# Transforming Non-Recyclable Plastics to Fuel Oil Using Thermal Pyrolysis

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# I. Executive Summary

The goal of this project was to design and simulate a process that converts non-recyclable plastics (NRP) from municipal solid waste (MSW) produced in New York to high value oils. The NRP to fuel process was designed based on Golden Renewable Energy (GRE)'s Renewable Fuel Production (RFP) unit in Yonkers, New York. This unit takes a feed stream of 8-10 tons per day (TPD) of NRP from of all grades excluding No.3 (PVC) and converts it into No.2 home heating oil. The plant produces approximately 4.8 barrels of oil (B.O.) per ton of NRP.

In GRE's process, the plastic feedstock is pretreated before entering the RFP unit. The pretreatment consists of removing unwanted materials (i.e., metals, paper, glass and PVC) and shredding the plastic to 0.75"-1" flakes. In the RFP unit, the plastics are melted in an extruder and then sent through two screw pyrolysis reactors in series, where they are converted to pyrolysis gas (pygas) and char. Then, the pygas is converted to oil by condensation and separation using a series of 8 cyclones. Light gases that do not condense from the pygas are recycled back into the process for energy recovery. GRE's process has a carbon conversion of NRP to pygas of 95% and a pyrolysis energy efficiency of 80%, approximately.

This report provides a quantitative detailed design analysis of a NRP to fuel process for a capacity of 10 TPD of NRP to produce about 4.8 B.O. per ton of NRP. Aspen Plus was used to simulate this process using a feedstock composed of 60% Polypropylene (PP) and 40% Polyethylene (PE) at 77$^{o}$F and atmospheric pressure. The results from the Aspen sensitivity analysis showed that it is possible to simulate a process that converts NRP to fuel. The simulation resulted in a carbon conversion of 93%, an oil to gas selectivity of 3.2:1, a production rate of 4.2 B.O. per ton of NRP, and an energy efficiency of 84% at 1000 $^{o}$F.

Finally, an economic analysis was done on the NRP to fuel process. The fixed capital cost was calculated by adding up the cost of the major equipment and installation costs. Operation and maintenance (O&M) costs were determined by accounting for the cost to labor, rent, water, electricity, and wastewater disposal along with monthly maintenance and insurance costs. The results from the economic analysis showed a total capital cost of $2,232,959, a net profit per year of $968,145, a ROI of 26.6% and a payback period of 2.9 years.

## II. Introduction

Transforming non-recyclable plastics (NRP) to high value oils have gained momentum over the past years due to the increasing rate of plastic waste production coupled with the environmental impacts of municipal solid waste (MSW) landfilling. For instance, in the US, the amount of plastic waste increased from 34.2 million tons in 2011 to 39.3 million tons in 2014.[1] Also, according to *"Transforming the Non-Recycled Plastics of New York City to Synthetic Oil"* about 26 million tons of $CO_2$ are generated every year due to landfilling.[2]

One way to reduce plastic landfilling is by transforming NRP to oils using pyrolysis. In a pyrolysis process, large chains of hydrocarbons are broken down to smaller chains of hydrocarbons to produce high value oils. This reaction occurs at temperatures ranging typically from 572 $^{o}$F to 1112$^{o}$F under an oxygen-free environment and atmospheric pressure.[2,3] The pyrolysis process results in the production of oil, non-condensable gases, and char which composition depends on the characteristics of the feedstock.

### A. Commercial Pyrolysis Techniques

The 3 main commercial technologies for NRP pyrolysis are thermal, thermal-catalytic and microwave pyrolysis. Thermal pyrolysis requires temperatures between 572$^{o}$F and 2192$^{o}$F depending on the feedstock composition. In addition, it may require long residence times compared to catalytic processes.[3] Thermal pyrolysis is ideal for plastics that thermally degrade at relatively low temperatures like polystyrene (PS).

In thermal-catalytic pyrolysis, a catalyst is used to accelerate the depolymerization reactions and to improve the fuel quality. It can be done at temperatures as low as 392$^{o}$F. The addition of a catalyst improves the quality of products and reduces the residence time. The main disadvantage of thermal-catalytic pyrolysis is that catalysts are usually expensive, must be regenerated after the pyrolysis reaction and suffer from deactivation due to coke deposition.[2,3,4]

Microwave pyrolysis breaks down NRP using microwave radiation. Since plastics have low dielectric constant, they are required to be mixed with materials like graphite and carbon which are microwave radiation absorbents. Cracking temperatures in microwave pyrolysis range from 932 $^{o}$F to 1292$^{o}$F. The major advantage of this technique is that it allows for an even heat transfer in the pyrolysis reactor.[2,4]

Many researchers have noted that thermal-catalytic pyrolysis is more efficient compared to other types of pyrolysis techniques.[3,4] However, thermal pyrolysis is still more popular among commercial scale NRP to oil plants. A 2015 review on plastic to fuel producers done by the Ocean Recovery Alliance, shows that out of 14 plastics-to-oils producers only 5 use thermal-catalytic pyrolysis. The popularity of thermal pyrolysis over catalytic pyrolysis could be due to the capital expense associated with the use of a catalyst. Table 1 shows a list of producers that use thermal and catalytic pyrolysis including GRE and this design.[5]

**Table 1:** Plastic to Oil Producers, Capacity, Pyrolysis Methods, Costs, and Products[5]

| ***Producers*** | ***Capacity*** | ***Type of Pyrolysis*** | ***Products*** | ***Production Rate*** | ***Fixed Capital Cost*** |
|---|---|---|---|---|---|
| *This Design* | 10 TPD | Thermal | No. 2 Home Heating Oil | 177 gallons/ton | $1.6 Million |
| *MK Aromatics Limited* | 11 TPD | Catalytic | Light Sweet Synthetic Crude | 195 gallons/ton | $3.5 Million |
| *Golden Renewables* | 24 TPD | Thermal | Diesel Blendstock, Gasoline Blendstock, No. 2 Home Heating Oil | 190 gallons/ton | $5-$6 Million |
| *JBI* | 20-30 TPD | Catalytic | Naphtha, Diesel Blendstock, Fuel Oil No. 6 | 190 gallons/ton | $5-$8 Million |
| *Nexus Fuels* | 50 TPD | Thermal | Light Sweet Synthetic Crude and Distillate fuel | 220-280 gallons/ton | $9-$12 Million |
| *Vadxx* | 60 TPD | Thermal | Light End/Naphtha Middle Distillate Fuel Oil No. 2 | 210 gallons/ton | $17-$18 Million |

## B. GRE's Approach

GRE, located in Yonkers, New York takes plastic waste from Recommunity Beacon, a material recovery facility in New York, and converts it to No.2 home heating oil, syngas and a char byproduct using thermal pyrolysis. In their process, a feed stream of 8-10 TPD of NRP of all grades plastics (primarily PP and PE) excluding PVC is pyrolyzed in an oxygen free environment (PVC is not used as a feedstock because it releases chlorine gases that can potentially corrode the equipment). The plastic material is converted to 75% oil, 20% gas and 5% char, approximately and the company has a production rate of 4.8 B.O. per ton of NRP. Also, GRE produces emissions such as NOx, $SO_2$, VOC, CO, $CO_2$ and particulate matter that are all within the New York State Department of Environmental Conservation (DEC) limits.[6]

GRE's process is a closed loop system. The non-condensable gases produced from the pyrolysis reaction are looped back to the process to offset energy requirements. Natural gas is used for the reactor furnaces only during equipment start-up.[6]

The goal of this project is to design and simulate in Aspen a NRP to fuel plant based on GRE's RFP unit. GRE's design will be optimized to improve the NRP carbon conversion, plastic to oil selectivity and the overall process energy efficiency.

## III. Process Description

Plastic waste will be pretreated by removing unwanted materials such as, metals, paper, glass and PVC. Metal and glass will be removed using selective vacuuming (based on feedstock density) and the rest of the contaminants will be sorted out manually. Plastics that have an amount of moisture greater than 10% will be dried using a hot air drier. Then, 10 TPD of the pretreated plastic material will be mechanically shredded twice to 0.75-1" flakes and sent from a hopper to an extruder where the plastics melt at 900 $^{o}$F. The extruder eases the flow of the plastics to a rotary screw pyrolysis reactor. This reactor operates between 700 and 1212$^{o}$F. Plastic material that do not thermally degrade remains as char and is collected at the bottom of the reactor.

The non-condensable gases in the pygas will be separated from the oil fractions by a series of 8 cyclones operating at temperatures between 350$^{o}$F and 14$^{o}$F and different residence times. The first cyclone separates out the heaviest oil fractions while the last cyclone the lightest fractions. The 8$^{th}$ cyclone will have an ethylene glycol cooling jacked and chiller to achieve the final operating temperature.

The oil fractions collected from each cyclone will be mixed in a single stream to make No.2 home heating oil that can be sold and used directly into furnaces and generators. The energy content of the non-condensable gases resulting from the process will be used to run the pyrolysis process without the input of external energy during steady state operations. This process will operate at atmospheric pressure.[6]

The major difference between this process and GRE's process is that this design includes the drying of plastics in the pretreatment to decrease the energy consumption associated with the moisture content. Also, while GRE pyrolyzes the plastics in two screw reactors in series, this design utilizes a single rotary screw pyrolysis reactor. This reactor provides a plastic to oil conversion greater than 75%.

Figure 1 and 2 shows the overall process material and energy balances. Mass streams are depicted as horizontal solid lines and energy streams as horizontal dashed lines. A feed composition of 60% PP and 40% PE was assumed based on GRE's average feedstock distribution (refer to fig. A-1 in the appendix).[6] To calculate the energy in and out of the pyrolysis reactor, the high heating value (HHV) of the components were estimated using the HHV provided by references 2 and 7. The energy out the char out was calculated using the HHV reported by GRE. To close the energy balance out, the remaining energy was assumed to be energy losses.

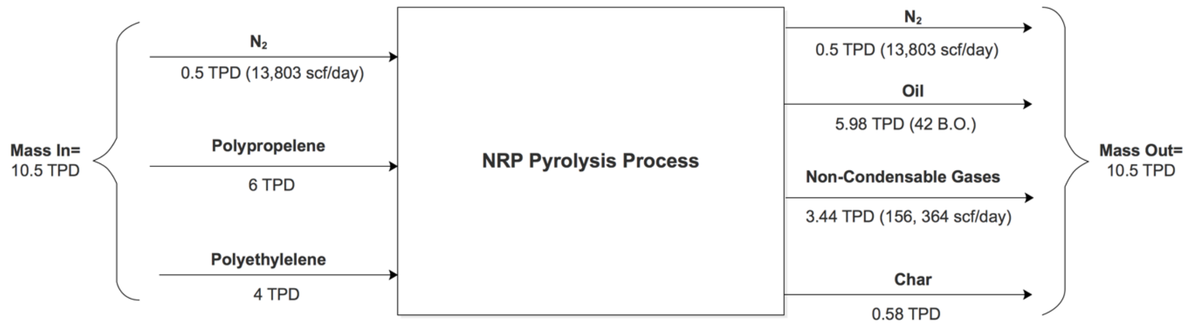


**Fig.1.** Overall NRP Pyrolysis Process Mass Balance

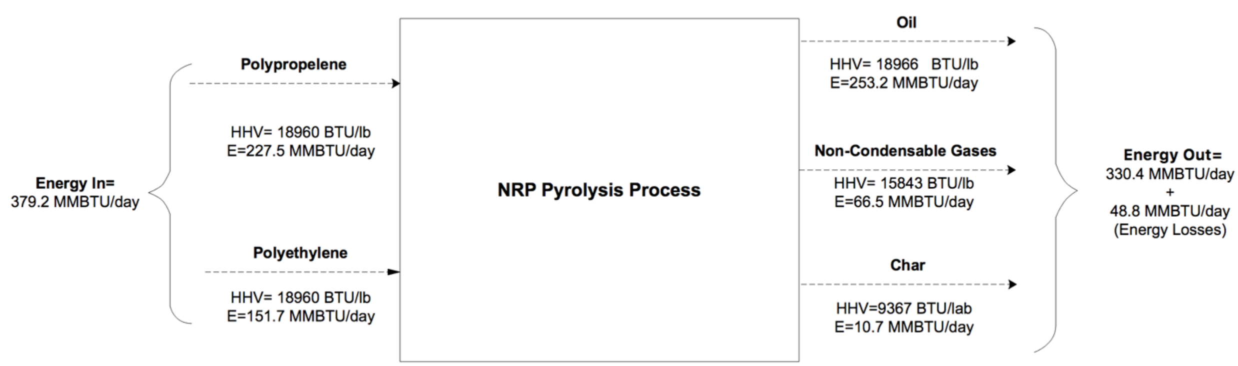


**Fig.2.** Overall NRP Pyrolysis Process Energy Balance

Figure 3 is a detailed process flow diagram (PFD) showing the major process units and specifications, mass flow rates process operating conditions. The composition of each stream in a weight percent basis is shown in Table A-2 of the appendix.

