# Design and Development of 15,000 Barrel per day (BPD) Capacity of Modular Crude Oil Refinery Plant

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***Abstract***
*The design of 15,000BPD capacity of a crude oil modular refinery was developed. It is a modular refinery because of its small processing capacity as compared to the conventional refinery. This report covers the material and energy balances across the major units, the preliminary and detail design of the major equipment, HAZOP studies, environmental safety, as well as economic and profitability analysis of the plant. The expected products include; kerosene, gasoline, diesel, heavy gas oil (HGO), and long product residue (LPR). A total capital investment (TCI) of N3,736,953,937.00 only is needed to carry out the project and a sum of N16,819,418,455.38 as net-profit (NP) is expected yearly with a payback period (PBP) of 2.36 years after investment.*

**Keywords***:* *Modular refinery, low capital cost, small scale, speed and easy to construction*

## 1.0 Introduction

A petroleum refinery is a manufacturing operation where crude petroleum - the raw material, is converted into usable and economic finished products, that is, it is the manufacturing phase of the oil industry. Mini (or modular) refineries are particularly effective in areas where there is a ready supply of crude but limited product distribution or refining capacity, where transportation costs or capability present a problem, such as remote areas or offshore platforms.

Refining adds value by converting crude oil (which in itself has little end-use value) into a range of refined products, including transportation fuels. The primary economic objective in refining is to maximize the value added in converting crude oil into finished products. Petroleum refineries are large, capital-intensive manufacturing facilities with extremely complex processing schemes. They convert crude oils and other input streams into dozens of refined and or co-products, including: liquefied petroleum gases (LPG), gasoline, aviation fuel, kerosene, diesel fuel, petrochemical feedstock, lubricating oils and waxes, as well as fuel oil etc. Of these, the transportation fuels have the highest value; fuel oils and asphalt the lowest value. Many refined products, such as gasoline, are produced in multiple grades, to meet different specifications and standards (e.g., octane levels, sulphur content).
Modular refineries, ranging from simple diesel production units to more sophisticated cracking refineries are increasingly becoming a flexible and cost-effective supply option for crude producers on small scale. The relatively low capital cost, speed and ease of construction are key advantages of a modular refinery.

### 1.1 Problem Statement

A prominent country like Nigeria is one of the top oil-producing nations in the world. But processing this oil into finished products has been a major challenge. The country has only four (4) refineries which has been under epileptic or zero operations over the years. These scenarios remain serious problems that need urgent attention. These 4 refineries is nothing as compared with the amount of crude oil we produce and what is obtainable in other countries like the U.S with over 200 refineries in full operations. Therefore, the need to boost our processing capacity and being self-reliant in refining and possibly exporting processed crude.

### 1.2 Significance of the Study

To achieving the development of a 15,000 BPD modular crude oil refinery capable of processing into key products like: petrol (PMS), kerosene, diesel, etc., and the development of local content capacity in refinery process and equipment designs.

## 2.0 Background Studies on Petroleum Refining

The petroleum refining sector has undergone significant rationalization in the last three decades. In the 1980s and 1990s surplus refining capacity globally triggered increasing competition among refiners and declining margins. Weak commercial conditions, together with tougher environmental regulations, led to closure of the majority of the less efficient, smaller refineries worldwide. The historic low returns, typically below the cost of capital, also resulted in significant under-investment in the sector and industry concentration with re-investment only into the larger, more efficient complex refineries.

The first modular refinery was installed more than thirty-five years ago (Stinger, 2011). This plant was a 1,000 BPD plant on a single skid containing an electronic generator, a horizontally mounted tower for hand cranking to a vertical position, and permanently mounted hand jacks for jacking the skid off a truck. A topping plant was later designed with design features which substantially reduce the plant requirements for operation and maintenance. To understand the fundamentals of petroleum refining, one must begin with crude oil.

### 2.1 Overview of African Refining

There are a total of 42 refineries in Africa, with a total name-plate capacity of 3,217,600 BPD. The major refining countries are Egypt with 9 refineries (774,900 bpd); Algeria with 5 refineries (303,700 bpd); Libya with 5 refineries (380,000 bpd); South Africa with 4 refineries (545,000); and Nigeria with 4 refineries (445,000 bpd) approximately.

More than half (i.e. 51.7%) of Africa’s refining capacity is in North Africa. According to McKinsey’s database, most of these are State-Owned (59%). 29% are based on joint ownership with government and 12% are joint-venture (JV) arrangements between International Oil Companies (IOC’s). These national refineries operate at different levels of efficiency. Considering data of average national capacity utilizations from 2006-2009, the efficiency levels for these countries are: Egypt (81%), Algeria (94%), Libya (87%), South Africa (85%), and Nigeria (18%), The Vanguard (2014).

