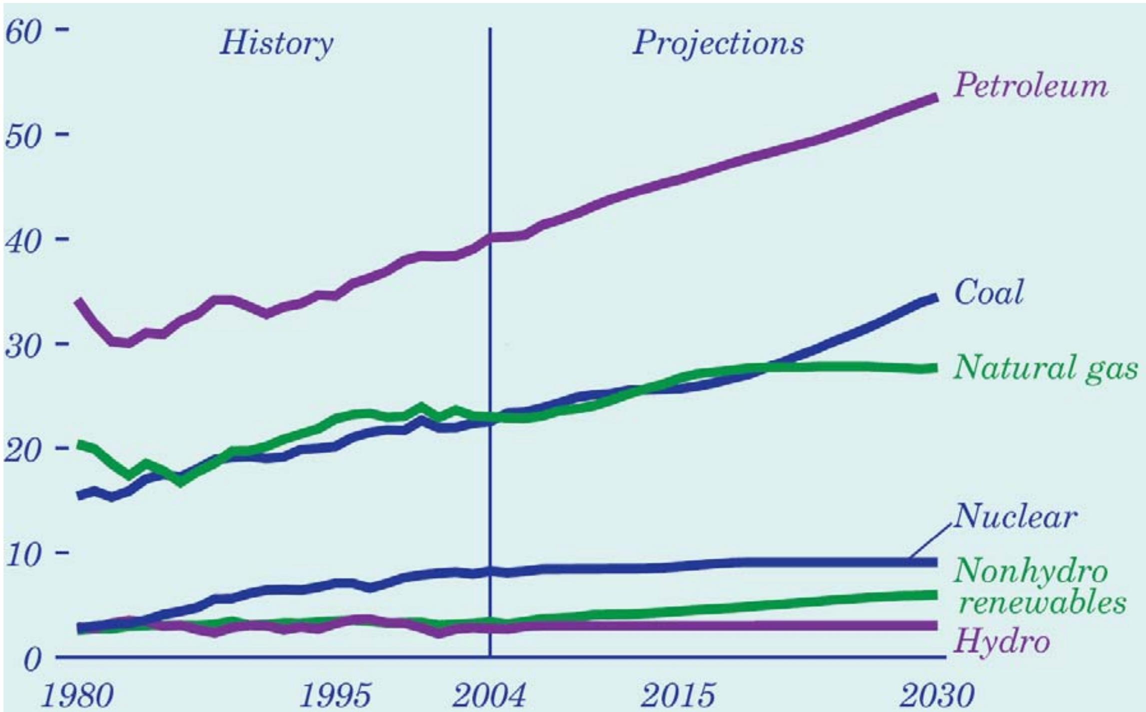

Figure 1 U.S. Energy Consumption by Fuel, 1980-2030 (quadrillion Btu) [From: AEO2006 Reference Case]

2. Demand is Outpacing Discovery

In the words of author and investment banker Matthew R. Simmons, commenting on oil extraction economics, "nobody saves the best for last." It makes economic sense to extract the cheapest oil first. Much of this easily accessible or cheap oil has been discovered, and now the world will have to work harder, and pay more for, future oil. As shown in Figure 2, consumption is increasing while documented discoveries are significantly decreasing. This situation is not sustainable in the long term.

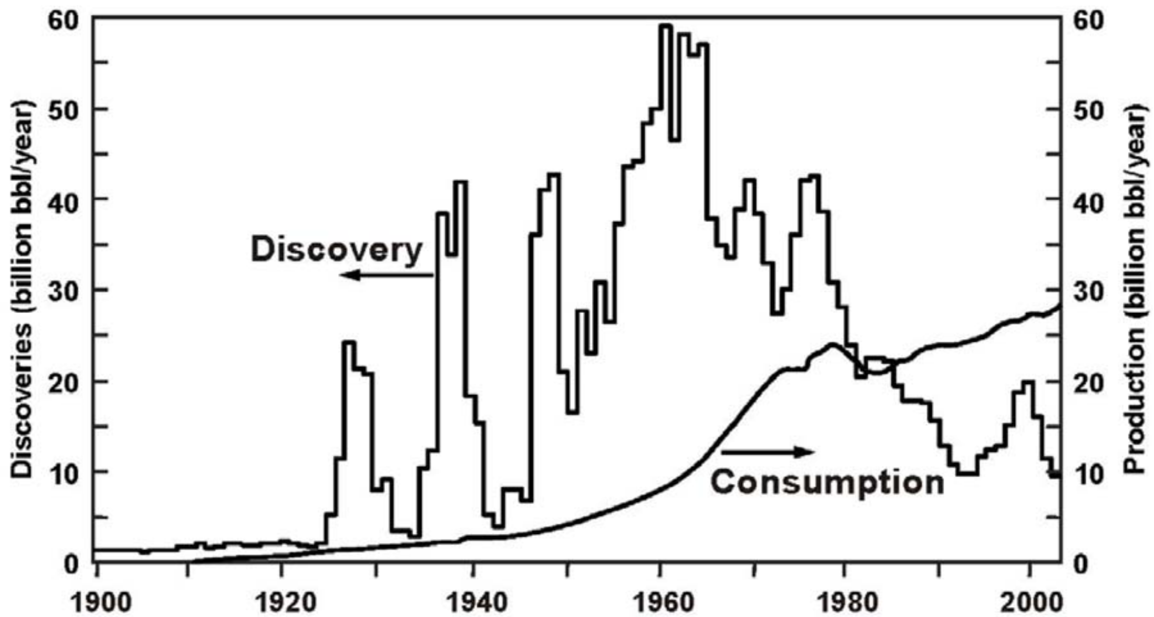

Figure 2 Growing Gap Between World Crude Oil Discovery and World Crude Oil Consumption [From: Schultz]

3. U.S. Import Gap is Increasing

The U.S. is the world leader in total energy consumption. According to a 2004 EIA report, the U.S. consumes approximately 24 percent of the world's energy, equal to the combined consumption of China (13 percent), Russia (7 percent) and India (3 percent). As noted in the EIA AEO2006 "reference case," the gap between domestic energy production and consumption will grow from 29 percent in 2004 to an estimated 33 percent in 2030. The gap will need to be filled by energy imports, and many analysts contend that this dependence on foreign sources of energy could lead to national security issues. Figure 3 illustrates total U.S. energy production, total U.S. energy consumption and the associated gap growing from 1980 to 2030.

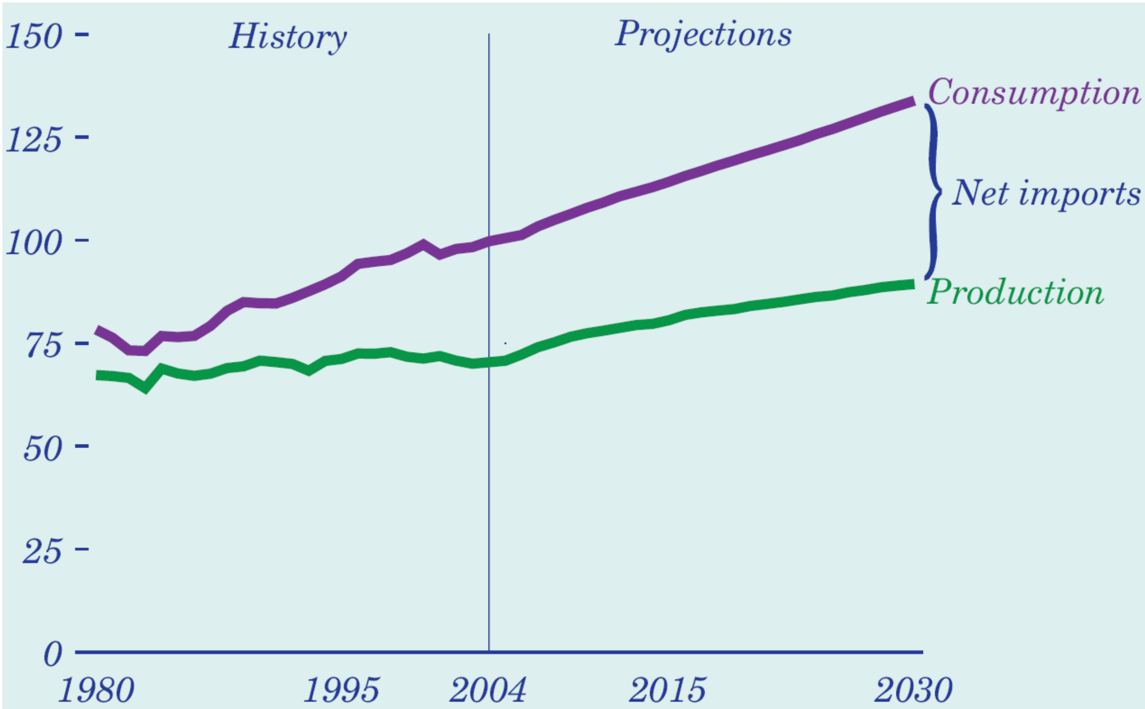

Figure 3 U.S. Total Energy Production and Consumption, 1980-2030 (quadrillion Btu) [From: AEO2006 Reference Case]

4. The U.S. Military May Always Have Access to Fuel, but Will Pay Ever-increasing Prices

The Defense Production Act (DPA) of 1950 authorized the President of the United States to require preferential treatment of materials and resources in support of national defense or emergency. Depending on the circumstances of a specific crisis, the President could invoke the DPA in response to an energy crisis [Swink], thereby assuring the Department of Defense (DoD) access to any available domestic fuel (as discussed in a later section, the U.S. domestically produces 37.5 percent of petroleum consumed, more than enough to satisfy any DoD requirement). Under DPA, the U.S. Government pays market price, which during an extended crisis affecting fuel availability would be elevated, causing the government to purchase the fuel at these higher prices.

In addition to paying an addition price per barrel of fuel, the U.S. military will pay other costs beyond fiscal costs. As discussed in later sections, instability of supplying regions of the world and global competition, questions America's access to petroleum in the future. All oil from overseas regions must be transported to the U.S. or, in the case of the military operating overseas, fuel must be transported to where it is needed. If the U.S.

has to compete for open sea lanes, access to fuel will become an even more important issue. There are several possible scenarios where the U.S. military will not have ready access to petroleum. Delays in fuel deliveries and protecting lines of supply could add burdens to the military and threaten U.S. missions.

5. Green House Gases (GHG) and Air Quality

There is a vigorous debate on whether the U.S. will eventually adopt some form of CO_2 emissions controls. As with other environmental protection regulations (e.g., non detrimental weapon demilitarization, protection of endangered species, and controls on aircraft painting to avoid air pollution [Cohn]), any emission controls adopted by the U.S. will eventually be extended to the DoD. In that case, the U.S. Navy will have to develop a program to control CO_2 emissions and may eventually require a "zero net" CO_2 standard.

C. SYNTHETIC FUEL PROGRAM IS AN OPTION

Although there is no near term fuel availability crisis facing the DoD at this time, the future situation of increasing global demand and the depletion of known fuel reserves suggest it is prudent for the DoD to take action now. The problem will evolve over decades, and the solution will also take decades to develop.

1. Secure Domestic Feedstocks

Synthetic fuels can be developed from various feedstocks to include coal, energy crops, biomass, ranch and slaughter house waste, and municipal solid waste. Unlike fuel obtained from petroleum, these feedstocks are domestically available in quantities, in part or as a whole, to support domestic demand.

a. Coal

The U.S. has 246 billion metric tons of proven coal reserves or 27 percent of the world's known reserves. At current production rates, this is approximately a 240+ year supply of coal. [American Energy Security SSEB] Although production rates may increase, this is enough time to find alternative replacement for liquid hydrocarbons derived from petroleum. Total U.S. coal reserves are equivalent to 800 billion barrels of oil. [Bajura] At the rate the U.S. consumes crude oil today, these coal supplies would take over 100 years to deplete. In addition, the U.S. has oil shale reserves estimated to be equivalent to 750 billion additional barrels of recoverable oil. [AEO2006]

b. Biomass

In April 2005, the U.S. Department of Agriculture (USDA) and the Department of Energy (DOE) released a joint study named "Biomass as Feedstock for Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply." The study stated forestland and agricultural land alone have a potential for 1.3 billion dry tons of biomass feedstock per year. This study concluded that the U.S. has sufficient land resources to produce a sustainable supply of biomass to displace approximately 30 percent of the country's present annual petroleum consumption.

c. Waste

There seems to be no shortage of solid waste in the U.S. In 2005, U.S. residents, businesses, and institutions produced more than 245 million tons of Municipal Solid Waste (MSW), or approximately 4.5 pounds of waste per person, per day. [EPA] Figure 4 shows the components of U.S. municipal solid waste. Changing World Technologies (CWT) has a proprietary process call Thermal Conversion Process (TCP) which can use food waste, grease waste, municipal solid waste and plastic or solid waste and convert it into fuels. Although CWT's TCP is a flexible process, it is not capable of converting all U.S. waste into fuel, but this feedstock has great promise. Today CWT operates a plant in Carthage, Missouri that converts food processing waste, agricultural waste, municipal solid waste and mixed plastics into 5,370 barrels of diesel per day.

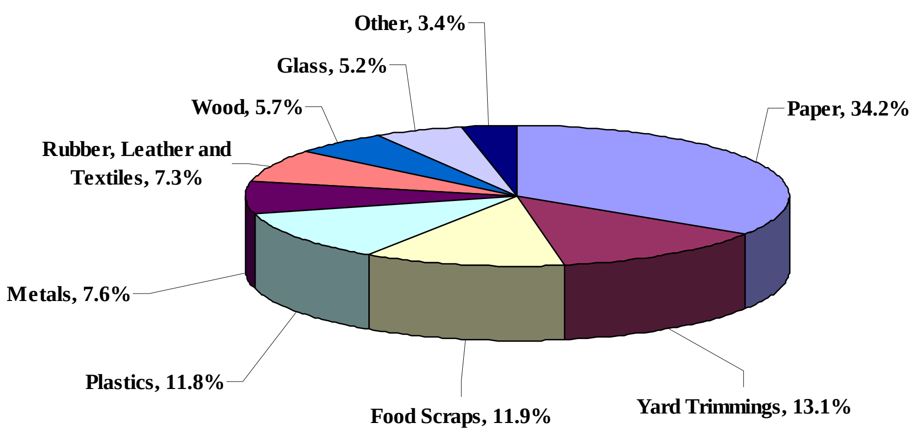

Figure 4 2005 U.S. Municipal Solid Waste Generation Components – 245M Tons [After: EPA]

2. Price Stability

Recent oil prices have been more volatile than coal prices. This can be seen in the EIA AEO2006 reference case, where the price of coal in U.S. is predicted to remain stable through 2025 (minemouth coal price of 20.00 dollars per ton, in 2004 dollars, until 2021 and increasing to 20.63 dollars in 2025), while the price of oil fluctuates between 47.29 and 56.97 dollars from 2005 to 2025, all in 2004 dollars. Notably, the EIA AEO2006 projections are slightly outdated, as oil prices were around 70 dollars per barrel for several months during 2006. The prices that EIA predicts for petroleum, natural gas, coal and nuclear energy can be seen in Figure 5.

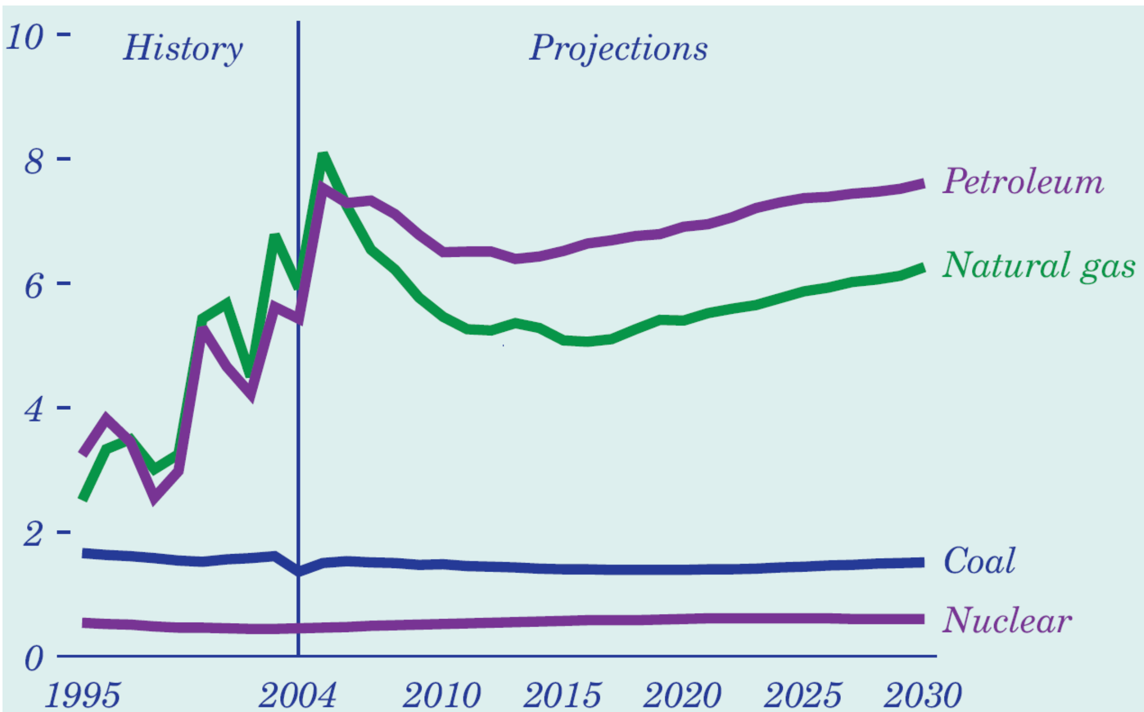

Figure 5 Fuel Prices to Electricity Generators, 1995 -2030 (2004$ per million Btu) [From: AEO2006]

In addition, in "Oil and Energy Price Volatility," Regnier analyzed price volatilities of oil and various other commodities. The article defines price volatility as the standard deviation over a five year period of log difference in monthly producer price index (PPI). Note, the log difference calculation was conducted by starting with a sequence $X(t)$, then it was constructed into the sequence $Y(t) = \ln(X(t)) - \ln(X(t-1))$ and the standard deviation was calculated using 60 sequential $Y(t)'s$.

As shown by the shaded boxes in Table 2, the price of crude oil was more volatile than the price of coal 86 percent of the time, during the period from 1971 to 2005. Note, the above article included analysis dating back to 1945, but Table 2 has data restricted to 1971 since during that period oil price volatility has been much higher and it is a better representation of price volatility of today and the near future.

	1971–1975	**1976–1980**	**1981–1985**	**1986–1990**	**1991–1995**	**1996–2000**	**2001–2005**
Coal	**0.0516**	0.011	0.0146	0.0176	0.0182	0.0189	0.0158
Crude Oil	0.0361	**0.0225**	**0.0294**	**0.116**	**0.0681**	**0.1106**	**0.0976**

Table 2 Average Price Volatility of Coal and Crude Oil from 1971 to 2005 [After: Regnier]

Energy derived from domestically produced crops exhibits moderate price stability. Although crop pricing is sensitive to weather and global commodity pricing, over a long period, crops have price stability due to the fact that agricultural production is well established and understood. The energy crop fuel production plant would determine its recurring agricultural requirements and purchase them on the agricultural market, if available. If not available, this new demand will cause a new market sector to form. For example, switchgrass is a candidate as an energy crop, but as of 2006, the market for switchgrass is scarce, primarily supporting research and development. If the use of switchgrass as a fuel feedstock is found to be viable, demand will be established, the market will expand, and production will meet the new demand.

With regard to feedstocks which support a TCP plant which processes slaughter house residual products, future legislation could drastically change the cost of the feedstock. Slaughterhouse and rendering plants produce, as part of their overall rendering process, what might be called residual "products" or residual "waste." These products are animal offal, blood or innards. Currently, these products can either be sold to farmers, to be recycled into the food chain, or they can be sold to TCP plants as a fuel feedstock. However, if the U.S. adopts regulations similar to those in Europe and Canada that prohibit the first choice (i.e., recycling into the food chain), then the resulting change in demand for these products would certainly change market prices. In particular, rendering plants currently sell the residual product and they would have to switch to paying to remove the residual waste. To illustrate, CWT *pays* 20 dollars a ton for turkey offal, but if there is a change in U.S. regulations which restricts the feeding of animal parts back to animals, CWT might be *paid* 20 dollars a ton to remove the turkey offal.

3. Emissions Reduction

Alternative energy sources provide opportunities for reduction of green house gas emissions. For example, a well balanced biomass fuel production plan can effectively be CO_2 neutral, since all CO_2 burnt into the atmosphere during the utilization process was originally absorbed from the atmosphere during plant growth. Also, during the Fischer-Tropsch (FT) process, there is an opportunity to sequester CO_2, and use it in enhanced oil recovery (EOR) or store it in the Earth for the long term or, according to General Atomics, it can be even further processed as a feedstock for additional fuel production. [Schultz] Finally, FT diesel is ultra low sulfur diesel, which is an attractive characteristic from the perspective of reducing emissions.

II. PROBLEM AND BACKGROUND

A. LIQUID HYDROCARBONS BENEFITS

1. Energy Density

Energy density is a useful metric for describing fuels since fuels can be stored as solids, liquids or gases. Both the energy per unit mass and energy per unit volume are useful metrics to be considered. As shown in Figure 6, liquid hydrocarbons have the highest energy density per unit volume and highest energy density per unit mass, when disregarding the energy density of uranium.

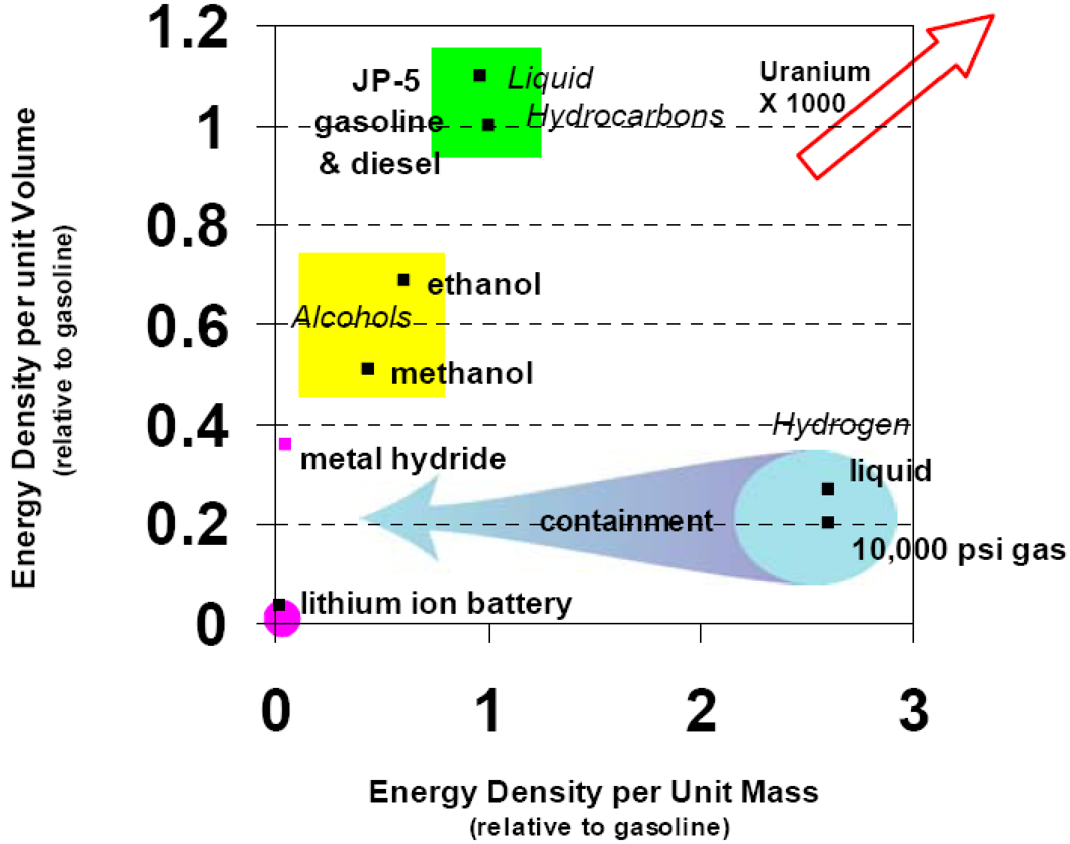

Figure 6 Energy Densities [From: Andrews, et al.]

2. Safety and Stability

The DON currently relies on nuclear power and liquid hydrocarbons for its energy. Nuclear power has a limited number of applications. Liquid hydrocarbon fuels are the DON's primary energy source due to their attractive characteristics of high energy density, high flashpoints, interoperability with other U.S. as well as international services and the ease of transporting and storing them. Liquid hydrocarbons are safer than low volume dense gasses which must be kept at high pressure and in the case of liquid hydrogen, low temperatures, to be useful. Today's tactical vehicles have a limited fuel volume and fuel weight capacity. Furthermore, tactical vehicles are subject to severe environments and must provide protection or hardening to protect the onboard fuel source. The characteristics of today's tactical vehicles necessitate the use of liquid hydrocarbons as a primary fuel source.

B. FUTURE PLATFORMS WILL REQUIRE LIQUID HYDROCARBONS

Most current mobile military platforms use liquid hydrocarbons as their primary fuel source. With the exception of nuclear powered aircraft carriers and submarines, all major platforms in inventory, in construction or in development require liquid hydrocarbons as the primary energy source. Given the expected life of various platforms, the military will be dependent on liquid fuels for many decades into the future.

Additionally, liquid hydrocarbons are well understood in terms of their chemistry, performance and reliability. The engines and power plants that use liquid hydrocarbons have been engineered over many decades to optimize performance.

Notwithstanding the above cited advantages, the problem with current liquid hydrocarbons is that they are, currently, primarily derived from petroleum. For the reasons stated above, DoD needs to investigate alternative sources for liquid hydrocarbons.

C. ENERGY ENVIRONMENT

1. World Energy Environment

The global oil market is approximately 85 million barrels per day. The world is dependent on petroleum for transportation fuels, electricity, chemicals and food production (in the form of fertilizer consumption to support agriculture). World oil prices have risen sharply since 2000 due to increasing of demand and the tightening of supply. Figure 7 shows U.S. and world crude oil prices (in 2004 dollars) and corresponding significant world events.