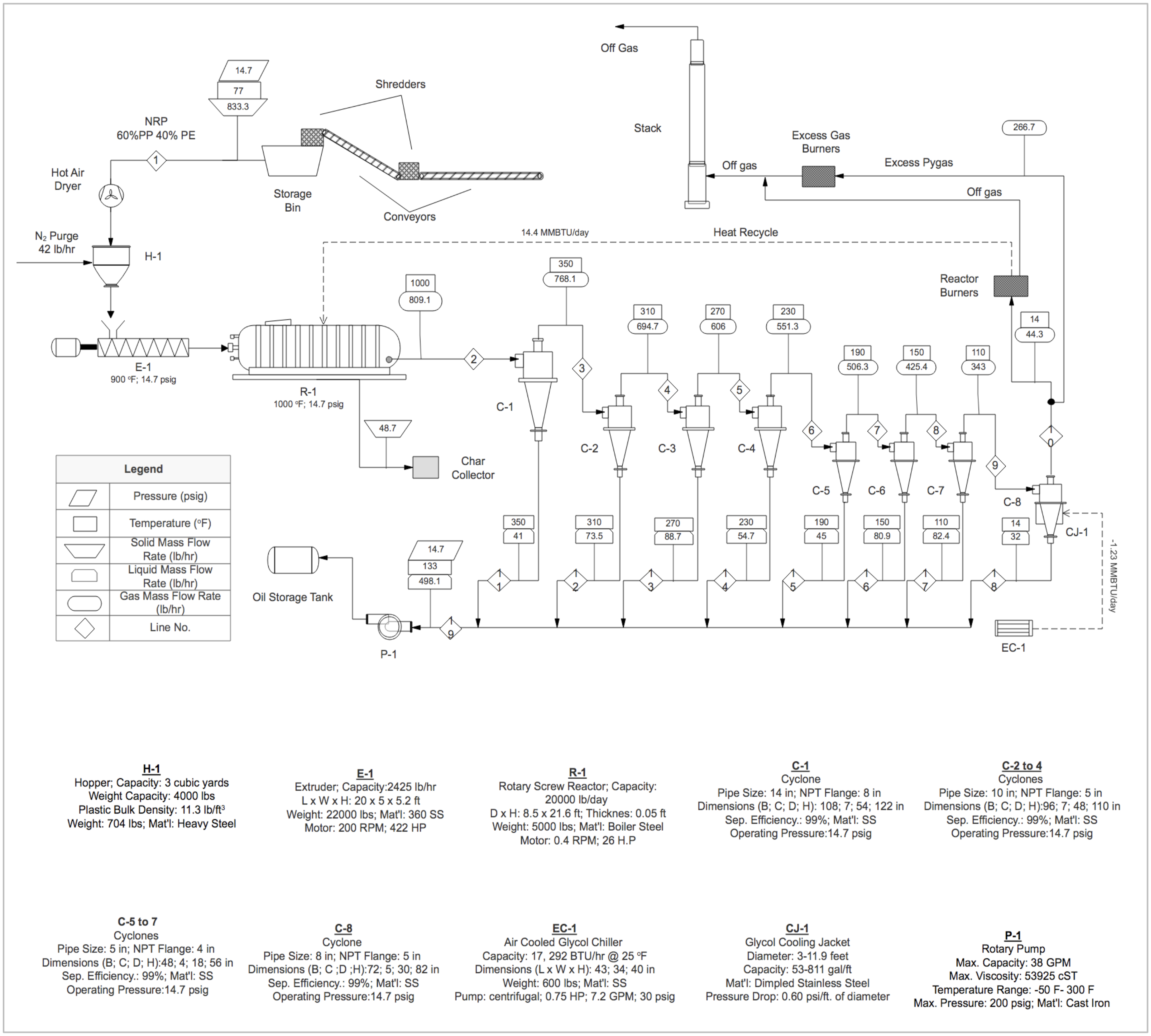


**Fig. 3.** NRP to fuel process flow diagram

## IV. Major Equipment Specifications

Table 2 shows the major equipment specifications for the NRP to fuel process. A detailed spreadsheet of each individual equipment and drawing is shown in Appendix B.

**Table 2:** Major Equipment Specifications

| ***Equipment ID*** | ***Equipment Type*** | ***Manufacturer*** | ***Equipment Specifications*** |
|---|---|---|---|
| ***H-1*** | Storage Hopper | McCullough Industries[8] | Capacity: 3 cubic yards<br>Weight Capacity: 4000 lbs.<br>Material of Construction: Heavy Steel |
| ***E-1*** | Extruder | Toshiba Machine[9] | Screw Diameter: 19.7 in<br>Effective L/D Ratio: 28<br>Max Screw Speed: 200 RPM<br>Motor Power Requirement: 110-315 kW<br>Heater Capacity: 63 kW<br>Extrusion Output Range: 420-1,100 kg/h<br>Hopper Capacity: 400 L<br>Material of Construction: 316 Stainless Steel<br>Operating Temperature: 900 $^{o}$F<br>Operating Pressure: 14.7 psi |
| ***E-1*** | Rotary Screw Reactor | Henan Doing Mechanical Equipment[10] | Capacity: 10 TPD<br>Total Power: 19 kW<br>Rotate Speed: 0.4 RPM<br>Oil Yield: 4.5-5.5ton/10 ton of Plastic<br>Material of Construction: Boiler Steel Plates<br>Operating Temperature: 1094-1212$^{o}$F<br>Operating Pressure: 14.7 psi<br>Carbon conversion: 94%<br>Conversion rate: 4.5 B.O./day |
| ***EC-1*** | Ethylene Glycol Chiller | Advantage[11] | Type: Air Cooled Modular Indoor Chiller<br>Compressor Power: 3 HP<br>Cooling Capacity: 5.068 kW/hr @ 25 $^{o}$F Glycol temperature<br>Percentage of glycol to water: 25/75<br>Refrigerant Type: R-410 A<br>Reservoir Capacity: 7.5 gallon<br>Material of Construction: Stainless Steel<br>Process Pump: centrifugal; 0.75 HP; 7.2 GPM; 30 psig |
| ***CJ-1*** | Ethylene Glycol Cooling Jacket | Santa Rosa Stainless Steel[12] | Pressure: 0-50 psi<br>Glycol Flow rate:0-40 GPM<br>Capacity: 53-811 gal/ft<br>Material of Construction: 304 Dimpled Stainless Steel<br>Pressure Drop: 0.60 psi/ft. of diameter<br>Operating Pressure: 14.7 psig<br>Operating Temperature:14 $^{o}$F |

| | | | |
|---|---|---|---|
| ***C-1 to 8*** | Gas/Liquid Cyclone Separator | Eaton[13] | Gas/Oil Separation Efficiency: 99%<br>Material of Construction: Fabricated Carbon Steel<br>Max. Pressure: 600 psig<br>Max. Temperature:1000ºF<br>Operating Pressure: 14.7 psig |
| | | | C-1: Pipe Size: 14 in; NPT Flange: 8 in<br>Operating Flow Rate: 767 lb/hr<br>Operating Temperature: 350ºF |
| | | | C-2 to 4: Pipe Size: 10 in; NPT Flange: 5 in<br>Operating Flow Rates: 509-653 lb/hr<br>Operating Temperatures: 310-230ºF |
| | | | C-5 to 7: Pipe Size: 5 in; NPT Flange: 4 in<br>Operating Flow Rates: 509-653 lb/hr<br>Operating Temperatures: 190-110ºF |
| | | | C-8: Pipe Size: 8 in; NPT Flange: 5 in<br>Operating Flow Rate: 35 lb/hr<br>Operating Temperature: 14 ºF |
| ***P-1*** | Rotary Pump | Gorman-Rupp Pumps[14] | Max. Capacity: 38 GPM<br>Max. Viscosity: 53925 cST<br>Max. Pressure: 200 psig<br>Min. Temperature: -50 F<br>Max. Temperature: 300 F<br>Material of Construction: Cast Iron<br>Operating Flow rate: 1.23 gallons/min |

**See Appendix-B for more details.*

## V. Aspen Simulation

### A. Simulation Overview

The NRP to fuel process was modeled using ASPEN Plus as shown in figure 4. In this simulation, the equation of state PR-BM was used to estimate the physical properties of the conventional components. HCOALGEN and DCOALIGT were used to calculate the enthalpy and density of the NRP (non-conventional component) based on its proximate and ultimate analysis. The ultimate and proximate analysis of the plastic feedstock used in this simulation are shown in Table 3 and 4, respectively.[6] The ultimate and proximate analyses provide the composition of the plastic feedstock such as elemental composition, the amount of moisture, fixed carbon, volatiles and ash.

