ENGINEERING PRACTICE

VOLUME 10 NUMBER 47

NOVEMBER 2024

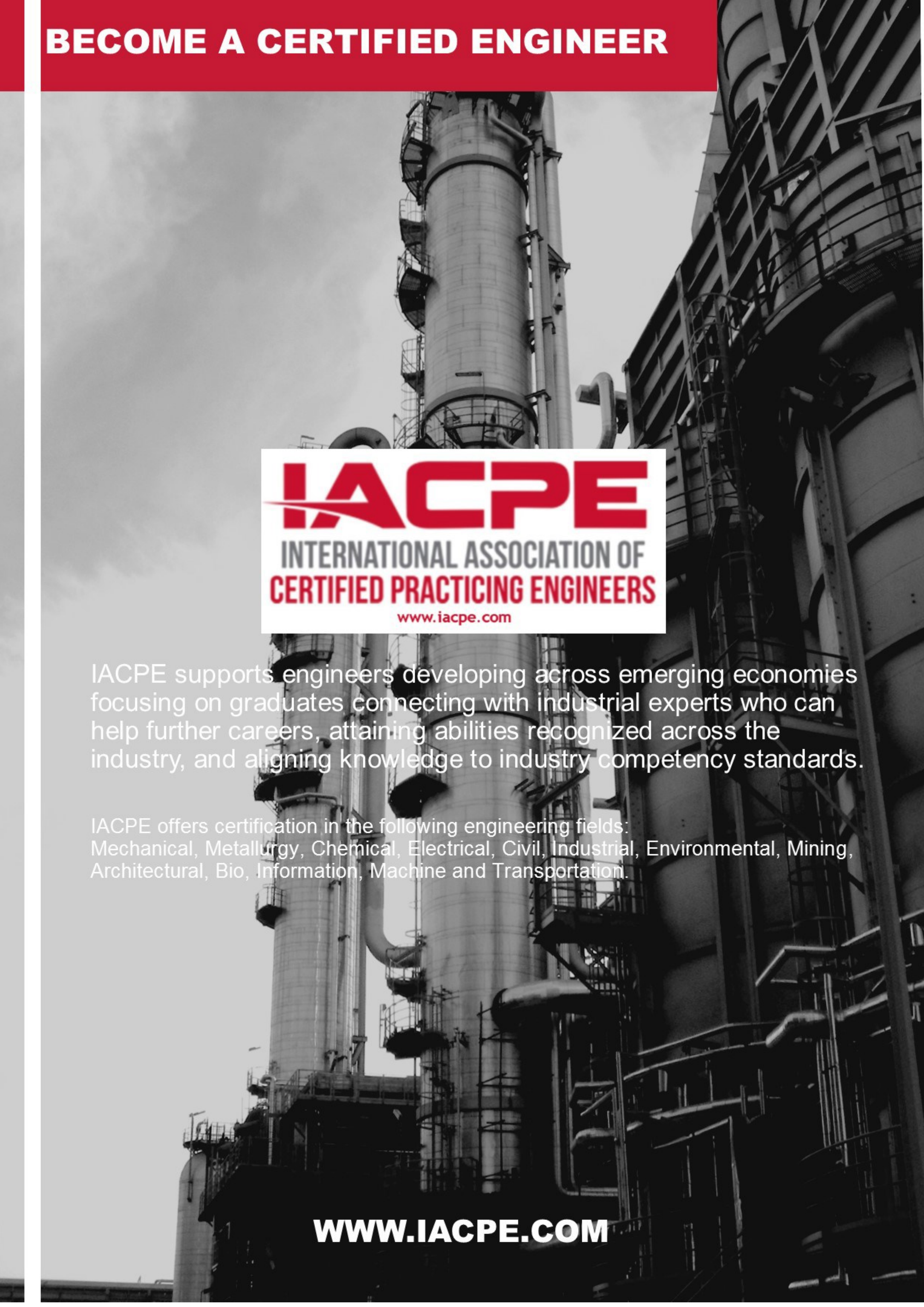
IACPE
INTERNATIONAL ASSOCIATION OF
CERTIFIED PRACTICING ENGINEERS

WWW.IACPE.COM

In This Issue

Volume 10 | Number 47

SPECIAL FEATURES


BECOME A CERTIFIED ENGINEER
IACPE
INTERNATIONAL ASSOCIATION OF
CERTIFIED PRACTICING ENGINEERS
www.iacpe.com
IACPE supports engineers developing across emerging economies focusing on graduates connecting with industrial experts who can help further careers, attaining abilities recognized across the industry, and aligning knowledge to industry competency standards.
IACPE offers certification in the following engineering fields:
Mechanical, Metallurgy, Chemical, Electrical, Civil, Industrial, Environmental, Mining, Architectural, Bio, Information, Machine and Transportation.
WWW.IACPE.COM