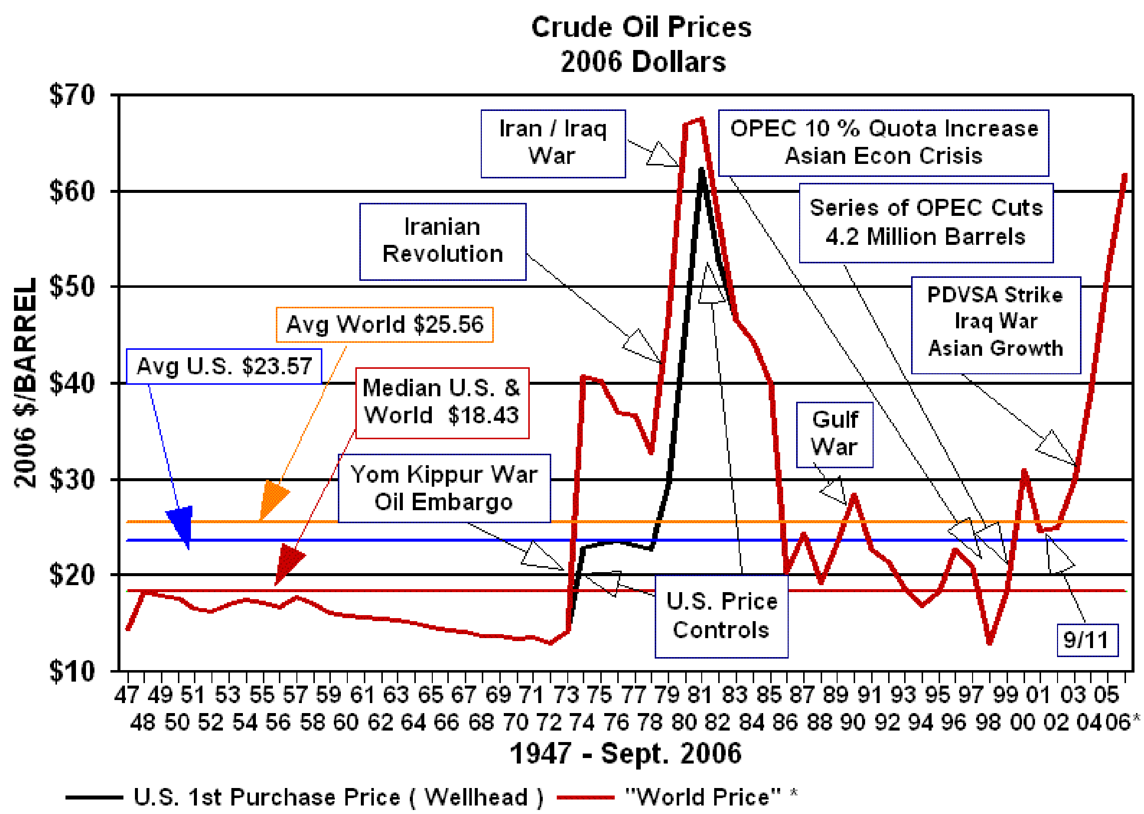

Figure 7 World and U.S. Crude Oil Prices [From: Williams]

a. Oil Reserves are Located in Unstable Regions of the World

According to the *Oil & Gas Journal*, North America has only 16.5 percent of the world's proven oil reserves. Notably, 57.2 percent of the world's proven oil reserves are held in the Middle East as shown in Figure 8. [Radler] In addition, many of the countries in the Middle East treat contributions of state owned fields to the value of national oil reserves as a state secret, so these reserves have not been validated by international organizations. [Simmons]

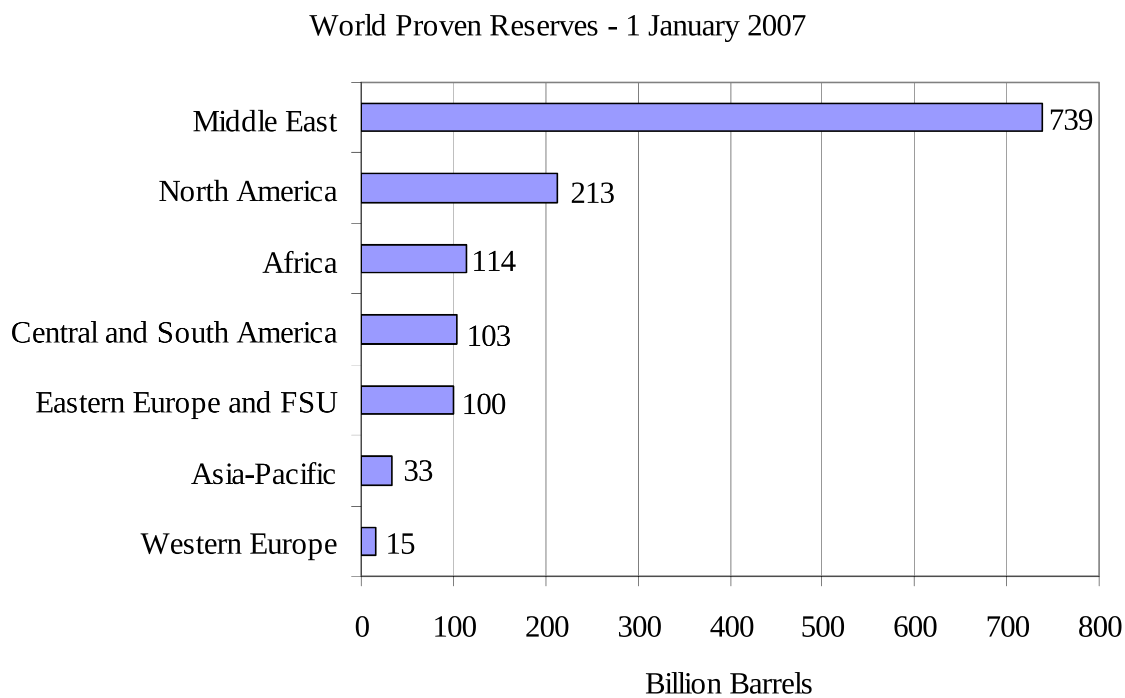

Figure 8 World Proven Reserves by Region [After: Radler]

Much of the crude oil supply is located in politically unstable nations. Furthermore, a substantial portion of the oil the U.S. imports comes from unstable nations susceptible to production interruptions. Specifically, as shown in Table 3, five of the top seven sources of U.S. imports, Saudi Arabia, Venezuela, Nigeria, Algeria and Iraq cannot be considered secure sources of supply. These five nations provide 39.9 percent of U.S. imports and account for 25 percent of domestic oil consumption.

Rank	Country	August 2006 Imports (Thousand Barrels Per Day	% Of Total Imports	% Of Domestic Product Supplied
1	Canada	2,335	17.5%	11.0%
2	Mexico	1,560	11.7%	7.3%
3	Saudi Arabia	1,513	11.3%	7.1%
4	Venezuela	1,376	10.3%	6.5%
5	Nigeria	1,026	7.7%	4.8%
6	Algeria	794	6.0%	3.7%
7	Iraq	620	4.6%	2.9%
8	Angola	544	4.1%	2.6%
9	Russia	485	3.6%	2.3%
10	Virgin Islands *	377	2.8%	1.8%
	Other	2,704	20.3%	12.7%
	Total	13,334	100.0%	62.5%
	OPEC Countries	5,644	42.3%	26.5%
	Persian Gulf Countries	2310	17.3%	10.8%

* Supplier of products made from crude oil

Table 3 Estimated Crude and Products Imports to the U.S. from Leading Supplier Countries [After: American Petroleum Institute]

Saudi Arabia is considered to be a major swing producer since they are the only country producing crude below their peak capacity. Also there are growing doubts about Saudi Arabia's ability to meet the world's increasing demand and continue maintain a significant "surge" capability. Matthew R. Simmons' book *Twilight in the Desert* argues Saudi Arabia's production is at or very near its peak sustainable volume and he proposes production will go into a marked decline in the "very foreseeable future." [Simmons]

In Gal Luft and Anne Korin's *Journal of International Security Affairs* article "Terror's Next Target," the authors conclude that a terrorist attack on a couple of Saudi Arabia's critical oil complex hubs would have devastating consequence on world oil availability and prices: "A single terrorist cell hijacking an airplane in Kuwait or Dubai and crashing it into Abqaiq or Ras Tanura, could turn the complex into an inferno.

This could take up to 50 percent of Saudi oil off the market for at least six months and with it most of the world's spare capacity, sending oil prices through the ceiling." [Luft, et al.]

In the case of Venezuela, the current government is openly hostile to the U.S. and Venezuela's President Hugo Chávez has threatened to cut off oil exports.

In Nigeria and Algeria, there is political and civil unrest, adding to the questionable availability of future oil exports.

Finally, in Iraq, civil unrest and political instability has marked a decline in oil exports since 2001. Additionally, insurgents have targeted oil pipelines and production facilities, threatening long term interruptions.

b. Global Competition for Resources is Increasing

The U.S. leads the world in vehicle density, with 771 cars for every 1000 people. [DOE EERE] Demand for vehicles and fuel to operate them will increase in the future and this growth will be most dramatic in developing countries. As Table 4 illustrates, China had only 1.9 vehicles per 100 people in 2004, but it experienced a 134 percent increase from the per capita number in 1994. The impact on fuel consumption can be illustrated using China as an example. Today China consumes approximately 6.5 Mbbl/day when approximately 2 in 100 of its population own cars. It is anticipated that China will experience a threefold to fivefold increase in its vehicle fleet between 2002 and 2020. Due to the increased automobile fleet alone, it is estimated that China's total fuel consumption will more than double by 2020 despite estimated gradual improvements in vehicle fuel efficiency. [Compton]

Country/Region	Vehicles per 1000 People		% Growth 1994 to 2004
	1994	2004	
China	7.9	18.5	134.2%
Europe, East	155.7	223.2	43.4%
Asia, Middle East	67.4	85.9	27.4%
Asia, Far East	35.8	44.6	24.6%
Central & South America	94	112.4	19.6%
Europe, West	486.8	570.8	17.3%
Pacific	472.4	507.4	7.4%
United States	766.94	771.47	0.6%
Canada	596	569	-4.5%
Africa	24.2	22.5	-7.0%

Table 4 Vehicles Per Capita Around the World [After: DOE EERE]

China's economy has been growing at an average of nine percent per year for the last two decades, and its demand of energy has increased accordingly. Due to its limited domestic resources, China's demand for oil resources has significantly impacted the world oil market. According to the U.S. Energy Information Administration, China has accounted for 40 percent of total growth in global demand for oil in the last four years. To maintain access to world oil, China has courted Canada, Mexico, Venezuela and many African countries including Sudan, Chad, Nigeria, Angola, Algeria, Gabon, and Equatorial Guinea. Chinese official sources state that in the first ten months of 2005, Chinese companies invested a total of 175 million dollars in African countries, primarily in oil exploration projects and infrastructure. China is aggressively moving into six of the top ten countries that supply the U.S., which, according to Table 3 above, accounts for 57.3 percent of the U.S. import market.

c. Global Disruption Theories

Oil is a fungible global commodity where any change in supply or demand anywhere will result in a change in the price everywhere. The White House study "Oil Shockwave" predicted a 4 percent disruption in global supply would result in a 177 percent increase in world price. [Securing America's Future Energy] Today, supply and demand are roughly balanced and any significant disruption in world crude oil supply leads to large fluctuations in world crude oil price.

2. U.S. Energy Environment

a. Domestic Resource Availability

U.S. oil consumption is approximately 21 million barrels per day, of which approximately 13 million barrels a day are imported. The U.S. has a great reserve of energy in coal. Known U.S. coal reserves are equivalent to 800 billion barrels [Bajura], which in energy context is equivalent to 250 years of supply, at current production rates

b. Lessons Not Learned, Demand Continues to Increase

In 1973, during the Arab Oil Embargo, the U.S. imported 34.5 percent of its crude oil and refined petroleum products, with 4.9 percent of U.S. oil supply coming from the Persian Gulf. Today over 60 percent of U.S. crude oil and refined petroleum products are imported with 11.5 percent being provided by Persian Gulf sources. Today, more than any time in history, the U.S. is more dependent on imported oil and petroleum products.

Although the historical record is mixed, recent experience has shown that U.S. oil consumption is essentially price inelastic. This means that consumers generally do not reduce their consumption in proportion to price increases. [Copulos 2006] This fact was demonstrated during the summer of 2006, when the price of crude oil hovered around 70 dollars per barrel and there was no appreciable change in demand. Figure 1 shows increasing U.S. demand for energy. The U.S. has weathered several oil crises but this fact has done little to change public opinion regarding oil consumption and has not meaningfully tempered increasing U.S. demand and dependence on oil.

c. U.S. Refining Capacity

A critical step in the process of providing energy to the U.S. economy is the refining process. Refining is a series of complex processes that turns crude oil and other hydrocarbons into finished petroleum products. Refining starts with simple distillation, or boiling off crude oil into its "fractions" which are the broad categories of component hydrocarbons (e.g., naphtha, kerosene or heavy gas oil). Today's refineries use additional sophisticated processes and equipment to produce the mix of products that the market demands. Generally, these additional sophisticated processes try to minimize the production of heavier, lower value products (e.g., residual fuel oil) in favor of lighter, higher value products (e.g., gasoline). [EIA Oil Market Basics]

As shown in Figure 9, oil refineries have been running at 94 percent of capacity over the last ten years and at peak times of the year, even higher. As of 2006, there were 148 operating refineries in the U.S., a decline from 324 in 1981. Also, no new refinery has been constructed in the United States since 1976. Moreover, future refining capacity within the U.S. will become scarcer in the future, since many U.S. refineries are surpassing their designed life spans and no new refineries are currently being built. [Baardson]

Approximately 47 percent of U.S. refining capacity is in the Gulf states and 28 percent of U.S. oil production is concentrated offshore in the Gulf of Mexico. As hurricanes Katrina and Rita demonstrated, natural disasters can quickly bring U.S. oil production and refining to a standstill. In the immediate aftermath of Katrina alone, U.S. refining capacity was reduced by more than 2 million barrels per day, which is almost 10 percent of total U.S. consumption.

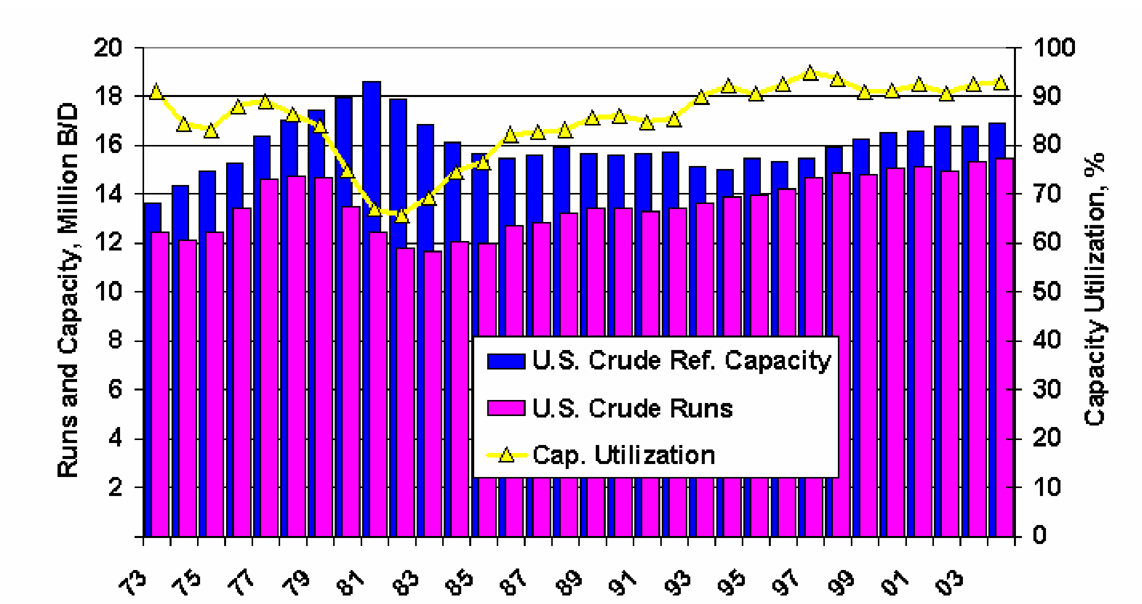

Figure 9 U.S. Crude Oil Refining Capacity 1973 to 2004 [From: EIA Oil Market Basics]

3. Department of Defense and Navy Energy Environment

a. DoD is the Single Biggest User of Refined Fuels

DoD consumes approximately 300 thousand barrels per day (1.4 percent of U.S. consumption) and is considered the largest single domestic user of refined fuels. In fiscal year (FY) 2005, the DoD spent 7.8 billion dollars on fuel and other energy resources of which, the Navy spent 2.5 billion dollars. [DESC FY05 Factbook] As shown in Figure 10, DoD experienced a 2.7 billion dollar (53.4 percent) unplanned increase in fuel expenditures compared to the average expenditure from FY01 to FY04. The Navy experienced a 773 million dollar (43.2 percent) increase over its average expenditure over the same period.

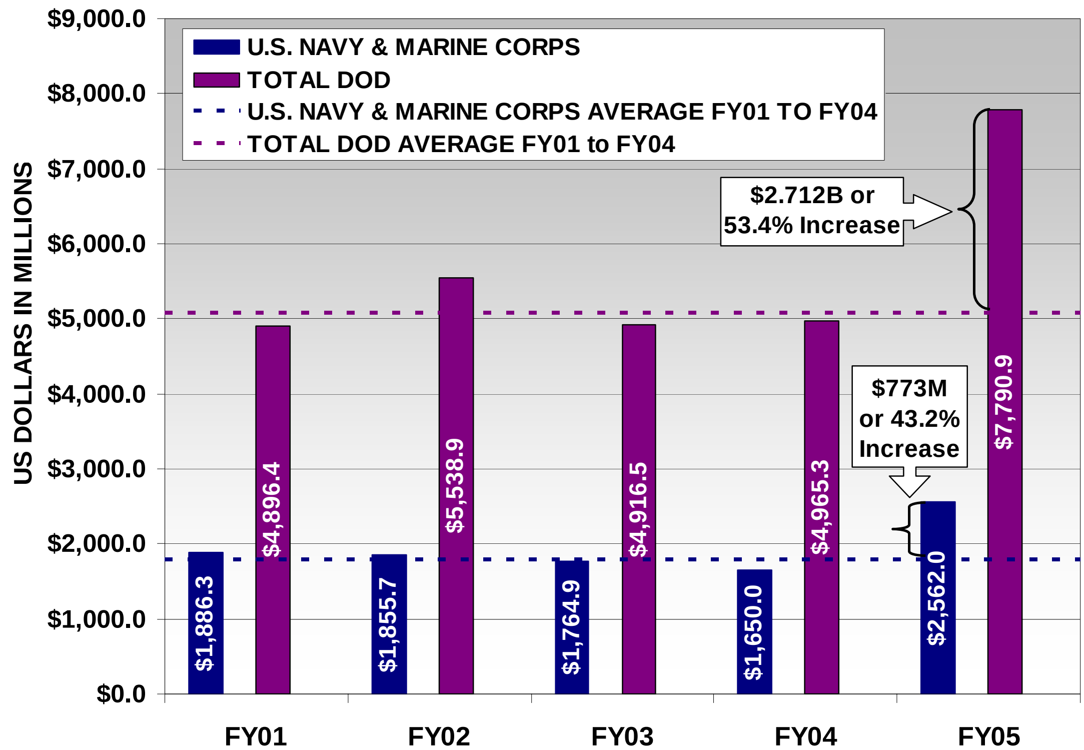

Figure 10 DoD and Navy Fuel Expenditures FY01 to FY05 (then year million dollars) [After: DESC Fact Books]

b. Longevity of Military Vehicles and Platforms

Most military platforms have lifecycles between 20 and 50 years. For example, the M1 Abrams tank is now 27 years old, the Navy's Oliver Hazard Perry ship class is 30 years old and the B-52 Stratofortress entered service in 1952, although the remaining models flying date from the 1960s. With only the exception of nuclear powered aircraft carriers and submarines, all major platforms in inventory, in construction or in development require liquid hydrocarbons as the primary energy source. Therefore, it is prudent to plan on DoD continuing to be a major consumer of liquid hydrocarbons for the foreseeable future.

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III. OPTIONS FOR ANALYSIS

A. STATUS QUO

When decision makers investigate options available for changing the course of an organization, one option that should always be considered is maintaining the status quo, that is, the option to do nothing, or to stay on the current course. When decision makers within DoD look at the rising costs of fuel and a volatile and insecure future energy environment, they can decide to continue on the current path of paying market price and purchasing required fuel from any available source. When asked his opinion about the Navy pursuing alternative fuel options, a senior individual within DON stated "if there is fuel in the world, and we need it, we will buy in. The price we pay is irrelevant." Clearly the status quo or laissez-faire approach is one option.

B. SYNTHETIC FUELS PROGRAM

1. Current State of the Technology

Synthetic fuel (synfuel) is any liquid fuel obtained from sources other than petroleum. Normally the feedstock is coal, natural gas, or biomass material. Occasionally, synfuels also refer to fuels derived from other solids such as oil shale, tar sand, waste plastics, or from the fermentation of biomatter.

The maturity of synfuel technology varies significantly. For clarification, Table 5 was developed as a sample of the various feedstocks, processes and outputs that are possible in creating various synthetic fuels. This list is not exhaustive, and it does suggest the richness of the number of feedstocks, the variety of processes and each respective end product.

Feedstock	Process	Output
Coal		
Feedstock	**Process**	**Output**
Coal	Fischer Tropsch - (Indirect Liquefaction) - Gasification, Water Gas Shift, Synthesis, Hydrocracking	Diesel
		Kerosene (Jet Fuels)
		Chemicals
		Naphtha
Coal	Fischer Tropsch - Gasification, Water Gas Shift, Synthesis, Hydrocracking	Electrical Power
Coal	Bergius Process (Direct Coal Liquefaction (DCL)	Diesel
		Gasoline
Natural Gas		
Feedstock	**Process**	**Output**
Natural Gas	Fischer Tropsch - Gasification, Water Gas Shift, Synthesis, Hydrocracking	Diesel
		Kerosene (Jet Fuels)
		Chemicals
		Electrical Power
Dimethyl Ether (DME)	Gasification, Water Gas Shift, Synthesis	Biodimethylether (Methanol)
Biogas	Digestion, CO_2/H_2O-removal	SNG from biogas
Biogas	Digestion, Steam Reforming/Water Gas Shift, CO_2 Removal	Hydrogen from biogas
Energy Crops		
Feedstock	**Process**	**Output**
Wood, Grass, Corn, Sugar	Fischer Tropsch - Gasification, Water Gas Shift, Synthesis, Hydrocracking	Diesel
		Kerosene (Jet Fuels)
		Chemicals
		Electrical Power
Wood, Grass, Corn, Sugar	Direct Thermal Liquefaction (DTL)	Diesel
Ranch/Slaughterhouse Waste	Direct Thermal Liquefaction (DTL)	Diesel
Sugar, Starch, Cellulosics (Woody Material)	Fermentation, Distillation	Bioethanol
Sugar, Starch, Cellulosics	Advanced Hydrolysis, Fermentation, Distillation	Bioethanol
Cellulosics	Pyrolysis, Hydrogeneration	Bioethanol
Cellulosics	Gasification	Flue Gas (Electricity & Heating)
Cellulosics	Pelletization	Pellets (Heating)
Wet Biomass	Anaerobic Fermentization	Biogas (Heating)
Oils		
Feedstock	**Process**	**Output**
Straight Vegetable Oil (SVO)	Cold Press, Extraction, Refining	BioDiesel
Seeds	Transesterfication, Refining	BioDiesel
Waste Oils and Fats	Transesterfication, Refining	BioDiesel

Table 5 Synthetic Fuels Various Feedstocks, Processes and Products

2. FT Coal to Liquid and Gas to Liquid

Appendix A, taken from Steve Bergin's "Annual Report for the Ultra-Clean Fischer-Tropsch Fuels Production and Demonstration Project," provides a technical background and discussion of the details of the Fischer-Tropsch process.

a. FT Process History

The Fischer-Tropsch (FT) process was originally developed in the 1920's by Germany's Franz Fischer and Hans Tropsch. During World War II, Germany utilized domestic resources and FT to mitigate the problem of increasingly interrupted oil imports. The process started by converting natural gas into a transportation fuel in a process now known as gas to liquid (GTL). At the peak of German synthetic fuel production during WWII there were nine FT plants built and operating in Germany. [Bajura] The process was further advanced from 1950 to mid 1980's South Africa's oil imports were strictly limited by sanctions due to international objection to apartheid. To circumvent these sanctions, South Africa developed three coal to liquid (CTL) facilities. Today, the Sasol II and Sasol III plants produce 150,000 barrels of fuel per day or 23 percent of current South African consumption. [Sichinga, et al.] In both cases, Germany and South Africa, circumstances and the government were the catalysts to invest and develop synthetic fuel industries. [Malone]

The FT technology for CTL plants is proven and the process works. There are over 250,000 barrels per day of current production and another 500,000 barrels per day of capacity under construction. [Bergin]

b. FT Process Overview

In short, the FT process gasifies coal and then reforms the gas at the molecular level into the desired liquid product. This process involves gasifying coal to produce a syngas, which is a mixture of CO and H_2. The syngas is converted to a liquid fuel, either via the FT process or by a non-FT process such as Mobil's Methanol to Gasoline (MTG) process. Cogeneration, or a facility optimized to produce liquids and another product like electricity, appears to have overall higher energy efficiency than strictly producing liquid fuels alone. [Bajura] Modern plant designs often include a cogeneration lineup that is designed to resell excess electricity to the local power grid to offset the retail selling price of the produced fuel.

c. Compatibility with Existing Systems

FT fuels are compatible with the existing motor fuels market and infrastructure. Sasol supplies FT based jet fuel to commercial airliners at Tambo International Airport in Johannesburg. In the fall of 2006, the U.S. Air Force conducted a study using FT synthetic fuel and JP-8 fuel in a 50/50 mix through a series of tests. The study included to in flight tests for two of eight engines on a B-52 burning the 50/50 synthetic fuel mixture. On 15 December 2006, the U.S. Air Force study demonstrated flying a B-52 with all eight engines burning the 50/50 mix. It was reported that there was no discernible difference between flying with the synthetic fuel mix and standard JP-8 fuel. [Matthews]

In addition, since FT fuels are produced at the molecular level, the resulting synfuel is inherently cleaner than raw crude oil and requires less refining. This reduced refining requirement results in a cost savings over the cost to refine crude oil.

d. Environmental Concerns

Coal is widely considered to be an environmentally unfriendly resource due to both poor and unsafe mining techniques as well as its toxic emissions during combustion. However, the mining industry has made significant improvements in mining methods and is now required to adhere to strict federal regulations which require reclamation plans for future coal mining sites.

The FT process allows for CO_2 capture during the fuel production process. These carbon sequestering opportunities can add to the production cost of FT fuels, but reduce CO_2 emissions during the synfuels manufacturing process.

Processing coal into a synfuel through gasification is recognized as one of the cleanest ways to convert the energy content of coal. Since gasification breaks down coal into its basic chemical constituents, many of the undesirable components of the coal (sulfur, mercury and non-combustible minerals) can be removed effectively without significant atmospheric emissions. For example, the sulfur contained in the coal leaves the process as a product that can be captured and processed into marketable materials.

An example of a CTL synfuel that has superior properties is Rentech's FT Diesel. The cetane index measures 72, the volume percent aromatics measures less than 4 percent and the sulfur content measures less than 1 part per million (ppm). Each of these traits are favorable compared to 2006 EPA regulations for standard diesel that requires a cetane index of at least 40, volume percent aromatics of no more than 35 percent, and no more than 15 ppm of sulfur. [Rentech]

The cetane index is a measure of the combustion quality of diesel fuel and is an expression which contributes to the overall fuel quality. Cetane number is really a measure of a fuel's ignition delay (the time period between the start of fuel injection and fuel ignition) and higher cetane fuels will have shorter ignition delay periods than lower cetane fuels. This shorter ignition delay allows more time for the fuel combustion process to be completed, therefore, allowing engines to operate more effectively.

e. Risks and Ramifications

CTL fuel price is dominated by the significant upfront capital costs to build the facility. Therefore, world oil price is the primary driver which determines the economic attractiveness of CTL. If crude oil remains cheap (a Mitretek study [Grey, et al.] suggested sustained crude price under 25 dollars per barrel) CTL fuels can not economically compete. This study intends to identify the conditions under which domestic coal to liquid (CTL) production facility investments would be viable as well the conditions where it would not be viable.

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IV. METHODOLOGY

The methodology employed in the design of the model is shown in Figure 11. The paragraphs below provide an introduction to these steps, and the detailed descriptions are provided in the subsequent chapters.

- The research started with collecting cost data on various synthetic fuel plants from public and private sources. The data were organized into two components: the cost to build a plant, also known as capital expenses (CAPEX), and the annual cost to run the plant, also known as operating expenses (OPEX). All further analysis on CAPEX and OPEX were conducted in parallel as appropriate.

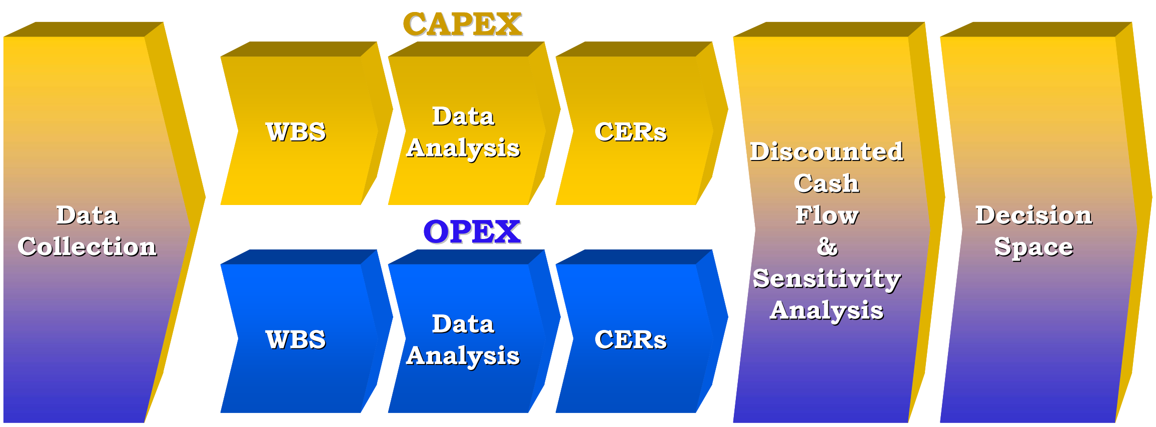

Figure 11 Methodology Overview

- After data collection, the next step in the process was to organize the data into a work breakdown structure (WBS). This WBS is shown in Table 6, with two major components, CAPEX and OPEX, identified as Level 1 work breakdown structure (WBS) elements. For some of the CTL plant data, there was enough fidelity in the data to organize it into a Level 2 WBS. For the data that was down to a Level 2 WBS, the data were reallocated, where appropriate, and as discussed in the next section. Then the Level 2 data were analyzed by using standard cost estimating techniques, including Monte Carlo simulation.
- In the next step, the CTL data that was not detailed enough to be included in the WBS Level 2 analysis, were analyzed at the Level 1 WBS (i.e., CAPEX and OPEX) using regression. The two results, the Monte Carlo simulation model and the regression model, were directly compared to one another and found to be consistent, thereby providing greater confidence in the validity of these results.

- In the next step, the CAPEX and annual OPEX data were merged to find total program cost, or life cycle cost (LCC), over a given period, initially calculated over a period of 30 years (this lifetime is conservative as petroleum plant lifetimes range from 30 to 45 or more years).
- Next, discounted cash flow (DCF) and internal rate of return (IRR) analysis were used to estimate a minimum retail selling price of the synfuel product for the life of a plant. The minimum retail selling price was calculated to cover capital and operating costs and also included a reasonable profit for a private company operating the plant.
- Then retail selling price was examined over various possible coal and crude oil prices over the life of the plant to develop a decision space for pursuing a synthetic fuels program.