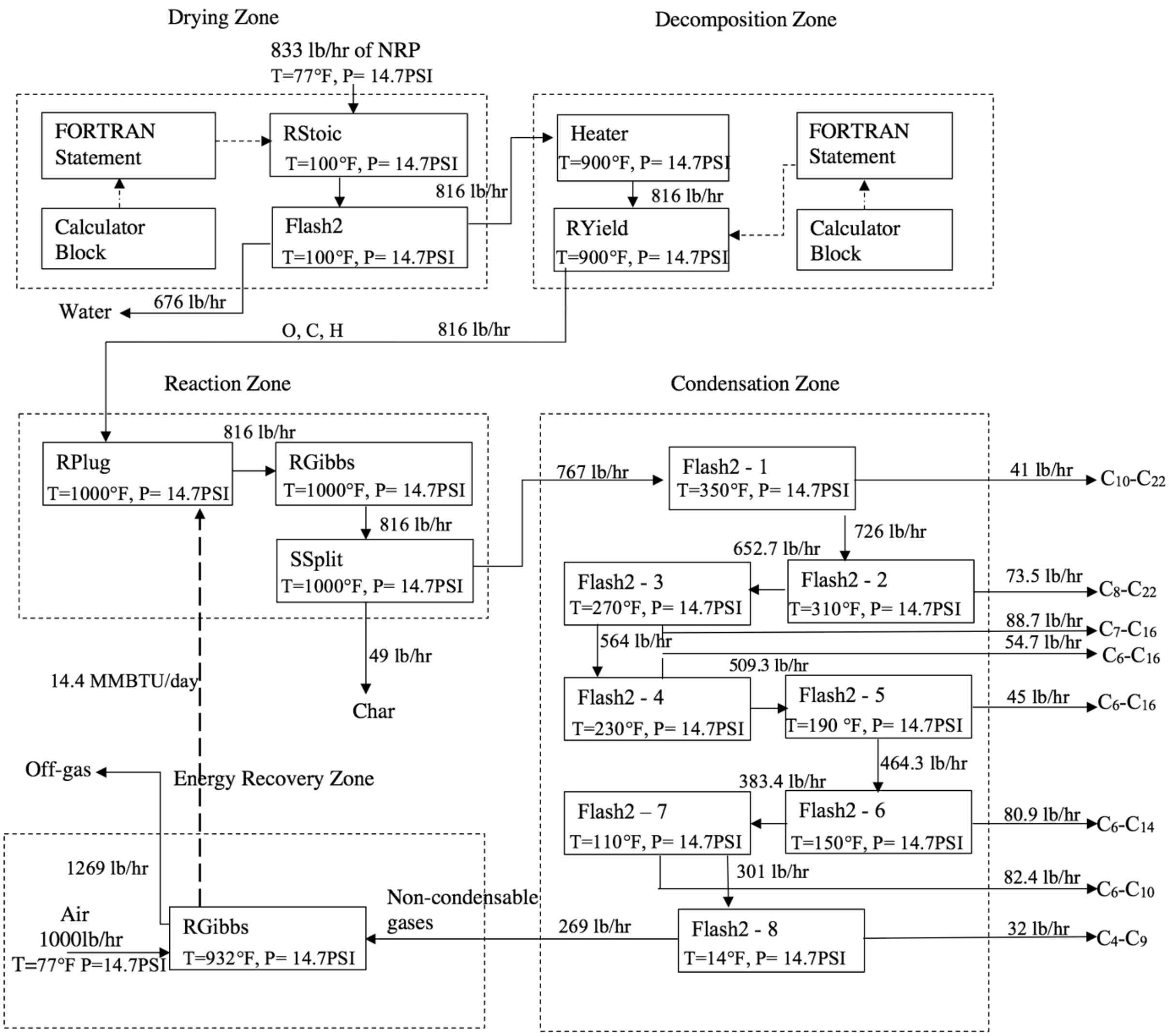


**Fig. 4.** Aspen simulation of NRP to fuel pyrolysis process

**Table 3:** Proximate analysis (wt%) of NRP feedstock[6]

| ***Component*** | ***wt%*** |
|---|---|
| *Ash* | 0.44 |
| *Volatiles* | 99.54 |
| *Moisture* | 0.05 |
| *Fixed Carbon* | 0.03 |

**Table 4:** Ultimate analysis (wt%) of NRP feedstock[6]

| ***Element*** | ***wt%*** |
|---|---|
| *C* | 84.0 |
| *H* | 13.1 |
| *O* | 2.90 |

The simulation is divided into 5 stages. In the drying zone, a feedstock 10 TPD of NRP is fed into an RStoic block. The RStoic block is used to simulate the reduction of moisture in the plastic feedstock. The Flash2 block separates the dried NRP from the water vapor. In this section, a FORTRAN subroutine and a calculator block were used to calculate the water content remaining in the NRP (see appendix A).

In the decomposition zone, the dried NRP enters a RYield block that decomposes the NRP into conventional components (i.e., C, H, and O). In this section, a FORTRAN subroutine is also used to carry out the mass balance calculations for the decomposition of NRP (see appendix A).

In the reaction zone, the feed enters an RPlug block followed by an RGibbs block, which models the pyrolysis reactor. The RPlug is based on the reaction kinetics from a similar pyrolysis process as shown in Table A-1 (see appendix). These assume that only C and $H_2$ participate in the reactions and that the reactions follow power law kinetics with a first order dependence on $H_2$. The RGibbs block produces other products such as CO and $CO_2$ that are normally present in the pygas by minimizing the Gibbs free energy. Also, in this section a SSplit is used to separate the gas products from the char byproduct.

In the condensation zone, the gas product is cooled down using a cooler and it enters a series of FLASH2 (1-8) blocks that model the gas/oil cyclonic separation. The Flash2 blocks operate at temperatures ranging from 350°F to 14°F. The non-condensable gases exiting the condensation zone enter the heat recovery zone where the they are burned, and the energy is recycled back to the process.

### B. Simulation Results

Sensitivity analysis was done on the RPlug reactor to find the operating conditions that best approximated GRE's average product distribution (i.e., 20% gas, 75% oil and 5% char), carbon conversion and energy efficiency (i.e., 95% and 80%, respectively). The temperature of the Rplug reactor was varied from 700°F to 1200°F. Figure 5 shows the product distribution (in a dry basis) in wt% at temperatures between 700 $^{o}$F and 1200 $^{o}$F and at atmospheric pressure. It shows that at 1000 $^{o}$F, the product distribution is the closest to GRE's product distribution. At this temperature, the pygas product distribution is 22.5% gas, 71.3% oil and 6.2% char.

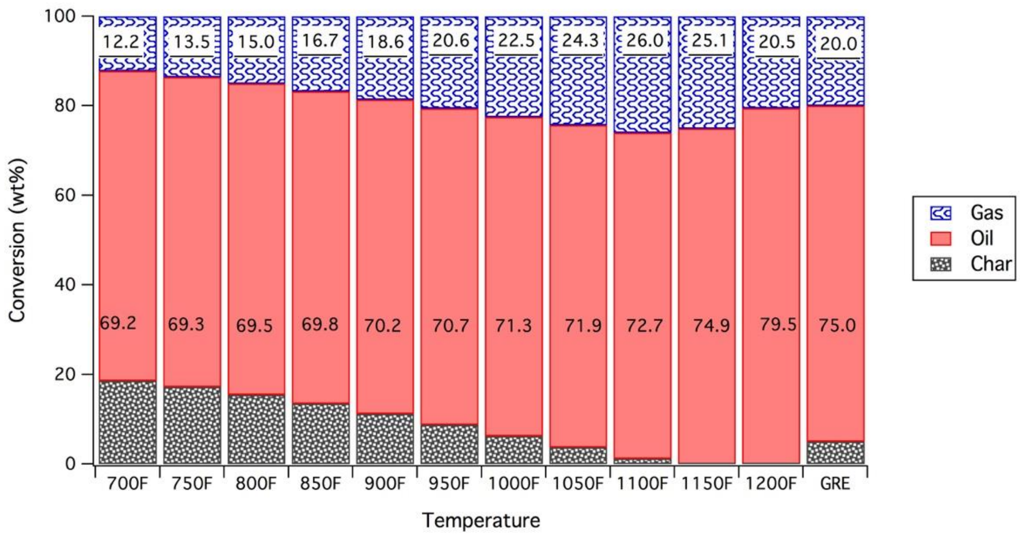


**Fig. 5.** Product distribution out of the reaction zone as a function of temperature

To assess the performance of this process, energy efficiency has been defined as the ratio between the energy of the liquid oil and non-condensable gases out of the reaction zone to the total energy in (see equation 1). In addition, carbon conversion has been defined as the ratio of the amount of carbon in the NRP in minus the amount of carbon in the char byproduct to the amount of carbon in the NRP in (see equation 2). At 1000 $^oF$, the carbon conversion is 93% and the energy efficiency is 84% (see figures 6 and 7). Tables 5, 6 and 7 show the calculations for the carbon conversion and energy efficiency at 1000 $^oF$. Detailed calculations for the carbon conversion and energy efficiency at the rest of the temperatures are shown in Appendix C.

$$Energy\ Efficiency = \frac{Enthalpy\ of\ oil + Entalpy\ of\ Gas\ Out\ [\frac{MMBTU}{hr})}{Enthalpy\ of\ NRP\ in\ (\frac{MMBTU}{hr})} x100 \qquad \text{Eq. 1}$$

$$Carbon\ Conversion\ = \frac{Carbon\ in\ Plastic - Carbon\ in\ Char\ (\frac{lb}{hr})}{Carbon\ in\ Plastic\ \ (\frac{lb}{hr})} x100 \qquad \text{Eq.2}$$

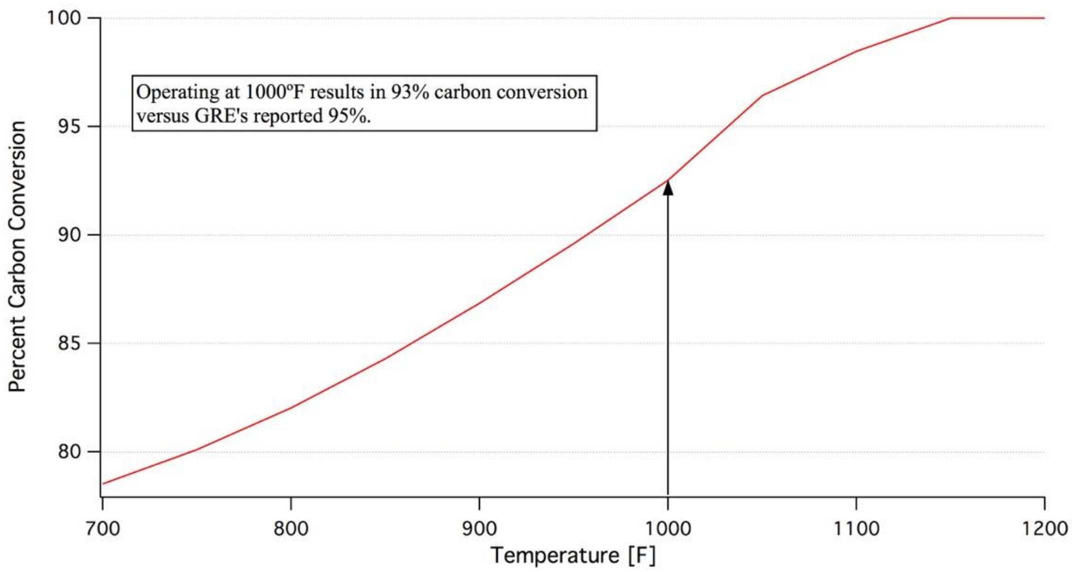


**Fig. 6.** Process carbon conversion as a function of temperature

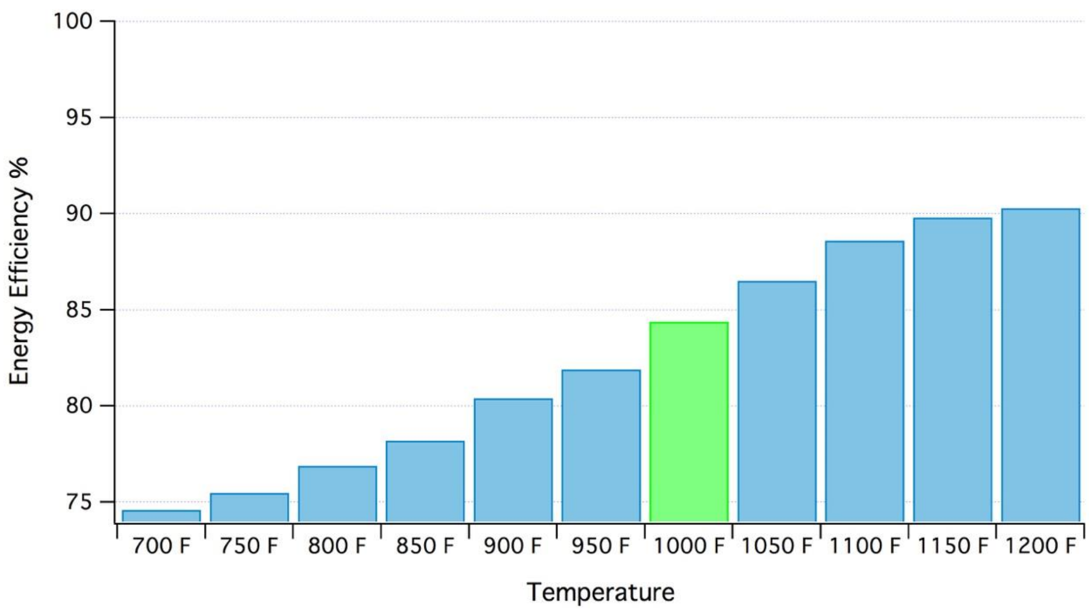


**Fig. 7.** Pyrolysis energy efficiency as a function of temperature

**Table 5:** Carbon Conversion at 1000 °F

| *Temperature (K)* | *Carbon in NRP (lb/hr)* | *Carbon in Char (lb/hr)* | *Carbon Conversion (%)* |
|---|---|---|---|
| *1000* | 651 | 48.7 | 92.51920123 |