### 2.2 Overview of Nigerian Refineries

Nigeria's state-held refineries (Port Harcourt I and II, Warri, and Kaduna) having a combined capacity of 438,750 BPD approximately. But problems including sabotage, fire, poor management and lack of quality regular maintenance contribute to the low current capacity of around 214,000 BPD. Plans for several small, independently-owned refineries are also being developed, with the Nigerian government planning for three new refineries to come on-stream since 2008 and is presently not been achieved. The $1.5-billion Tonwei refinery in

Bayelsa State appears set to be the first private refinery in Nigeria, with a planned initial capacity of 100,000 BPD. In the past 15-years, the only refinery built in Nigeria is the 1,000 BPD Ogbele Diesel Plant owned by Niger Delta Petroleum Company (NDPC) located in Bayelsa State.

The U.S. Export-Import Bank has agreed to provide a loan guarantee for $10 million of the $29.8 million total cost of the 12,000 BPD to make Modular Refinery in Eket-Akwa Ibom State. Production at Phase 1 of the refinery was expected to begin by mid-2005. Phase 2 of the refinery was for 6,000 BPD distillation unit, expected to be operational in mid-2006. Dangote oil refinery company (DORC) limited is constructing two modular refineries located one in Lekki, Lagos and Ondo state with the capacity of more than 600,000 BPD, largest in Africa, which can cost $9bn USD, and is expected to begin operations in 2017 (Aliko, 2015). Recently, the federal government has concluded plans to issue 23 licenses to establish modular refineries that may be in units from 4000 to 30,000 BPD (FG, 2015). The NNPC's four oil refineries, its numerous petrochemicals plants, and its Pipelines and Products Marketing Company (PPMC) are due to be sold in Nigeria's continuing effort to privatize state entities. Although the Nigerian government planned to offer 51 percent stakes in each of its four refineries, attempts to privatize the Port Harcourt refinery in 2004 elicited no bids from the oil majors. Because multinational oil companies have shown little interest in investing in refinery privatization, the Nigerian government recently opened negotiations with Libyan, Indian, and Chinese investors[3].

### 2.3 Petroleum (Crude Oil)

Petroleum is a substance occurring naturally in the earth in solid, liquid, or gaseous state and composed mainly of mixtures of chemical compounds of carbon and hydrogen, with or without other nonmetallic elements such as sulfur, oxygen, and nitrogen. In some cases, especially in the measurement of oil and gas, petroleum refers only to oil a liquid hydrocarbon and does not include natural gas or gas liquids such as propane and butane. Bulk of petroleum is made up of saturated compounds like paraffin's; naphthenic and unsaturated cyclic compounds mainly aromatics (Rao, 1990).

#### 2.3.1 Chemical and Physical Properties of Crude Oil

Generally, Crude oil is a complex mixture of free-flowing hydrocarbon liquid found beneath earth's crust. It varies in composition from one oil field to another. Crude oils range in consistency from water to far-like solid, and in colour from clear to black. Specific gravity lies between 1.00 and 0.80 API scale. Crude oil contains about 84% carbon, 10 – 14% hydrogen, 1 – 3% sulphur and less than 1% each of Nitrogen and oxygen. Crude oil also contains traces of Vanadium, Nickel and Sodium. The major hydrocarbon present in crude oil includes the paraffin (Alkanes) which normally consists of Isoprenoid, the naphtenes (cyclopentenes, cyclohexane) and aromatics (alkyl benzene, naphthalene). The non-hydrocarbon classes include Sulphur compounds (hydrogen sulfides, cyclic sulfides) and oxygen compound like, saturated fatty acids, phenols and pyroles. Each crude oil is a unique mixture, not matched exactly in composition or properties by any other sample of crude oil. Two typical crude oils, for example, have been characterized by the American Petroleum Institute as shown in Figure 2. Although the mid-points of their respective boiling ranges are similar, they differ considerably in other physical properties, hydrocarbon composition and distribution and sulphur content. The bulk of the compounds present in crude oils are hydrocarbons (Speight, 1980), in addition crude oils generally contain the classes of other hydrocarbons and compounds.