FT CTL WORK BREAKDOWN STRUCTURE (WBS)	
LEVEL 1 WBS	**LEVEL 2 WBS**
Capital Expenses (CAPEX)	
	Solids Handling
	Air Separation Unit
	Gasification System
	Liquids Area
	Power Block
	Refining Area
	Balance of Plant *
	Other * (e.g. Owner Contingencies, License or Design)
Operating Expenses (OPEX)	
	Feedstock
	Catalyst & Chemicals
	Labor & Overhead
	Administrative Labor
	Taxes & Insurance
	Other *

* Elements eventually reallocated into other elements

Table 6 FT CTL Work Breakdown Structure Level 1 and Level 2 Elements

V. DATA AND COST ESTIMATES

A. DATA COLLECTION

1. Consolidate Data from Diverse Sources

This study draws on data from 53 different sources. They are companies and other organizations that plan, build or operate CTL plants. These data originate in studies funded by government or the private sector. Some data were in the public domain. Proprietary data has been presented in a manner so as to protect its nature.

As often happens in the data collection phase of analysis, we found that many studies reference the same original data. When this was recognized, the duplicated data were omitted. Still, some studies may have used the same fundamental source, and the data were modified to fit the reports unique characteristics. In these cases, it was impossible to identify if data were duplicated, so the data remained in the population.

2. Variation in Collected Data

There are inconsistencies within the data that affect the capital and operating expenses of each cost study. For example if the feedstock is coal, there are many different coal qualities with different energy values, measured in Btu. Even within a specific quality of coal, there are different energy values associated with the region of the country where the coal is mined. Also, there can be variance of energy values of the coal from different areas of the same mine. These situations were handled by including all of these diversities into the model and this fact contributes to some of the resulting variance in the developed models.

The studies we examined accounted for many different cost and planning elements (e.g., taxes, permitting, depreciation, transportation, etc.) and these were noted throughout the data collection process. As more studies were added to the data, it was evident that the data were inconsistent. For example, some studies documented taxes as a cost element in the estimated operating expenses, while others did not directly discuss taxes. The studies that did not discuss taxes may have included taxes elsewhere in the operating expenses or, quite possibly, not at all; it would be impossible to know which the case was. Although every effort was made to make the data consistent, the situations where inconsistencies within each cost element could not be resolved were handled by including the best known data, including diversities, into the model. This fact also contributes to some of the resulting variance in the developed models.

3. Normalization for Inflation

There was another inconsistency across the data that had to be accounted for and corrected. Specifically, the collected data consisted of the cost estimates from many different years. Considering the fact that a dollar spent today buys more than it will in the future, but buys less than it did in the past, all the data had to be adjusted to account for the effects of inflation over time. [Nussbaum] During data collection, cost estimates were noted to be in terms ranging from 1994 dollars to 2006 dollars.

For purposes of this study, all cost estimates were normalized to 2006 dollars using Gross Domestic Product (GDP) Implicit Price Deflator (IPD) indices. [Economagic] The GDP IPD uses the ratio of GDP in current prices divided by GDP in constant prices and is used to account for the effects of inflation, by identifying the change in the prices of the bundle of goods that make up the GDP as well as the changes to the bundle itself.

B. WORK BREAKDOWN STRUCTURE DEVELOPMENT FOR CTL PLANTS

A critical first step in a cost estimate is to develop a Work Breakdown Structure (WBS). The concept of a WBS is to divide the system into pieces that, as a complete group, encompass the entire program. Synthetic fuels plants, regardless of size, overall configuration, location or feedstock, share common process elements. In developing and operating a synthetic fuels plant the major cost categories consist of building the plant, also known as capital expenses (CAPEX) and the annual cost to run the plant, also known as operating expenses (OPEX). The paragraphs below refine the WBS to levels below the CAPEX and OPEX levels.

1. CTL Plant CAPEX

In this analysis the CAPEX was initially broken into a Level 2 WBS, which consisted of the following major work breakdown structure elements (WBSE) of a FT CTL fuel plant:

1. Solids Handling (SH)
2. Air Separation Unit (ASU)
3. Gasification System (GS)
4. Liquids Area (LA)
5. Power Block (PB)
6. Refining Area (RA)
7. Balance of Plant (BOP)
8. Other (e.g., Owner Contingencies, License or Design) (OTH)

WBSE 7 (BOP) and WBSE 8 (OTH) showed great inconsistencies across the data. For example, some data sets completely lacked these elements. To remove this source of irregularity, these two elements were reallocated into the top six elements. This reallocation was completed in a weighted fashion. For example, if SH consisted of 7.5 percent of the total cost and the sum of the BOP + OTH was 10 percent of the total cost, then SH was recomputed as follows:

$$SH_{new} = SH_{old} + \frac{0.075}{0.90} * (BOP + OTH)$$

The result maintained the integrity of the total cost, preserved the common parts of the WBS, and reallocated the highly inconsistent elements proportionally into the primary elements.

The removal of balance of plant and other resulted in the following as the CAPEX WBS used in this study:

1. Solids Handling (SH)
2. Air Separation Unit (ASU)
3. Gasification System (GS)
4. Liquids Area (LA)
5. Power Block (PB)
6. Refining Area (RA)

The summary data for CAPEX used in this study can be found in Appendix B. A schematic line-up of a typical FT CTL plant is shown in Figure 12.

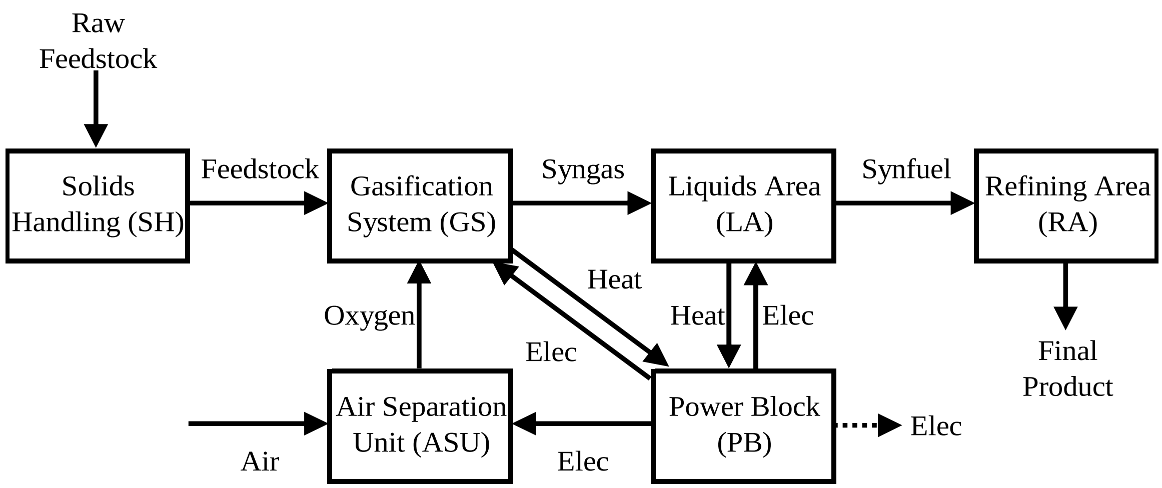

Figure 12 Schematic Line-Up of a Typical CTL Plant

a. Solids Handling (SH)

The solids handling element is the equipment that handles the feedstock solids from their receipt to the gasifier. These elements could include lay down areas, long term storage facilities, conveyor systems and initial feedstock processing equipment. Depending on the location of the facility, the feedstock material can be shipped to the facility by truck, rail or barge. Whatever mode of transport is used, each requires specific unloading areas and equipment. If coal is used as a feedstock, there are different handling requirements for different types of coal. For example, the coal may need to be crushed to the appropriate product size and possibly dried to the appropriate moisture content.

b. Air Separation Unit (ASU)

The air separation unit in takes air and makes oxygen for use in the gasification process and nitrogen for the handling processes. Most air separation units consist of many stages of compressors and are a significant energy load on the process.

c. Gasification System (GS)

The gasification process is a complex process to convert the feedstock into a synthetic gas or syngas. There are many approaches to how to conduct this process. These include single or multi stage, slurry or dry feed, quench and non-quench, oxygen or air blown, to name a few. Other components of this element include coolers, slag handling equipment, particulate removal equipment, water treatment plant and acid gas removal equipment.

d. Liquids Area (LA)

The liquids area is the area of the plant that converts the syngas into a liquid state. This area includes FT reactors, catalyst handling, heat exchangers, separators, tail gas handling equipment, and possibly recycle-loops, depending on the exact process used. This area produces crude naphtha, crude middle distillate and crude wax, which are sent to the refining area. Additional equipment can be added to this area for carbon dioxide removal and compressed for offsite storage or use in enhanced oil recovery (EOR) processes.

e. Power Block (PB)

The power block collects excess heat from the gasification system and the liquids area, uses that energy to power a steam generator, which then provides electricity to the rest of the facility. The major electrical power loads are the air separation unit, the gasification system and the liquids area. Some designs include the option to take excessive electrical energy produced but not used within the facility, and sell it to the local power grid to offset the cost of fuel production.

f. Refining Area (RA)

The refining area takes the synfuel produced in the liquids area and upgrades the fuel to saleable naphtha and high quality diesel fuel by using either hydrotreating or hydrocracking. This area also consists of holding and transfer tanks for commodity storage.

2. CTL Plant OPEX

The major elements for OPEX for synthetic fuels plants was also broken into a Level 2 WBS, which initially consisted of the following major elements of a synthetic fuels plant:

1. Feedstock
2. Catalyst & Chemicals
3. Labor & Overhead
4. Administrative Labor

5. Taxes & Insurance
6. Other

Similar to the discussion of the inconsistencies in WBSE 7 and WBSE 8 in CAPEX, there is a similar problem with OPEX WBSE 6 (Other). Also similarly to the reallocation process in CAPEX, this element was reallocated into the top five OPEX elements. This reallocation was completed in a weighted fashion, similar to how the BOP and OTH were handled in the CAPEX section. This resulted in maintaining the integrity of the total cost, preserved the common parts of the WBS, and reallocated the highly inconsistent element proportionally into the remaining elements.

The removal of other resulted in the following as the OPEX WBS used in this study:

1. Feedstock
2. Catalyst & Chemicals
3. Labor & Overhead
4. Administrative Labor
5. Taxes & Insurance

These WBS elements are self explanatory and will not be further explained in this report. The summary data for OPEX used in this study can also be found in Appendix B.

C. DEVELOP COST ESTIMATING RELATIONSHIPS (CER)

1. Monte Carlo Simulation for CTL Plants

a. Monte Carlo Simulation Background

According to Moore and Weatherford, a simulation model is “a series of logical and mathematical operations that provides a measure of effectiveness for a particular set of values of the parameters and decisions.” [Moore, et al.] In other words, the simulation emulates the behavior of a real system.

A Monte Carlo simulation uses generation of random variables, similarly to generation of random numbers in casinos, as in the famous Monte Carlo casinos in Monaco.

> The random behavior in games of chance is similar to how Monte Carlo simulation selects variable values at random to simulate a model. When you roll a die, you know that a 1, 2, 3, 4, 5, or 6 will come up, but you don't know which for any particular roll. It's the same with the variables

> that have a known range of values but an uncertain value for any particular time or event (e.g., interest rates, staffing needs, stock prices, inventory, phone calls per minute). … Spreadsheet risk analysis uses both a spreadsheet model and simulation to automatically analyze the effect of varying inputs on outputs of the modeled system. One type of spreadsheet simulation is Monte Carlo simulation, which randomly generates values for uncertain variables over and over to simulate a model. [Decisioneering]

There are two main advantages of using simulation to gain an understanding of system behavior. Simulation is used when a mathematical model is too complex to analyze and when a mathematical method may return only the most likely result of a random experiment. Simulation, on the other hand, can simulate a complex model, and it gives a spectrum of outcomes and their likelihood.

The costs associated with a synthetic fuels plant is subject to a number of variables, whose values are not known with certainty in advance. Rather, these variables have different values which may be modeled as random variables, with each variable described by a distribution of values. Therefore, using the Monte Carlo simulation allows for a cost estimate to be established when the work breakdown structure elements are uncertain. The cost of work breakdown structure elements are random variables and their behavior can be described by a probability distribution. [Moore, et al.]

b. Monte Carlo Simulation for CTL Plants

The first approach to developing a CER for CAPEX and OPEX was to conduct a Monte Carlo simulation for each of the major cost categories: CAPEX and OPEX. Within each major cost category, the costs associated with the WBS elements were statistically analyzed and developed into a distribution.

Our database has CAPEX values down to the Level 2 WBS described above for ten data points of CTL plants. These plants ranged from daily plant capacity of 23,800 barrels per day (bpd) to 60,000 bpd, with CAPEX ranging from 1.6 billion dollars to 4.7 billion dollars (2006 dollars). To normalize these data points, the CAPEX of each WBS element was divided by the daily plant capacity, thereby providing a transformed cost, equal to CAPEX per bpd.

A similar approach was used for the seven data points available for the OPEX of CTL plants. Their plant capacities ranged from 30,000 bpd to 60,000 bpd and had OPEX ranging from 240 million dollars per year to 670 million dollars per year (2006 dollars). The annual OPEX was normalized by dividing the OPEX of each WBS element by the daily plant capacity, thereby providing a transformed cost, equal to annual OPEX per bpd.

c. Tests for Normality for CTL Plants

During the initial Monte Carlo simulation trials, the distributions describing the WBSE were thought to be varied. Initially, it appeared some elements were best described with a uniform distribution, and others were thought to be described by a normal distribution. Analysis conducted later in model development proved that normal distributions were adequate to describe the distributions for each of the WBSE for use in development of the final model.

Normality of the distributions describing each WBSE was tested by using the Lilliefors/Van Soest test of normality, which is a modification of the Kolomogorov-Smirnov goodness of fit test. In this test, the null hypothesis is that the error is normally distributed with an alternative hypothesis that the error is not normally distributed. This test first estimates the population mean and variance based on the data, then it evaluates the maximum difference between the empirical distribution and the cumulative distribution function (CDF) of the normal distribution (using the estimated mean and estimated variance). This maximum difference is the test statistic for the Lilliefors test. Finally the test statistic is evaluated to be statistically significant, which would require rejecting the null hypothesis, by comparing it to the Lilliefors distribution. Note, since the hypothesized CDF is based on the sample data, it has been influenced by the data, so the Lilliefors critical value (or α -value) is made smaller than the Kolomogorov-Smirnov alpha value for a given sample size.

d. Test for Normality Results for CTL Plants

For each WBS element, Lilliefors test for normality was conducted. The results to the Lilliefors normality tests can be seen in Appendix C, specifically in Table 18 for CAPEX and Table 19 for OPEX. Each WBS element passed (i.e., we could not reject the null hypothesis) the test for normality at a Lilliefors' critical value with $\alpha = 0.10$. This means that the analysis proceeded with the assumption that each WBSE can be described by a normal distribution.

As stated earlier, during initial trials of the Monte Carlo simulation it was believed some elements of the WBS were best modeled using either a uniform distribution (e. g. cost of administrative labor) or a normal distribution. This additional complexity warranted the use of Monte Carlo simulation.

However, later analysis showed each element of the WBS was sufficiently represented by a normal distribution, which makes a Monte Carlo simulation unnecessary. In this case the Monte Carlo simulation is not required because the statistical results would be the same as combining the mean and variance of each WBS element to get the total mean and variance for the total cost distribution. It is well known that under conditions of normality, it is straightforward to compute the mean and standard deviation of a sum of random variables. That is, if $X_1, X_2, \cdots, X_n$ are random variables with means $\mu_1, \mu_2, \cdots, \mu_n$ and variances $\sigma_1^2, \sigma_2^2, \cdots, \sigma_n^2$, and if $X = X_1 + X_2 + \cdots + X_n$, with mean μ and variance σ^2, then it is always true that $\mu = \mu_1 + \mu_2 + \cdots + \mu_n$, and, if $X_1, X_2, \cdots, X_n$ are all normal, then $\sigma^2 = \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_n^2$.

In our case, showing that the cost of each WBSE is normally distributed allows us to avoid Monte Carlo simulation to evaluate mean and standard deviation for CAPEX and OPEX. In particular, for CAPEX:

$$\mu_{CAPEX} = \mu_{SH} + \mu_{ASU} + \mu_{GS} + \mu_{LA} + \mu_{PB} + \mu_{RA}$$

and the standard deviation of CAPEX:

$$\sigma = \sqrt{\sigma_{SH}^2 + \sigma_{ASU}^2 + \sigma_{GS}^2 + \sigma_{LA}^2 + \sigma_{PB}^2 + \sigma_{RA}^2}$$

Similar calculations are applicable to OPEX.

Through the evolution of this work, the Monte Carlo simulation was initially completed. Later, a colleague asked if Monte Carlo simulation was necessary. In fact, if the underlying distributions can be shown to be normal, then a closed form solution, rather than a Monte Carlo simulation, could be used. The tests for normality were conducted and found utilization of all normal distributions was indeed statistically sufficient. Nevertheless, the Monte Carlo model is included here in the interest of complete reporting of the research done on this thesis.

2. Regression Analysis for CTL Plants

As discussed in the methodology section, some data were specific enough to examine the data at each element of the Level 2 WBS. Specifically, there were ten CAPEX data points and seven OPEX data points of this kind. Unfortunately, this left 22 CAPEX and 14 OPEX data points unexamined, and we were motivated to capture these data to further our understanding of the cost drivers for CTL plants. See Table 7 for a list of the data specificity.

So, the next step in the process was to evaluate all the collected data at the Level 1 WBS. The process is described in the Data Regression for CAPEX and Data Regression for OPEX paragraphs below. Just as was done in the Monte Carlo Simulation, the CAPEX and OPEX data were initially handled independently.

	Level 1 Only	Level 1 and Level 2	Total
CAPEX	22	10	32
OPEX	14	7	21

Table 7 CAPEX and OPEX Data Specificity

a. Data Splitting

This analysis used a data splitting technique, also commonly known as cross validation. In this analysis, collecting new data for validation purposes was not possible, so the data were split into estimation data and prediction data. The estimation data were used to build cost estimating relations (CER) and the prediction data were used to study and validate the predictability of the models. [Montgomery, et al.]

Specifically, the data used in the Monte Carlo simulation (ten CAPEX and seven OPEX data points) were segregated and set aside as the prediction data. The remaining data (22 CAPEX and 14 OPEX data points available at the Level 1 WBS) were used as the estimation data to develop the cost estimating relations. Then the prediction data were tested against the models by evaluating if the prediction data fell within two standard deviations of the values predicted by the developed CERs.

b. Regression Analysis for CAPEX

Each of the 22 data points provided, at the Level 1 WBS, was simply a point cost estimate for total CAPEX at the corresponding plant capacity. In this portion of the CAPEX analysis, these 22 data points are the database for developing the CAPEX regression model. A list of the data used for the CAPEX regression can be found in Appendix B, Table 16.

These 22 data points were normalized to 2006 dollars to adjust the data for inflation, since the original data had CAPEX in different fiscal years. A scatter plot of the data, with plant capacity as the independent variable (x axis) and CAPEX as the dependent variable (y axis), showed that there existed some structure and gave us an expectation that regression analysis would provide fruitful insights. The scatter plot of the estimation data can be seen in Figure 13. Regression analysis was conducted to find the best fit for the data, by looking at linear, logarithmic, power and exponential equations.

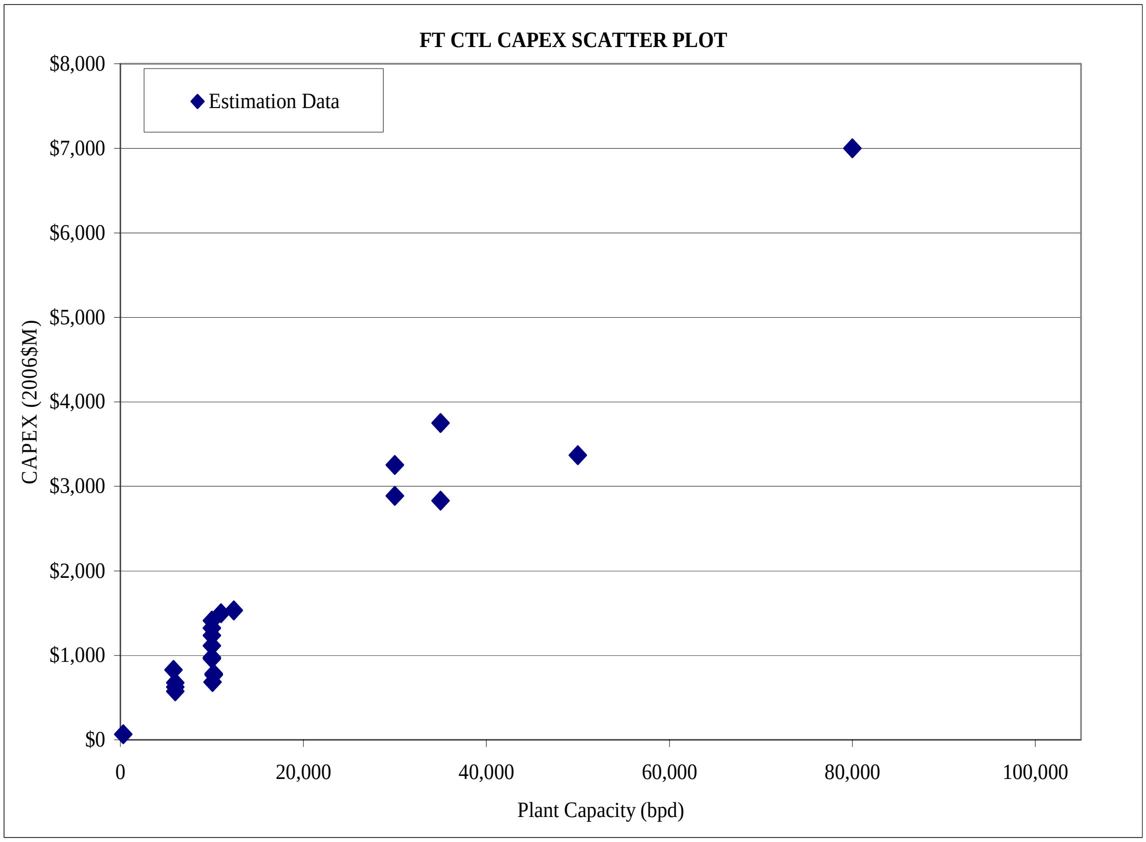

Figure 13 FT CTL CAPEX Scatter Plot of Estimation Data

c. Regression Analysis for OPEX

Similar to CAPEX, the OPEX Level 1 WBS simply gave point estimates for the cost estimate for annual OPEX and a corresponding plant capacity. In this portion of the OPEX analysis, there were 14 data points used as estimating data to develop the OPEX regression model. A list of the data used for the OPEX regression can be found in Appendix B, Table 17.

Again, the original data were in various dollar years, so the data were normalized to 2006 dollars. Next, the data were plotted on a scatter plot with plant capacity as the independent variable and OPEX as the dependent variable. The scatter plot of the estimation data can be seen in Figure 14. Regression analysis was conducted to find the best fit for the data.

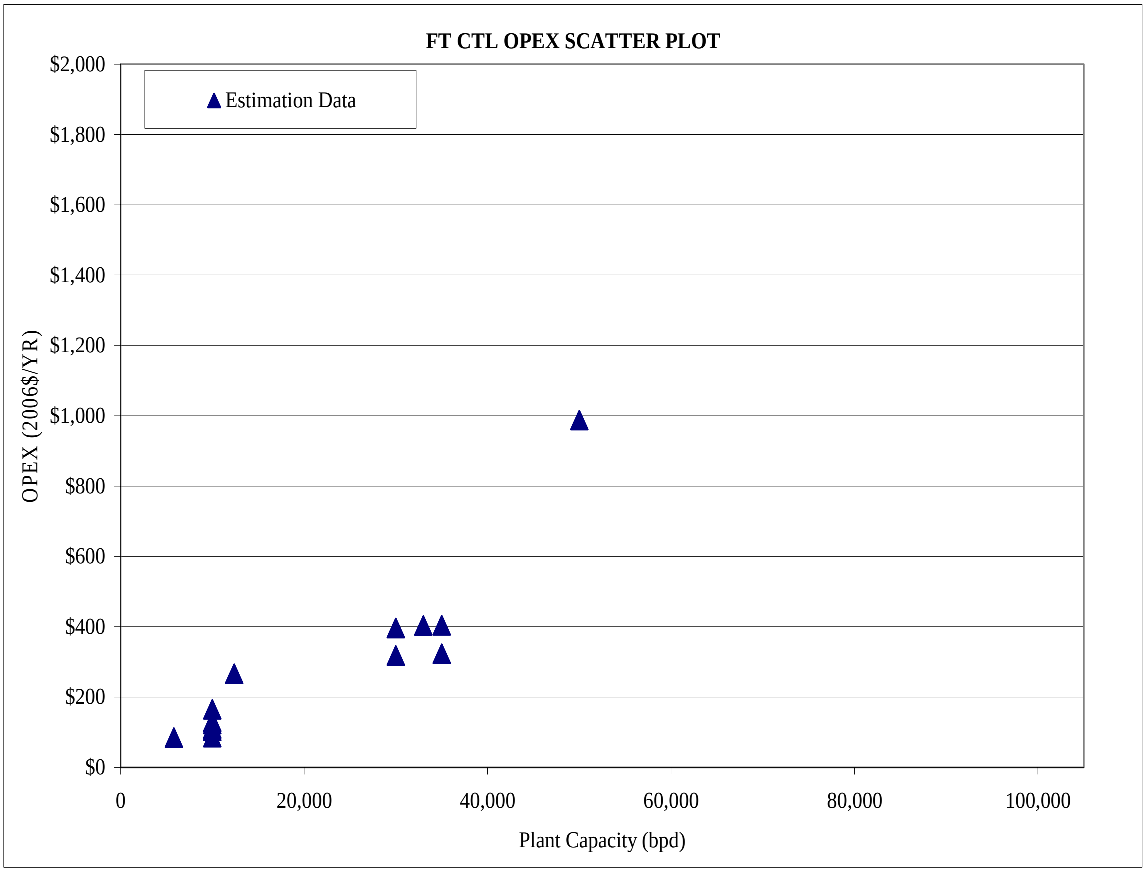

Figure 14 FT CTL OPEX Scatter Plot of Estimation Data

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VI. OBSERVATIONS

A. MONTE CARLO SIMULATION FINDINGS

1. CAPEX Findings

The data for CAPEX, found in Appendix B, Table 12, were analyzed by finding the mean and standard deviation of each element of the Level 2 WBS. The statistical data for the CAPEX data sets can be found in Appendix B, Table 13. The mean and standard deviation for each WBSE were used to build normal distributions (all distributions were assumed to be normal, and these assumptions were subjected to tests of normality, as discussed above). One trial of the Monte Carlo simulation consisted of picking a value from each of the WBSE distributions and summing these values to find the total CAPEX cost for a theoretical "one barrel per day plant." The Monte Carlo simulation was run for 1000 trials.

Due to removing plant size from the data, or normalizing the data to create a theoretical "one barrel per day plant" (this was done by taking each element of the data and divided by the plant capacity), this model was independent of the plant size. This methodology presumes the intercept equals zero. Each run of the Monte Carlo simulation produced a CAPEX cost for a plant that produced one barrel per day. To use this CAPEX for a one barrel per day plant cost and convert it to a plant that produces a given volume each day, the CAPEX for a one barrel per day plant was multiplied by a desired plant capacity. This resulted in a linear model to estimate CAPEX for any plant size within the range of the data used (for this part of the analysis the range of data was approximately 20,000 bpd to 60,000 bpd).

As described in the paragraph above the results of the Monte Carlo simulation were used to find the estimated CAPEX cost of a 30,000 barrel per day plant. The histogram and the cumulative distribution function (CDF) can be seen in Figure 15. The median price (or 50th percentile) was approximately 2.32 billion dollars (2006 dollars). The results of the Monte Carlo simulation were also used to find the cost of a 60,000 barrel per day plant. The histogram and CDF of a 60,000 barrel per day plant are shown in Figure 16, and has a median price of 4.64 billion dollars (2006 dollars).