**Table 6:** Enthalpy of Non-Condensable Gas at 1000 °F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 10.3 | 23811.0 | 245172.1 |
| *CO* | 10.8 | 5431.2 | 58429.9 |
| *CO2* | 25.6 | 0.0 | 0.0 |
| *CH4* | 62.3 | 17119.1 | 1066593.6 |
| *C2H6* | 12.6 | 18150.0 | 229029.8 |
| *C2H4* | 54.0 | 21884.0 | 1182148.3 |
| ***Total Flow Rate*** | =175.6 | ***Average HHV (BTU/hr)*** | =2781373.6 |
| | | ***Average HHV (BTU/lb)*** | =15842.9 |

**Table 7:** Enthalpy of Oil at 1000 °F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 43.0 | 16707.0 | 718241.8 |
| *C4H10* | 5.7 | 57635.8 | 329827.8 |
| *C9H18* | 41.5 | 20469.5 | 849911.4 |
| *C6H6* | 35.8 | 17460.0 | 625067.3 |
| *C7H8* | 108.2 | 18228.7 | 1971946.4 |
| *C8H10* | 76.4 | 18651.0 | 1424464.0 |
| *C14H28* | 151.8 | 18826.0 | 2858620.8 |
| *C16H34* | 69.3 | 18843.0 | 1305904.1 |
| *C22H46* | 24.4 | 18992.0 | 463791.1 |
| ***Total Flow Rate*** | =556.2 | ***Average HHV (BTU/hr)*** | =10547774.6 |
| | | ***Average HHV (BTU/lb)*** | =18965.5 |

**Table 8:** Energy Efficiency at 1000 °F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.8 | 10.5 | 84.4 |

The difference between the results from the simulation and the results reported by GRE could be attributed to the kinetics used to model the RPlug reactor resulting in a different gas and oil carbon distribution. Since GRE only reports the oil carbon distribution per carbon number, hydrocarbons with the same carbon number were assumed the to be the products from the pyrolysis reactions. Figures 8 and 9 show the respective oil and gas mol% composition of $C_6$-$C_{22}$ at 1000°F exiting the reaction zone. Figures 10 and 11 show the oil and gas product distributions reported by GRE.[6]

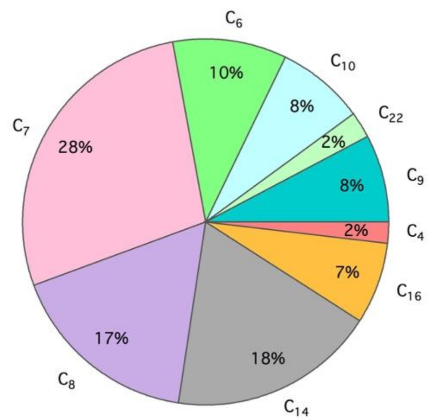


**Fig.8.** Oil composition out of the reaction zone in wt.% (in a dry basis) at 1000 °F and atmospheric pressure for an oil molar flow rate of 4.23 lbmol/hr.

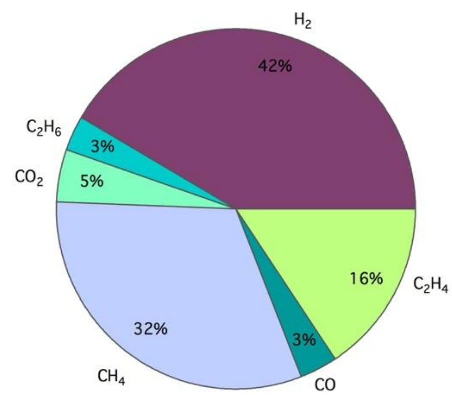


**Fig .9.** Gas composition out of the reaction zone in wt.% (in a dry basis) at 1000 °F and atmospheric pressure for a gas molar flow rate of 12.30 lbmol/hr.

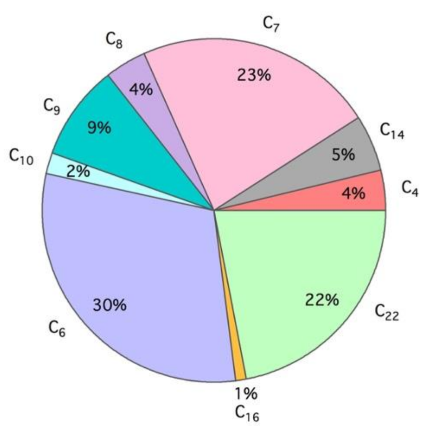


**Fig.10.** Oil composition of GRE's final product

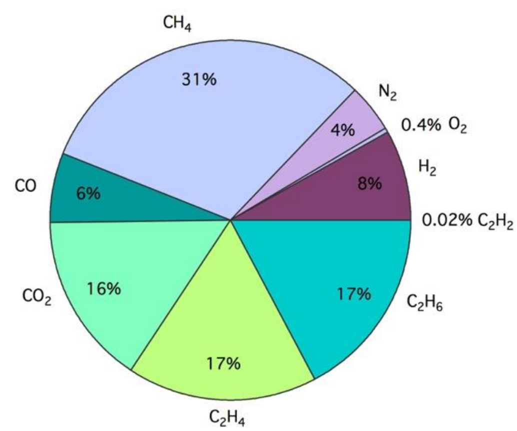


**Fig.11.** Gas composition of GRE's final product

At 1000 °F compositions the HHVs of the oil and gas were calculated to be 18966 and 15843 BTU/lb, respectively (see appendix C). The HHV of the oil produced is similar to the average HHV of diesel (i.e., 19604 BTU/lb). Table 9 compares the results from the sensitivity analysis to the values reported by GRE.[6] It shows that the results from the sensitivity analysis at 1000 °F fairly approximate the results reported by GRE. These results can be optimized by better adapting the kinetics shown in Table A-1

**Table 9**: Comparison of Aspen Simulation Results at 1000 °F vs GRE's Reported Values[6]

| | ***Aspen Simulation*** | ***GRE*** |
|---|---|---|
| *% Carbon Conversion* | 92.5 | 95 |
| *Oil %* | 71.3 | 75 |
| *Gas%* | 22.5 | 20 |
| *Char%* | 6.2 | 5 |
| *% Energy Efficiency* | 84.4 | 80 |
| *Production Rate* | 4.2 B.O./ton NRP | 4.8 B.O./ ton NRP |
| *HHV Oil* | 18966 BTU/lb | 15,973 BTU/lb |
| *HHV Gas* | 15843 BTU/lb | 1000 BTU/lb |

Also, at 1000 °F the process results in the production of 2.11 TPD of non-condensable gases that can be used to run the process without the input of external energy. The results from Aspen simulation showed that the pyrolysis process requires 14.4 MMBTU/day of energy input. If the heat transfer from the combustion of the non-condensable gases to the reactor is 100% efficient, only 0.45 TPD of non-condensable gases are required to run the pyrolysis process. Thus, the process results in the production of excess syngas. GRE also reports a production of excess non-condensable gases from their RFP unit. One possible use of the excess gas is to store it to be used during equipment start-up.

Table 10 shows the results from the condensation zone. It shows the hydrocarbon distribution exiting cyclones 1-8. It shoes that most of the heaviest hydrocarbons exit trough cyclones 1-4, while the lightest trough cyclones 5-8.

**Table 10:** Hydrocarbon distribution for cyclones 1-8 in wt. %

| $C_4$-$C_{22}$ (wt.%) | Cyclone 1 | Cyclone 2 | Cyclone 3 | Cyclone 4 | Cyclone 5 | Cyclone 6 | Cyclone 7 | Cyclone 8 |
|---|---|---|---|---|---|---|---|---|
| $C_4$ | --- | --- | --- | 0.01 | 0.02 | 0.04 | 0.083 | 0.11 |
| $C_6$ | 0.20 | 0.40 | 0.79 | 1.80 | 6.08 | 10.89 | 7.74 | 16.76 |
| $C_7$ | 0.50 | 0.92 | 1.64 | 3.29 | 8.73 | 21.33 | 38.61 | 63.76 |
| $C_8$ | 0.69 | 1.35 | 2.58 | 5.55 | 15.63 | 31.29 | 32.10 | 16.54 |
| $C_9$ | 0.48 | 0.94 | 1.81 | 3.83 | 9.04 | 14.88 | 16.93 | 2.51 |
| $C_{10}$ | 1.22 | 2.59 | 5.16 | 11.17 | 25.65 | 18.13 | 4.41 | 0.41 |
| $C_{14}$ | 23.58 | 46.82 | 62.11 | 64.19 | 33.27 | 3.40 | 0.13 | --- |
| $C_{16}$ | 27.63 | 39.54 | 25.61 | 10.14 | 1.56 | 0.04 | --- | --- |
| $C_{22}$ | 45.49 | 7.44 | 0.27 | --- | --- | --- | --- | --- |

## VI. NRP to Oil Economic Analysis

An economic analysis on the NRP to fuel process was done by obtaining the equipment specifications through the aspen design and matching it up to equipment specifications provided by manufacturers and resellers. The main plant design consists of a hopper, an extruder, a horizontal screw reactor, a glycol chiller, a cooling jacket, eight cyclones, and a rotary pump. Costs for the reactor, hopper, cyclones, and glycol chiller were obtained from the manufacturer and reseller. The NRP was assumed to be delivered to the plant at $30/ton of NRP. The values were calculated assuming that the process runs continuously for a month with one day of downtime for maintenance. Table 11 shows the overall economics of the plant, including fixed capital cost, operations and maintenance costs, profit and revenue of the plant, the return on investment (ROI) and the payback period of the plant. Further details on the economics can be found in Appendix
C.

**Table 11:** Economic Analysis of a NRP to Fuel Process

| | ***Value*** |
|---|---|
| ***Fixed Capital Cost***[5,15,16,17] | |
| *Horizontal Screw Reactor* | $62,800.00 |
| *Hopper* | $1,070.30 |
| *Cooling Jacket* | $9,975.00 |
| *Extruder* | $86,553.00 |
| *Air-Cooled Glycol Chiller* | $7,935.00 |
| *8 Cyclones* | $42,941.00 |
| *Rotary Pump* | $1,900.00 |
| *Working Capital* | $683,010.59 |
| *Total Fixed Capital Cost* | $1,549,948.00 |
| ***Operations and Maintenance (yearly)***[18,19] | |
| *Rent* | $133,000.00 |
| *Labor* | $600,000.00 |
| *Water Consumption* | $32.40 |
| *Waste-Water Disposal* | $51.52 |
| *Electricity Cost* | $100,087.99 |
| *Maintenance* | $557,981.28 |
| *Insurance* | $22,329.59 |
| *Total O&M* | $1,413,482.77/year |
| ***Revenue***[20] | |
| *Approximate B.O./TPD NRP* | 4.2 |
| *Delivered NRP* | $30/ton |
| *Price No.2 Oil* | $3.2/gallon |
| *Total NRP Revenue/year* | $109,500 |
| *Approximate No.2 Oil Revenue/year* | $2,032,128 |
| *Total Revenue/year* | $2,141,628 |
| ***Plant Life Time*** | 30 years |
| ***Tax Rate*** | 33% |
| ***Inflation*** | 3% |
| ***Net Profit/Year 1*** | 968,145.23 |
| ***ROI*** | 26.55% |
| ***Payback Period*** | 2.89 years |

**See Appendix-C for more details.*

Figure 12 shows a straight-line depreciation for the equipment used in this design. The salvage value for each unit at the end of the plant operating time was determined by the resale value of the materials of construction or 20% of initial sales price. The total income from reselling the equipment after 30 years of plant operation is $41,387.40. This value was added onto the cumulative cash flow diagram of the plant at year 30 (see fig. 13).