### 2.3.2 Classification of Nigerian Crude Oil

Some of the crude oil found in Nigeria are classified and presented in Table 1 below:

**Table 1: Classification of various crude oil**

| ***Property measured*** | ***Agbami*** | ***Bonny light*** | ***Usan*** | ***Pennington*** | ***Escravos*** | ***Bonny medium*** | ***Brass brand*** | ***Forcados brand*** |
|---|---|---|---|---|---|---|---|---|
| Gravity (API) | 48.28 | 36.50 | 29.90 | 35.30 | 32.40 | 9.0 | 7.5 | 8.7 |
| Gravity (sp.gr) | 0.79 | 0.85 | 0.86 | 0.85 | 0.86 | 0.9 | 0.75 | 0.087 |
| Sulphur (wt. %) | 0.04 | 0.15 | 0.26 | 0.10 | 0.17 | 0.28 | 0.1 | 0.20 |
| Total Nitrogen (ppm) | 384.46 | 1084.85 | 2064.88 | 590.08 | 1391.94 | - | - | - |
| Acid no. mg KOH/g | 0.05 | 0.23 | 1.10 | 0.20 | 0.56 | 0.44 | 0.45 | 0.21 |
| Pour point ($^{o}$C) | 13.36 | -11.48 | -44.98 | 6.00 | -9.00 | 2.8 | 20 | 24 |
| Vanadium (ppm) | 0.10 | 0.44 | 2.30 | 0.09 | 0.76 | - | - | - |
| Nickel (ppm) | 2.01 | 4.13 | 13.15 | 2.17 | 6.66 | - | - | - |
| Rams bottom Carbon (wt. %) | 0.59 | 1.02 | 2.76 | 0.55 | 1.31 | - | - | - |
| Asphaltenes (H. C7) wt.% | 0.11 | 0.01 | 0.06 | 0.01 | 0.02 | 0.29 | 0.14 | 0.05 |
| Viscosity | - | - | - | - | - | 16.44 | 2.24 | 5.40 |
| Wax | - | - | - | - | - | 2.1 | 6.8 | 4.1 |

