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Refining Crude Oil – Part 1

Crude oil is what we extract out of the ground; refined products (such as gasoline and diesel) are what we consume. As of end-2007, there were 657 refineries around the world with a combined crude processing capacity of 85 million barrels per day (bpd). This briefing note provides technical background information on the characteristics of fuels which refineries produce and the refining processes that are needed to make the fuels. The next briefing note will describe what key global trends are affecting the refining industry.

The Petroleum Sector Briefing Notes up to this issue have focused on upstream exploration and production. But crude oil has to be traded, refined, and marketed before it can be used. This note describes what is involved in refining. It outlines the characteristics of various refined petroleum products, followed by a brief summary of main refining processes.

Fuels Produced

Crude oil comprises a large number of compounds, consisting mostly of hydrocarbons (which are made up of carbon and hydrogen), but also such “contaminants” as sulfur, nitrogen, metals, salts, and acids. The lower the levels of these contaminants, the more desirable—and higher priced—the crude is. At its simplest, processing units at refineries take crude oil, separate these various components, convert them through chemical reactions, and produce gas (used internally as a refinery fuel), liquefied petroleum gas (LPG), gasoline, kerosene, diesel, heating oil, and residual fuel oil. These refined products in turn consist of numerous hydrocarbons of varying size and shape. Depending on its configuration, a refinery may also produce lubricants, asphalt, and petroleum coke.

LPG

Also known as bottled or cooking gas when used by households and restaurants for cooking, LPG is a gas at room temperature and atmospheric pressure. LPG is a clean cooking and transportation fuel and behaves similarly to natural gas. Pressurizing it in a container liquefies LPG. It takes much less space to store a given amount of fuel as a liquid than as a gas, and LPG is always sold as a liquid under pressure.

Gasoline

Gasoline is used primarily as an automotive fuel. An important characteristic of gasoline is its octane number, which is a measure of the fuel’s resistance to self-ignition (or knocking). A vehicle’s octane requirement is determined by the compression ratio of its engine—the higher the compression ratio, the higher the fuel economy and the higher the octane requirement. There are no benefits to using gasoline with an octane number higher than that which the vehicle engine requires. If the octane number is lower than required, however, the resulting knock can damage the engine. Modern gasoline engines require a research octane number (octane number that is applicable in city, as opposed to highway, driving conditions) of 91–92 or higher, depending on the engine’s compression ratio.

For environmental and health reasons, other characteristics that are increasingly regulated around the world include gasoline’s volatility (temperature stability) and amount of sulfur, metals, and aromatics (a type of hydrocarbon, one of which is benzene). If gasoline is too volatile, it may cause vapor locks during driving (resulting in a temporary loss of power or even stalling) as well as excessive evaporation of light hydrocarbons. Light hydrocarbons can contribute to ground-level ozone air pollution, and for this reason tight volatility limits are imposed in cities with ozone problems. High ambient concentrations of ozone can cause respiratory illnesses and even premature mortality.

Growing environmental health concerns in recent years have called for lower levels of sulfur, metals, and aromatics. Sulfur interferes with the operation of catalytic converters—by far the most effective means of reducing pollution from gasoline vehicles. The United States, Europe, and Japan are now mandating the so-called sulfur-free gasoline and diesel. It is not possible to rid gasoline (or diesel) of sulfur completely, but the automotive fuels in these areas have the vast majority of sulfur removed during refining, at great expense. In addition to interfering with the operation of catalytic converters, high sulfur levels in gasoline (and diesel) can contribute to acid rain and fine particulate formation in the atmosphere. Fine particulate air pollution is the most serious threat to public health from urban air pollution in most developing country cities.

Environmental health concerns have also led to fuel standards requiring no measurable amounts of heavy metals, the most famous of which is lead. Historically, lead has been added to gasoline as an octane enhancer. But mounting evidence of the damaging public health impact of lead, and particularly on the intellectual development of children, has resulted in a worldwide call for a ban on the use of lead in gasoline. Gasoline in most countries is lead-free today.

Lastly, aromatics enhance gasoline's octane number but are associated with two environmental health problems. One is that some aromatics break down inside engines during combustion and are emitted as benzene, a cancer-causing agent. Benzene in gasoline may also be emitted out of the tailpipe unburned. Another is that larger-size aromatics can lead to ozone air pollution. Before these problems became widely known, aromatics were used extensively without limits as an octane enhancer, especially after gasoline lead phase-out began. Today, alternative sources of high-octane gasoline components are sought.

Kerosene, diesel, and heating oil

These fuels are collectively known as middle distillates; diesel and heating oil are also known as gasoil. Kerosene is used as an aviation fuel as well as for cooking, heating and lighting. The fuel specifications for kerosene are not as severe as those on gasoline and diesel.