Guidelines for Palm Oil Plantation Management

Karl Kolmetz

Importance of Palm Oil

Palm oil is an incredibly efficient crop, producing more oil per land area than any other equivalent vegetable oil crop. Globally, palm oil supplies 31% of the world's vegetable oil demand on just under 6% of the land used to produce all vegetable oils. To get the same number of alternative oils like soybean, coconut, or sunflower oil you would need anything between 4 and 10 times more land. Furthermore, there are millions of smallholder farmers who depend on producing palm oil for their livelihoods.

For 2021 the amount of Palm Oil produced was 72 million metric tons, which constituted 31.4% of the world's oil and fat production. With the expansion of its traditional applications in pharmaceutics, beauty, personal, and home care to newly discovered possibilities from human nutrition to bioenergy technical use palm oil production is increasing. The kernel cake by product is suitable for cattle feeding, with high protein content and oil residues.

Palm Oil Plantations

Apart from cultivation productivity and high commodity demand worldwide, plantation best practices for growing oil palm offer several extra agricultural benefits:

- relatively high pest and weed resistance
- possibility of intercropping in cultivation
- all-year-round harvesting in plantations
- monthly income (during the fruit-bearing stage)
- absence of irrigation under sufficient rainfall conditions.

The above-mentioned advantages make the plantation industry rather favorable for many to enter. Even though planting the crop is highly efficient, growing it does require certain knowledge and efforts before its producers can benefit from plantation yields.

First, the plant needs specific soil and climate conditions. Second, the growth of oil palm starts after land and seed preparation. Third, the cultivation method for oil palms includes pest and weed control, irrigation and fertilization, ablation of early inflorescences, and harvesting.

The economic lifespan of the tree in plantations is rather long and is 25-30 years. In wild nature, oil palms can grow up to 200 years, but they get too tall and reduce yields, which complicates harvesting and, thus, their commercial use.

Oil palm is the best oil-containing crop in terms of yield capacity, even though planting oil palms won't give immediate returns. The crop's productivity depends on tree species, soil type, climatic conditions, oil palm plantation management, and cultivation practices.

In fact, the cost inputs during the first thirty months (prior to the first harvesting) are rewarded with up to 25 tons of fresh fruit bunches per ha in mature trees. Plantations give about four tons of crude palm oil per ha, which is eight times more productive than sunflower oil yield.

Palm Oil Sustainability

Pillars of Sustainability

Sustainability is a societal goal that broadly aims for humans to safely co-exist on planet Earth over a long time. The quality of causing little or no damage to the environment and therefore able to continue for a long time. These are great goals, to reduce the impact on the environment.

The four main pillars of Sustainability are 1) Reduce, 2) Recycle, 3) Recover, and 4) Renewables. Each of these needs to be reviewed and utilized. The energy in every process can be reduced. Recycling plastics and other items is cost effective. Recovering waste is essential for long-term improvements. Renewables will keep our lifestyle more environmentally friendly.

Growing the crop in plantations, oil palms or any farming cannot be completely environmentally friendly; still, its negative cultivation effects can be minimized. Plantation owners must also contribute to environmental sustainability by improving cultivation practices:

- avoid rainforest clearing
- rehabilitate abandoned and infertile lands for agricultural oil palm plantation use
- restrain from slash-and-burn practices in cultivation
- protect the environment and encourage tropical biodiversity (e.g., by growing wildlife corridors nearby or in-between plantations)
- operate plantations ethically and legally
- provide decent working conditions for their employees
- optimize plantation performance with sustainable growing methods (e.g., with more productive seeds)
- minimize chemical applications in cultivation with precision agriculture techniques.