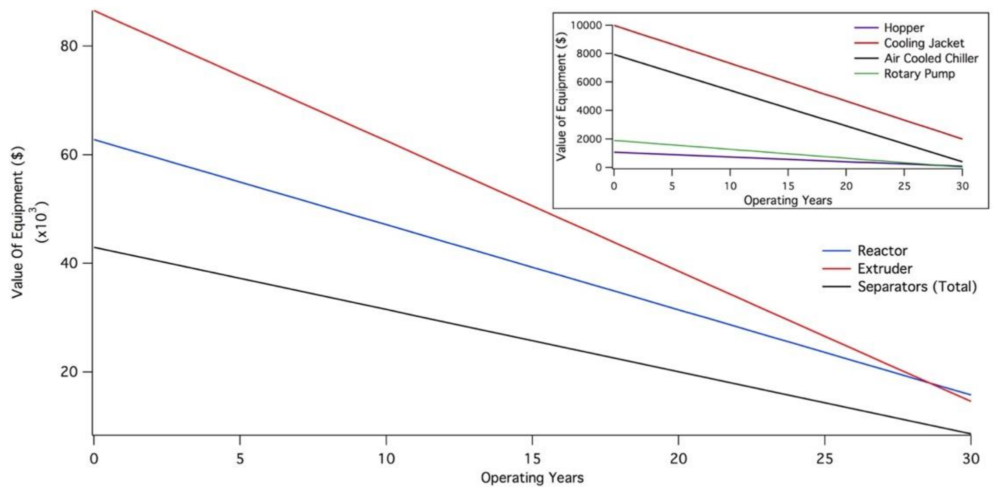


**Fig. 12.** Straight-line depreciation of equipment used in the plastics to oil plant.

Fig. 13 shows the accumulation of cash flow over the plant's lifetime. It takes into consideration a 3% annual inflation rate on the delivered NRP and No. 2 oil after the first year of operation. Taking into account the final depreciated value after 30 years of operations, the total profit of the plant is $33,489,495.20 at the end of its lifetime.

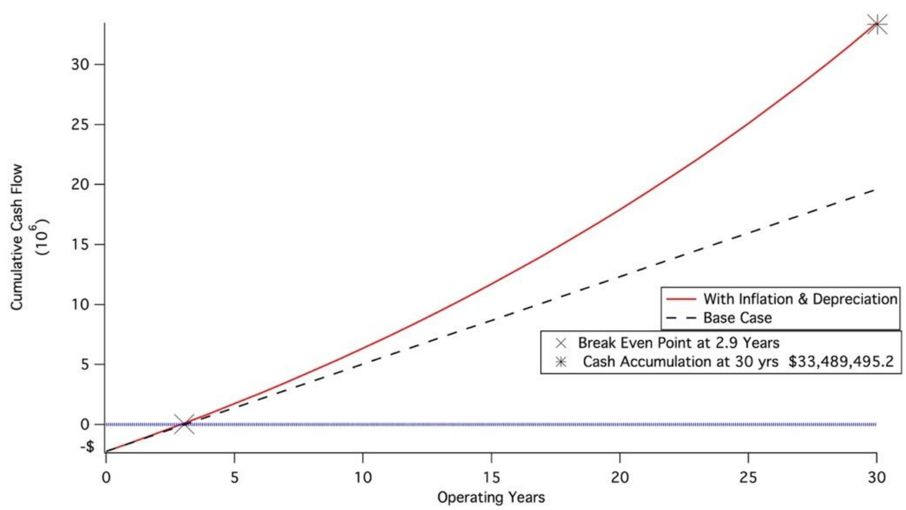


**Fig. 13.** Cumulative cash flow diagram for a 30-years (after start-up) of a NRP to fuel plant

## VII. Potential Applications of Char

Char is a carbon rich solid that "consists of non-combustibles and unburned organic content".[6] The char byproduct resulting from this process can be either disposed of it as a waste or used as a material. As a material, char can be used as a cheaper and cleaner alternative to burning charcoal. Studies have shown that for char to have more uses, it needs to go through a carbonization process.[23] The carbonized char will then have the potential to be an adsorbent for containments and as an inexpensive metal scrubber for gases. The carbonized char can also be converted to activated char with steam or carbon dioxide which shows excellent removal capacity for organics from aqueous solutions. Currently GRE is selling the char byproduct to distributors for cement and concrete applications due to its high energy density, low surface area and porosity.

## VIII. Conclusion

Aspen plus was used to simulate the production of No2. home heating oil from NRP based on GRE's RFP unit. The optimum operating conditions were found by doing sensitivity analysis on the temperature. The results from the Aspen sensitivity analysis showed that at 1000 $^{o}$F and atmospheric pressure the pygas product distribution, composition, carbon conversion and energy efficiency best match the values reported by GRE. Thus, the process would operate at 1000 $^{o}$F and atmospheric pressure. At these conditions, the simulation resulted in a product distribution of 22.5% gas, 71.3% oil and 6.2% char. This product distribution results in a carbon conversion of 93% and an energy efficiency of 84%. At this product distribution the oil produced has a HHV of 18966 BTU/lb which is similar to the HHV of diesel (i.e., 19604 BTU/lb). The non-condensable gases have an HHV of 15843 BTU/lb. At this HHV, only 0.45 TPD of non-condensable gases are required to run the pyrolysis process without the input of external energy. Thus, the process results in the production of excess non-condensable gases.

The results from the economic analysis showed that a total profit of $33.5 million can be obtained after 30 years of operation. The process has a payback period of 2.9 years and an ROI of 26.5%.

This report showed that it is possible to simulate a process that converts NRP to oil. The results from the Aspen model fairly represent the results from the pyrolysis of NRP to oil reported by GRE. Also, the economic analysis on the process show that the process is economically feasible.

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# X. APPENDIX

## A. Auxiliary Information

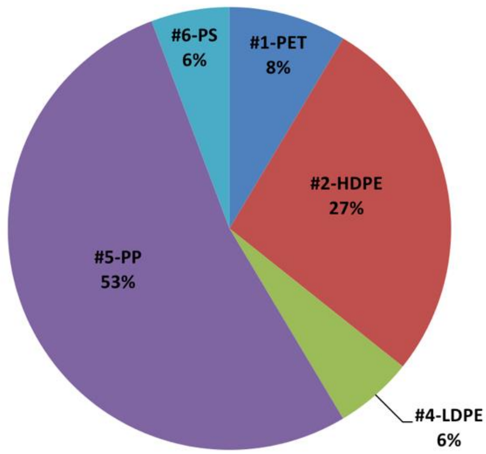



**Fig. A-1.** GRE's average feedstock composition in a weight percent basis

**Table A-1:** Pyrolysis Reactions for RPlug modeling in Aspen Plus[21]

| ***Reaction*** | ***A ($s^{-1}$)*** | ***E (kJ/kmol)*** | ***N(temperature coefficient)*** |
|---|---|---|---|
| $C + 2H_2 \rightarrow CH_4$ | 4.877 | 23100 | 0 |
| $2C + 3H_2 \rightarrow C_2H_6$. | 0.52 | 23010 | 0 |
| $2C + 2H_2 \rightarrow C_2H_4$ | 2.386 | 23010 | 0 |
| $4C + 5H_2 \rightarrow C_4H_{10}$ | 0.122 | 23010 | 0 |
| $12C + 6H_2 + O_2 \rightarrow 2C_6H_6O$ | 0.497 | 33890 | 0 |
| $6C + 3H_2 \rightarrow C_6H_6$ | 1.654 | 33890 | 0 |
| $7C + 4H_2 \rightarrow C_7H_8$ | 7.305 | 33890 | 0 |
| $8C + 5H_2 \rightarrow C_8H_{10}$ | 4.476 | 33890 | 0 |
| $9C + 9H_2 \rightarrow C_9H_{18}$ | 0.017 | 1590 | 0 |
| $10C + 4H_2 \rightarrow C_{10}H_8$ | 0.979 | 33890 | 0 |
| $10C + 7H_2 \rightarrow C_{10}H_{14}$ | 1.058 | 33890 | 0 |
| $14C + 14H_2 \rightarrow C_{14}H_{28}$ | 118.294 | 6300 | -1.089 |
| $16C + 17H_2 \rightarrow C_{16}H_{34}$ | 46.822 | 6300 | -1.089 |
| $22C + 23H_2 \rightarrow C_{22}H_{46}$ | 12.08 | 6300 | -1.089 |

**Table A-2:** NRP to Fuel Process Stream Composition in a Weight Percent Basis by Stream Number

| Weight % | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water | 4.61 | 4.87 | 5.41 | 6.25 | 6.91 | 7.56 | 9.00 | 11.0 | 1.35 | 0.03 | 0.04 | 0.06 | 0.10 | 0.26 | 0.73 | 1.65 | 31.4 | 5.79 |
| H2 | 1.34 | 1.42 | 1.58 | 1.83 | 2.02 | 2.22 | 2.69 | 3.42 | 5.04 | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| CO | 1.40 | 1.48 | 1.65 | 1.91 | 2.11 | 2.32 | 2.81 | 3.57 | 5.27 | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| CO2 | 3.33 | 3.52 | 3.92 | 4.53 | 5.02 | 5.50 | 6.66 | 8.48 | 12.5 | --- | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.04 | 0.02 |
| CH4 | 8.12 | 8.58 | 9.55 | 11.0 | 12.2 | 13.4 | 16.2 | 20.7 | 30.5 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| C2H6 | 1.65 | 1.74 | 1.93 | 2.24 | 2.48 | 2.71 | 3.29 | 4.18 | 6.15 | --- | --- | --- | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 |
| C2H4 | 7.04 | 7.44 | 8.27 | 9.57 | 10.6 | 11.6 | 14.1 | 17.9 | 26.4 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.05 | 0.06 | 0.03 |
| C4H10 | 0.75 | 0.79 | 0.88 | 1.01 | 1.12 | 1.23 | 1.48 | 1.86 | 2.70 | --- | 0.01 | 0.01 | 0.01 | 0.02 | 0.04 | 0.08 | 0.07 | 0.04 |
| C6H6 | 4.67 | 4.92 | 5.43 | 6.16 | 6.62 | 6.68 | 5.81 | 5.32 | 2.39 | 0.20 | 0.40 | 0.79 | 1.80 | 6.06 | 10.8 | 7.61 | 11.5 | 5.49 |
| C7H8 | 14.1 | 14.9 | 16.4 | 18.8 | 20.4 | 21.6 | 21.7 | 17.2 | 4.65 | 0.50 | 0.92 | 1.64 | 3.28 | 8.70 | 21.2 | 37.9 | 43.6 | 17.5 |
| C8H10 | 9.96 | 10.5 | 11.5 | 12.9 | 13.7 | 13.5 | 9.82 | 3.88 | 0.34 | 0.69 | 1.35 | 2.58 | 5.54 | 15.6 | 31.0 | 31.5 | 11.3 | 13.4 |
| C9H18 | 5.41 | 5.69 | 6.23 | 6.92 | 7.25 | 7.08 | 5.46 | 2.40 | 2.72 | 0.48 | 0.94 | 1.81 | 3.83 | 9.02 | 14.8 | 16.6 | 1.72 | 6.39 |
| C10H8 | 5.60 | 5.85 | 6.22 | 6.39 | 5.87 | 3.96 | 1.00 | 0.10 | 0.01 | 1.22 | 2.59 | 5.16 | 11.2 | 25.6 | 18.0 | 4.33 | 0.28 | 7.63 |
| C14H28 | 19.8 | 19.6 | 16.5 | 9.36 | 3.49 | 0.61 | 0.03 | --- | --- | 23.6 | 46.8 | 62.1 | 64.1 | 33.2 | 3.37 | 0.12 | --- | 27.0 |
| C16H34 | 9.03 | 7.99 | 4.44 | 1.11 | 0.14 | 0.01 | --- | --- | --- | 27.6 | 39.5 | 25.6 | 10.1 | 1.56 | 0.04 | --- | --- | 12.3 |
| C22H46 | 3.18 | 0.79 | 0.04 | --- | --- | --- | --- | --- | --- | 45.7 | 7.44 | 0.27 | --- | --- | --- | --- | --- | 4.34 |