Diesel is used first and foremost as an automotive fuel, and also for power generation. Specifications for automotive diesel are increasingly tightening. The equivalent of the octane number for diesel fuel is cetane: automotive diesel fuel must meet a minimum requirement for the cetane number. The same drive to minimize sulfur in gasoline is also leading to fuel specifications that call for sulfur-free diesel. Ultra low-sulfur diesel enables adoption of advanced exhaust emissions control devices to control the emissions of fine particles and oxides of nitrogen (NO_x). Fine particulate emissions from diesel engines are among the most damaging pollutants and have been receiving considerable attention from policymakers, environmentalists, and health specialists. NO_x is responsible for acid rain, ground-level ozone, and fine particulate formation in the atmosphere. Advanced exhaust emission control devices can make diesel vehicles virtually as clean as advanced gasoline and even natural gas vehicles.

Heating oil is similar to diesel fuel and is burned in furnaces in buildings. Kerosene, diesel, and heating oil can be used interchangeably to a considerable extent without the user noticing marked differences, at least in the short run. Illegal adulteration of diesel—which must meet the most stringent fuel specifications—with kerosene or heating oil occurs in many developing countries.

Residual fuel oil

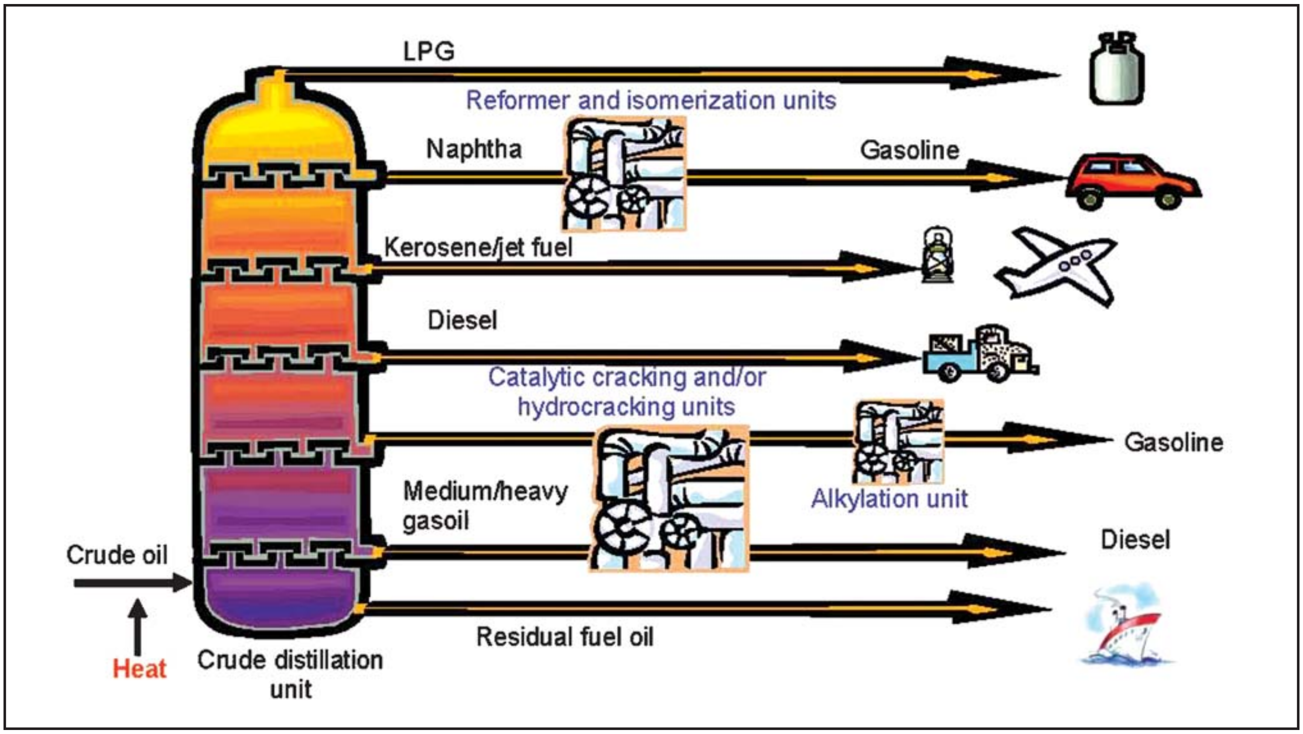
Residual fuel oil is what is left over after other fuels are produced. It is used to power ships' engines, for generating electricity at power plants, and as a fuel for industrial boilers. Two important characteristics of residual fuel oil are its viscosity and sulfur content. Viscosity can be thought of as the ease with which a fluid flows—water is much less viscose than residual fuel oil. As with gasoline and diesel, the sulfur specifications for residual fuel oil are increasingly being tightened.

Refinery Processing Units

There is wide range of refineries, from simple topping refineries to very large, complex refineries integrated with petrochemicals plants. The tighter the fuel specifications that a refinery must meet, the larger, more complex and expensive the refinery is likely to be. A simplified diagram of a refinery is sketched below.

Crude distillation Units

Every refinery has one or more crude distillation units and the entire crude is fed to these units first, where it is heated. Distillation separates the various components of crude oil according to their boiling points. The tem-



peratures at which compounds boil are affected by pressure. Atmospheric crude distillation units, which every refinery has, operate at normal pressure. Some refineries have vacuum distillation units, which operate below atmospheric pressure to separate residual fuel oil further into different components.