Palm Oil Industry sustainability can be achieved through governmental guidance and the joint efforts of palm oil growers, manufactures, and end consumers.

Palm Oil Productivity

Palm Oil Productivity is dependent on several factors 1) Tree Species 2) Soil Type 3) Climate Conditions 4) Management of plantation and 5) Cultivation Practices

Tree Species

The oil palm tree (Elaeis guineensis) represents the Elaeis genus belonging to the Arecaceae family and originating from West Africa. There are three main crop types for cultivation in plantations:

- dura – with a thick shell (2-8 mm);
- pisifera – with no shell;

tenera – a hybrid of the above two.

Tenera is the most commercially valuable type, having a thinner shell and a bigger kernel, which is the most precious growing quality for plantations. Crop cultivation is performed mainly close to the equator in Latin America, West Africa, and Southeastern Asia.

Oil palm includes the palm species native to Africa, Elaeis guineensis, and the species native to South and Central America, Elaeis oleifera. Both species are perennial tropical trees in the family Arecaceae which are grown for their oil which is used in cooking and in industry. Oil palm trees are unbranched with a long stout single stem, or trunk, terminating in a crown of 7–100 leaves.

The leaves are pinnate and can reach 3–5 m (9.8–16.4 ft) in length. The tree produces large, spherical red fruits in bunches. Up to 200 fruits can be produced per bunch and the oil is extracted from the pulp and kernel. Oil palm can reach heights of 20–30 m (65.6–98.4 ft) and has an economic lifespan of 25–30 years, at which point they become too tall to be managed efficiently and are cut down. Left alone, oil palm has been known to live for periods up to 200 years. Oil palm may also be referred to as African oil palm and originated from West Africa.

Soil Type

The best soil types for the crop's cultivation are loamy or alluvial well-drained earths:

- at least one meter deep for root development;
- rich in organic matter;
- with pH 4.0 to 6-8.0;
- having sufficient soil moisture.

Soil salinization, alkalinization, or waterlogging is negative for oil palm tree growth. Since soil conditions matter, farmers are advised to perform soil testing to check area suitability before planting.

Climate Conditions

Oil palm plantations embrace subtropical and tropical latitudes, providing the best climate for the crops to thrive. Growth and production of oil palm are popular in Nigeria, India, Equador, Guatemala, Papua New Guinea, Colombia, Thailand, etc. Alongside Indonesia, vast oil palm plantations in Malaysia rank top among global market suppliers.

The plant is tropical, so it grows best in stable-warm areas with sufficient soil moisture all year round. The optimal temperatures for the cultivation of oil palm are 30–32°C (86–89.6°F) for 80 days minimum. Temperatures below 20°C (68°F) and above 40°C (104°F) are critical for growing and adversely affect crop production.

Proper development of oil palm in plantations is secured with at least 5-6 hours of bright daily sunshine and 75-100% humidity. As for precipitations, the plant thrives under evenly distributed rainfalls of 2,500-4,000 mm per year. Under a lack of uneven distribution of rainfalls in plantations, it is necessary to ensure water supply with irrigation.

Weather History

- favorable climate conditions for plantation growing.
- costs needed to compensate for lacking or abundant precipitation and temperature.
- forecasts for a general shift of meteorological patterns in the region.
  how these factors will affect the plantation yield because it may be more reasonable to grow another crop in the specific field instead.

Oil palm is typically grown in tropical lowland regions over large areas. The tree requires deep soil and stable high temperatures (30–32°C/86–89.6°F for at least 80 days) for optimum productivity. Temperatures below 20°C (68°F) will severely reduce the growth of both species, while the African oil palm will also suffer a reduction in growth at temperatures above 40°C (104°F).

Palms will grow in a variety of deep tropical soils and will tolerate a pH between 4.0 and 8.0. Oil palms have a requirement for continuous moisture throughout the year. The trees can tolerate 2–3 months of dry conditions but it can affect yields

Management of Plantations

Preparation of Seeds

Oil palms for plantations are typically propagated with seeds taken from fruits. Seed treatment is a responsible stage in oil palm cultivation and management because improperly prepared seeds will germinate after a couple of years due to long dormancy time.