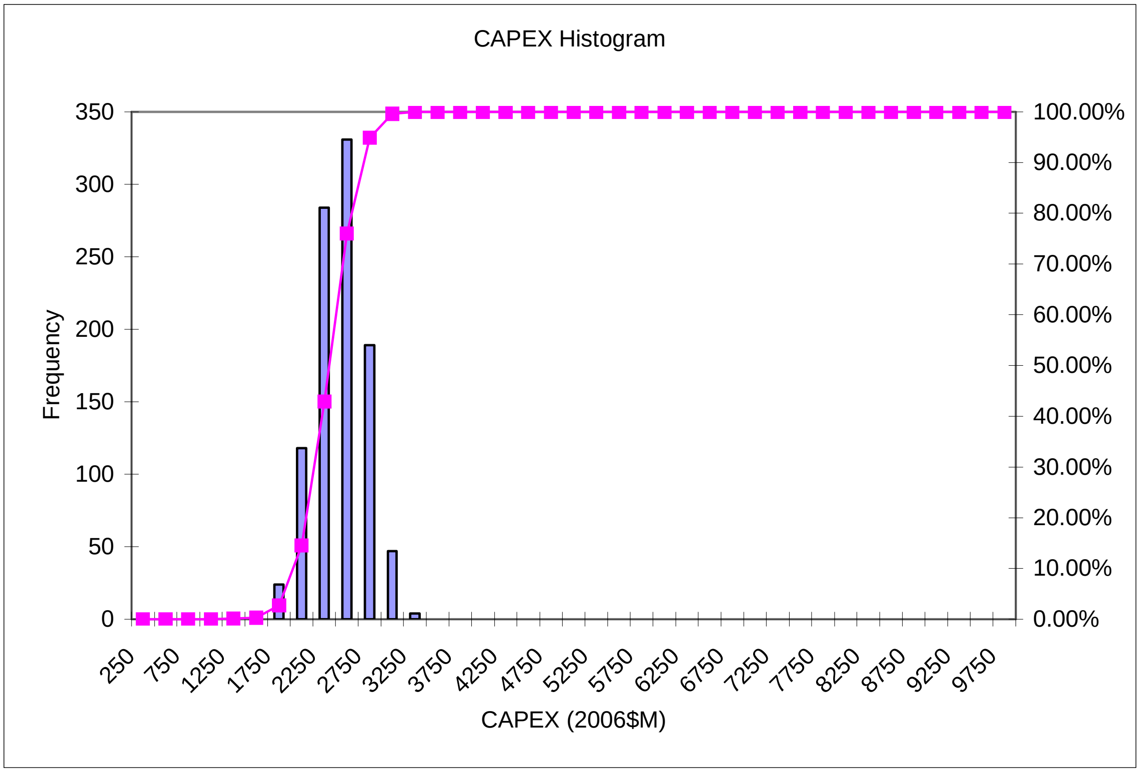

Figure 15 MC Simulation Histogram CAPEX Range for 30,000 bpd Plant

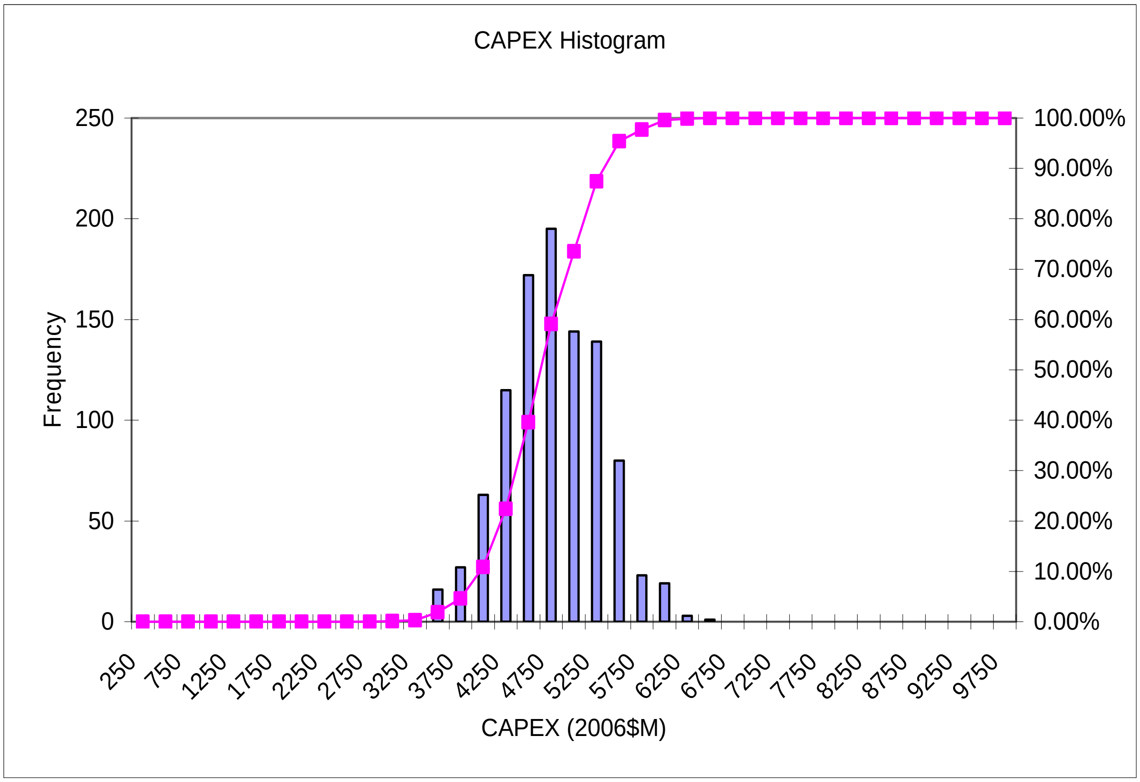

Figure 16 MC Simulation Histogram CAPEX Range for 60,000 bpd Plant

To extend the Monte Carlo simulation results across the range of data, the following equations were developed using a linear regression of several of Monte Carlo simulation results to find the median CAPEX cost and plus/minus 2 standard deviations:

$$y_{MC\ CAPEX} = CAPEX\ \ (2006\$M)$$
$$x = Plant\ Capacity\ (bpd)$$
$$y_{MC\ CAPEX\ +2SD} = 0.0947x + 6.0316$$
$$y_{MC\ CAPEX\ median} = 0.0772x - 2.6929$$
$$y_{MC\ CAPEX\ -2SD} = 0.0597x - 11.417$$

The coefficients in the above equations (i.e. 0.0947, 0.0772 and 0.0597) represent the estimated cost (in 2006 millions of dollars) of adding one additional unit of capacity at the median cost estimate (or plus or minus two standard deviations). Note, the *y* intercept values (i.e. 6.0316, -2.6929 and -11.417) are effectively zero, when considering the scale of the y axis (the data ranges from 0 to 9,500). Figure 17 is a plot of the above equations and graphically shows the relationship between CAPEX and plant capacity.

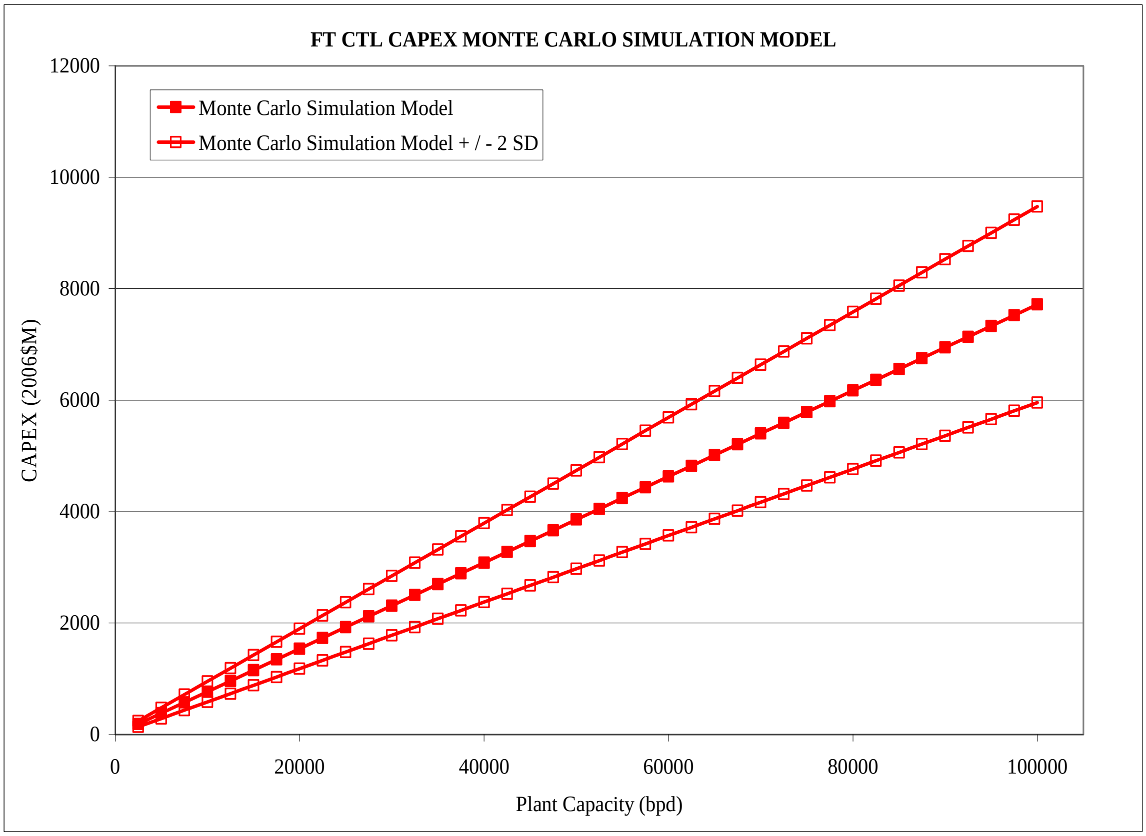

Figure 17 MC Simulation CAPEX (2006 million dollars) vs. Plant Capacity (bpd)

2. OPEX Findings

The model for OPEX was developed similarly to the CAPEX model. The data for OPEX, found in Appendix B, Table 14, were analyzed by finding the mean and standard deviation of each element of the WBS at Level 2. The statistical data for the OPEX data sets can be found in Appendix B, Table 15. The mean and standard deviation for each WBSE were used to build a normal distribution. One trial of the Monte Carlo simulation consisted of picking a value from each of the WBSE distributions and summing these values to find the total annual OPEX cost for a theoretical "one barrel per day plant." The Monte Carlo simulation was run for 1,000 trials.

Similar to CAPEX, the OPEX model was independent of plant size. Each run of the Monte Carlo simulation produced an annual OPEX cost for a plant that produced one barrel per day. To use this one barrel per day plant cost and convert it to a plant that produces a given volume each day, the OPEX for a one barrel per day plant was multiplied by a desired plant capacity. This resulted in a strictly linear model which was able to find an estimate of annual OPEX, for any plant size within the range of the data used (for this part of the analysis the range of data was approximately 30,000 bpd to 60,000 bpd).

The results of the Monte Carlo simulation were used to find the estimated annual OPEX cost of a 30,000 barrel per day plant. The histogram and the cumulative distribution function (CDF) can be seen in Figure 18. The median operating cost (or 50th percentile) was approximately 273 million dollars per year (2006 dollars). The results of the Monte Carlo simulation were also used to find the cost of a 60,000 barrel per day plant. The histogram and CDF of a 60,000 barrel per day plant are shown in Figure 19 and has a median price of 543 million dollars per year (2006 dollars).

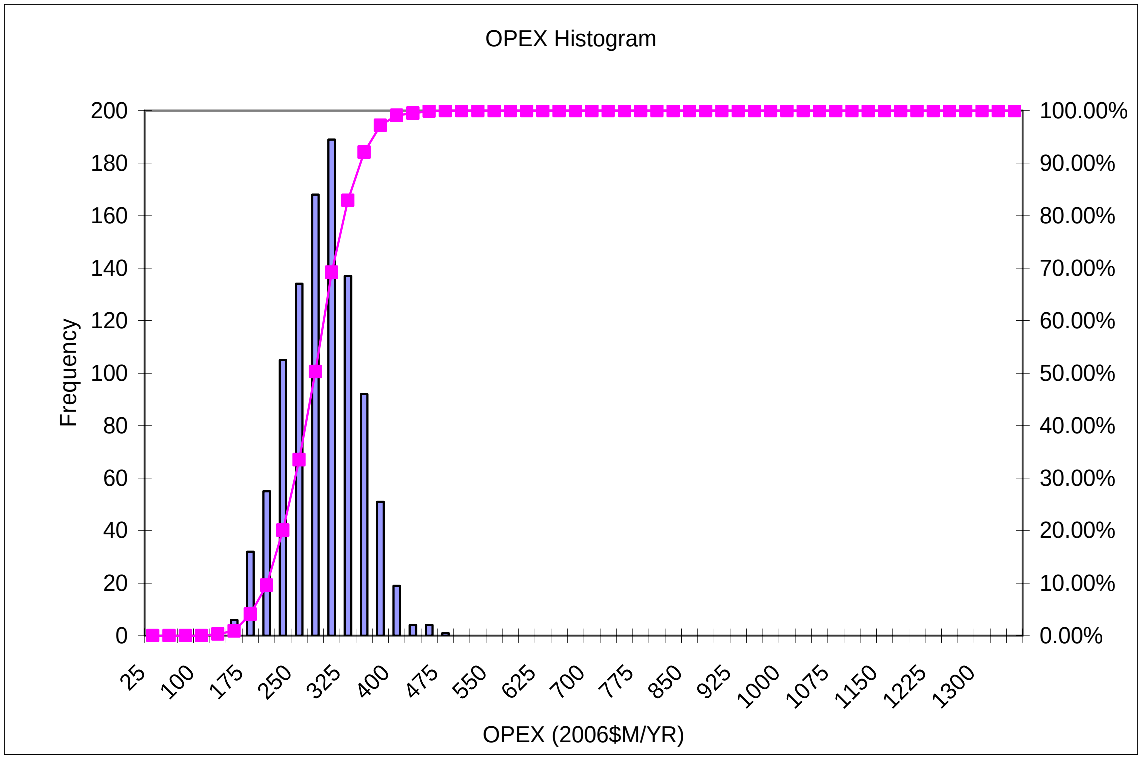

Figure 18 MC Simulation Histogram Annual OPEX Range for 30,000 bpd Plant

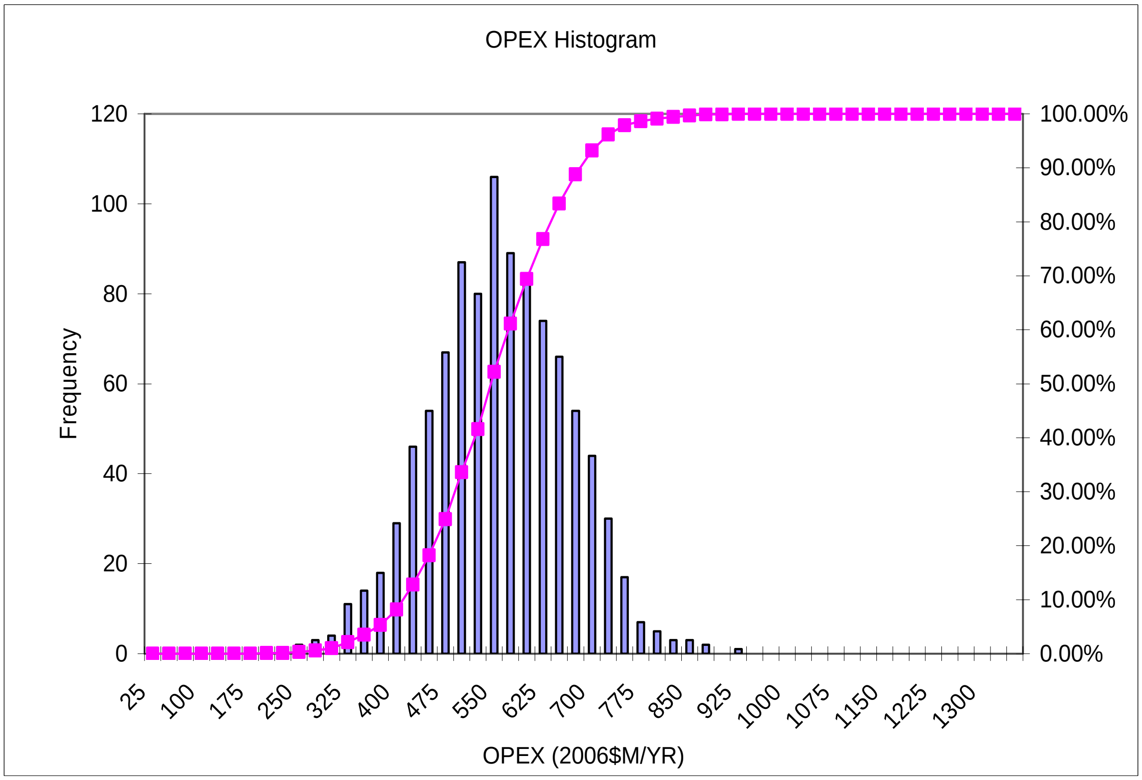

Figure 19 MC Simulation Histogram Annual OPEX Range for 60,000 bpd Plant

To extend the Monte Carlo simulation results across the range of data, the follow equations were developed for the median OPEX cost and plus/minus 2 standard deviations:

$$y_{MC\ OPEX} = OPEX\ \ (2006\$M\ /\ YR)$$
$$x = Plant\ Capacity\ \ (bpd)$$
$$y_{MC\ OPEX\ +2SD} = 0.0128x - 1.0675$$
$$y_{MC\ OPEX\ median} = 0.0091x - 0.4044$$
$$y_{MC\ OPEX\ -2SD} = 0.0053x + 0.2588$$

The coefficients in the above equations (i.e. 0.0128, 0.0091 and 0.0053) represent the estimated cost (in 2006 millions of dollars per year) of adding one additional unit of capacity. Note, the *y* intercept values (i.e. -1.0675, -0.4044 and 0.2588) are effectively zero, when considering the scale of the y axis (the data ranges from 0 to 1,300). Figure 20 is a plot of the above equations and graphically shows the relationship between OPEX and plant capacity.

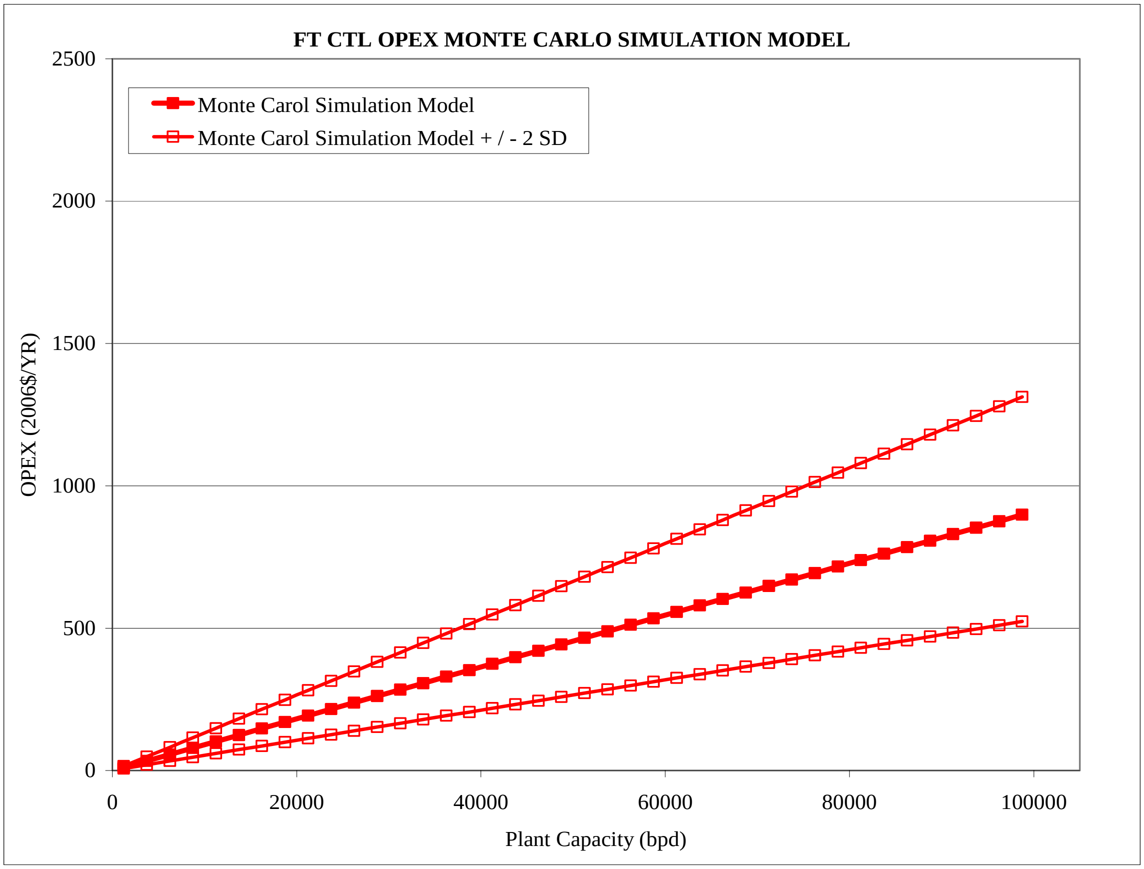

Figure 20 MC Simulation OPEX (2006 million dollars per year) vs. Plant Capacity (bpd)

B. REGRESSION ANALYSIS FINDINGS

1. CAPEX Findings

Using regression analysis, the best fit equation was found to be a power function and the following equation is the CAPEX CER:

$$y_{REG\ CAPEX} = CAPEX\ \ (2006\$M)$$
$$x = Plant\ Capacity\ (bpd)$$
$$y_{REG\ CAPEX} = 0.5040x^{0.8326}$$

This regression analysis was conducted by initially transforming the *x* and *y* values to a log-log scale by taking the log of independent and dependent variables, thereby allowing for a linear regression analysis. Specifically, the initial equation $y = ax^b$ was transposed to $\log y = \log a + b \log x$.

The CER displays expected characteristics such as

- Increasing CAPEX costs for increasing plant capacity
- Economies of scale; doubling plant capacity results in less than doubling CAPEX

The CAPEX regression statistics are shown in Table 8. Using a confidence level of 95 percent, this model appears to fit the data very well considering the very small t statistics of -1.67 for the intercept and 19.11 for the *x* coefficient, with corresponding *P*-values of 0.1103 and $2.55x10^{-14}$, respectively. The *t* statistic tests the marginal contribution of the independent variable to the reduction of the unexplained variation. The *t* statistic for the *x* coefficient is based on the null hypothesis (H_o) that states $b = 0$ and the alternative hypothesis (H_1) that $b \neq 0$. In other words, the null hypothesis tests the relationship between *y* and *x* by testing the strength of the coefficient *b*. If the *b* value can be zero, the *x* value is not well related to the *y* value, so the *x* value can be dropped from the model. Since the *P*-value is effectively zero, it means that there is negligible probability that the *x* values are not related to the *y* value, and the model with *b* is preferred over the model without *b*. In other words, reject the null hypothesis, and keep the x^b term in the model.

The one-way ANOVA table is also shown in Table 8. A very large ratio of the mean squares (the *F*-statistic) implies that the amount of variation explained by plant capacity is large in comparison with the residual error. For this model the *F*-statistic is 365, with an associated significance *F* (or *p*-value) of $2.55x10^{-14}$. Since the significance *F* is less than 0.05, the plant capacity effect is statistically significant at the $\alpha = 0.05$ level ($2.55x10^{-14} \prec 0.05$). Therefore, the plant capacity effect is an important factor for consideration.

Regression Statistics	
Multiple R	0.973709038
R Square	0.948109291
Adjusted R Square	0.945514755
Standard Error	0.219703309
Observations	22

$$y = 0.5040\, x^{0.8326}$$

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	17.63891994	17.63891994	365.4254507	2.555E-14
Residual	20	0.965390884	0.048269544		
Total	21	18.60431082			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept (log scale)	-0.6852654	0.4101097	-1.6709321	0.1103105	-1.5407392	0.1702084
X = ln(Capacity)	0.8326212	0.0435560	19.1161045	2.555E-14	0.7417650	0.9234775
a (Intercept linear) = e^Int =	0.503956459					

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
REG CAPEX 01	4.063824982	0.152127366	0.709521233
REG CAPEX 02	6.529908125	0.19031203	0.887614305
REG CAPEX 03	6.558135277	-0.20665192	-0.963823465
REG CAPEX 04	6.558135277	-0.119640543	-0.558002862
REG CAPEX 05	6.558135277	-0.039597835	-0.184684096
REG CAPEX 06	6.983459537	-0.116515835	-0.543429242
REG CAPEX 07	6.983459537	-0.100130156	-0.467006518
REG CAPEX 08	6.983459537	0.034198925	0.159503604
REG CAPEX 09	6.983459537	0.13675037	0.637803005
REG CAPEX 10	6.983459537	0.205058935	0.956393789
REG CAPEX 11	6.983459537	0.268197455	1.250871515
REG CAPEX 12	6.988440336	-0.460714469	-2.148769854
REG CAPEX 13	6.999947624	-0.35173236	-1.640477872
REG CAPEX 14	6.999947624	-0.336976894	-1.571658458
REG CAPEX 15	7.062816816	0.250403571	1.167880936
REG CAPEX 16	7.161020026	0.173516091	0.809278134
REG CAPEX 17	7.898187453	0.07033632	0.328048224
REG CAPEX 18	7.898187453	0.188825717	0.88068215
REG CAPEX 19	8.026536582	-0.078504591	-0.366145
REG CAPEX 20	8.026536582	0.202970537	0.946653514
REG CAPEX 21	8.323511713	-0.201051426	-0.937702793
REG CAPEX 22	8.714846714	0.138818714	0.647449752

PROBABILITY OUTPUT

Percentile	*Y*
2.272727273	4.215952348
6.818181818	6.351483357
11.36363636	6.438494734
15.90909091	6.518537441
20.45454545	6.527725867
25	6.648215265
29.54545455	6.66297073
34.09090909	6.720220155
38.63636364	6.866943701
43.18181818	6.883329381
47.72727273	7.017658461
52.27272727	7.120209907
56.81818182	7.188518471
61.36363636	7.251656991
65.90909091	7.313220387
70.45454545	7.334536117
75	7.948031991
79.54545455	7.968523773
84.09090909	8.08701317
88.63636364	8.122460287
93.18181818	8.229507119
97.72727273	8.853665428

Table 8 CAPEX Regression Model Statistics

After examining the residual output, see the bottom of Table 8, there appears to be only one outlier. Observation 12, or the data point named REG CAPEX 12, has a standard residual error of -2.15, which is slightly greater than two standard deviations from the predicted *y*. Recall that under a 95 percent confidence interval, 95 percent of the population falls within two standard deviations of the mean. This means for this data set of 22 values, one would expect one of the observations to be an outlier, which is the case here.

Next, residuals were plotted, as shown in Figure 21 and there is no appreciable pattern in the residual plot, (e.g., there is no evidence of a non-normal distribution, heteroscedasticity or a curvilinear relation). So the linear model is appropriate and no further transformations are required.

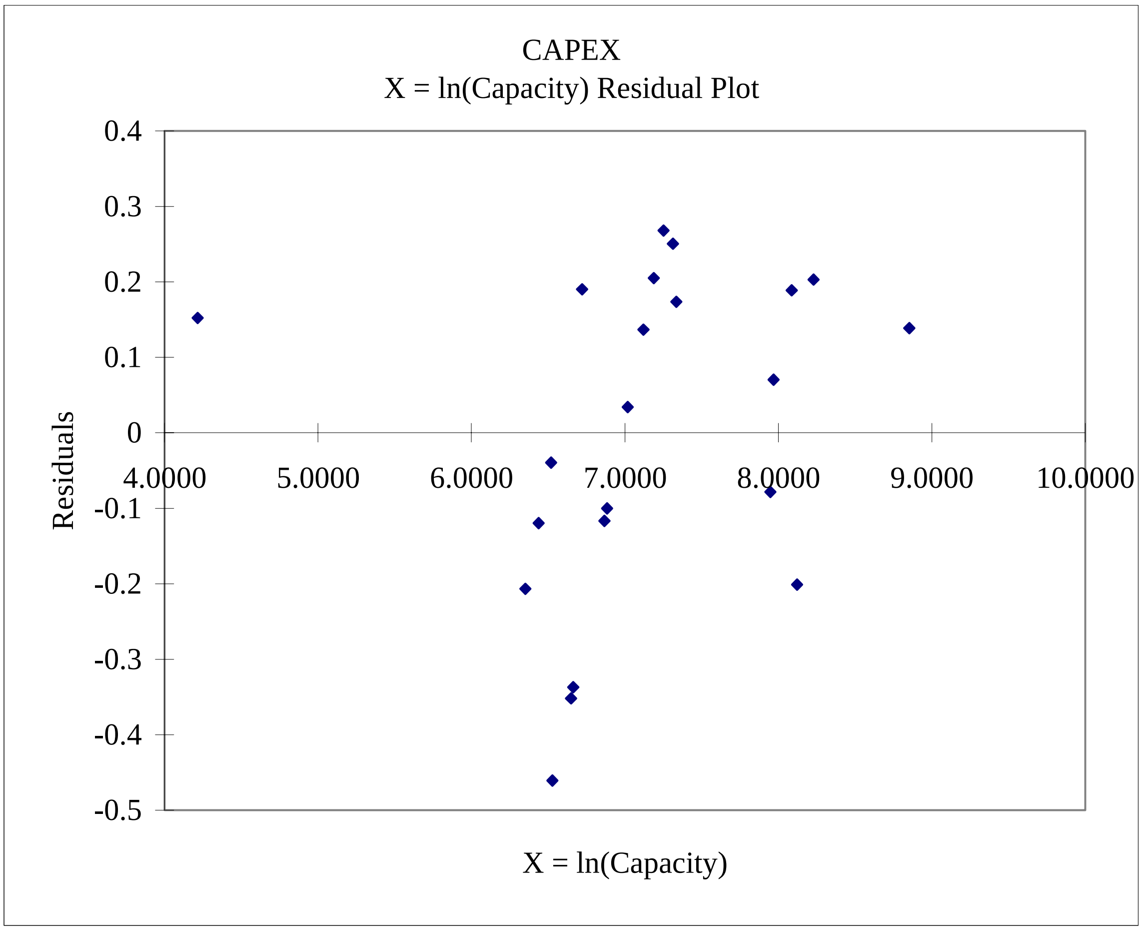

Figure 21   CAPEX Regression Model Residual Plot

Figure 22 shows the scatter plot of the data used to build the CAPEX and a graph of the CAPEX CER.