**Source: SPDC (2016) *(www.shell.com/nigeriancrudeassay)***

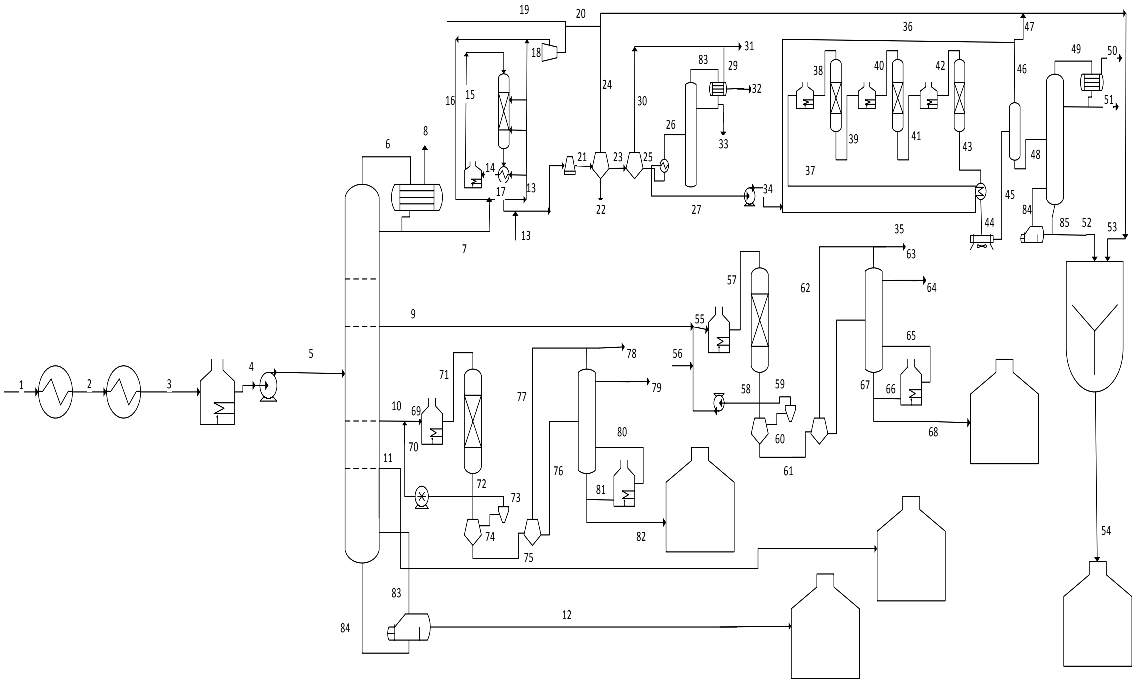

**Figure 1:** Complete process flow diagram developed of a mini-modular refinery.

### 3.0 Process Description

Crude oil contains salts, water and contaminant sediments which can be harmful to downstream equipment and must be removed. To remove the salts, water (about 3 – 10% of the crude oil volume) is mixed with the crude oil and typically heated to temperatures between about $215^0$F to about $280^0$F and allowed to separate in the *Desalter*. The desalted crude enters another heat exchanger networks called the *pre-heating train* which make use of the vapors of the main column condenser, the pump-around circuit streams, and the products that need to be cooled. In the preheating train, the crude is under pressure to suppress vaporization. In the case of light crude, the pressure required to suppress vaporization is too high. The solution is to separate some light components before heating the crude further in the preheat train. The preheated crude enters the *crude charge furnace*, where it is heated to about 340 - $372^0$C (644 - $700^0$F). The partially vaporized crude is fed into the feed region (called *flash zone*) of the atmospheric column, where the vapour and liquid separate. The vapour includes all the components that comprise the products, while the liquid is the residue with a small amount of components in the range of gas oil. These components are removed from the residue by steam stripping at the bottom of the column. Products such as *naphtha, kerosene, diesel, and gas oil*, are withdrawn from the side of the column and side strippers are used to help controlling the composition of light components. In addition, to more effectively remove heat, liquid is extracted at various points of the column and cooled down to be re-injected at a different position on the column. Cooling water and sometimes air coolers are used in the heat exchangers, but it is always more advantageous to have these streams release their heat to the raw crude oil in the heat exchanger networks (pre-heating trains).

The topped crude, *atmospheric residue (*also called *long residue)* leaving the atmospheric tower still contains significant amount of valuable oils. These oils cannot be distilled at atmospheric pressure because the temperature required would be so high that severe thermal cracking takes place. Usually, these oils are sent to a vacuum distillation unit where they are further treated and separated into lighter components, but in this case of a modular refinery, vacuum distilling the oil is out of the scope and instead the long residue is considered one of the final products of the refinery, therefore, these oils are sent to the tank farm for storage before subsequent processing in any of the conventional refineries or selling.

The naphtha obtained from the atmospheric still is subjected to further treatment under *Naphtha Hydrotreating Unit* (NHU), where hydrogen is added to get rid of the sulphur in form of $H_2S$ gas. The treated naphtha is then separated into light and heavy naphtha; both products then undergo *upgrading processes* where the light naphtha is isomerized to give an *isomerate* and the heavy reformed. The reformation of the heavy naphtha takes place under the *Catalytic Reforming Unit* (CRU), where it is treated in the presence of catalyst to give a product termed *reformate*. Both reformate and isomerate are then *blended* in the *gasoline blending pool* to give the highly useful *gasoline* (petrol), which then undergoes *Quality Control Test* (QCT) before being sent to the tank farm for storage and subsequent marketing.
Similarly, the kerosene and diesel products obtained from the atmospheric tower are hydrotreated, tested and stored in the tank farm before selling as well. The complete details of the process description could be found (Nafiu, 2016). A typical mini-refinery is shown in Figure 2.

**Figure 2:** 150BPD Mini-refinery located at Papua New Guinea. (*www.minirefinery.com*)

## 4.0 Process Reactions Analysis

## 4.1 Some Reactions Processes

### 4.1.1 Typical Hydro treating Reactions

**1. Desulfurization**

- **a.** Mercaptans: $RSH + H_2 \rightarrow RH + H_2S$
- **b.** Sulfides: $R\text{-}S\text{-}R + 2H_2 \rightarrow 2RH + H_2S$
- **c.** Disulfides: $R\text{-}S\text{-}S\text{-}R' + 3H_2 \rightarrow RH + R'H + 2H_2S$:

**2. Denitrification**

- **a.** Pyrrole: $C_4H_4NH + 4H_2 \rightarrow C_4H_{10} + NH_3$
- **b.** Pyridine: $C_5H_5N + 5H_2 \rightarrow C_5H_{12} + NH_3$

**3. Oxidation**

- **a.** Phenol: $C_6H_5OH + H_2 \rightarrow C_6H_6 + H_2O$
- **b.** Peroxides: $C_7H1_3OOH + 3H_2 \rightarrow C_7H_{16} + 2H_2O$

**4. Dehalogenation**

- **a.** Chlorides: $RCl + H_2 \rightarrow RH + HCl$

**5. Hydrogenation**

- **a.** Pentene: $C_5H_{10} + H_2 \rightarrow C_5H_{12}$

**6. Hydrocracking** (Breaking of large molecules / minor)

- **a.** Decane: $C_{10}H_{22} + H_2 \rightarrow C_4H_{10} + C_6H_{14}$

- Smaller compounds are desulfurized more easily than larger ones.
- Difficulty of sulphur removal increases in the order; Paraffins, naphthenes, then aromatics.
- Nitrogen removal requires more severe conditions (T&P) than sulphur removal.

(Albahri, 2001-2015).