Dried for about 2.5 months in stable hot rooms (40°C) and soaked for 4-5 days in daily changed water, seeds are supposed to germinate in about 12 days (3-3.5 months after extraction).

Immediately after germination, sprouts are planted into plastic (polyethylene) bags or containers with equal ratios of topsoil, sand, and properly decomposed cattle manure. Sprouts for cultivation remain in the bags for about 4-5 months (until they develop a bifid leaf).

Then, bifid-leaved sprouts continue in a plantation nursery, where they grow further for about a year. Finally, seedlings with about twelve-fifteen leaves and at least one meter high are mature enough and ready for growing in palm oil plantations.

The oil palm tree has a stem and leaves with no branching. It grows from the sole bud on the stem. If the bud is damaged, the plant is lost.

Field Preparation, Spacing, And Planting

Oil palm cultivation needs soil preparation before planting. The plantation soil should be fertilized with well-decomposed organic matter and cleaned from weeds. Plantation tilling improves the soil structure.

The optimal timing for planting is the rainy season from June to September. This way, plants can establish their root systems before the period of droughts.

To get a good yield from cultivation, oil palm trees must be planted at the right density. The plant sprouts are spaced in a triangular pattern with enough spacing for growing (9x9x9 m) in pits about 60 cm3. This planting method allows placing around 145 plants per hectare.

Benefits Of Intercropping and Cover Cropping in Plantations

During the first three years after planting, the land use can be intensified with intercropping or cover cropping. Thus, plantation owners can get additional yields and cattle forage prior to the cash crop fruit. However, operations and movement of oil palm plantation machinery for intercropping must not disturb the cash crop's roots.

Another point to consider in cultivation is that not all plants are suitable for neighbors with palms. Plantation intercrop plants must tolerate shade and not compete for nutrients, sunlight, and moisture with the cash crop. Besides, damaging plant fronds or pruning in oil palm plantations should be avoided because the more leaves a tree has, the more yields it can give.

Pineapple, ginger, turmeric, flowers, vegetables, banana, or tobacco growing are the best options for intercropping. Leguminous plants are an additional source of nitrogen fixation for cash crop growth.

Typical cover crop plants for oil palm plantations are Mucana, Centrosema prutascens, Pueraria phaeseoloides, Mimosa invisa, Calopogonium mueconoides, etc.

Cultivation Practices

Water Needs and Irrigation

The plant can resist several-month droughts, yet the yields will significantly drop. For this reason, oil palms grow under natural rainfall, with compensating irrigation when rain-fed soil moisture in plantations is not enough.

Each tree requires about 150-200 mm daily, and mature plants take even more. Several common precision irrigation methods satisfy the crop's water needs: micro-sprinklers, basin, and drip irrigation. The last one is the most economical and thus beneficial for plant cultivation.

Mulching In Oil Palm Cultivation

Base mulching helps retain soil moisture and creates a favorable microclimate for plant growing. Additionally, it suppresses weeds in oil palm plantations. Male flowers, coconut husk, empty bunches, straw, leaves can serve as natural mulch material in cultivation.

Pollination In Oil Palm Plantations

The plant's pollination occurs with the help of Elaeidobius kamerunicus and wind. However, mere wind pollination is not enough; this is why the insects are released on plantations after 2.5-3 years of tree growing.

The Elaeidobius kamerunicus weevils live for about 11-13 days. Adult insects feed on another filament, putting eggs into male flowers of the plant. The food for Elaeidobius kamerunicus larvae is spent flowers of plants.

Flowering and the Necessity of Ablation

The oil palm has male and female flowers that are cross-pollinated. Both male and female flowers grow in separate inflorescence spikes on the same plant. There are only male flowers for several months at first, and then there are only female ones. Oil palm fruit development happens in fertilized female flowers of the plant.

The palm oil tree bursts into bloom at the age of 14-18 months. Yet, for better growing and strong vegetation, it is necessary to cut or pull both male and female flowers off the trees during the first 2-3 years of plant cultivation.