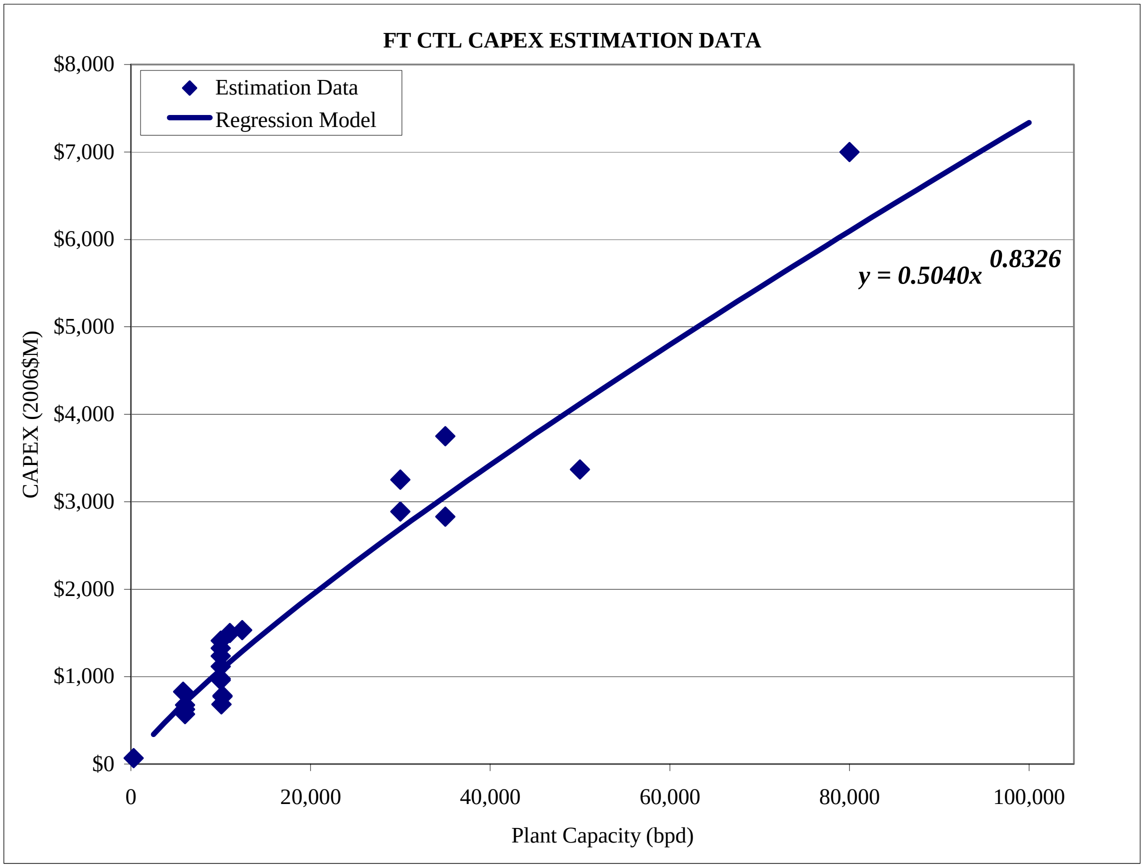

Figure 22 Regression CAPEX (2006 million dollars) vs. Plant Capacity (bpd)

Figure 23 shows the CAPEX CER, with a dashed line showing plus and minus two standard deviations. The prediction data, or the data withheld from building the cost estimating model, are also plotted. All the prediction data falls within two standard deviations of the cost estimating model. This observation is a validation of the CER.

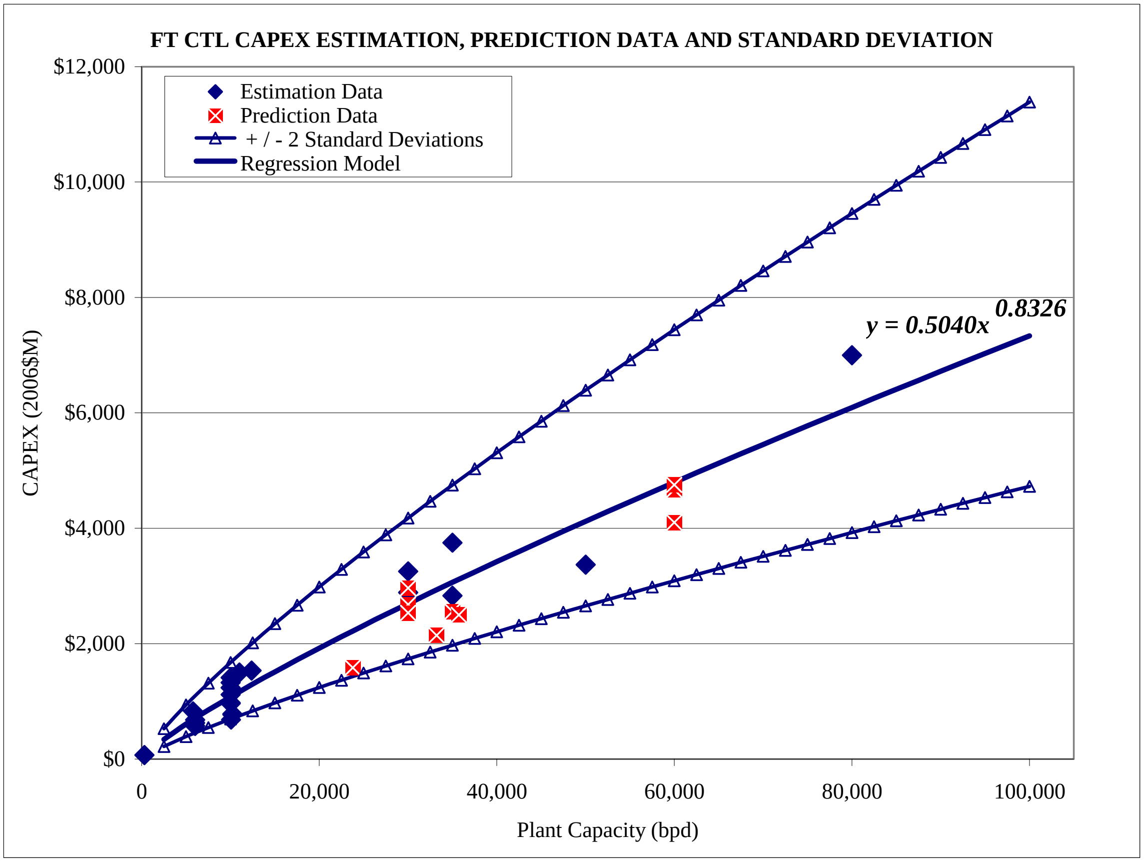

Figure 23 Regression Cost Estimating Relation CAPEX (2006 million dollars) vs. Plant Capacity (bpd)

2. OPEX Findings

Using regression analysis, the best fit equation was found to be a power function and the following equation is the OPEX CER:

$$y_{REG\ OPEX} = OPEX\ \ (2006\$M / YR)$$
$$x = Plant\ Capacity\ (bpd)$$
$$y_{REG\ OPEX} = 0.01256x^{1.0014}$$

Similar to CAPEX, this regression analysis was conducted by initially transforming the *x* and *y* values to a log-log scale by taking the log of independent and dependent values.

The CER, as expected, is increasing, but shows no economies of scale. In fact, it is very nearly linear, the exponent of x being within one-seventh of one percent of one.

The OPEX regression statistics are shown in Table 9. This analysis also used a confidence level of 95 percent. Again, this model appears to fit the data very well considering the small *t* statistics of -4.05 for the intercept and 9.03 for the *x* coefficient, with corresponding *P*-values of 0.0016 and $1.07x10^{-6}$, respectively. Similar to the CAPEX section, the *t* statistic tests the marginal contribution of the independent variable to the reduction of the unexplained variation. The relationship between *y* and *x* is very strong, so the null hypothesis can be rejected and the x^b term should remain in the model.

The OPEX one-way ANOVA table is also shown in Table 9. For this model the *F*-statistic is 81.5, with an associated significance *F* (or *p*-value) of $1.07x10^{-6}$. Since the significance *F* is less than 0.05, the plant capacity effect is statistically significant at the $\alpha = 0.05$ level ($1.07x10^{-6} \prec 0.05$). Therefore, the plant capacity effect is an important factor for consideration.

Regression Statistics	
Multiple R	0.933612249
R Square	0.871631831
Adjusted R Square	0.860934483
Standard Error	0.276988196
Observations	14

$y = 0.01256\,x^{1.0014}$

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6.251431874	6.251431874	81.48111812	1.07009E-06
Residual	12	0.920669527	0.076722461		
Total	13	7.172101401			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept (log scale)	-4.376907224	1.08117313	-4.048294487	0.001615266	-6.732581108	-2.021233339
X = ln(OPEX)	1.001408591	0.110938636	9.026689212	1.07009E-06	0.759694068	1.243123115
a (Intercept linear) = e^Int =	0.012564157					

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
REG OPEX 01	4.300912281	0.135839253	0.510440444
REG OPEX 02	4.846406754	-0.033451672	-0.125700678
REG OPEX 03	4.846406754	0.260303942	0.978138912
REG OPEX 04	4.846406754	-0.390823118	-1.468588209
REG OPEX 05	4.846406754	-0.141762986	-0.532699935
REG OPEX 06	4.846406754	-0.204355947	-0.767904252
REG OPEX 07	4.846406754	0.023786006	0.089380198
REG OPEX 08	5.059961962	0.525340985	1.974063304
REG OPEX 09	5.946566539	0.036381954	0.136711742
REG OPEX 10	5.946566539	-0.183242068	-0.68856505
REG OPEX 11	6.042010972	-0.042342668	-0.159110195
REG OPEX 12	6.100934354	-0.099519476	-0.373962344
REG OPEX 13	6.100934354	-0.323282031	-1.214790417
REG OPEX 14	6.458111707	0.437127825	1.642586481

PROBABILITY OUTPUT

Percentile	*Y*
3.571428571	4.436751534
10.71428571	4.455583636
17.85714286	4.642050807
25	4.704643769
32.14285714	4.812955083
39.28571429	4.87019276
46.42857143	5.106710696
53.57142857	5.585302947
60.71428571	5.763324471
67.85714286	5.777652323
75	5.982948493
82.14285714	5.999668304
89.28571429	6.001414878
96.42857143	6.895239533

Table 9 OPEX Regression Model Statistics

After examining the residual output, see the bottom of Table 9, there are no outliers. Figure 24 shows the OPEX residual plot and there is no appreciable pattern to the plotted data, so the linear model is appropriate and no further transformations are required.

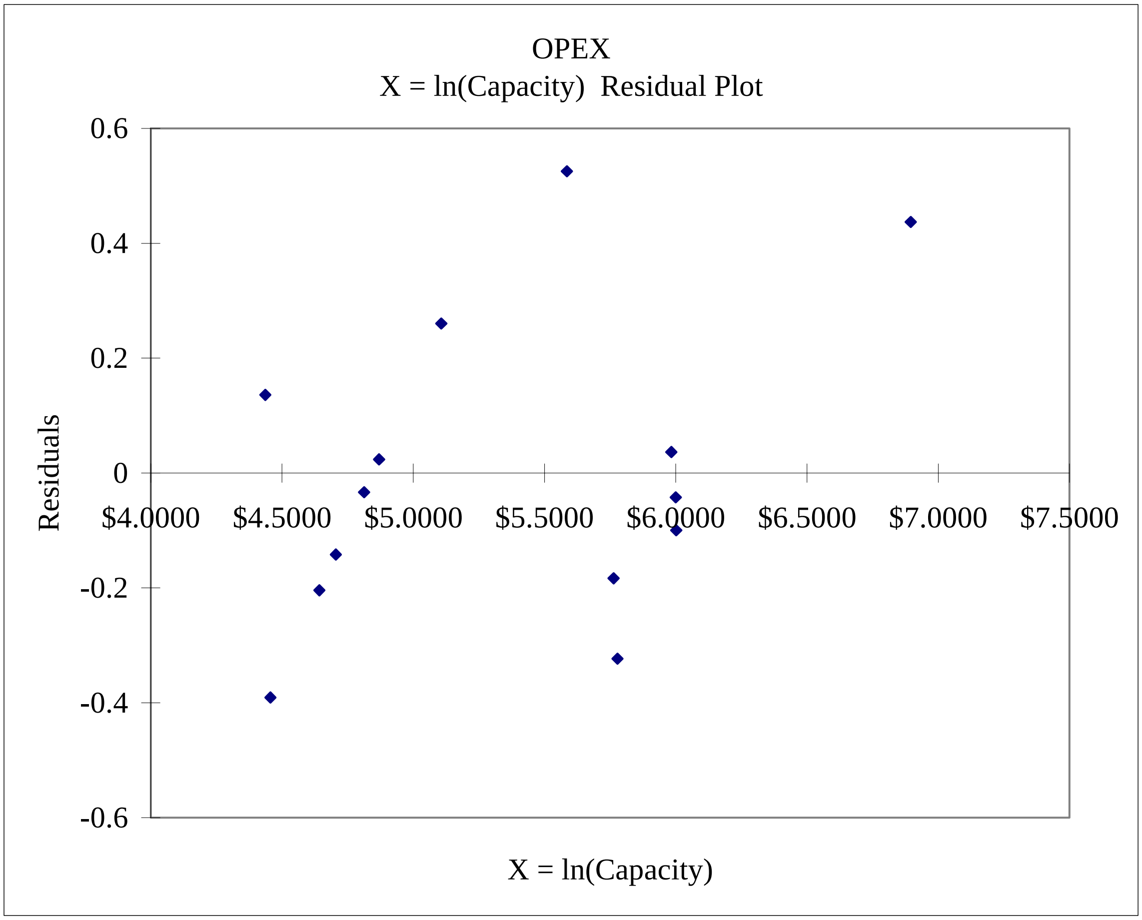

Figure 24 OPEX Regression Model Residual Plot

Figure 25 shows the scatter plot and a graph of the OPEX CER. This figure only shows the data used to build the cost estimating model.

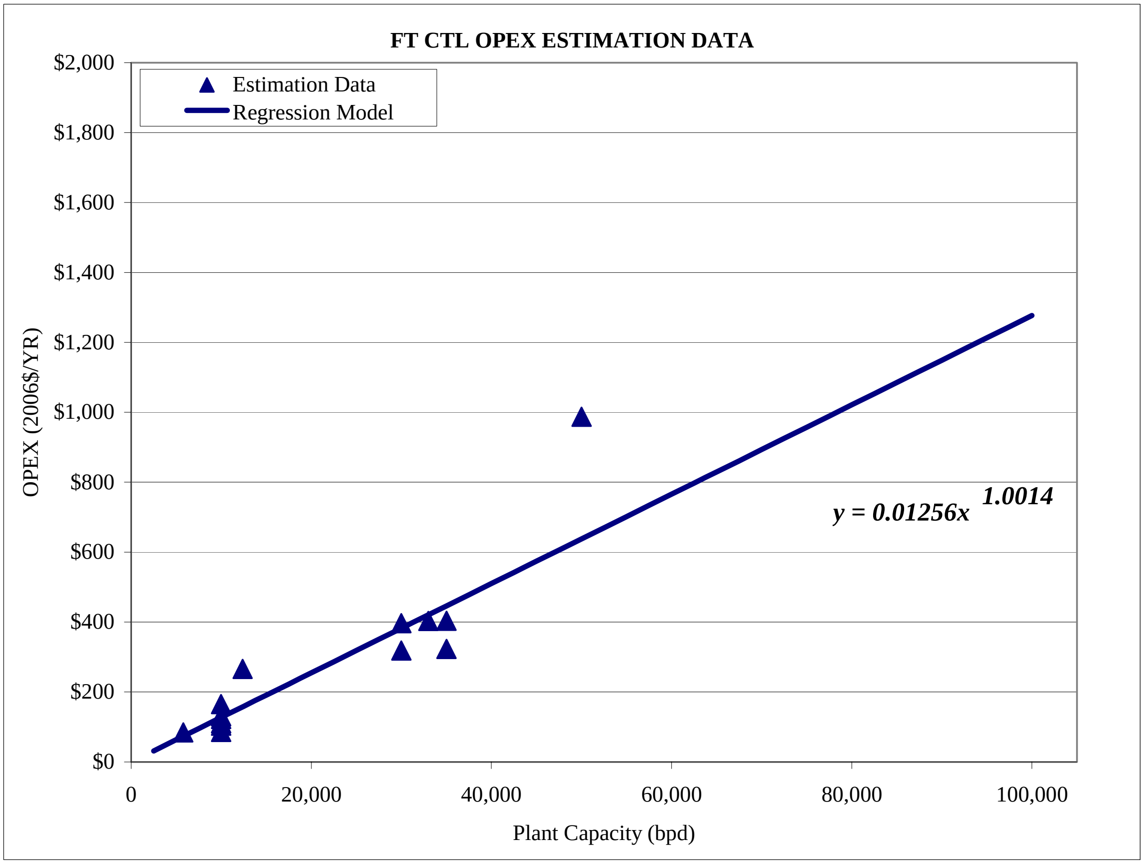

Figure 25 Regression OPEX (2006 million dollars) vs. Plant Capacity (bpd)

Figure 26 shows the OPEX CER, with a dashed line showing plus and minus two standard deviations. The prediction data, or the data withheld from building the cost estimating model, are also plotted. With only one exception, all the prediction data falls within two standard deviations of the cost estimating model.

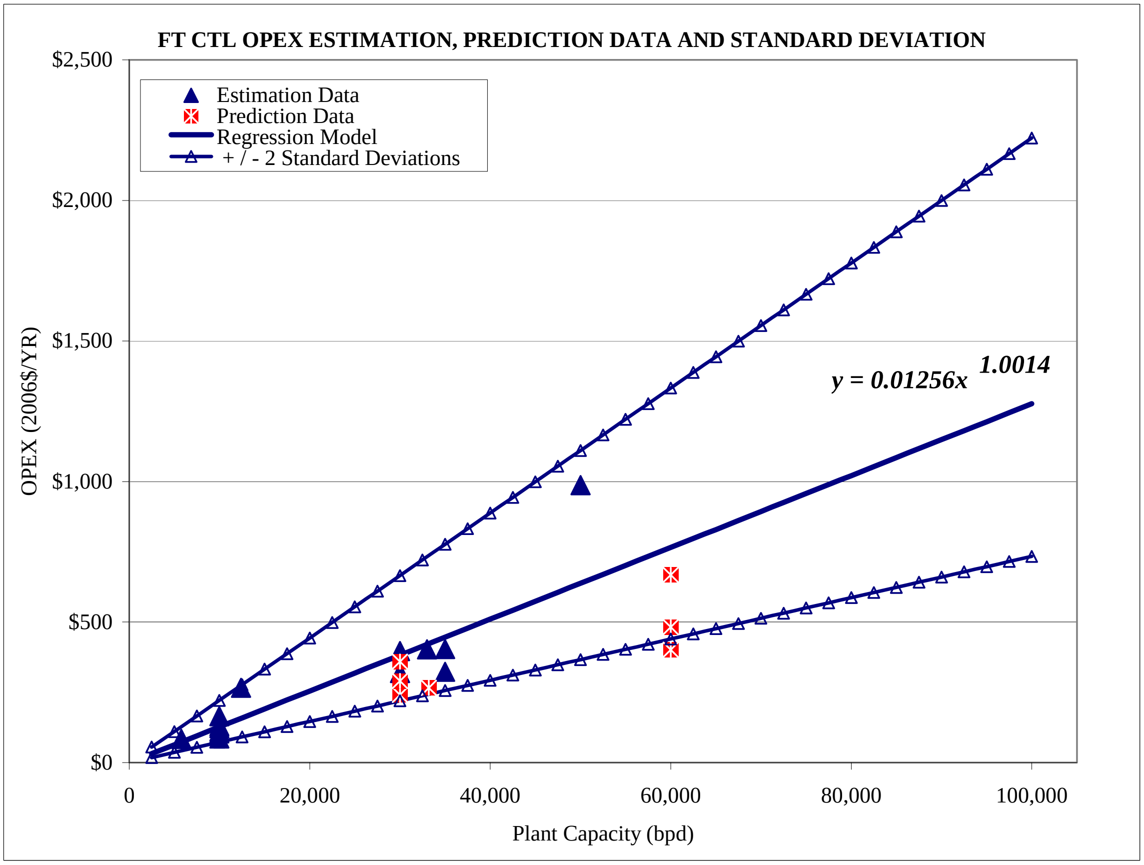

Figure 26 Regression Cost Estimating Relation OPEX (2006 million dollars) vs. Plant Capacity (bpd)

3. Comparison of Monte Carlo CERs and Regression CERs

This section addresses the question of how similar or dissimilar were the two CERs that were developed? Figure 27 and Figure 28 illustrate the answer to this question for CAPEX and OPEX, respectively. For CAPEX, Figure 27 shows that the MC model lies completely inside the regression CER, plus or minus two standard deviations, and the medians are almost overlapping.

For OPEX, Figure 28 shows that the MC model overlaps a large portion of the bottom half of the regression CER, plus or minus two standard deviations. For values greater than 20,000 barrels of plant capacity, the lower bound of the MC model is situated completely below the lower bound of the regression model.

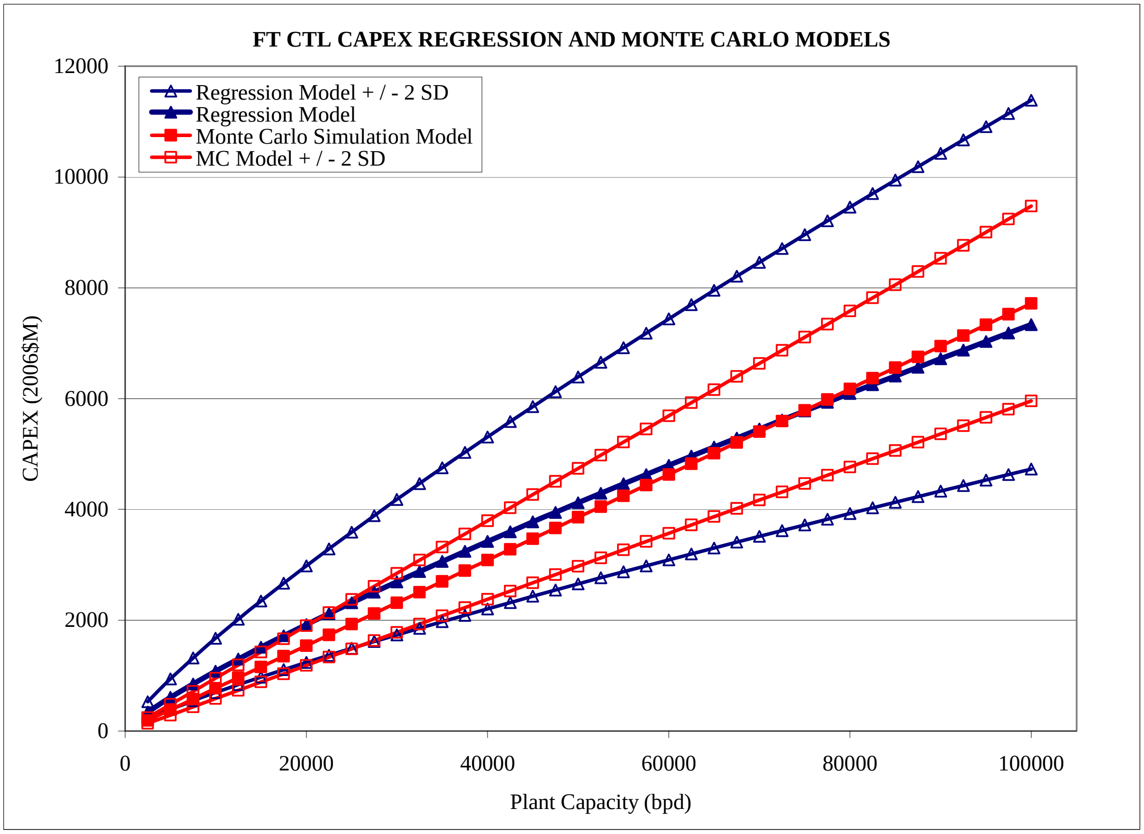

Figure 27 FT CTL CAPEX Monte Carlo CER vs. Regression CER

To evaluate how the CAPEX regression model median and the CAPEX Monte Carlo model median compared to each other, the relative error between the two medians was calculated and is plotted against plant capacity in Figure 29. Relative error, for capacity x, was calculated using the following equation:

$$\text{Relative Percent Error}_x = \left(1 - \frac{\text{Reg Model Median}_x}{\text{Monte Carlo Simulation Median}_x}\right) * 0.01$$

Since the regression model is a power function and the Monte Carlo model is a linear function, the plotted smooth curve is expected. What is not expected, but remarkable, is the fact that the relative percent error is centered on zero error and have a very small magnitude (the absolute relative percent error maximum is only 0.0025 percent or one in 40,000).

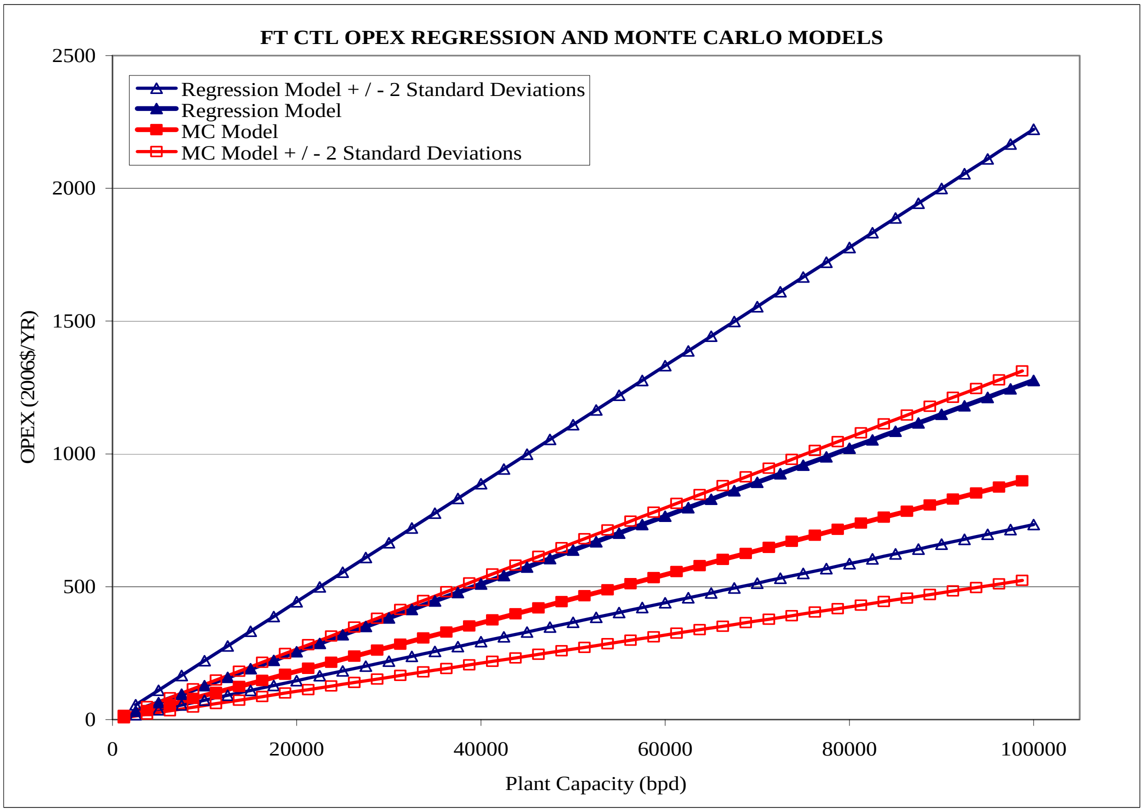

Figure 28 FT CTL OPEX Monte Carlo CER vs. Regression CER

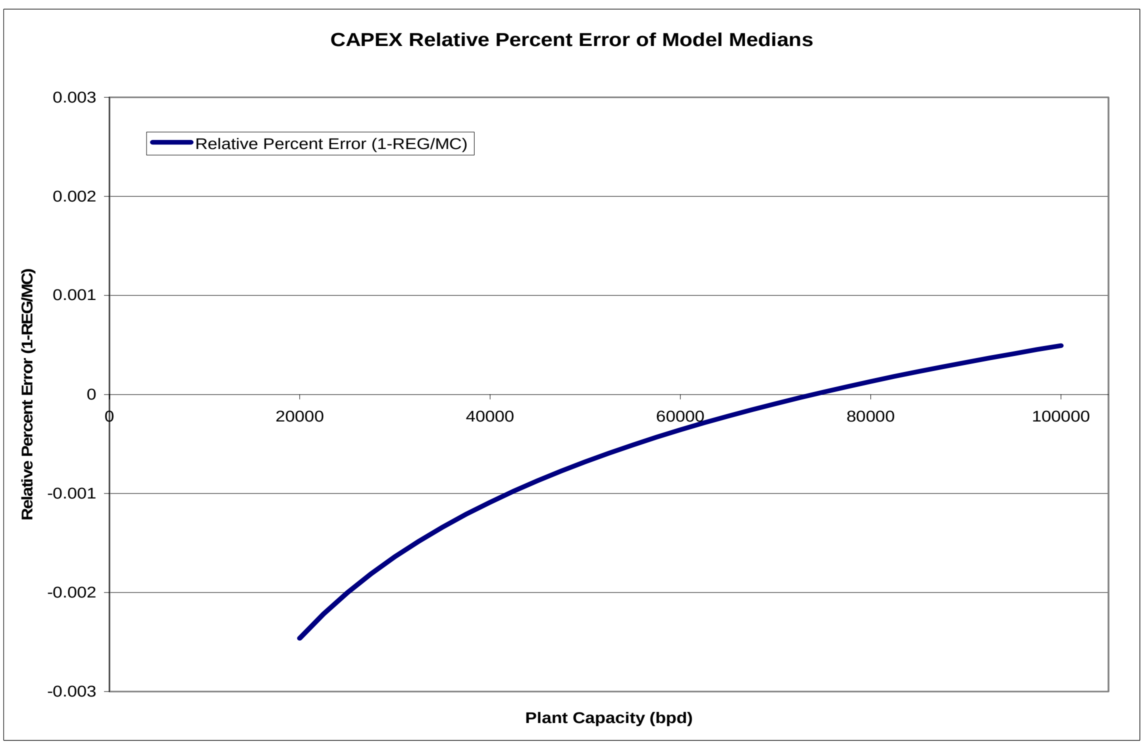

Figure 29 CAPEX Relative Error Between Regression Model Median and Monte Carlo Model Median

Similar to CAPEX, the OPEX regression model and the OPEX Monte Carlo model medians were compared to each other, using the relative error between the two medians and it is plotted in Figure 30.