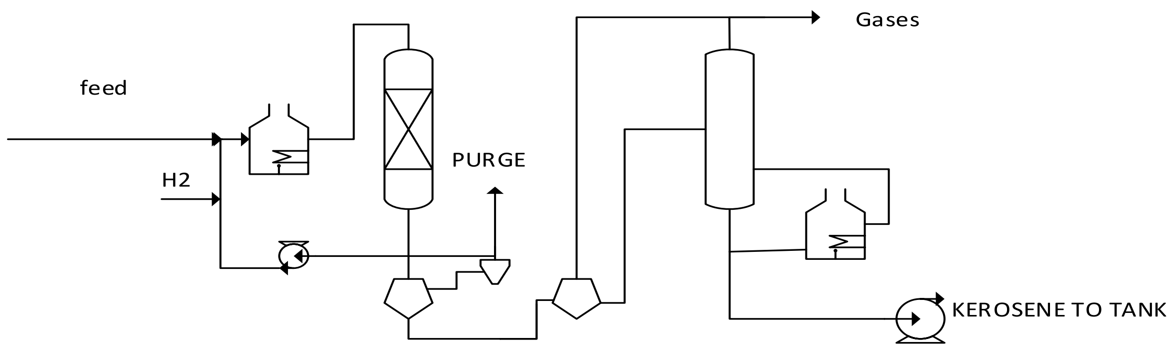


**Figure 3:** Kerosene hydro-treating unit process flow diagram

### 4.1.2 Diesel Hydrotreating Unit (DHTU)

Fresh feed from the surge drum is heated with stripper bottoms, and then mixed with recycle hydrogen. The combined feed is further heated by reactor effluent, and then brought to reactor inlet temperature in the charge heater. Reactor inter bed quench may be required in one or more locations, depending on the volume of cracked stocks (FCC LCO, light Coker gas oil) in the feed. This flow diagram shows recycle gas being used as quench. Reactor effluent exchanges heat with the combined feed and flows to the hot, high-pressure separator (HHPS). Vapours from the HHPS are used to heat recycle gas and stripper charge before being cooled in the reactor effluent air cooler (REAC) and entering the cold, high-pressure separator (CHPS). Wash water is injected upstream of the REAC to remove ammonium bisulphide. HHPS liquid is combined with heated CHPS liquid and to the product stripper.

### 4.1.3 Catalytic Reforming Unit (CRU)

In the CRU, the heavy naphtha from NHU is converted, after it has been heated to a high temperature under the presence of a catalyst, to a more highly rated product, called reformate. This reformate is of high octane number. The reactions in CRU are:

- Dehydrogenation (endothermic),
- Isomerization (endothermic),
- Hydro-cracking (exothermic) and
- Dehydrocyclization (endothermic).

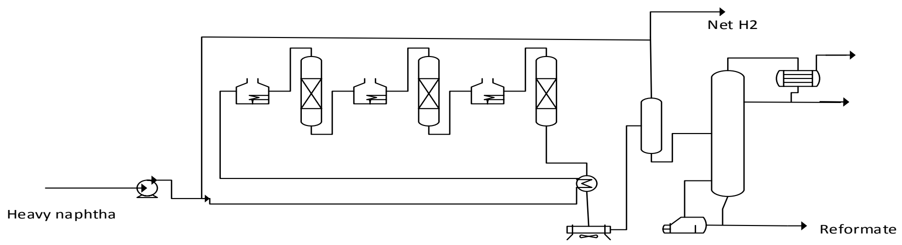


**Figure 4:** Catalytic reformate unit process flow

### 4.2 Blending Process

We must ask the reason for Blending Crude Oil? These answers are:

1. To upgrade or downgrade product.
2. To allow crude to meet benchmarks and transport specifications.
3. To allow access to market for poor quality un-transportable crude, and

**4.** To meet Sulphur specifications

Blending is the physical mixture of a number of different liquid hydrocarbons to produce a finished product with certain desired characteristics. Additives including octane enhances anti-oxidants, anti-knock agents, gum and rust inhibitions, detergents etc. are added during and/or after blending to provide specific properties not inherent in hydrocarbons (Berger, 1978).

Rising crude prices and availability of lower cost, heavy, high Sulphur, viscosity and TAN crudes makes inline blending one of the most economic methods to optimize profitability. Blending lower value oil with higher specification crudes to optimize both quality and cost can deliver multi-million dollar returns (Cameron, 2012).

Product blending, the operation at the back end of every refinery, regardless of size or overall configuration, blends refinery streams in various proportions to produce finished refined products whose properties meet all applicable industry and government standards, at minimum cost. The various standards pertain to physical properties (e.g., density, volatility, boiling range); chemical properties (e.g., sulfur content, aromatics content, etc.), and performance characteristics (e.g., octane number, smoke point) (Meyers, 2003).

## 5.0: Material and Energy Balance

The tables below present the summarized mass and energy balances across the whole plant.