**Aspen Fortran Codes**[22]

- **Aspen Simulation Calculator Fortran Code (Drying Zone):**

```
H2ODRY=5
CONV=(H2OIN-H2ODRY)/(100-H2ODRY)
```

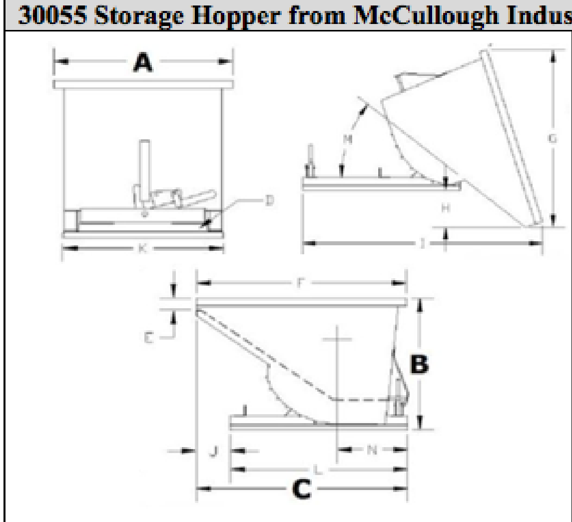
Note: Moisture of wet NRP is 7%

- **Aspen Simulation Calculator Fortran Code (Decomposition Zone):**

```
C FACT IS THE FACTOR TO CONVERT THE ULTIMATE ANALYSIS TO
C A WET BASIS.
      FACT = (100 - WATER) / 100
      H2O = WATER / 100
      ASH = ULT(1) / 100 * FACT
      CARB = ULT(2) / 100 * FACT
      H2 = ULT(3) / 100 * FACT
      N2 = ULT(4) / 100 * FACT
      CL2 = ULT(5) / 100 * FACT
      SULF = ULT(6) / 100 * FACT
      O2 = ULT(7) / 100 * FACT
```

## B. Equipment Specifications

**30055 Storage Hopper from McCullough Industries**[8]

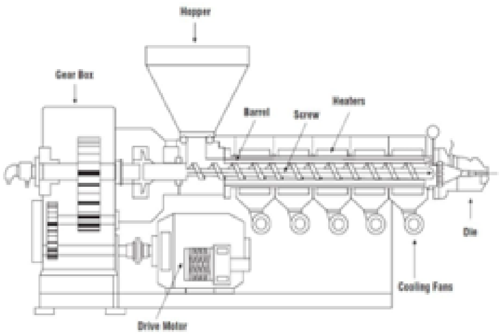



| | | |
|---|---|---|
| **Dimensions** | | |
| Weight (approx.) | 704 lbs. | |
| Dimensions (AxBxC) | 70.5 in x 57.75 in x 55 in | |
| Fork Opening (D) | 3 by 28 1/2 in | |
| Container Length (F) | 70 1/2 in | |
| Dump Clearance Height (G) | 73 in | |
| Dump Clearance Bottom (H) | 10 in | |
| Dump Clearance Length (I) | 93 3/4 in | |
| Front Clearance Length (J) | 15 in | |
| Base With (K) | 36 1/2 in | |
| Base Length (L) | 54 in | |
| Dump Angle (M) | 32 º | |
| Center of Gravity (N) | 30 1/2 in | |
| Pouring Lid (E) | 20 in | |
| **Capacity** | | |
| Volumetric | 3 yards | |
| Weight | 4000 lbs. | |
| **Operating Conditions** | | |
| Temperature | 986 °F | |
| Pressure | 14.7 psig | |

**Description**

The storage hopper will be used to store shredded plastics that will be sent to the Extruder through selective vacuuming.

**CV Extruder from Toshiba Machine[9]**

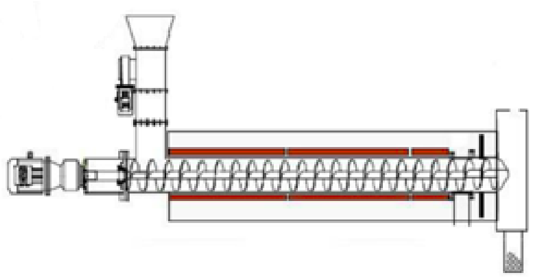



**Description**

The extruder takes the NRP from the Hooper and melts the plastics at 900 °F. It consists of a stainless-steel screw that rotates and moves the plastic feed toward the pyrolysis reactor.

| | |
|---|---|
| **Performance** | |
| Motor Power Requirement | 110-315 kW |
| Max Screw Speed | 200 RPM |
| Drive System | V-Belt drive |
| Effective L/D Ratio | 28 |
| **Dimensions, Weight and Materials** | |
| Screw Diameter | 19.7 in |
| Effective L/D Ratio | 28 |
| Dimensions (LxWxH) | 240 in x 59 in x 63 in |
| Approximate Weight | 10,000 kg |
| Materials of Construction | 316 Stainless Steel |
| **Capacity** | |
| Hopper Capacity | 400 L |
| Heater Capacity | 63 kW |
| Extrusion Output Range | 420-1,100 kg/h |
| **Operating Conditions** | |
| Temperature | 986 °F |
| Pressure | 14.7 psig |
| | |

**BLJ-10 Rotary Screw Reactor for Henan Doing[10]**



**Description**

The screw reactor receives the molten plastics from the extruder and further heats it via pyrolysis to produce gas. The screw rotates allowing the materials to move along the length of the reactor. At the end, the solid residue, char, falls into the bottom, and the produced gases rise.

| | |
|---|---|
| **Dimensions and Capacity** | |
| Structural Form | Horizontal Rotation |
| Weight | 36 US Tons |
| Reactor Size (DxL) | 8.53 ft x 21.65 ft |
| Reactor Thickness | 0.63 in |
| Weight Capacity | 11 US Tons |
| **Energy Supply** | |
| Type of Fuel | Natural Gas |
| Fuel Consumption | 1849.3 Gallons/Ton Feed |
| Mode of Cooling | Water |
| Water Consumption | 264-528.3 Gallons/Day |
| Power Consumption | 30 kW/hr |
| **Performance** | |
| Screw Rotational Speed | 0.4 RPM |
| **Operating Conditions** | |
| Temperature | Up to 1212 F |
| Pressure | 14.7 psig |
| **Product Yield** | |
| Liquid Yield | 5.5-6.5 US Ton |
| Carbon Conversion | 94% |
| Conversion Rate | 189 Gallons per Day |

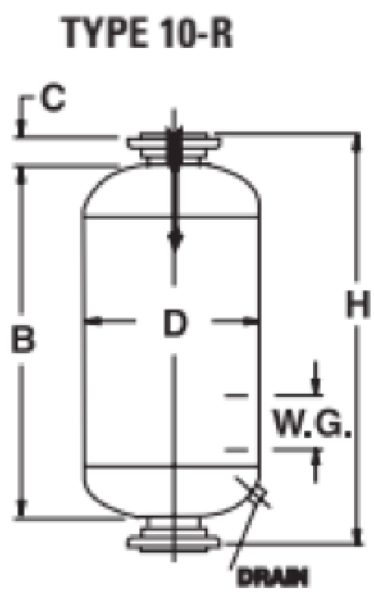
**BC series Ethylene Glycol Chiller from Advantage**[11]

| | |
|---|---|
| **Performance** | |
| Compressor Power | 3H |
| Process Pump Power | 0.75 HP |
| Max. Pump Pressure | 30 psig |
| **Dimensions, Weight and Materials** | |
| Dimensions (LxWxH) | 43 in x 34 in x 40 in |
| Process Connections | 1 in |
| Approximate Weight | 600 lbs. |
| Materials of Construction | Stainless Steel |
| Refrigerant Type | R-410 A |
| **Capacity** | |
| Cooling Capacity | 17292 BTU/hr @ 25 °F Glycol T |
| Reservoir Capacity | 7.5 gallon |
| Pump Capacity | 7.2 GPM |
| **Operating Conditions** | |
| Temperature | 14°F |
| Pressure | 14.7 psig |
| Percentage of Glycol to water | 25/75 |

**Description**

The pygas in cyclone 8 using an ethylene jacket connected to an air cooled modular indoor glycol chiller. The cooling jacket and chiller will cool the pygas to 14 °F, allowing the naphtha and gasoline fractions to condense.

**Gas/Liquid Cyclone Separator Type 10-R**[13]




| | |
|---|---|
| **Performance** | |
| Gas/Oil Separation Efficiency | 99% |
| Material of Construction | Fabricated Carbon Steel |
| Max Pressure | 600 psi |
| Max Temperature | 1000 °F |
| Operating Pressure | 14.7 psi |
| **Dimensions (B; C; D; H)** | |
| Cyclone 1 | 108 in.; 7 in.; 54 in.; 122 in. |
| Cyclone 2-4 | 96 in.; 7in.; 48 in.; 110 in. |
| Cyclone 5-7 | 48in.; 4in.; 18 in.; 56 in. |
| Cyclone 8 | 72in.; 5in.; 30 in.; 82 in. |
| **Total Volume** | |
| Cyclone 1 | 129.95 $ft^3$ |
| Cyclone 2-4 | 91.15 $ft^3$ |
| Cyclone 5-7 | 5.22 $ft^3$ |
| Cyclone 8 | 23.34 $ft^3$ |
| **NPT Flange** | |
| Cyclone 1 | 8 in. |
| Cyclone 2-4 | 5 in. |
| Cyclone 5-7 | 4 in. |
| Cyclone 8 | 5 in. |
| **Operating Temperatures** | |
| Cyclone 1 | 350 °F |
| Cyclone 2-4 | 310-230 °F |
| Cyclone 5-7 | 190-110 °F |
| Cyclone 8 | 14 °F |
| **Operating Flow Rates** | |
| Cyclone 1 | 767 lb/hr |
| Cyclone 2-4 | 509-653 lb/hr |
| Cyclone 5-7 | 301-464 lb/hr |
| Cyclone 8 | 35 lb/hr |

**Description**

The resulting liquid oils and gas from the pyrolysis reaction will fractionated using a series of cyclones. These cyclones are designed for liquid slugs or heavy liquid loads.