Although the regression model is a power function, it is very nearly linear, as the exponent of x is within one-seventh of one percent of one. Therefore, relative percent error between two effectively linear models is plotted as an almost straight line. What is noteworthy, is the fact that the line completely sits below zero, which means the Monte Carlo simulation median consistently underestimates OPEX costs compared to the regression model median.

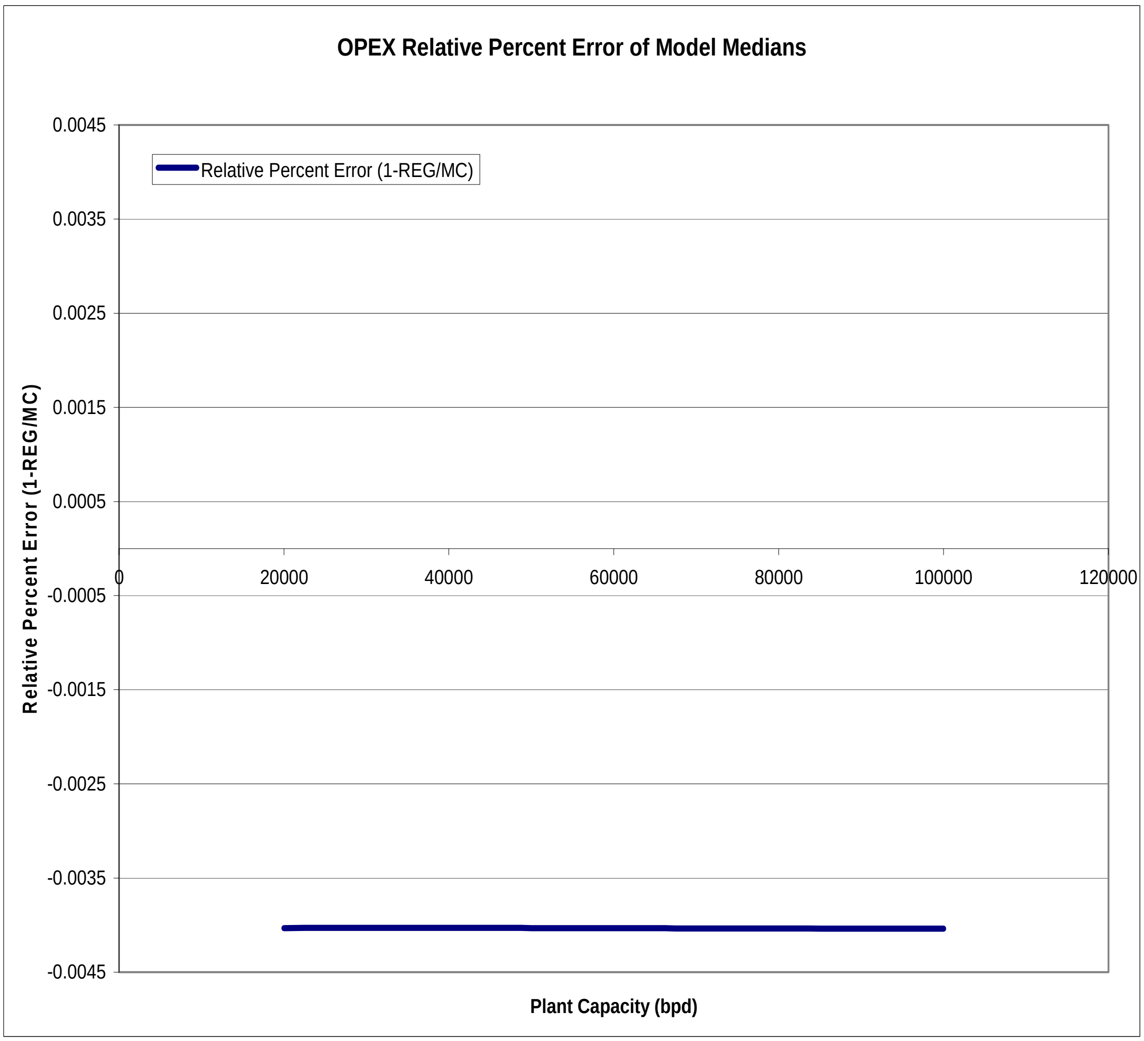

Figure 30 OPEX Relative Error Between Regression Model Median and Monte Carlo Model Median

4. Life Cycle Costs (LCC)

The CAPEX and OPEX CERs are summarized as follows:

WBS	*CER*(2006$)	R^2	R^2_{ADJ}
CAPEX	$y = 0.5040x^{0.8326}$	94.8%	94.6%
OPEX	$y = 0.01256x^{1.0014}$	87.1%	86.1%

With regard to life cycle costs of a plant of capacity *x*, over N years, the following equation may be used:

$$LCC = CAPEX + N * OPEX$$

$$LCC = 0.5040x^{0.8326} + N * (0.01256x^{1.0014})$$

C. DISCOUNTED CASH FLOW FINDINGS

1. Internal Rate of Return with Various Plant Lives

One question identified during the data collection phase of this project is how long does it take to pay off the CAPEX of building a new facility and the relationship of how different time periods directly affect the *minimum retail selling price* (again, the *minimum retail selling price* is the price required to cover capital costs, operating costs and a reasonable profit). Some studies discussed a plan to recapture construction costs within five years, while other studies required the plant to be in continuous operation for forty years. The following analysis examined how various plant lives, without regard to engineering specifications or maintenance requirements, would affect the minimum retail selling price under different internal rates of return. Figure 31 shows minimum retail selling price and various internal rates of return for plant lives of 5, 10, 15, 20, 30 and 40 years. Three conclusions are apparent from Figure 31. The first two conclusions are expected; the third is surprising and insightful:

- The minimum retail selling price is an increasing function of the internal rates of return. That is, the higher internal rates of return that is required, the higher the minimum retail selling price.
- The minimum retail selling price is a decreasing function of the plant life. That is, a longer plant life requires lower minimum retail selling price.
- While the minimum retail selling price is a decreasing function of the plant life, it is decreasing at a decreasing rate. In particular, it shows diminishing returns when calculating plant lives beyond 20 years.

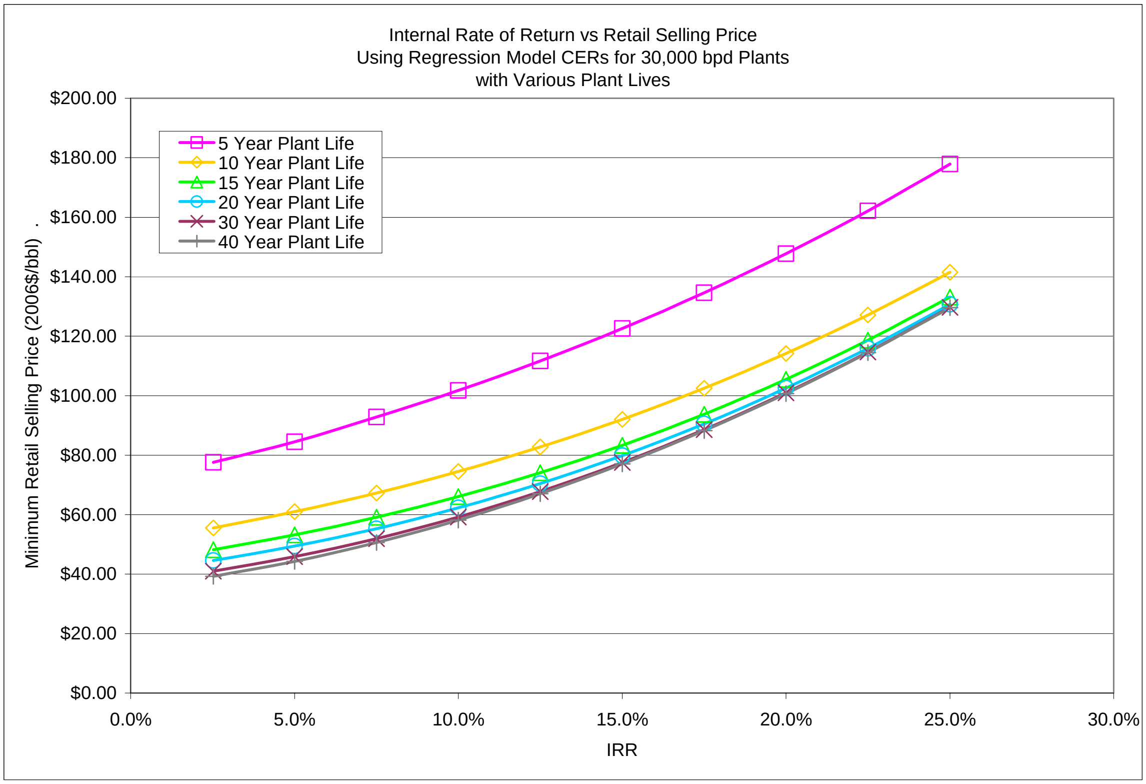

Figure 31 Retail Selling Price (2006 dollars/bbl) vs. Internal Rate of Return for a 30,000 bpd Plant with Various Plant Lives

2. Internal Rate of Return for Various Plant Sizes

Figure 32 shows minimum retail selling price of the fuel produced from a CTL plant for the Monte Carlo CER and the regression CER. First, the regression model demonstrated the benefits of economy of scale. Specifically, under the same IRR, a plant with a higher capacity could sell the product produced at a lower price than a plant with a lower capacity. Also, the Monte Carlo simulation model demonstrated a retail selling price that lies in between the regression model plant capacity of 30,000 barrels per day and 100,000 barrels per day, further reinforcing the similarity between the Monte Carlo model and the regression model.

With fuel prices remaining above 60 dollars per barrel, an internal rate of return of 10 percent can be successfully achieved. Notably, the fuel produced from a CTL plant only needs limited refining, as compared to the amount of refining required for crude oil. The retail selling price is competing with the prices of refined products, not against the world crude oil price.

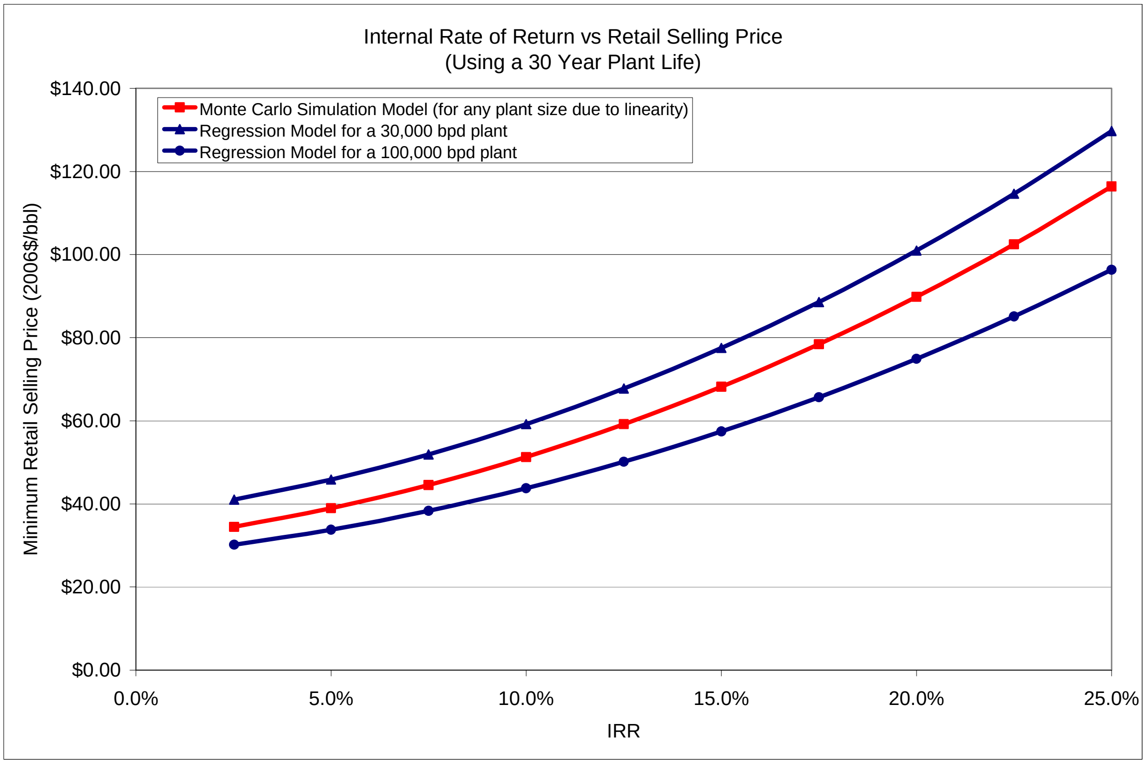

Figure 32 Retail Selling Price (2006 dollars per barrel) vs. Internal Rate of Return

D. SENSITIVITY ANALYSIS

Thus far, this analysis had furthered the understanding of estimated capital and operating costs of CTL plants through the use of the developed CERs. With these tools, the question of whether CTL is economically worth pursuing can be addressed. Just one facet of the above question is completely dependent on future pricing of petroleum and coal. To understand the conditions where CTL fuel production facility investment is practical and the conditions where it is impractical, a sensitivity analysis was conducted on various projected crude oil prices (crude oil which is then refined into finished fuels) versus various projected coal prices (coal which is used as the feedstock in a CTL plant and processed into synfuel). Although this study does not attempt to predict future prices, EIA energy price projections can be useful to give a glimpse of possible future scenarios. For this analysis, EIA AEO2006 fuel price projections were used extensively, and these projections are used in the next section to compare pursuing CTL fuel production directly to the status quo of continuing utilization of petroleum resources.

The EIA has been projecting world oil prices for several years. When projecting, the EIA uses a reference case, a high case and a low case, and for world oil they are described as:

> The high and low price cases in AEO2006 are based on different assumptions about world oil supply. The AEO2006 reference uses the mean oil and gas resource estimate published by the U.S. Geological Survey (USGS). The high price case assumes that the worldwide crude oil resource is 15 percent smaller and is more costly to produce than assumed in the reference case. The low price case assumes that the worldwide resource is 15 percent more plentiful and is cheaper to produce than assumed in the reference case. Thus, the major price differences across the three cases reflect uncertainty with regard to both the supply of resources (primarily undiscovered and inferred) and the cost of producing them. [AEO2006]

Illustrated below, Figure 33 gives the historical oil prices from 1990 to 2006 and the EIA AEO2006 crude oil reference, high and low price projections from 2006 to 2030.

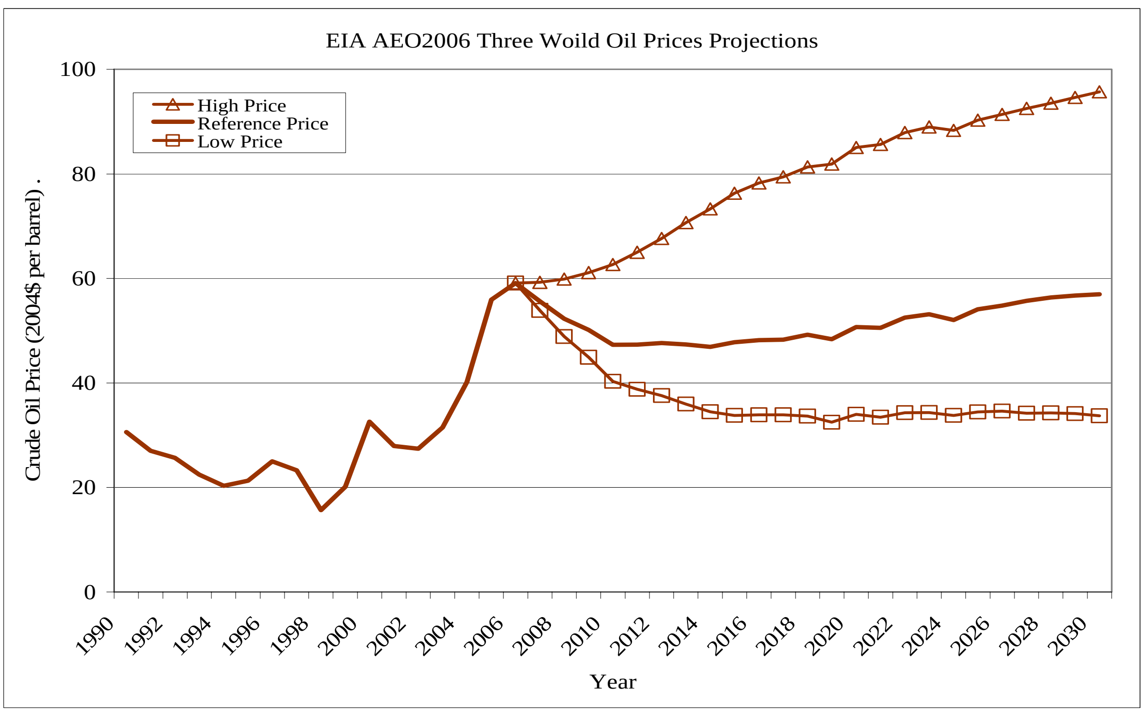

Figure 33 World Oil Prices and Three AEO2006 Cases, 1990 to 2030 (2004 dollars per bbl) [After: AEO2006]

In addition to projecting costs of world oil, they also develop projections for various other commodities, including coal. Again, EIA's projection is based on a reference case and two alternative cases, a high price and a low price. For the two alternative coal cost cases, EIA examined the impacts on U.S. coal markets with alternative assumptions regarding mining productivity, labor costs and mine equipment costs on the production side, and railroad productivity and rail equipment costs on the transportation side. [AEO2006] Figure 34 gives the historical coal prices from 1990 to 2006 and EIA's three projection for coal prices from 2006 to 2030.

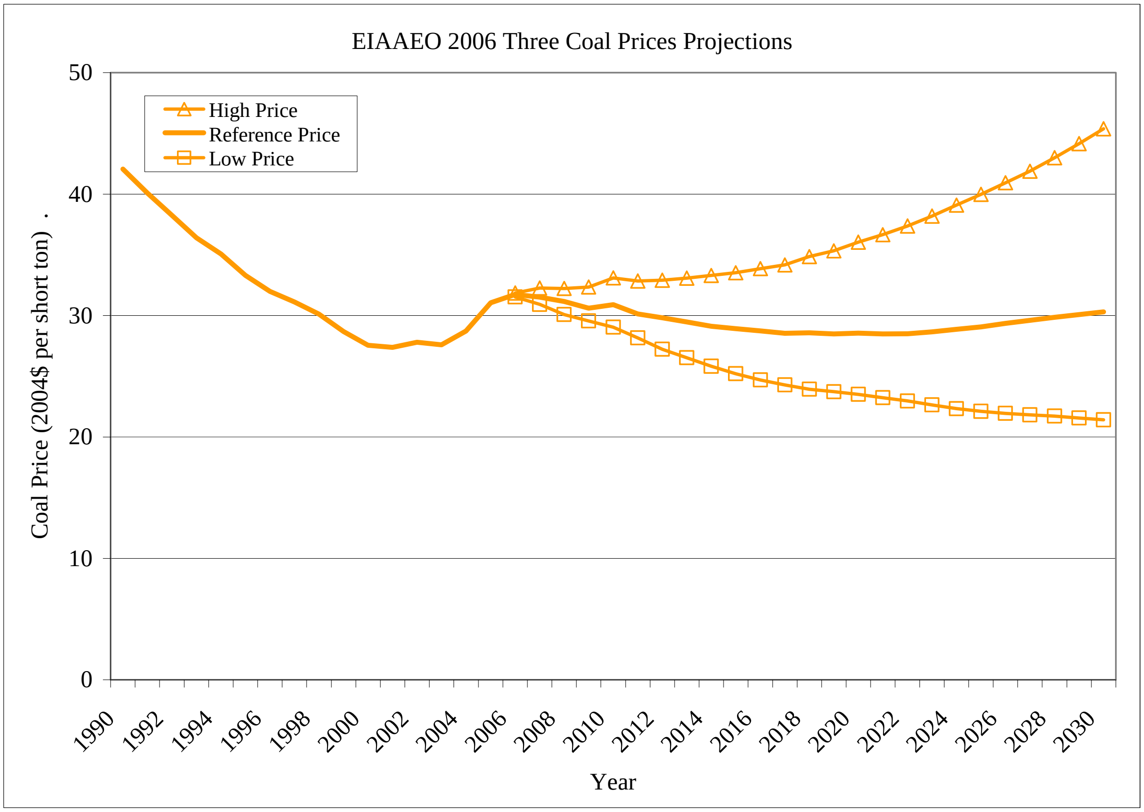

Figure 34 Average Coal Prices in Three Cases, 1990 to 2030 (2004 dollars per short ton) [After: AEO2006]

1. Decision Space for Pursuing a CTL Based Fuels Program

To compare pursuing CTL fuel production directly to the status quo of continuing utilization of petroleum resources, total fuel expenditures over a 20 year period, from 2011 to 2030, were calculated and compared. To conduct this analysis the following assumptions were made:

- Jet fuel consumption for the Navy was considered constant, at 40 million barrels per year, over the evaluation period. Although not statically true, this assumption allows for equivalent comparison of two resources.
- Synthetic jet fuel was assumed to be energy equivalent to jet fuel from petroleum. [Rentech]

- For synthetic jet fuel analysis:
  - Assumed DON was in an arrangement that isolates the price of synthetic fuel production from the world petroleum price (through a guaranteed off-take agreement or similar contract).
  - Allowed for a 10 percent IRR.
  - Used regression equations to estimate CAPEX and OPEX since they are more conservative than the Monte Carlo CER equations.
  - Assumed plant size of 60,000 barrels per day plant, with a plant life of 30 years (note, to meet the Navy's annual fuel requirements, two 60,000 barrels per day plants were used in the analysis).
  - Allowed for CTL Plant constructed from 2007 to 2010 and assumed the plant operated at full capacity from 2011-2040 (although only the first 20 years of operation was considered due to the limitation of the EIA projections).
  - Transportation cost of the synthetic fuel to the stock point was not included. This assumption favors synthetic fuels, because DESC purchases fuel at a price as delivered to the stock point.
- All costs are in 2006 dollars.

The first step in the decision space analysis was to normalize the EIA forecast costs for crude oil and coal to 2006 dollars. This was completed by using Gross Domestic Product Implicit Price Deflator indices. Further calculations and results are in constant 2006 dollars, to simplify the comparison of the two options.

Next, the crude oil prices were increased by a factor of 40 percent ($Final\ Cost_{JetFuel} = 1.4 * Oil\ Cost_{CrudeOil}$) to account for refining costs to upgrade crude oil to jet fuel. This factor was found by taking the average of EIA's World Crude Oil price and comparing it to EIA's New York Harbor Kerosene-Type Jet Fuel Spot Price. The supporting data for this factor can be found in Table 20, located in Appendix D.

Then, using each of the three crude oil EIA projection prices, the total fuel expenditures were calculated by summing the total annual costs over the 20 year period, using the assumed Navy fuel consumption of 40 million barrels per year. The total cost to the Navy for jet fuels from petroleum from 2011 to 2030 under the three EIA projections can be found in Table 10.

For the synthetic jet fuel, the three coal EIA projection prices were used to recalculate the feedstock cost for each year. This analysis found that the price of coal comprised 43 percent of the annual OPEX costs. Using the coal to OPEX ratio (per the analysis) and the inflated coal price (per the EIA projection), the OPEX was adjusted to reflect the increase or decrease from the previous year's OPEX cost. The CAPEX cost was unaffected by variability of the coal price. The total cost to the Navy for synthetic jet fuel from a CTL plant, from 2011 to 2030, under the three EIA projections, can be found in Table 10.

TOTAL COST TO NAVY FROM 2011 TO 2030 (2006$B)		
	JET FUEL FROM PETROLEUM	**SYNTHETIC JET FUEL**
EIA AEO2006 HIGH PRICE	$93.4	$54.1
EIA AEO2006 REFERENCE PRICE	$57.3	$51.8
EIA AEO2006 LOW PRICE	$38.6	$50.0

Table 10 Total Fuel Cost to DON from 2011 to 2030 (2006 billion dollars)

Three interesting conclusions and a several additional questions are drawn from Table 10:

- The cost of petroleum based jet fuel is highly variable, as noted by the 54.8 billion dollar range of cost estimates (from a high of 93.4 billion dollars to a low of 38.6 billion dollars).
- The cost of synthetic jet fuel does not demonstrate high variability, as noted by only a 4.1 billion dollar range of cost estimates (from a high of 54.1 billion dollars to a low of 50.0 billion dollars).
- A one percent relative increase in the cost of petroleum resulted in a 574 million dollar increase in the total annual cost over the 20 year period, while a one percent increase in the cost of coal resulted in only a 0.184 million dollar increase over the same period.
- Is there a benefit to choosing a source of fuel that has high price stability over a long period (as in the synthetic fuel case)? Do additional costs result from price instability (as in the petroleum case)? Does utilization of a domestic resource (coal) have security benefit, even in the instances

where it may be at an additional cost? Are there other macro economic benefits (e.g., create jobs or increase GDP) to developing a domestic synthetic fuel industry?

The actual costs can by any combination of the range of values of the coal and crude oil input. With this realization, the each total cost of the synthetic fuel cost was individually compared to each of the total costs for the fuel from petroleum. This resulted in a three by three matrix that was simplistic with low resolution and is shown in Figure 35. It shows that:

- Petroleum is preferred only when crude oil prices consistently remain low and coal is preferred when crude oil prices consistently remain at or above the crude oil reference price.
- At this scale, the decision space is dominated by the price of crude oil and, within the range of the EIA projections, the price of coal is irrelevant.

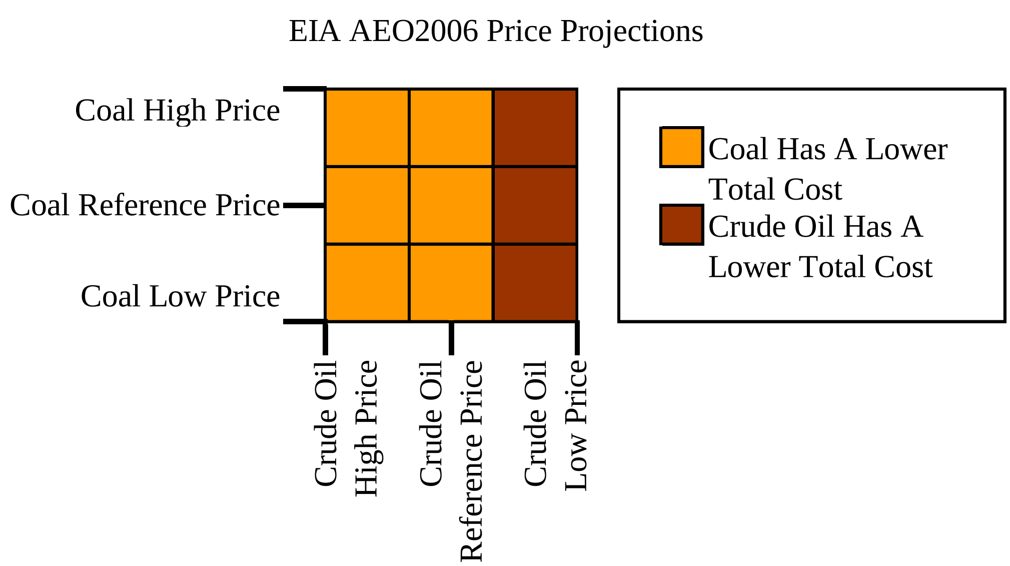

Figure 35 Preliminary Decision Space

In order to provide greater granularity and insight to the analysis, the above three by three matrix, with nine values, was linearly transformed into a 21 by 21 matrix, with 441 values. This was accomplished by

- Dividing the interval between the high AEO2006 coal price projection and the reference AEO2006 coal price projection into 10 equal subintervals, and
- Dividing the interval between the reference AEO2006 oil price projection and the low AEO2006 oil price projection into 10 equal subintervals,

This linear transformation resulted in a higher resolution picture of the interaction between the two cost sets. The resulting graph, known as the Detailed Decision Space, can be seen in Figure 36. Using the EIA AEO2006 projections:

- The region to the left of the bold line is the region where synthetic fuels results in a lower total cost over the 20 year period than the petroleum fuels, and
- The region to the right of the bold line is the region where petroleum fuels are lower in cost over the same period.