### 5.1 Material Balance

**Table 1: Material balance for Desalter**

| ***Stream*** | ***Liquid Volume (%)*** | ***Volumetric Flow rate (ltr/hr)*** | ***Specific Gravity (Sp.gr)*** | ***Mass Flow (kg/hr)*** | ***Sulphur Content. (wt. %)*** | ***Sulphur Mass Flow (kg/hr)*** |
|---|---|---|---|---|---|---|
| Crude oil | 100 | 70,000 | 0.876 | 61,308.1 | 2.639 | 1,617.92 |
| Water | 7 | 4,900 | 1 | 4,900 | - | - |
| Salts | 90 | 4,410 | 2.510 | 11,069.10 | - | - |

**Table 2: Material balance for CDU**

| ***Stream*** | ***Liquid Volume (%)*** | ***Volumetric Flow rate (ltr/hr)*** | ***Specific Gravity (Sp.gr)*** | ***Mass Flow (kg/hr)*** | ***Sulphur Content. (wt. %)*** | ***Sulphur Mass Flow (kg/hr)*** |
|---|---|---|---|---|---|---|
| Gas+ Naphtha | 22.8 | 15,960 | 0.716 | 11,427.36 | 0.011 | 1.27 |
| Kerosene | 8.8 | 6160 | 0.803 | 4,946.48 | 0.353 | 17.46 |
| LGO | 10.6 | 7,420 | 0.842 | 6,247.64 | 1.22 | 76.22 |
| HGO | 5.8 | 4,060 | 0.877 | 3,560.62 | 2.049 | 72.96 |
| Atm. Res. | 52 | 36,400 | 0.965 | 35,126 | 4.281 | 1,503.74 |
| Crude Oil | *100* | *70,000* | *0.876* | *61,308.1* | *2.639* | *1,617.92* |

**Table 3: Material balance for Kerosene Hydrotreater**

| ***Stream*** | ***Liquid Volume (%)*** | ***Volumetric Flow rate (ltr/hr)*** | ***Specific Gravity (Sp.gr)*** | ***Mass Flow (kg/hr)*** | ***Sulphur Mass Flow (kg/hr)*** |
|---|---|---|---|---|---|
| LGO Feed | 7420 | 0.842 | 1.22 | 6,247.64 | 76.22 |
| $H_2$ Required | 5,079.17 | 11 | 0 | 55,870.87 | 0 |
| Total Feed | 90 | 4,410 | 2.510 | 11,069.10 | - |
| Diesel Prod. | 5,214.29 | 0.8353 | 0.21 | 4,355.50 | 9.1466 |
| Naphtha | 2,355.66 | 0.79 | 0.08 | 1,860.97 | 1.4888 |
| Gas to $C_5$ | 23,464.31 | 55 | 70 | 1,290,537.10 | 903,375.97 |
| Vent Gas | 1,953.62 | 37 | 76.54 | 72,283.94 | 55,326.13 |

**Table 4: Material balance for Diesel Hydrotreater**

| ***Stream*** | ***Liquid Volume (%)*** | ***Volumetric Flow rate (ltr/hr)*** | ***Specific Gravity (Sp.gr)*** | ***Mass Flow (kg/hr)*** | ***Sulphur Mass Flow (kg/hr)*** |
|---|---|---|---|---|---|
| Kerosene Feed | 6160 | 0.803 | 0.353 | 4,946.48 | 17.46 |
| $H_2$ Required | 1,466.70 | 11 | 0 | 16,133.7 | 0 |
| Kerosene | 6,147.68 | 0.7994 | 0.00356 | 4,914.46 | 0.1750 |
| Vent gas + LE | 1,466.70 | 128.60 | 7.248 | 188,617.62 | 1,367.10 |

**Table 5: Material flow for Naphtha Consolidation**

| ***Stream*** | ***Volumetric Flow rate (ltr/hr)*** | ***Specific Gravity (Sp.gr)*** | ***Sulphur Mass (wt. %)*** |
|---|---|---|---|
| Gas + Naphtha (From CDU) | 15,960 | 0.716 | 0.011 |
| Gas | 1197 | 0.465 | 0 |
| CDU Naphtha Stream | 14,763 | 0.7364 | 0.0116 |
| LGO Naphtha | 2,355.66 | 0.79 | 0.08 |

**Table 6: Material flow for Light Naphtha (LN) Consolidation**

| ***LN Source*** | ***LN Flow rate (ltr/hr)*** | ***LN Specific Gravity (Sp.gr)*** | ***LN Sulphur Mass (wt. %)*** |
|---|---|---|---|
| CDU | 6,255.08 | 0.698 | 0.005 |
| LGO | 602.81 | 0.7652 | 0.04 |
| TOTAL | 6,827.89 | - | - |