**Ethylene Glycol Cooling jacket from Santa Rosa Stainless Steel[12]**

| | |
|---|---|
| **Performance** | |
| Pressure Drop | 0.60 psi/ ft. of diameter |
| **Dimensions, Weight and Materials** | |
| Diameter | 3-11.9 ft. |
| Material of Construction | Dimpled Stainless Steel |
| **Capacity** | |
| Flow Capacity | 0-40 GPM |
| **Operating Conditions** | |
| Temperature | 14°F |
| Pressure | 14.7 psig |
| Glycol Flow rate | 0-40 GPM |
| Pressure | 0-50 psi |

**Rotary Pump (GHC Series) by Gorman Rupp[14]**

| | |
|---|---|
| **Performance** | |
| Max Viscosity | 53925 cST |
| Max Pressure | 200 psig |
| Min. Temperature | -60 °F |
| Max. Temperature | 300 °F |
| **Size, Weight and Materials** | |
| Suction and Discharge | 1 ½ in |
| Weight | 62 lbs. |
| Casing | Cast Iron |
| Impeller/Rotor | Ductile Iron |
| Seal | Mechanical or Packing |
| **Capacity** | |
| Max Capacity | 38 GPM |
| **Operating Flow Rate** | |
| Pump Flow Rate | 0.14 gallons/min |
| **Operating Conditions** | |
| Temperature | 133 °F |
| Pressure | 14.7psig |

**Description**

The liquid oils from each cyclone stream will be pumped in a single line Using a rotary pump. This pump is Ideal for viscous fluids.

## C. Calculations

### i. Carbon Conversion

**Table C-1: Carbon Conversion**

| *Temperature (K)* | *Carbon in NRP (lb/hr)* | *Carbon in Char (lb/hr)* | *Carbon Conversion (%)* |
|---|---|---|---|
| *700* | 651 | 139.81 | 78.52380952 |
| *750* | 651 | 129.54 | 80.10138249 |
| *800* | 651 | 117.02 | 82.02457757 |
| *850* | 651 | 102.3 | 84.28571429 |
| *900* | 651 | 85.65 | 86.84331797 |
| *950* | 651 | 67.65 | 89.60829493 |
| *1000* | 651 | 48.7 | 92.51920123 |
| *1050* | 651 | 23.31 | 96.41935484 |
| *1100* | 651 | 9.98 | 98.46697389 |
| *1150* | 651 | 0 | 100 |
| *1200* | 651 | 0 | 100 |

### ii. Energy Efficiency

**Table C-2**: Average HHV of Plastic Feedstock

| *Plastic* | *Wt.%* | *HHV (BTU/lb)* | *HHV (BTU/LB) *Wt.%* |
|---|---|---|---|
| ***PP*** | 60.0 | 18960 | 11,380.8 |
| ***PE*** | 40.0 | 18960 | 7,5979.2 |
| | **Total**=100% | | **Average HHV** =18960 |

**Table C-3:** Enthalpy of Gas at 700 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 13.4 | 23811.0 | 319999.4 |
| *CO* | 0.1 | 5431.2 | 426.1 |
| *CO2* | 1.1 | 0.0 | 0.0 |
| *CH4* | 7.9 | 17119.1 | 135668.5 |
| *C2H6* | 37.0 | 18150.0 | 672266.7 |
| *C2H4* | 32.2 | 21884.0 | 705209.7 |
| ***Total Flow Rate*** | =91.8 | **Average HHV (BTU/hr)** | =1833570.4 |
| | | **Average HHV (BTU/lb)** | =19973.3 |

**Table C-4:** Enthalpy of Oil at 700 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 16.9 | 16707.0 | 282240.9 |
| *C4H10* | 3.4 | 57635.8 | 196758.5 |
| *C9H18* | 56.3 | 20469.5 | 1153316.3 |
| *C6H6* | 14.1 | 17460.0 | 245627.0 |
| *C7H8* | 42.5 | 18228.7 | 774897.9 |
| *C8H10* | 30.0 | 18651.0 | 559758.7 |
| *C14H28* | 221.0 | 18826.0 | 4159683.8 |
| *C16H34* | 100.8 | 18843.0 | 1900267.6 |
| *C22H46* | 35.5 | 18992.0 | 674879.2 |
| ***Total Flow Rate*** | =520.6 | **Average HHV (BTU/hr)** | =9947429.9 |
| | | **Average HHV (BTU/lb)** | =19108.5 |

**Table C-5:** Energy Efficiency at 700 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 1.8 | 9.9 | 74.6 |

**Table C-6:** Enthalpy of Gas at 750 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 12.8 | 23811.0 | 305837.3 |
| *CO* | 0.2 | 5431.2 | 1250.8 |
| *CO2* | 2.4 | 0.0 | 0.0 |
| *CH4* | 41.7 | 17119.1 | 713911.4 |
| *C2H6* | 8.5 | 18150.0 | 153721.8 |
| *C2H4* | 36.3 | 21884.0 | 793442.3 |
| ***Total Flow Rate*** | =101.9 | **Average HHV (BTU/hr)** | =1968163.6 |
| | | **Average HHV (BTU/lb)** | =19305.4 |

**Table C-7:** Enthalpy of Oil at 750 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 20.7 | 16707.0 | 345364.7 |
| *C4H10* | 3.8 | 57635.8 | 221376.1 |
| *C9H18* | 53.7 | 20469.5 | 1099925.4 |
| *C6H6* | 17.2 | 17460.0 | 300562.0 |
| *C7H8* | 52.0 | 18228.7 | 948205.5 |
| *C8H10* | 36.7 | 18651.0 | 684950.0 |
| *C14H28* | 208.7 | 18826.0 | 3929118.0 |
| *C16H34* | 95.3 | 18843.0 | 1794939.1 |
| *C22H46* | 33.6 | 18992.0 | 637471.6 |
| ***Total Flow Rate*** | =521.7 | **Average HHV (BTU/hr)** | =9961912.3 |
| | | **Average HHV (BTU/lb)** | =19093.9 |

**Table C-8:** Energy Efficiency at 750 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.0 | 10.0 | 75.5 |

**Table C-9:** Enthalpy of Gas at 800 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 12.2 | 23811.0 | 290467.8 |
| *CO* | 0.6 | 5431.2 | 3328.4 |
| *CO2* | 5.0 | 0.0 | 0.0 |
| *CH4* | 46.3 | 17119.1 | 792148.9 |
| *C2H6* | 9.4 | 18150.0 | 170459.1 |
| *C2H4* | 40.2 | 21884.0 | 879833.1 |
| ***Total Flow Rate*** | =113.7 | **Average HHV (BTU/LB)** | =2136237.3 |
| | | **Average HHV (BTU/lb)** | =18789.5 |

**Table C-10:** Enthalpy of Oil at 800 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 24.8 | 16707.0 | 413741.7 |
| *C4H10* | 4.3 | 57635.8 | 245479.7 |
| *C9H18* | 51.2 | 20469.5 | 1047524.6 |
| *C6H6* | 20.6 | 17460.0 | 360068.6 |
| *C7H8* | 62.3 | 18228.7 | 1135935.6 |
| *C8H10* | 44.0 | 18651.0 | 820559.5 |
| *C14H28* | 196.7 | 18826.0 | 3702300.5 |
| *C16H34* | 89.8 | 18843.0 | 1691322.4 |
| *C22H46* | 31.6 | 18992.0 | 600672.1 |
| ***Total Flow Rate*** | =525.2 | **Average HHV (BTU/hr)** | =10017604.6 |
| | | **Average HHV (BTU/lb)** | 19074.7 |

**Table C-11:** Energy Efficiency at 800 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.1 | 10.0 | 76.9 |

**Table C-12:** Enthalpy of Gas at 850 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 11.6 | 23811.0 | 276282.6 |
| *CO* | 1.5 | 5431.2 | 7968.9 |
| *CO2* | 9.2 | 0.0 | 0.0 |
| *CH4* | 46.3 | 17119.1 | 792148.9 |
| *C2H6* | 9.4 | 18150.0 | 170459.1 |
| *C2H4* | 40.2 | 21884.0 | 879833.1 |
| ***Total Flow Rate*** | =118.1 | **Average HHV (BTU/LB)** | =2126692.6 |
| | | **Average HHV (BTU/lb)** | =18008.1 |

**Table C-13:** Enthalpy of Oil at 850 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 24.8 | 16707.0 | 413741.7 |
| *C4H10* | 4.3 | 57635.8 | 245479.7 |
| *C9H18* | 51.2 | 20469.5 | 1047524.6 |
| *C6H6* | 32.6 | 17460.0 | 568918.0 |
| *C7H8* | 62.3 | 18228.7 | 1135935.6 |
| *C8H10* | 44.0 | 18651.0 | 820559.5 |
| *C14H28* | 196.7 | 18826.0 | 3702300.5 |
| *C16H34* | 89.8 | 18843.0 | 1691322.4 |
| *C22H46* | 31.6 | 18992.0 | 600672.1 |
| ***Total Flow Rate*** | =537.1 | **Average HHV (BTU/hr)** | =10226454.0 |
| | | **Average HHV (BTU/lb)** | =19038.7 |

**Table C-14:** Energy Efficiency at 850 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.1 | 10.2 | 78.2 |

**Table C-15:** Enthalpy of Gas at 900 F

| ***Compound*** | ***Flow Rate (lb/hr)*** | ***HHV (BTU/LB)*** | ***Enthalpy (BTU/lb)*** |
|---|---|---|---|
| *H2* | 11.1 | 23811.0 | 264420.4 |
| *CO* | 3.1 | 5431.2 | 17108.1 |
| *CO2* | 14.6 | 0.0 | 0.0 |
| *CH4* | 54.8 | 17119.1 | 938820.6 |
| *C2H6* | 11.1 | 18150.0 | 201791.2 |
| *C2H4* | 47.6 | 21884.0 | 1041554.5 |
| ***Total Flow Rate*** | =142.4 | **Average HHV (BTU/LB)** | =2463694.9 |
| | | **Average HHV (BTU/lb)** | =17295.7 |

**Table C-16:** Enthalpy of Oil at 900 F

| ***Compound*** | ***Flow Rate (lb/hr)*** | ***HHV (BTU/lb)*** | ***Enthalpy (BTU/lb)*** |
|---|---|---|---|
| *C10H8* | 33.6 | 16707.0 | 562001.8 |
| *C4H10* | 5.0 | 57635.8 | 290601.2 |
| *C9H18* | 46.2 | 20469.5 | 945930.3 |
| *C6H6* | 28.0 | 17460.0 | 489095.6 |
| *C7H8* | 84.6 | 18228.7 | 1542986.5 |
| *C8H10* | 59.8 | 18651.0 | 1114598.5 |
| *C14H28* | 173.4 | 18826.0 | 3265074.1 |
| *C16H34* | 79.2 | 18843.0 | 1491584.2 |
| *C22H46* | 27.9 | 18992.0 | 529735.3 |
| ***Total Flow Rate*** | =537.8 | **Average HHV (BTU/hr)** | =10231607.4 |
| | | **Average HHV (BTU/lb)** | =19025.0 |

**Table C-17:** Energy Efficiency at 900 F

| ***Energy Plastic In (MMBTU/hr)*** | ***Energy Gas out (MMBTU/hr)*** | ***Energy Oil Out (MMBTU/hr)*** | ***Efficiency (%)*** |
|---|---|---|---|
| *15.8* | 2.5 | 10.2 | 80.4 |

**Table C-18:** Enthalpy of Gas at 950 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 10.7 | 23811.0 | 254257.4 |
| *CO* | 6.1 | 5431.2 | 33125.0 |
| *CO2* | 20.5 | 0.0 | 0.0 |
| *CH4* | 54.8 | 17119.1 | 938820.6 |
| *C2H6* | 11.9 | 18150.0 | 216007.9 |
| *C2H4* | 50.9 | 21884.0 | 1114934.7 |
| ***Total Flow Rate*** | =155.0 | **Average HHV (BTU/LB)** | =2557145.6 |
| | | **Average HHV (BTU/lb)** | =16498.3 |