The region in which synthetic fuels is preferred is approximately 57 percent of the area and the region in which petroleum is preferred is approximately 43 percent of the area. The graduated colors are based on the percentage of the difference from the maximum value to the minimum delta value (recall this value was found by taking the difference between total synthetic fuel costs and total petroleum fuel cost over a 20 year period). The center section labeled "too close to call" is only 10 percent around the break even line, which is not a definitive difference between the two alternatives. The other graduated colors are identified as follows: "marginally decisive" (10 percent to 25 percent), "clearly decisive" (25 percent to 50 percent) and "highly decisive" (>50 percent).

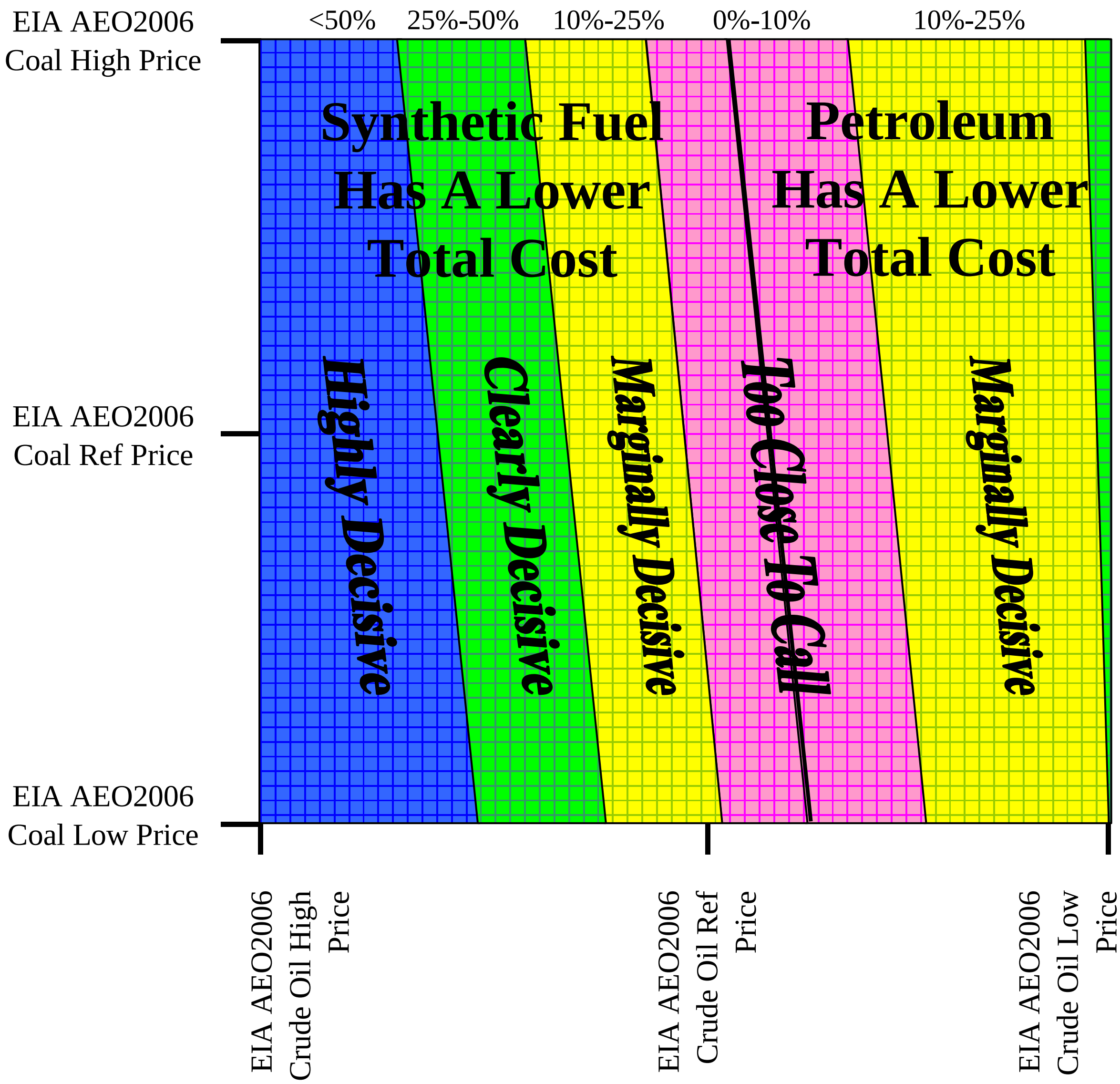

Figure 36 Detailed Decision Space

An alternative way to display the same data in Figure 36, is shown in Figure 37, which, shows the two dimensional information above, but a *z* axis, or a third dimension, is added to graph the delta value (the difference of the two options). The section below the $z = 0$ plane is the amount of savings by pursuing synthetic fuels in billions of dollars. The section above the $z = 0$ plane is the savings with continuing with petroleum.

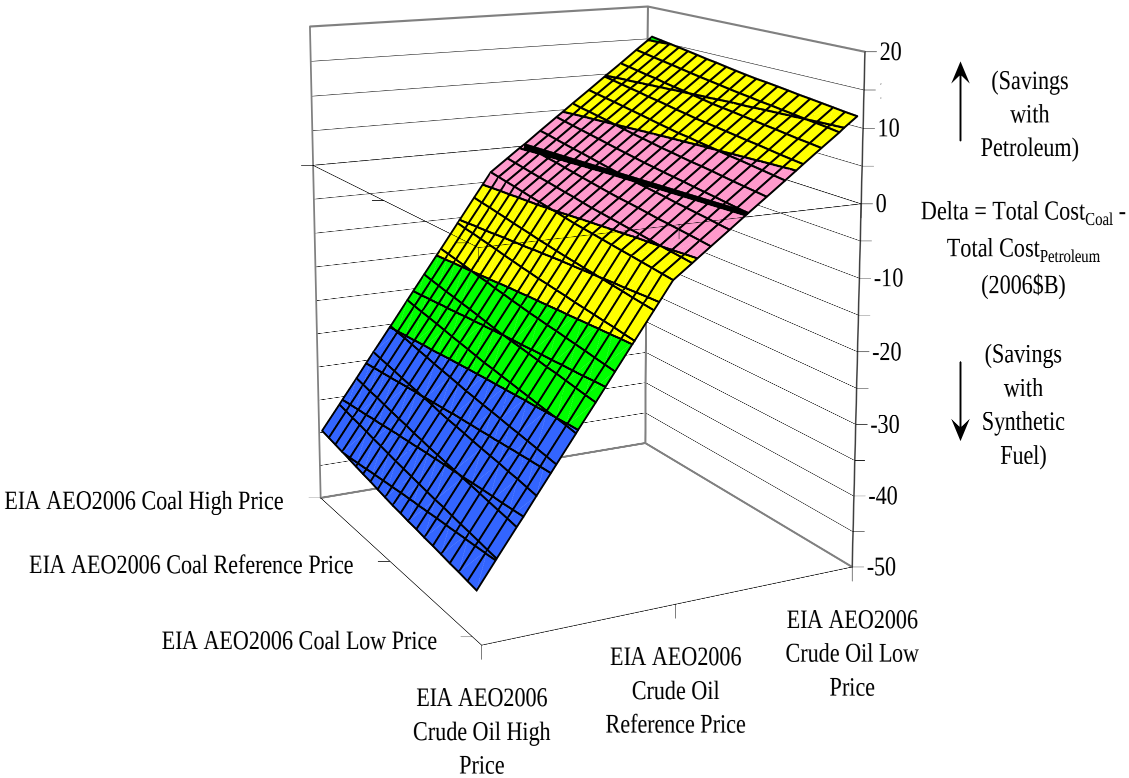

Figure 37 Decision Space with Third Dimension of Delta Value

2. Critical Oil Price for Breakeven between Synthetic Fuel and Fuel from Petroleum

The intersection between the two regions in Figure 36 and Figure 37 (illustrated as bold lines), is the circumstance where the two cases are equivalent. Since the total cost of petroleum fuel is a result of a 20 year series of crude oil prices, one single crude price cannot be identified as the critical price to decide to pursue synthetic fuels or remain with the status quo.

In the aggregate, over the 20 year period, the results did show that the breakeven price was approximately 32 percent below the EIA AEO2006 Crude Oil Reference price. Also, due to the limited variability of coal pricing's effect on changing the final price of synthetic fuel, the coal reference price was not used in developing the petroleum breakeven price. This breakeven price is illustrated on Figure 38. Note, this breakeven price is not definitive on any specific data and simply represents an estimated price, relative to the reference price, over the 20 year period.

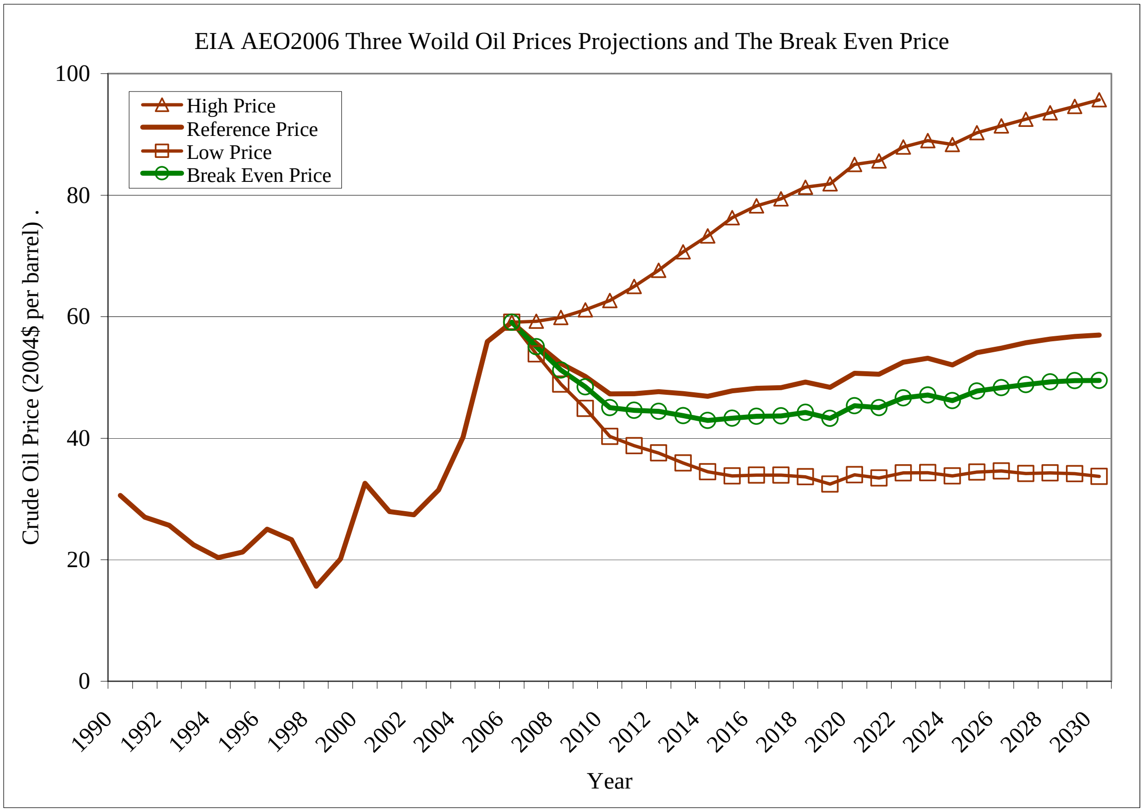

Figure 38 Three World Oil Price Cases and the Break Even Price (2004 dollars per bbl) [After: AEO2006]

VII. CONCLUSIONS AND RECOMMENDATIONS

A. RESULTS

This thesis started with data collection from the varied landscape of many different alternative energy resources and processes. The primary analysis investigated coal to liquid plants. A work breakdown structure was developed that captured the cost elements common to coal to liquid facilities. Next, cost estimating relations were developed for CAPEX and OPEX and each was:

- Underpinned by the data collected,
- Developed in accordance with professional cost estimating practices, and
- Accompanied by the relevant goodness-of-fit statistics.

The cost estimating relations are summarized as follows:

CAPEX

$$y_{CAPEX} = CAPEX \ (2006\$M)$$
$$x = Plant\ Capacity\ (bpd)$$

MONTE CARLO CER

$$y_{MC\ CAPEX} = 0.0772x - 2.6929$$

REGRESSION CER

$$y_{REG\ CAPEX} = 0.5040x^{0.8326}$$
$$\alpha = 0.05$$
$$R^2 = 94.8\% \quad Adj\ R^2 = 94.6\%$$
$$P\ value_{COEF} = 2.6\ x\ 10^{-14}$$

OPEX

$$y_{OPEX} = OPEX \ (2006\$M/YR)$$
$$x = Plant\ Capacity\ (bpd)$$

MONTE CARLO CER

$$y_{MC\ OPEX} = 0.0091x - 0.4044$$

REGRESSION CER

$$y_{REG\ OPEX} = 0.01256x^{1.0014}$$
$$\alpha = 0.05$$
$$R^2 = 87.2\% \quad Adj\ R^2 = 86.1\%$$
$$P\ value_{COEF} = 1.1\ x\ 10^{-6}$$

The Monte Carlo results are linear, while the regression results are a power function. Both results show a clear increase in costs with increasing plant capacity, while the regression shows benefits for economy of scale with increasing plant capacity.

The Monte Carlo CERs were compared to the regression CERs. For CAPEX, Monte Carlo CER lies completely inside the regression CER, plus or minus two standard deviations, and the medians are almost overlapping. This result means the two relations give very similar results and could be used almost interchangeably within the range of the data.

For OPEX, the Monte Carlo CER overlaps a large portion of the lower range of the regression CER (plus or minus two standard deviations from the regression CER median). For values greater than 20,000 barrels of daily plant capacity, the median Monte Carlo CER consistently estimates less than the median of the regression CER. This result means the regression CER will estimate higher costs, and if a conservative estimate is desired (i.e., an estimate which will give a higher cost), the regression CER should be utilized.

The operating expenses are estimated on a cost per year basis and to find an estimated total life cycle cost (LCC) of a plant with life N years, the following equation would be used: $LCC = CAPEX + N * OPEX$. Even with multiplying $N * OPEX$, the overall life cycle cost is dominated by CAPEX. If overall life cycle costs want to be reduced, effort and research need to be invested in reducing the CAPEX costs of CTL plants. A list of sample CAPEX and OPEX estimates using the above CERs for various plant capacities can be found in Table 11.

Plant Capacity (bpd)	CAPEX (2006$M)	OPEX (2006$M/YR)
Monte Carlo CERs		
20,000	$1,541	$182
40,000	$3,085	$364
60,000	$4,629	$546
80,000	$6,173	$728
100,000	$7,717	$910
Regression CERs		
20,000	$1,921	$255
40,000	$3,421	$510
60,000	$4,794	$765
80,000	$6,092	$1,021
100,000	$7,336	$1,276

Table 11 Sample CAPEX and OPEX Estimates for Various Plant Capacities

Next, return on investment (ROI) analysis was developed. This analysis related the estimated *minimum retail selling price* (the *minimum retail selling price* was the price required to cover capital costs, operating costs and a reasonable profit) to various internal rates of return. First, the number of years a plant had to operate (also known as plant life) was examined, and the minimum retail selling price was plotted against various internal rates of return for various plant lives. The following conclusions were found:

- The minimum retail selling price is an increasing function of the internal rates of return. That is, the higher internal rates of return that is required, the higher the minimum retail selling price.
- The minimum retail selling price is a decreasing function of the plant life. That is, longer plant life requires lower minimum retail selling price.
- While the minimum retail selling price is a decreasing function of the plant life, it is decreasing at a decreasing rate. In particular, it shows diminishing returns when calculating plant lives beyond 20 years.

The second part of the ROI analysis consisted of comparing minimum retail selling price and IRR for the Monte Carlo CER and the regression CER. First, regression model showed the benefits of economy of scale. Specifically, under the same IRR, a plant with a higher capacity could sell the product produced at a lower price than a plant with a lower capacity. Also, the Monte Carlo simulation model demonstrated a minimum retail selling price that fell between the regression model plant capacity of 30,000 barrels per day and 100,000 barrels per day. Additionally, the analysis showed that with fuel prices remaining above 60 dollars per barrel, an IRR of 10 percent can be successfully achieved.

The above CERs furthered the understanding of estimated capital and operating costs of CTL plants, but the following question still remained: Should the Navy or Defense Department initiate a synthetic fuel program or remain with petroleum based fuel? This question was investigated through extensive use of the EIA AEO2006 energy price projections. The following conclusions were found:

- Jet fuel from petroleum price was highly variable over the evaluation period.
- Synthetic jet fuel pricing remained relatively stable over the evaluation period.
- Jet fuel pricing was very sensitive to price fluctuations, while synthetic fuel was far more stable.

- Synthetic fuel's price insensitivity relative to coal price fluctuation is due to the large CAPEX costs relative to the cost of the feedstock. CAPEX is the dominant factor which drives the minimum retail selling price of synthetic fuel.
- For the landscape of possible projected prices for crude oil and coal, 57 percent of the cases favored synthetic fuel and 43% of the cases favored fuel from petroleum.
- This study's results can be extended from supporting the Navy fuel requirements to supporting the Department of Defense fuel requirements, by assuming the DoD needs six 60,000 barrel per day plants, to supply 120 million barrels per year, compared to the Navy's use of two 60,000 barrel per day plants. This is a conservative statement since lessons will be learned during the construction of the first two plants and can be used to optimize the construction or operation of the third to sixth plants.

B. AREAS FOR FUTURE RESEARCH

This thesis contains many possibilities for investing future alternative energy sources to provide liquid hydrocarbons for use by the Navy and Department of Defense. Many alternative energy resources have been left unexplored. Many extensions are possible. Natural continuations of this work would include the following:

- Investigate inclusion of the additional cost of CO_2 sequestration. Identify how green-house emissions can influence the decision to pursue CTL synthetic fuel.
- Investigate CTL water consumption requirements and costs associated with the disposition of contaminated water which might result from the process.
- Explore how off-take agreements or contracts for synthetic fuel can effectively isolate the DON or DoD from petroleum market volatility.
- Consider the additional transportation costs if a CTL plant was located in one location and compare the results to DESC's currently policy of purchasing fuel around the world at a *delivered cost*.
- Investigate if the utilization of a domestic resource, such as coal, has an intrinsic security benefit, even if there are periods where it may be obtained at an additional cost.
- Identify the possible benefit to choosing a source of fuel that has high price stability over a long period (as in the CTL synthetic fuel case).
- Investigate if additional costs result from price instability (as in the petroleum case).
- Extend work to non CTL processes.

- Explore if there other macro economic benefits such as job creation or multipliers to GDP to developing a domestic synthetic fuel industry.
- This study looked into an alternative to the *supply-side* of military fuel consumption. Alternatively, there may be great benefits found in reducing the *demand-side* of military fuel consumption. Specifically, explore end use efficiencies for military platforms, some of which are road mapped in Lovins' Winning the Oil Endgame.

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APPENDIX A

FISCHER–TROPSCH PROCESS OVERVIEW

This appendix is provided as background on the Fischer-Tropsch process and is taken from Steve Bergin's "Annual Report for the Ultra-Clean Fischer-Tropsch Fuels Production and Demonstration Project."

The Fischer-Tropsch Process

Different companies have been developing the Fischer-Tropsch (F-T) process throughout the world since the 1930s. While most people associate the F-T process with the gas-to-liquid process (GTL), F-T got its start using coal in Germany and later in South Africa, referred to as coal to liquid (CTL). More recently, bio-mass (BTL) has been used to generate the synthesis gas for the F-T process – creating "green" or bio-renewable energy. All three programs, GTL, CTL and BTL share the same three steps; first, syn-gas generation; second, the F-T conversion; and third, products upgrading. Regardless of the resource input, the second and third steps are identical. Natural gas is reformed (Alaska's Agrium Corp. ammonia and urea fertilizer plant and the BP GTL test plant are examples) while solids; coal and bio-mass are gasified to produce a syn-gas (*hydrogen* $\boldsymbol{H_2}$ *and carbon monoxide* ***CO***). A synthesis gas (or syn-gas) is the common supply for the F-T process, as well as methanol and ammonia processes, and for electrical generation and sulfur reduction in refineries

Figure 1 shown here illustrates the F-T process and how different natural resources can be used to make the syn-gas needed in the F-T conversion. The Fischer-Tropsch Process (F-T) has three main processing steps shown here, all of which are commercially proven.

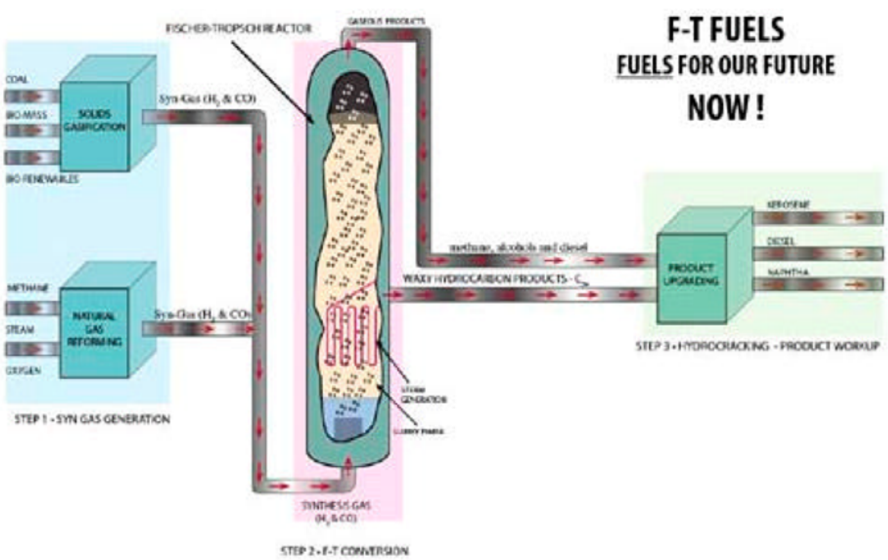


Figure 1

STEP 1:

Syn-gas generation typically represents 50-plus percent of the total cost of an F-T plant.

STEP 2:

F-T Conversion is typically 25 percent of the total cost.

STEP 3:

Product Upgrading is usually 15 percent to 25 percent of the cost.

The type of Syn-Gas Generation, gas reformation or gasification of solids, depends upon the raw material or feed stock available. Around the world stranded natural gas is the choice; however, in the US with the exception of North Slope natural gas, coal, and bio-mass (municipal, timber and agricultural waste) represent the majority of available feedstock for a U.S. based F-T program.

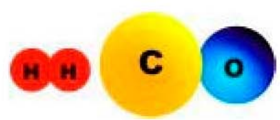
Comparing F-T diesel costs with conventional diesel prices

The estimated cost and resulting wholesale price of producing Fischer-Tropsch (F-T) diesel in a small-footprint F-T plant must be weighed against the wholesale price of conventional diesel fuel available in a given region. To compare Fischer-Tropsch fuel costs with conventional, we consider the plant "tailgate" costs, shown in tables for the respective scenarios, as wholesale prices for the F-T fuel available at the plant.

To compare this with conventional fuel, in each section we report a 2004 average wholesale price of conventional diesel reported from fuel distributors or wholesale purchasers for the region. We also consider an additional cost to conventional fuel for the ultra-low sulfur diesel (ULSD) that will be required by U.S. Environmental Protection Agency regulations effective in 2006 for road diesel and 2010 for all diesel.

Since F-T fuels already meet the EPA 2006 and 2010 clean-diesel standards, we compare the F-T costs with future estimated prices for ULSD conventional diesel.

How the process works:

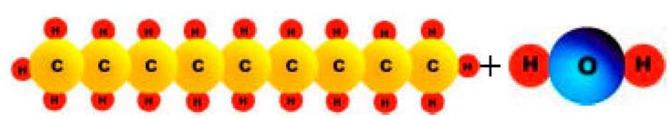


The first step converts natural gas, coal or bio-mass into synthesis gas, a mixture of carbon monoxide (CO) and hydrogen (H_2) – syn-gas.

This mature process technology has been used in many commercial facilities as the first step for producing ammonia, hydrogen, F-T fuels, petrochemicals and methanol. Sasol, a leader in F-T technology uses both gas reformation and coal gasification to produce syn-gas for its F-T production.

Step two, the Fischer-Tropsch conversion, was discovered in Germany in the early 1900's, it upgrades the syn-gas into a waxy long chain hydrocarbon. Simplified, this reaction is:

$$CO + 2H_2 = CH_2 + H_2O$$



The length of the hydrocarbon chain is determined by the composition (ratio of H_2 to CO) of the syn-gas, the catalyst selectivity and the reaction conditions (temperature and pressure.)

Sasol has pioneered several types of F-T conversion technologies to produce over 150 different products from the company's plants in South Africa. The hydrocarbon stream (CH_2) is sent to product workup and the water (H_2O) is sent to a water recovery unit. One disadvantage of today's F-T technology is that for every barrel of product produced one barrel of water is also produced. Water disposal is, therefore, a consideration.

The third step: product upgrading:

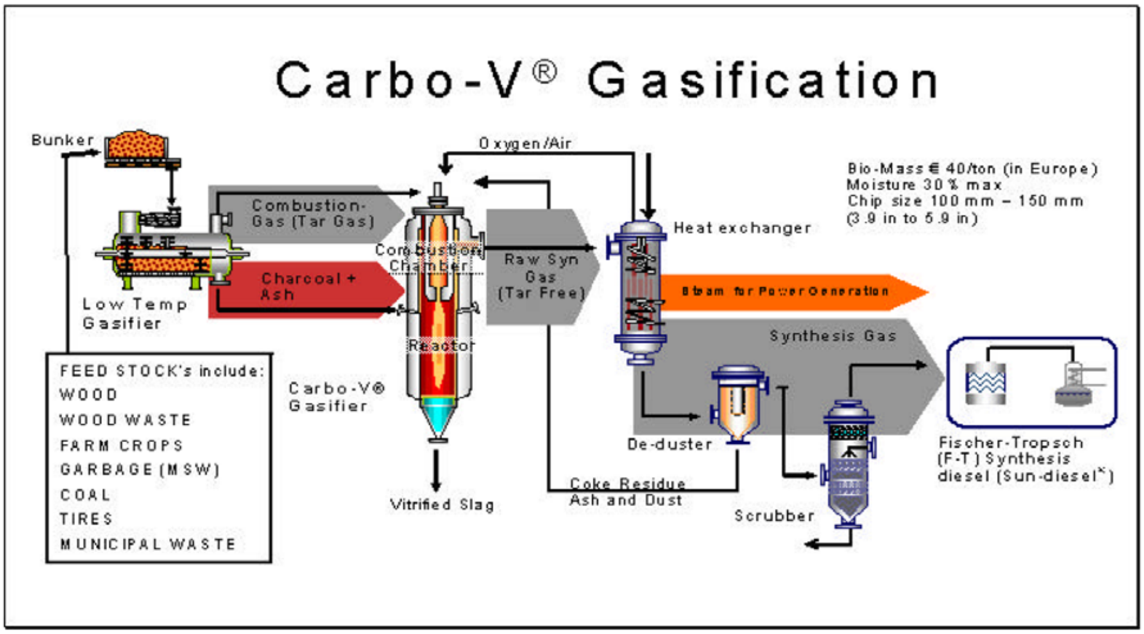
Upgrading can produce a wide range of commercial products including gasoline, diesel and specialty products of use for petrochemical manufacturing. For a U.S. based F-T program we would recommend middle distillate fuels: kerosene, diesel and naphtha. If exports are possible, an Alaska-based F-T plant could also make gasoline, which is in short supply in the U.S. west coast, as well as diesel.

The final product workup makes use of standard hydrocracking and hydro-isomerisation processes commonly found in the refinery world. As with the first step, syngas production, suitable technology is widely available from several licensors around the world.

The F-T process produces fuels that contain essentially no sulfur, aromatics or ring chain hydrocarbons that are toxic and harmful to the environment. As with a crude oil refinery, the F-T process does produce CO_2 but it is in a pure stream and is contained so that it can be sold or sequestered through injection into underground storage reservoirs or used in Enhanced Oil Recovery.

F-T diesel may be one of the cleanest motor fuels available. In the early 1990's UNOCAL Corp. asked the U.S. Environmental Protection Agency to approve F-T diesel from the South African Mossgas GTL plant for use as a drilling fluid in offshore waters. As a result of the tests performed by UNOCAL, the EPA determined that this form of F-T diesel is bio-degradable and non-toxic. *Note: The data can be found at EPA Water Docket, EB 57, Reference Docket No. W-98-26, UNOCAL data file 4.A.a, Vol 13.*

Choren, a German company has been operating a bio-mass gasifier to produce syn-gas for methanol and electric power production since the 1970's. This plant is considered one of the world's first bio-renewable gasifiers and has the distinction of producing fuels and electricity with a net zero impact on CO_2 production.



The Choren gasification process illustrated here provides the syn-gas necessary for F-T transport fuels, fertilizer, petrochemicals and electric power generation. It is in essence a bio-renewable generator of higher value energy products. The Choren gasification process has the distinction of being able to gasify coal and bio-mass (such as wood), both abundant in Alaska. One advantage of Choren's gasifier is that it could produce syn-gas from available resources, switching back and forth between coal and biomass on a seasonal basis. The illustration following provides a block flow diagram of the energy conversion process from resource to electricity and or transport fuels.