**Table 7: Material flow for Heavy Naphtha (HN) Consolidation**

| ***LN Source*** | ***HN Flow rate (ltr/hr)*** | ***HN Specific Gravity (Sp.gr)*** | ***HN Sulphur Mass (wt. %)*** |
|---|---|---|---|
| CDU | 8,507.92 | 0.7045 | 0.0159 |
| LGO | 1,752.85 | 0.7985 | 0.0932 |
| TOTAL | 10,260.77 | - | - |

**Table 8: Summary for Consolidated Naphtha + Gas Stream**

| *Stream* | *Vol. Flow rate (ltr/hr)* | *Specific Gravity (Sp.gr)* | *Sulphur Content (wt. %)* |
|---|---|---|---|
| Gas to $C_5$ | 1197 | 0.465 | 0 |
| Consolidated LN | 6,827.89 | 0.7039 | 0.0839 |
| TOTAL | 10,260.77 | 0.769 | 0.2190 |

**Table 9: Summary of light ends transferred to the butanizer**

| *Stream* | *Percentage Vol. (%)* | *Vol. flow (ltr/hr)* | *Mass Flow (kg)* |
|---|---|---|---|
| $C_1$ & $C_2$ | 13.03 | 886.25 | 37.79 |
| $C_3$ | 31.71 | 2156.67 | 83.90 |
| $iC_4$ | 22.69 | 1542.677 | 83.90 |
| $nC_4$ | 32.57 | 2215.21 | 88.96 |

**Table 10: Material balance for Final Products**

| *Stream* | *Flow rate (ltr/hr)* | *Mol. Wt. (or Sp. Gr)* | *Mass Flow (kg/hr)* |
|---|---|---|---|
| Debutanizer Overhead | 1448.32 | 0.5579 | 808.02 |
| Splitter feed | 18,665.25 | 0.7412 | 13,834.68 |
| Rich $H_2$ gas | 52,394.11 | 11 | 576,335.21 |

**Table 11: Material balance for Gasoline pool**

| *Stream* | *Volumetric (%)* | *Mass Flow rate (ltr/hr)* | *RON Factor* | *RON Products* |
|---|---|---|---|---|
| HC Naphtha | 12.43 | 1366.46 | 52,111.47 | - |
| LC Naphtha | 6827.89 | 62.11 | 38411.38 | - |
| Reformate | 2798.25 | 25.46 | 38411.38 | - |
| TOTAL | 10,992.6 | - | - | 90.66 |

Amount of butane added = 220.55ltr/hr
Total premium gasoline product: 10992.6 + 220.55 = 11213.15 litre/hour

## 5.2 Energy Balance

**Table 12: Energy balance for the CRU Heater**

| *Component* | *Mass flow rate (kg/hr)* | *$C_P$ (kJ/kgK)* | *$H_F$ (kJ/kg)* | *$H_P$ (kJ/kg)* | *$H_F$ = $H_P$ (kJ/kg)* | *Fuel Required (kg/hr)* |
|---|---|---|---|---|---|---|
| Paraffin | 6857.50 | 1.80 | 7319659.14 | 9541525.50 | - | - |
| Naphthenes | 5357.50 | 1.69 | 5383797.54 | 7018002.53 | 4385330.50 | 13098.36 |
| Aromatics | 1651.87 | 1.78 | 1743614.86 | 2272874.01 | - | - |
| Total | - | - | 14447071.54 | 18832402.04 | - | - |

**Table 13: Energy balance on 1st CRU Reactor (Dehydrogenation of Naphthenes to aromatics)**

| *Stream* | *Components* | *Mass flow rate (kg/hr)* | *$C_P$ Enthalpy of formation (kJ/kgK)* | *Enthalpy (kJ)* |
|---|---|---|---|---|
| **Feed** | Aromatics | 3223.28 | 124.40 | 3128.66 |
| | $H_2$ | 25.15 | -23.90 | -601.09 |
| | TOTAL | - | - | 2527.58 |
| **Product** | Naphthenes | 2148.86 | 1.69 | 2494890.93 |
| | Paraffins | 6857.50 | 1.80 | 8479984.50 |
| | Aromatics | 1651.87 | 1.78 | 2020005.75 |
| | TOTAL | - | - | 12994881.18 |

**Table 14: Energy balance on 2nd CRU heater; The feed enthalpy = 12994881.18kJ/kg**

| *Component* | *Components* | *Mass flow rate (kg/hr)* | *$C_P$ Enthalpy of formation (kJ/kgK)* | *Enthalpy (kJ)* |
|---|---|---|---|---|
| **Feed** | Aromatics | 3223.28 | 124.40 | 3128.66 |
| | $H_2$ | 25.15 | -23.90 | -601.09 |
| | TOTAL | - | - | 2527.58 |
| **Product** | Naphthenes | 2148.86 | 1.69 | 2494890.93 |
| | Paraffins | 6857.50 | 1.80 | 8479984.50 |
| | Aromatics | 1651.87 | 1.78 | 2020005.75 |
| | TOTAL | - | - | 12994881.18 |