The nameplate capacity of a refinery is the combined capacity of its atmospheric crude distillation units. Refineries that have only atmospheric distillation units are called topping refineries. Fuels made from distillation and with no further chemical reaction are called straight-run fuels. Absent tight fuel specifications, virtually all straight-run fuels can be used without further modification, except gasoline. The octane number of straight-run gasoline is normally too low and further upgrading is required.

Topping refineries are usually small and common in remote areas. Straight-run diesel and a few other fuels may be consumed locally, and the rest may be put into a pipeline to be sent to more sophisticated refineries.

Reforming units

Reformers increase the octane number of naphtha (and more specifically what is called heavy naphtha). Naphtha is a portion of distilled crude oil comprising components with the same boiling points as those making up gasoline. Reforming units increase octane by converting hydrocarbons to aromatics. This is needed up to a point, but recently environmental health concerns have led to limits on relying solely on aromatics for boosting octane.

Reformers are also an important source of hydrogen, which is needed for removing sulfur compounds. Reformers use catalysts (catalysts speed up chemical reactions) that are readily poisoned by sulfur, and therefore the feedstock to a reforming unit is treated first to reduce sulfur to a negligible level in a unit called a hydrotreater. All hydrotreaters consume hydrogen, typically sourced from the reformer.

Refineries with only distillation, reforming, and associated hydrotreating units are called hydroskimming refineries. They represent the simplest refinery configuration among refineries that produce usable refined products.

Isomerization units

Isomerization units take what is called light naphtha and, by means of a chemical reaction, increase its octane. There is no environmental health damage associated with the products of isomerization units. Isomerization units require a hydrotreated feedstock.

Catalytic Cracking units

Catalytic cracking units take heavier fractions of distilled crude oil and, using a catalyst, break them up into smaller components to make gasoline and middle distillates. Catalytic cracking products have a high sulfur content unless the feedstock has been pretreated to remove sulfur—which is an expensive process. Catalytic cracking produces high-octane gasoline components but poor-quality diesel. The sulfur in the cracked products can be lowered by reacting with hydrogen, but doing so typically lowers the octane number of the gasoline fraction. Catalytic cracking is an important source of a feedstock component for alkylation (see below).

Hydrocracking units

In hydrocracking, heavier components of distilled crude oil are cracked in the presence of hydrogen to produce high-quality middle distillates. Hydrocracking units require large amounts of hydrogen and are expensive.

Alkylation units

Alkylates are premium gasoline blending components: they have exceptionally high octane numbers, and, unlike aromatics, are relatively safe for public health. However, alkylation units require other processing units to produce the feedstock: catalytic cracking and (possibly) isomerization units. Alkylation units require hydrotreated feedstocks.

Hydrogen units

The drive to reduce sulfur in fuels is leading to a hydrogen imbalance in refineries. Hydrocracking and hydrotreating require hydrogen, with hydrocracking requiring far more than hydrotreating. The only source of hydrogen as a by-product of refining processes is reforming. The amount of hydrogen produced during reforming increases with increasing amounts of aromatics made, but with the new interest in limiting the aromatics content in gasoline, the amount of hydrogen produced by reforming units has been declining in recent years. To meet the demand for hydrogen, refineries are building dedicated hydrogen units, where hydrogen is made from methane. This adds to the cost of refining processes.

Economies of Scale

It is not possible to meet tight fuel specifications without hydrotreating and other processes, all of which benefit from large economies of scale. A standard rule of thumb used in the industry is that the cost per unit size increases with increasing overall size of the processing unit with a power of 0.6. For example, if a 15,000 bpd unit costs US$150 million to construct, building the same processing unit twice the size—30,000 bpd—will not double the cost to US$300 million but will increase it to US$227 million ($=150 \times 2^{0.6}$). That is, a 15,000 bpd unit costs US$10,000 per daily barrel (US$150 million divided by 15,000 bpd), but a 30,000 bpd unit costs US$7,579 per daily barrel. This scaling factor makes it cheaper to make refined products in large refineries. These economics are driving oil companies to build fewer and larger refineries.

Refining does not generate much employment. Valero, the largest refiner in the United States with 15 refineries, employs on average about 510 workers at each refinery which has an average size of 200,000 bpd. The number of employees at Valero increases with refinery capacity with a power of 0.89. The number ranges from 220 workers at an 88,000 bpd refinery to 820 at a 340,000 bpd refinery [1].

Observations

Refining is an important part of the petroleum supply chain and its economic structure is different from that in the upstream. The ease of refining a particular crude plays a role in determining the refinery economics, and the types of products that are increasingly in demand require more complex processing.

Small hydroskimming refineries continue to operate, usually under protection, in a number of developing countries. They are finding it increasingly difficult to meet modern fuel specifications, yet governments are often reluctant to take the politically difficult step of opening up the market to competition for fear that such a step might lead to eventual closure of the refinery. The next briefing note will deal with market trends in refining.

References

[1] Valero Energy Corporation at www.valero.com/.

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