APPENDIX B

A. CTL CAPEX DATA FOR MONTE CARLO SIMULATION

Data Set Name	MC CAPEX01	MC CAPEX02	MC CAPEX03	MC CAPEX04	MC CAPEX05	MC CAPEX06	MC CAPEX07	MC CAPEX08	MC CAPEX09	MC CAPEX10
Normalized to 2006 $	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006
Relative (%) Values										
PLANT CAPACITY (bpd)	23,780	30,000	30,000	30,000	33,200	35,000	35,714	60,000	60,000	60,000
	%	%	%	%	%	%	%	%	%	
Solids Handling	11%	6%	7%	9%	3%	6%	10%	6%	7%	9%
Air Separation Unit	12%	10%	8%	7%	16%	10%	20%	10%	7%	6%
Gasification System	30%	17%	18%	21%	35%	18%	37%	20%	21%	23%
Liquids Area	6%	11%	11%	9%	7%	14%	7%	10%	12%	10%
Power Block	18%	13%	14%	12%	20%	11%	3%	13%	12%	11%
Refining Area	6%	14%	15%	14%	7%	12%	17%	13%	15%	14%
Balance of Plant	17%	11%	9%	10%	13%	14%	6%	10%	9%	10%
Other	0%	19%	19%	18%	0%	15%	0%	18%	18%	18%
TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Straight Values (2006$M)										
PLANT CAPACITY (bpd)	23,780	30,000	30,000	30,000	33,200	35,000	35,714	60,000	60,000	60,000
	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M
Solids Handling	172	163	189	262	74	163	250	278	304	420
Air Separation Unit	193	265	194	206	337	256	500	455	283	301
Gasification System	474	460	460	614	745	460	925	921	844	1074
Liquids Area	94	282	278	281	147	362	175	474	474	474
Power Block	287	351	342	357	420	290	75	592	487	511
Refining Area	94	366	374	412	153	294	425	622	603	661
Balance of Plant	271	284	218	289	272	345	150	483	361	465
Other	0	506	475	542	0	385	0	845	744	845
TOTAL	1584.51032	2677	2531	2964	2147.163	2555	2500	4669	4100	4751
Reallocated Values (2006$M) (reallocated BOP and OTH proportionality into other factors)										
PLANT CAPACITY (bpd)	23,780	30,000	30,000	30,000	33,200	35,000	35,714	60,000	60,000	60,000
	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M
Solids Handling	207	231	261	365	84	228	266	388	416	579
Air Separation Unit	233	377	267	287	386	358	532	635	388	416
Gasification System	572	653	634	853	853	644	984	1287	1155	1483
Liquids Area	113	400	383	390	168	507	186	663	649	655
Power Block	346	498	471	496	480	406	80	828	666	705
Refining Area	113	519	516	572	175	412	452	869	826	913
TOTAL	1585	2677	2531	2964	2147.163	2555	2500	4669	4100	4751
Normalized Reallocated Values (2006$/capacity) (2006$M/bpd) (using reallocated numbers)										
PLANT CAPACITY (bpd)	23,780	30,000	30,000	30,000	33,200	35,000	35,714	60,000	60,000	60,000
	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd
Solids Handling	0.00872563	0.00770874	0.00870026	0.01215102	0.00253484	0.00652000	0.00744687	0.00646372	0.00693583	0.00965452
Air Separation Unit	0.00978328	0.01255313	0.00889495	0.00955699	0.01161801	0.01024000	0.01489374	0.01059045	0.00645922	0.00693340
Gasification System	0.02406158	0.02176995	0.02113766	0.02843747	0.02570044	0.01840000	0.02755341	0.02144172	0.01925561	0.02471791
Liquids Area	0.00475943	0.01331686	0.01276066	0.01301230	0.00506968	0.01448000	0.00521281	0.01104317	0.01081876	0.01091187
Power Block	0.01454271	0.01660450	0.01570022	0.01654972	0.01446970	0.01160000	0.00223406	0.01379344	0.01109997	0.01175452
Refining Area	0.00475943	0.01728781	0.01718425	0.01907784	0.00528091	0.01176000	0.01265968	0.01448265	0.01376694	0.01521895
TOTAL	0.06663206	0.08924100	0.08437800	0.09878533	0.06467358	0.07300000	0.07000056	0.07781517	0.06833633	0.07919117

Table 12 CTL CAPEX Data for Monte Carlo Simulation

B. CTL CAPEX DATA STATISTICS FOR MONTE CARLO SIMULATION

Reallocated Values (2006$M) (reallocated BOP and OTH proportionality into other factors)						
.	Solids Handling	Air Separation Unit	Gasification System	Liquids Area	Power Block	Refining Area
Mean	302.5854538	387.781503	911.8748605	411.3585562	497.651622	536.6843364
Standard Error	43.58877193	38.41283057	98.27622955	65.66479672	65.60723677	86.32065327
Median	263.4826131	381.1559155	853.1894074	394.9374096	488.4427884	517.080866
Standard Deviation	137.8397997	121.472036	310.7767252	207.6503197	207.4682992	272.9698735
Sample Variance	18999.81038	14755.45552	96582.17294	43118.65528	43043.09516	74512.55181
Minimum	84.15663364	232.6463565	572.1842822	113.1793086	79.78723404	113.1793086
Maximum	579.2710469	635.4267797	1483.074711	662.5904886	827.6066525	913.1371698
Sum	3025.854538	3877.81503	9118.748605	4113.585562	4976.51622	5366.843364
Count	10	10	10	10	10	10
Confidence Level(80.0%)	60.28452426	53.1260486	135.9188498	90.81630098	90.73669391	119.3839442
Normalized Reallocated Values (2006$/capacity) (2006$M/bpd) (using reallocated numbers)						
	Solids Handling	Air Separation Unit	Gasification System	Liquids Area	Power Block	Refining Area
Mean	0.007684143	0.010152316	0.023247576	0.010138554	0.012834885	0.013147847
Standard Error	0.000788313	0.000793479	0.001073143	0.001177823	0.001336695	0.001525595
Median	0.007577806	0.010011639	0.022915764	0.010977523	0.014131573	0.014124799
Standard Deviation	0.002492865	0.002509202	0.003393577	0.003724604	0.004227001	0.004824356
Sample Variance	6.21438E-06	6.29609E-06	1.15164E-05	1.38727E-05	1.78675E-05	2.32744E-05
Minimum	0.002534838	0.006459222	0.0184	0.004759433	0.00223406	0.004759433
Maximum	0.012151018	0.014893736	0.028437469	0.01448	0.016604504	0.019077844
Sum	0.076841428	0.101523155	0.232475758	0.101385538	0.128348849	0.131478474
Count	10	10	10	10	10	10
Confidence Level(80.0%)	0.00109026	0.001097405	0.001484188	0.001628964	0.001848688	0.002109942

Table 13 CTL CAPEX Data Statistics for Monte Carlo Simulation

C. CTL OPEX DATA FOR MONTE CARLO SIMULATION

Data Set Name	MC OPEX01	MC OPEX02	MC OPEX03	MC OPEX04	MC OPEX05	MC OPEX06	MC OPEX07
Normalized to 2006 $	2006	2006	2006	2006	2006	2006	2006
Relative (%) Values							
Plant Capacity (bpd)	30,000	30,000	30,000	33200	60,000	60,000	60,000
	%	%	%	%	%	%	%
Feedstock	55%	34%	34%	54%	56%	35%	36%
Catalyst & Chemicals	7%	11%	10%	15%	7%	12%	10%
Labor & Overhead	15%	21%	21%	13%	14%	20%	19%
Administrative Labor	2%	3%	3%	2%	2%	3%	3%
Taxes & Insurance	14%	20%	20%	14%	13%	20%	19%
Other	6%	11%	12%	2%	8%	10%	12%
TOTAL	100%	100%	100%	100%	100%	100%	100%
Straight Values (2006$M/yr)							
Plant Capacity (bpd)	30,000	30,000	30,000	33200	60,000	60,000	60,000
	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M
Feedstock	199	81	100	143	372	141	174
Catalyst & Chemicals	24	26	28	39	44	47	50
Labor & Overhead	54	52	60	36	92	81	93
Administrative Labor	8	8	9	6	14	12	14
Taxes & Insurance	51	49	57	38	90	79	92
Other	22	25	36	5	57	42	59
TOTAL	359	241	291	266	668	402	482
Reallocated Values (2006$M/yr) (reallocated OTHER proportionality into other factors)							
Plant Capacity (bpd)	30,000	30,000	30,000	33200	60,000	60,000	60,000
	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M	2006$M
Feedstock	212	91	114	146	406	157	199
Catalyst & Chemicals	26	29	32	40	48	52	56
Labor & Overhead	58	58	68	36	100	90	106
Administrative Labor	9	9	10	6	15	14	16
Taxes & Insurance	55	55	65	39	98	88	104
TOTAL	359	241	291	266	668	402	482
Normalized Reallocated Values (2006$M/(yr*capacity)) (2006$M/(yr * bpd))							
Plant Capacity (bpd)	30,000	30,000	30,000	33200	60,000	60,000	60,000
	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd	2006$M/bpd
Feedstock	0.00706698	0.00301719	0.00381659	0.00438951	0.00677159	0.00262372	0.00331168
Catalyst & Chemicals	0.00086688	0.00098005	0.00107800	0.00119144	0.00080474	0.00086986	0.00094113
Labor & Overhead	0.00193271	0.00192284	0.00227408	0.00109738	0.00166774	0.00150366	0.00177008
Administrative Labor	0.00028778	0.00028694	0.00034283	0.00018812	0.00025672	0.00023047	0.00027378
Taxes & Insurance	0.00182613	0.00181850	0.00217504	0.00116009	0.00163133	0.00146835	0.00173966
TOTAL	0.01198048	0.00802553	0.00968654	0.00802654	0.01113211	0.00669606	0.00803633

Table 14 CTL OPEX Data for Monte Carlo Simulation

D. CTL OPEX DATA STATISTICS FOR MONTE CARLO SIMULATION

Reallocated Values ($M/yr) (reallocated OTH proportionality into other factors)					
	Feedstock	Catalyst & Chemicals	Labor & Overhead	Administrative Labor	Taxes & Insurance
Mean	188.8824066	40.49049392	73.72308386	11.32880975	71.81040963
Standard Error	39.70964653	4.512325975	9.763073289	1.478071994	9.509868292
Median	157.4233253	38.7421875	68.22239555	10.28478325	65.25123594
Standard Deviation	105.0618494	11.93849236	25.83066395	3.910610916	25.1607465
Sample Variance	11037.99219	142.5275999	667.2232003	15.29287774	633.0631645
Minimum	90.51583824	26.00633775	35.68359375	6.1171875	37.72265625
Maximum	406.2952033	56.4676525	106.2048171	16.42695345	104.3796001
Sum	1322.176846	283.4334574	516.061587	79.30166825	502.6728674
Count	7	7	7	7	7
Confidence Level(80.0%)	57.17219182	6.496647257	14.05644088	2.128062649	13.69188753
Normalized Reallocated Values ($M/(yr*capacity)) ($M/(yr * bpd))					
	Feedstock	Catalyst & Chemicals	Labor & Overhead	Administrative Labor	Taxes & Insurance
Mean	0.004415284	0.000958227	0.001735132	0.000266109	0.001685033
Standard Error	0.000678546	4.83993E-05	0.000143104	1.8839E-05	0.000122653
Median	0.003816593	0.000941128	0.00177008	0.000273783	0.00173966
Standard Deviation	0.001795265	0.000128053	0.000378618	4.98433E-05	0.000324511
Sample Variance	3.22298E-06	1.63975E-08	1.43352E-07	2.48435E-09	1.05307E-07
Minimum	0.002623722	0.00080474	0.001074807	0.000184253	0.001136225
Maximum	0.007066983	0.001166933	0.00227408	0.000342826	0.002175041
Sum	0.030906988	0.006707586	0.012145925	0.001862763	0.011795232
Count	7	7	7	7	7
Confidence Level(80.0%)	0.000976941	6.96832E-05	0.000206035	2.71235E-05	0.000176591

Table 15 CTL OPEX Data Statistics for Monte Carlo Simulation

E. CTL CAPEX DATA FOR REGRESSION ANALYSIS

FT CTL CAPEX (Normalized to 2006$)		
Data Set Name	**Plant Capacity**	**CAPEX (2006$M)**
Estimation Data (used for model development)		
REG CAPEX01	300	$68
REG CAPEX02	5,800	$829
REG CAPEX03	6,000	$573
REG CAPEX04	6,000	$625
REG CAPEX05	6,000	$678
REG CAPEX06	10,000	$960
REG CAPEX07	10,000	$976
REG CAPEX08	10,000	$1,116
REG CAPEX09	10,000	$1,237
REG CAPEX10	10,000	$1,324
REG CAPEX11	10,000	$1,410
REG CAPEX12	10,060	$684
REG CAPEX13	10,200	$771
REG CAPEX14	10,200	$783
REG CAPEX15	11,000	$1,500
REG CAPEX16	12,377	$1,532
REG CAPEX17	30,000	$2,889
REG CAPEX18	30,000	$3,252
REG CAPEX19	35,000	$2,830
REG CAPEX20	35,000	$3,750
REG CAPEX21	50,000	$3,369
REG CAPEX22	80,000	$7,000
Prediction Data (used in model validation and MC sim)		
MC CAPEX01	23,780	$1,585
MC CAPEX02	30,000	$2,677
MC CAPEX03	30,000	$2,531
MC CAPEX04	30,000	$2,964
MC CAPEX05	33,200	$2,145
MC CAPEX06	35,000	$2,555
MC CAPEX07	35,714	$2,500
MC CAPEX08	60,000	$4,669
MC CAPEX09	60,000	$4,100
MC CAPEX10	60,000	$4,751

Table 16 CTL CAPEX Data for Regression Analysis

F. CTL OPEX DATA FOR REGRESSION ANALYSIS

FT CTL OPEX (Normalized to 2006$/YR)		
Data Set Name	**Plant Capacity**	**OPEX (2006$M/YR)**
Estimation Data (used for model development)		
REG OPEX01	5,800	$85
REG OPEX02	10,000	$123
REG OPEX03	10,000	$165
REG OPEX04	10,000	$86
REG OPEX05	10,000	$110
REG OPEX06	10,000	$104
REG OPEX07	10,000	$130
REG OPEX08	12,377	$266
REG OPEX09	30,000	$397
REG OPEX10	30,000	$318
REG OPEX11	33,000	$403
REG OPEX12	35,000	$404
REG OPEX13	35,000	$323
REG OPEX14	50,000	$988
Prediction Data (used in model validation and MC sim)		
MC OPEX01	30,000	$359
MC OPEX02	30,000	$241
MC OPEX03	30,000	$291
MC OPEX04	33,200	$266
MC OPEX05	60,000	$668
MC OPEX06	60,000	$402
MC OPEX07	60,000	$482

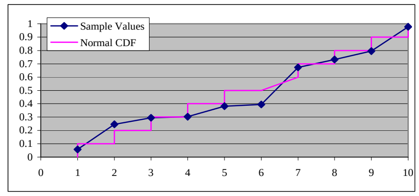
Table 17 CTL OPEX Data For Regression Analysis

APPENDIX C

NORMALITY TEST RESULTS

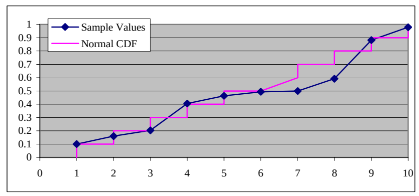
Solids Handling

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	84	0.05652213	0.00	0.056522	0.10	0.043478
sample mean	303	2	207	0.245141366	0.10	0.145141	0.20	-0.045141
sample variance	137.8397997	3	228	0.294718699	0.20	0.094719	0.30	0.005281
Lilliefors statistic	0.2048	4	231	0.302426209	0.30	0.002426	0.40	0.097574
10 Data Points		5	261	0.381464148	0.40	-0.018536	0.50	0.118536
Lstat crit α=0.20	0.2171	6	266	0.395224034	0.50	-0.104776	0.60	0.204776
Lstat crit α=0.15	0.2273	7	365	0.673428125	0.60	0.073428	0.70	0.026572
Lstat crit α=0.10	0.2410	8	388	0.731838986	0.70	0.031839	0.80	0.068161
Lstat crit α=0.05	0.2616	9	416	0.794998319	0.80	-0.005002	0.90	0.105002
Lstat crit α=0.01	0.3037	10	579	0.977641044	0.90	0.077641	1.00	0.022359



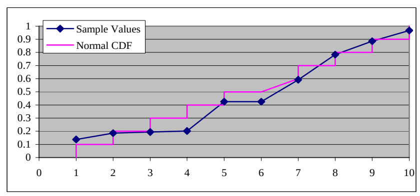
Air Separation Unit

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	233	0.100778809	0.00	0.100779	0.10	-0.000779
sample mean	388	2	267	0.1597311	0.10	0.059731	0.20	0.040269
sample variance	121.472036	3	287	0.202688111	0.20	0.002688	0.30	0.097312
Lilliefors statistic	0.2081	4	358	0.404437062	0.30	0.104437	0.40	-0.004437
10 Data Points		5	377	0.463309289	0.40	0.063309	0.50	0.036691
Lstat crit α=0.20	0.2171	6	386	0.49322299	0.50	-0.006777	0.60	0.106777
Lstat crit α=0.15	0.2273	7	388	0.499250693	0.60	-0.100749	0.70	0.200749
Lstat crit α=0.10	0.2410	8	416	0.591861165	0.70	-0.108139	0.80	0.208139
Lstat crit α=0.05	0.2616	9	532	0.882298628	0.80	0.082299	0.90	0.017701
Lstat crit α=0.01	0.3037	10	635	0.979260109	0.90	0.079260	1.00	0.020740



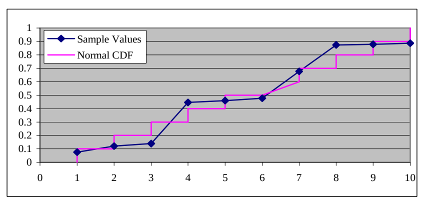
Gasification

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	572	0.137188693	0.00	0.137189	0.10	-0.037189
sample mean	912	2	634	0.18573793	0.10	0.085738	0.20	0.014262
sample variance	310.7767252	3	644	0.194356753	0.20	-0.005643	0.30	0.105643
Lilliefors statistic	0.1975	4	653	0.202513765	0.30	-0.097486	0.40	0.197486
10 Data Points		5	853	0.425028752	0.40	0.025029	0.50	0.074971
Lstat crit α=0.20	0.2171	6	853	0.425193567	0.50	-0.074806	0.60	0.174806
Lstat crit α=0.15	0.2273	7	984	0.59181533	0.60	-0.008185	0.70	0.108185
Lstat crit α=0.10	0.2410	8	1155	0.783302937	0.70	0.083303	0.80	0.016697
Lstat crit α=0.05	0.2616	9	1287	0.885986904	0.80	0.085987	0.90	0.014013
Lstat crit α=0.01	0.3037	10	1483	0.966966955	0.90	0.066967	1.00	0.033033



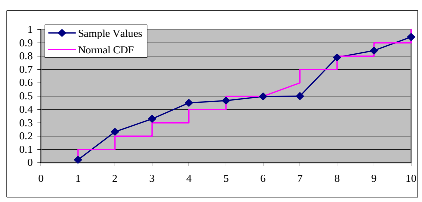
Liquids Area

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	113	0.075505701	0.00	0.075506	0.10	0.024494
sample mean	411	2	168	0.120909021	0.10	0.020909	0.20	0.079091
sample variance	207.6503197	3	186	0.139080577	0.20	-0.060919	0.30	0.160919
Lilliefors statistic	0.1739	4	383	0.445342609	0.30	0.145343	0.40	-0.045343
10 Data Points		5	390	0.45974276	0.40	0.059743	0.50	0.040257
Lstat crit α=0.20	0.2171	6	400	0.477240843	0.50	-0.022759	0.60	0.122759
Lstat crit α=0.15	0.2273	7	507	0.677107581	0.60	0.077108	0.70	0.022892
Lstat crit α=0.10	0.2410	8	649	0.87390274	0.70	0.173903	0.80	-0.073903
Lstat crit α=0.05	0.2616	9	655	0.879389436	0.80	0.079389	0.90	0.020611
Lstat crit α=0.01	0.3037	10	663	0.886837495	0.90	-0.013163	1.00	0.113163



Power Block

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	80	0.021998889	0.00	0.021999	0.10	0.078001
sample mean	498	2	346	0.23214436	0.10	0.132144	0.20	-0.032144
sample variance	207.4682992	3	406	0.3293307	0.20	0.129331	0.30	-0.029331
Lilliefors statistic	0.1991	4	471	0.448904868	0.30	0.148905	0.40	-0.048905
10 Data Points		5	480	0.466853648	0.40	0.066854	0.50	0.033146
Lstat crit α=0.20	0.2171	6	496	0.497769127	0.50	-0.002231	0.60	0.102231
Lstat crit α=0.15	0.2273	7	498	0.500929693	0.60	-0.099070	0.70	0.199070
Lstat crit α=0.10	0.2410	8	666	0.79144139	0.70	0.091441	0.80	0.008559
Lstat crit α=0.05	0.2616	9	705	0.841520952	0.80	0.041521	0.90	0.058479
Lstat crit α=0.01	0.3037	10	828	0.944126279	0.90	0.044126	1.00	0.055874



Refining

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	10	1	113	0.060394345	0.00	0.060394	0.10	0.039606
sample mean	537	2	175	0.092784435	0.10	-0.007216	0.20	0.107216
sample variance	272.9698735	3	412	0.323391826	0.20	0.123392	0.30	-0.023392
Lilliefors statistic	0.1554	4	452	0.378369606	0.30	0.078370	0.40	0.021630
10 Data Points		5	516	0.469110543	0.40	0.069111	0.50	0.030889
Lstat crit α=0.20	0.2171	6	519	0.473639113	0.50	-0.026361	0.60	0.126361
Lstat crit α=0.15	0.2273	7	572	0.55195576	0.60	-0.048044	0.70	0.148044
Lstat crit α=0.10	0.2410	8	826	0.855414553	0.70	0.155415	0.80	-0.055415
Lstat crit α=0.05	0.2616	9	869	0.888247051	0.80	0.088247	0.90	0.011753
Lstat crit α=0.01	0.3037	10	913	0.916068084	0.90	0.016068	1.00	0.083932

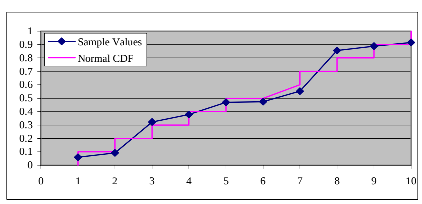
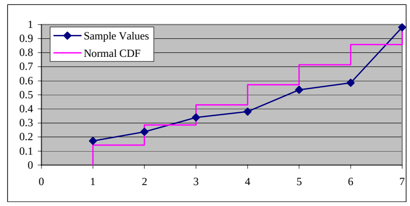


Table 18 CAPEX Work Breakdown Structure Elements Tests for Normality

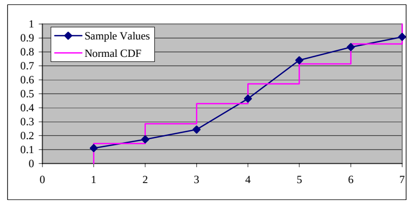
Feedstock

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	7	1	91	0.173028779	0.00	0.173029	0.14	-0.030172
sample mean	189	2	114	0.237757757	0.14	0.094901	0.29	0.047957
sample variance	104.8483063	3	146	0.338837903	0.29	0.053124	0.43	0.089734
Lilliefors statistic	0.2714	4	157	0.380515265	0.43	-0.048056	0.57	0.190913
7 Data Points		5	199	0.535681537	0.57	-0.035747	0.71	0.178604
Lstat crit α=0.20	0.2521	6	212	0.585698084	0.71	-0.128588	0.86	0.271445
Lstat crit α=0.15	0.2641	7	406	0.980750862	0.86	0.123608	1.00	0.019249
Lstat crit α=0.10	0.2802							
Lstat crit α=0.05	0.3041							
Lstat crit α=0.01	0.3504							



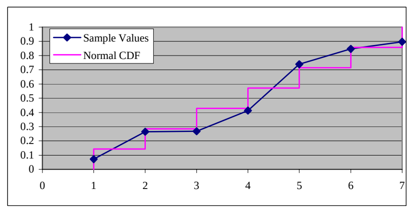
Catalyst & Chemicals

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	7	1	26	0.110363215	0.00	0.110363	0.14	0.032494
sample mean	41	2	29	0.173654991	0.14	0.030798	0.29	0.112059
sample variance	11.92258477	3	32	0.244037947	0.29	-0.041676	0.43	0.184533
Lilliefors statistic	0.1845	4	40	0.464879688	0.43	0.036308	0.57	0.106549
7 Data Points		5	48	0.740199147	0.57	0.168771	0.71	-0.025913
Lstat crit α=0.20	0.2521	6	52	0.834388262	0.71	0.120103	0.86	0.022755
Lstat crit α=0.15	0.2641	7	56	0.908294662	0.86	0.051152	1.00	0.091705
Lstat crit α=0.10	0.2802							
Lstat crit α=0.05	0.3041							
Lstat crit α=0.01	0.3504							



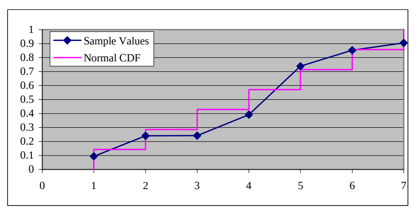
Labor/overhead

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	7	1	36	0.072404591	0.00	0.072405	0.14	0.070453
sample mean	74	2	58	0.264516023	0.14	0.121659	0.29	0.021198
sample variance	25.64764549	3	58	0.268306348	0.29	-0.017408	0.43	0.160265
Lilliefors statistic	0.1672	4	68	0.413463151	0.43	-0.015108	0.57	0.157965
7 Data Points		5	90	0.738596737	0.57	0.167168	0.71	-0.024311
Lstat crit α=0.20	0.2521	6	100	0.846816487	0.71	0.132531	0.86	0.010326
Lstat crit α=0.15	0.2641	7	106	0.896577184	0.86	0.039434	1.00	0.103423
Lstat crit α=0.10	0.2802							
Lstat crit α=0.05	0.3041							
Lstat crit α=0.01	0.3504							



Administrative Labor

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	7	1	6	0.094414375	0.00	0.094414	0.14	0.048443
sample mean	11	2	9	0.240239088	0.14	0.097382	0.29	0.045475
sample variance	3.882276639	3	9	0.242260041	0.29	-0.043454	0.43	0.186311
Lilliefors statistic	0.1863	4	10	0.39217749	0.43	-0.036394	0.57	0.179251
7 Data Points		5	14	0.738633421	0.57	0.167205	0.71	-0.024348
Lstat crit α=0.20	0.2521	6	15	0.851916834	0.71	0.137631	0.86	0.005226
Lstat crit α=0.15	0.2641	7	16	0.904640829	0.86	0.047498	1.00	0.095359
Lstat crit α=0.10	0.2802							
Lstat crit α=0.05	0.3041							
Lstat crit α=0.01	0.3504							



Local Taxes & Insurance

				Norm CDF	Lower	L Delta	Upper	U Delta
# of data	7	1	39	0.090569266	0.00	0.090569	0.14	0.052288
sample mean	72	2	55	0.243461914	0.14	0.100605	0.29	0.042252
sample variance	24.98302722	3	55	0.24633916	0.29	-0.039375	0.43	0.182232
Lilliefors statistic	0.1822	4	65	0.394705713	0.43	-0.033866	0.57	0.176723
7 Data Points		5	88	0.741354354	0.57	0.169926	0.71	-0.027069
Lstat crit α=0.20	0.2521	6	98	0.850585619	0.71	0.136300	0.86	0.006557
Lstat crit α=0.15	0.2641	7	104	0.90304912	0.86	0.045906	1.00	0.096951
Lstat crit α=0.10	0.2802							
Lstat crit α=0.05	0.3041							
Lstat crit α=0.01	0.3504							

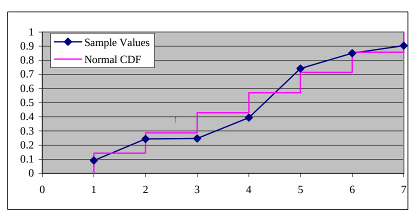


Table 19 OPEX Work Breakdown Structure Elements Tests for Normality

APPENDIX D

WORLD CRUDE OIL TO JET FUEL MARKUP

Year	Total World Crude Oil Price ($/barrel)	NY Harbor Kerosene-Type Jet Fuel Spot Price ($/barrel)	Jet Fuel/World Crude Oil
January-90	$18.91	$33.00	174%
January-91	$24.72	$26.85	109%
January-92	$16.22	$24.94	154%
January-93	$14.71	$23.33	159%
January-94	$12.37	$22.18	179%
January-95	$16.63	$21.77	131%
January-96	$19.61	$27.62	141%
January-97	$18.28	$24.62	135%
January-98	$11.82	$18.05	153%
January-99	$17.13	$21.87	128%
January-00	$27.07	$38.25	141%
January-01	$22.73	$31.24	137%
January-02	$23.47	$29.86	127%
January-03	$27.11	$36.33	134%
January-04	$34.62	$50.21	145%
January-05	$49.87	$72.06	145%
		Average =	143%

Table 20 World Crude Oil To Jet Fuel Markup [EIA Petroleum Navigator]

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