**Table 15: Energy balance for 2nd Reactor (Dehydrocyclization of Paraffins to aromatics)**

| *Component* | *Mass flow rate (kg/hr)* | *$C_P$ (kJ/kgK)* | *$H_F$ (kJ/kg)* | *$H_F$ = $H_P$ (kJ/kg)* | *Fuel Required (kg/hr)* |
|---|---|---|---|---|---|
| Paraffin | 6857.50 | 1.80 | 7319659.14 | - | - |
| Naphthenes | 2148.86 | 1.69 | 2807206.24 | 3788890.44 | 11316.88 |
| Aromatics | 3223.28 | 1.78 | 4435039.88 | | |
| Total | - | - | 16783771.62 | | |

**Table 16: Energy balance on 3rd CRU Reactor (Hydrocracking). Feed Enthalpy: 16783771.62kJ/Kg**

| *Components* | *Mass flow rate (kg/hr)* | *$C_P$ Enthalpy of formation (kJ/kgK)* | *Enthalpy (kJ)* |
|---|---|---|---|
| Isopropane | 4.1140 | 367.10 | 1510.25 |
| Ethane | 4.1140 | -84 | -345.58 |
| Naphtha | 2148.86 | 1.65 | 2740763.49 |
| Paraffins | 3702.28 | 1.8 | 5151352.39 |
| Aromatics | 7399.23 | 1.78 | 10180903.06 |
| Naphthenes | 2148.86 | 1.69 | 2807206.24 |
| TOTAL | - | - | 18140626.36 |

### 5.3 Economic Analysis

The detail on '*Economic Analysis'* can be found at (Nafiu, 2016).

### 5.3.1 Pay Back Period (PBP)

The PBP is the time that is required after the start of the project to pay off the initial investment from income. It is given as the reciprocal of the Rate of Return (ROR) (Timmerhaus, 1991). Therefore;

$$PBP = \frac{1}{ROR} \times year$$

$$PBP = \frac{1}{4.2206} \times year$$

PBP = **2.36 year**

### 5.3.2 Cash Flow

The Cash Flow (CF) is calculated as the difference between the amounts earned (TI) and the amount expended (TPC). In other words;

Cash Flow = TI - TPC

CF = (51,034,844,120) – (341,502,253.35)

**CF = 50,693,341,866.65 Naira**

***Note: This analysis was based on the Nigeria economic situation in the 2015/2016 fiscal year.***

### List of Symbols and Abbreviations

| | | |
|---|---|---|
| G | = | gravitational acceleration ($m/s^2$) |
| $H_{riser}$ | = | height of riser (m) |
| T | = | temperature (K) |
| HGO | = | Heavy gas oil |
| LPR | = | Long product residue |
| ROR | = | Rate of return |

## 6.0 Conclusion

The design objective of a modular refinery of 15,000bpd capacity was achieved using trusted calculations methodology for the material and energy balance. Similarly, economic evaluation of the project was carried out and from the expected products; kerosene, gasoline, diesel, heavy gas oil (HGO), and long product residue (LPR), a total product sales of about Six million, four-hundred and forty-three thousand, seven-hundred and nine-three naira, forty-five kobo (₦6,443,793.45) Naira per hour.

Furthermore, a Total Capital Investment (TCI) of Twenty-five billion, ninety-three million, six hundred and seventy-eight thousand, five hundred naira (₦25,093,678,500) will be needed to carry out the project and a sum of sixteen billion, Eight hundred and nineteen million, four hundred and eighteen thousand, four hundred and fifty-five naira, thirty eight kobo (₦16,819,418,455.38) as Net Profit (NP) is expected yearly, with a cash flow (CF) of fifty-eight billion, one hundred and seven-three million, thirty thousand and fifty naira (₦58,173,030,050) leading to a Pay Back Period (PBP) of 2.36 years.
Therefore, the project is an economic viable one, as installations of modular plants are known for their high cost.

### Recommendations

All the required 'health and safety' rules and regulations must be adhered to at all given time. During the preparation, construction and commission stages, the guidelines and principles on safely should be given accorded priority. The safety officers are the chief safety of the personnel and the whole units. Therefore, they must take full responsibility of the lives and properties in the project.

Furthermore, in order to improve plant operation and overall plant productivity, operating personnel should undergo routine training on improved-work-ethic to improve their knowledge of plant operation.

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