**Table C-19:** Enthalpy of Oil at 950 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 38.3 | 16707.0 | 639711.0 |
| *C4H10* | 5.4 | 57635.8 | 311074.7 |
| *C9H18* | 43.8 | 20469.5 | 897200.0 |
| *C6H6* | 31.9 | 17460.0 | 556733.1 |
| *C7H8* | 96.4 | 18228.7 | 1756366.6 |
| *C8H10* | 68.0 | 18651.0 | 1268736.9 |
| *C14H28* | 162.4 | 18826.0 | 3057705.7 |
| *C16H34* | 74.1 | 18843.0 | 1396851.9 |
| *C22H46* | 26.1 | 18992.0 | 496091.2 |
| ***Total Flow Rate*** | =546.5 | **Average HHV (BTU/hr)** | =10380471.2 |
| | | **Average HHV (BTU/lb)** | =18996.1 |

**Table C-20:** Energy Efficiency at 950 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.6 | 10.4 | 81.9 |

**Table C-21:** Enthalpy of Gas at 1000 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 10.3 | 23811.0 | 245172.1 |
| *CO* | 10.8 | 5431.2 | 58429.9 |
| *CO2* | 25.6 | 0.0 | 0.0 |
| *CH4* | 62.3 | 17119.1 | 1066593.6 |
| *C2H6* | 12.6 | 18150.0 | 229029.8 |
| *C2H4* | 54.0 | 21884.0 | 1182148.3 |
| ***Total Flow Rate*** | =175.6 | **Average HHV (BTU/hr)** | =2781373.6 |
| | | **Average HHV (BTU/lb)** | =15842.9 |

**Table C-22:** Enthalpy of Oil at 1000 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 43.0 | 16707.0 | 718241.8 |
| *C4H10* | 5.7 | 57635.8 | 329827.8 |
| *C9H18* | 41.5 | 20469.5 | 849911.4 |
| *C6H6* | 35.8 | 17460.0 | 625067.3 |
| *C7H8* | 108.2 | 18228.7 | 1971946.4 |
| *C8H10* | 76.4 | 18651.0 | 1424464.0 |
| *C14H28* | 151.8 | 18826.0 | 2858620.8 |
| *C16H34* | 69.3 | 18843.0 | 1305904.1 |
| *C22H46* | 24.4 | 18992.0 | 463791.1 |
| ***Total Flow Rate*** | =556.2 | **Average HHV (BTU/hr)** | =10547774.6 |
| | | **Average HHV (BTU/lb)** | =18965.5 |

**Table C-23:** Energy Efficiency at 1000 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.8 | 10.5 | 84.4 |

**Table C-24:** Enthalpy of Gas at 1050 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 9.9 | 23811.0 | 236120.3 |
| *CO* | 17.5 | 5431.2 | 94913.1 |
| *CO2* | 28.7 | 0.0 | 0.0 |
| *CH4* | 65.5 | 17119.1 | 1121824.7 |
| *C2H6* | 13.3 | 18150.0 | 240783.0 |
| *C2H4* | 56.8 | 21884.0 | 1242813.4 |
| ***Total Flow Rate*** | =191.7 | **Average HHV (BTU/hr)** | =2936454.5 |
| | | **Average HHV (BTU/lb)** | =15320.0 |

**Table C-25:** Enthalpy of Oil at 1050 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 47.7 | 16707.0 | 796554.7 |
| *C4H10* | 6.0 | 57635.8 | 346753.8 |
| *C9H18* | 39.3 | 20469.5 | 804287.4 |
| *C6H6* | 39.7 | 17460.0 | 693162.0 |
| *C7H8* | 120.0 | 18228.7 | 2186955.9 |
| *C8H10* | 84.7 | 18651.0 | 1579779.2 |
| *C14H28* | 141.8 | 18826.0 | 2668781.3 |
| *C16H34* | 64.7 | 18843.0 | 1219179.8 |
| *C22H46* | 22.8 | 18992.0 | 432991.0 |
| ***Total Flow Rate*** | =566.6 | **Average HHV (BTU/hr)** | =10728445.2 |
| | | **Average HHV (BTU/lb)** | =18934.0 |

**Table C-26:** Energy Efficiency at 1050 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 2.9 | 10.7 | 86.5 |

**Table C-27:** Enthalpy of Gas at 1100 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 9.5 | 23811.0 | 226822.6 |
| *CO* | 26.3 | 5431.2 | 143058.0 |
| *CO2* | 29.3 | 0.0 | 0.0 |
| *CH4* | 68.4 | 17119.1 | 1170809.2 |
| *C2H6* | 13.8 | 18150.0 | 251192.9 |
| *C2H4* | 59.2 | 21884.0 | 1296544.5 |
| ***Total Flow Rate*** | =206.6 | **Average HHV (BTU/hr)** | =3088427.3 |
| | | **Average HHV (BTU/lb)** | =14945.4 |

**Table C-28:** Enthalpy of Oil at 1100 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 51.8 | 16707.0 | 865255.5 |
| *C4H10* | 6.3 | 57635.8 | 361745.1 |
| *C9H18* | 37.1 | 20469.5 | 760372.0 |
| *C6H6* | 43.5 | 17460.0 | 760283.5 |
| *C7H8* | 131.6 | 18228.7 | 2398523.9 |
| *C8H10* | 92.9 | 18651.0 | 1732608.9 |
| *C14H28* | 132.2 | 18826.0 | 2488409.4 |
| *C16H34* | 60.3 | 18843.0 | 1136779.9 |
| *C22H46* | 21.3 | 18992.0 | 403726.8 |
| ***Total Flow Rate*** | =577.0 | **Average HHV (BTU/hr)** | =10907705.0 |
| | | **Average HHV (BTU/lb)** | =18904.2 |

**Table C-29:** Energy Efficiency at 1100 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 3.1 | 10.9 | 88.6 |

**Table C-30:** Enthalpy of Gas at 1150 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 7.6 | 23,811.0 | 179,794.6 |
| *CO* | 16.2 | 5,431.2 | 87,923.9 |
| *CO2* | 26.8 | 0.0 | 0.0 |
| *CH4* | 70.9 | 17,119.1 | 1,213,799.0 |
| *C2H6* | 14.3 | 18,150.0 | 260,315.3 |
| *C2H4* | 61.4 | 21,884.0 | 1,343,629.5 |
| ***Total Flow Rate*** | =197.2 | **Average HHV (BTU/hr)** | =3,085,462.4 |
| | | **Average HHV (BTU/lb)** | =15,643.9 |

**Table C-31:** Enthalpy of Oil at 1150 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 56.8 | 16707.0 | 948820.6 |
| *C4H10* | 6.5 | 57635.8 | 374882.2 |
| *C9H18* | 35.1 | 20469.5 | 718470.0 |
| *C6H6* | 47.3 | 17460.0 | 825735.8 |
| *C7H8* | 142.9 | 18228.7 | 2605011.5 |
| *C8H10* | 100.9 | 18651.0 | 1881766.5 |
| *C14H28* | 123.2 | 18826.0 | 2318461.4 |
| *C16H34* | 56.2 | 18843.0 | 1059143.2 |
| *C22H46* | 19.8 | 18992.0 | 376154.0 |
| ***Total Flow Rate*** | =588.7 | **Average HHV (BTU/hr)** | =11108445.3 |
| | | **Average HHV (BTU/lb)** | =18870.9 |

**Table C-32:** Energy Efficiency at 1150 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 3.1 | 11.1 | 89.8 |

**Table C-33:** Enthalpy of Gas at 1200 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/LB)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *H2* | 3.04177 | 23,811.0 | 72,427.6 |
| *CO* | 0.0269252 | 5,431.2 | 146.2 |
| *CO2* | 0.1982781 | 0.0 | 0.0 |
| *CH4* | 73.0452 | 17,119.1 | 1,250,467.1 |
| *C2H6* | 14.77032 | 18,150.0 | 268,081.3 |
| *C2H4* | 63.22953 | 21,884.0 | 1,383,715.0 |
| ***Total Flow Rate*** | =154.3 | **Average HHV (BTU/hr)** | =2,974,837.3 |
| | | **Average HHV (BTU/lb)** | =19,278.1 |

**Table C-34:** Enthalpy of Oil at 1200 F

| *Compound* | *Flow Rate (lb/hr)* | *HHV (BTU/lb)* | *Enthalpy (BTU/lb)* |
|---|---|---|---|
| *C10H8* | 61.1 | 16707.0 | 1020797.7 |
| *C4H10* | 6.698372 | 57635.8 | 386066.4 |
| *C9H18* | 33.14179 | 20469.5 | 678395.0 |
| *C6H6* | 50.9 | 17460.0 | 888696.5 |
| *C7H8* | 153.8035 | 18228.7 | 2803640.8 |
| *C8H10* | 108.5867 | 18651.0 | 2025250.5 |
| *C14H28* | 114.6402 | 18826.0 | 2158216.4 |
| *C16H34* | 52.32386 | 18843.0 | 985938.5 |
| *C22H46* | 18.437 | 18992.0 | 350155.5 |
| ***Total Flow Rate*** | =599.6 | **Average HHV (BTU/hr)** | =11297157.4 |
| | | **Average HHV (BTU/lb)** | =18840.2 |

**Table C-35:** Energy Efficiency at 1200 F

| *Energy Plastic In (MMBTU/hr)* | *Energy Gas out (MMBTU/hr)* | *Energy Oil Out (MMBTU/hr)* | *Efficiency (%)* |
|---|---|---|---|
| *15.8* | 3.0 | 11.3 | 90.3 |

### iii. Detailed Economics Calculation

**Table C-36:** Capital Investment

| *Direct Cost* | *Percent of Delivered Equipment Cost** | *Plant Cost* |
|---|---|---|
| *Purchased equipment delivered* | 100 | $213,174.34 |
| *Purchased-equipment installation* | 47 | $100,191.94 |
| *Instrumentation and controls* | 36 | $76,742.76 |
| *Piping (Installed)* | 68 | $144,958.55 |
| *Electrical Systems (Installed)* | 11 | $23,449.18 |
| *Buildings* | 18 | $38,371.43 |
| *Yard Improvement* | 10 | $21,317.38 |
| *Service Facilities (Installed)* | 70 | $149,222.04 |
| *Total Direct Cost* | 360 | $767,427.62 |
| | | |
| *Indirect Costs* | | |
| *Engineering and Supervision* | 33 | $70,347.53 |
| *Construction Expenses* | 41 | $87,401.48 |
| *Legal Expenses* | 4 | $8,526.97 |
| *Total Indirect Cost* | 144 | $933,703.61 |
| | | |
| *Contractor's Fee* | 22 | $205,414.79 |
| *Contingency* | 44 | $410,829.59 |
| | | |
| *Fixed Capital Investment* | 504 | $1,549,947.99 |
| *Working Capital* | 89 | $683,010.59 |
| *Total Capital Investment* | 593 | $2,232,958.58 |

*Ratio factors for estimating capital investment items based on delivered equipment cost

**Table C-37:** Operation and Maintenance

| | *Cost* | *1 year* | *30 years* |
|---|---|---|---|
| *Rent* | $133,000.00/year | $133,000.00 | $3,990,000.00 |
| *Labor* | $60,000.00/person (6) | $600,000.00 | $18,000,000.00 |
| *Water Cost* | $3.81/100cuft | $32.40 | $971.80 |
| *Electricity Cost* | $0.067/kwh | $100,087.99 | $3,002,639.62 |
| *Waste Water Disposal* | $6.06/100cuft | $51.52 | $1,545.66 |
| | | | |
| *Maintenance* | 3% FCC/month | $557,981.28 | $16,739,438.31 |
| *Insurance* | 1% TCC/year | $22,329.59 | $669.887.57 |
| | | | |
| *Total* | | $1,413,482.77 | $42,404,482.95 |

*FCC-Fixed Capital Cost, TCC- Total Capital Cost