Weed Management

Weed species in oil palm groves are quite diverse: a topic study counted 136 varieties. Among others, the list of common weeds in oil palm plantations includes:

- Chromolaena odorata,
- Clidemia hirta,
- Lantana camara,
- Aspillia Africana,
- Mimosa pudica,
- Panicum maximum,
- Melastoma malabathricum,

- Imperata cylindrical,
- Mallotus oppositifolius,
- Dicranopteris linearis,
- Nephrolepis,
- Stenochlaena palustris,
- Melanthera scandens,
- Ischaemum muticum,
- Paspalum conjugatum,
- Chloris barbata, and more.

The most invasive common weeds in oil palm plantations belong to Poaceae and Asteraceae families, competing for sunlight, moisture, and nutrients and impairing crop growing.

The common methods of weed control in oil palm plantations suggest physical removal by hand or chemical spraying.

Protection Against Pests or Infestations in The Development of Oil Palm

The plant typically suffers from rhinoceros beetles, bagworms, red palm weevils, and mealybugs. Widespread oil palm tree diseases are rots and wilts:

- stem wet rot,
- basal stem rot,
- bud rot disease, Bacterial bud rot Erwinia spp.

  Symptoms
  Parts of spear leaf petiole or rachi turning brown; discoloration may be associated with a wet rot; spear leaf may be wilted and/or chlorotic; leaves may be collapsing and hanging from the crown; infection of the bud results in buds becoming rotten and putrid, leading to death of the palm

  Cause
  Bacteria

  Comments
  Disease occurs in oil palm in Colombia, Costa Rica, Democratic republic of Congo, Ecuador, Nicarauga, Nigeria, Panama and Southeast Asia

  Management
  Plant oil palm varieties with resistance to the bacteria; rotting tissue on spear leaves should be removed to prevent bacteria spreading to buds; palm buds can be protected using copper-based fungicides

Pestalotiopsis leaf spot,

  Symptoms
  Tiny black spots on leaves which enlarge into 2 mm long elliptical, elongated lesions; lesions may expand and be surrounded by black tissue and chlorosis between lesions; lesions may be present on leaf petioles and rachis

  Cause
  Fungi

  Comments
  Disease has been reported worldwide

  Management
  If palm is severely diseased, it should be removed from plantation and destroyed; palms should be planted with adequate spacing to allow air to circulate between trees; remove weeds from around palms; applications appropriate broad spectrum foliar fungicides can help to protect the palms from disease

- oil palm wilt,

  Symptoms
  Symptoms of the disease vary with age of host; disease can affect seedlings and mature trees; seedlings exhibit retarded growth, reduced leaf size, chlorosis of older leaves and tip necrosis; field palms may exhibit a bright yellow chlorosis of leaves in the mid-canopy which starts at the tip pf the pinnae and moves towards petioles before affecting adjacent fronds and spreading to older leaves in the canopy; in older palms, lower leaves wilt and dry out and fronds break close to the base of the trunk; new fronds are chlorotic and stunted; the palm shows decline on one side and develops symptoms in the lower canopy; infection spreads rapidly upwards and infects the bud, killing the palm

  Cause
  Fungus

  Comments
  Fungus infests palms through the root system

  Management
  International quarantine procedures have limited the spread of the disease between major palm oil producing countries; dead

or dying trees should be felled and burned to prevent spread in plantations; if palms are replanted then new palm should be planted 3.9 m from infested stump; soil within a 3 m radius of infested stumps should be treated with dazomet and covered for a period of 30 days

- Ganoderma butt rot Ganoderma spp.

  Symptoms
  Reduced growth of palm, pale green foliage, older fronds turning chlorotic or necrotic; drooping fronds; on mature oil palms, spear leaves do not open, seedlings may exhibit a one-sided chlorosis or necrosis of the lower fronds; cross-sections of lower portion of trunk reveal a discoloration and softening of the central area and a distinct boundary is present between healthy and diseased tissue

  Cause
  Fungi

  Comments
  Serious disease in Far East

  Management
  There are currently no fungicides recommended for protecting palms from Ganoderma butt rot; palms should be monitored closely for signs of disease, especially if a palm has died or been removed nearby as fungi can colonize old stumps and release spores; infected trees should be removed as once symptoms are present in foliage, a large portion of the trunk is already rotted and the palm is unstable; do not replant palm in soil where an infected palm has been removed

- and others.

Even though pruning negatively impacts crop growing, infected and damaged plants must be fully or partially removed.

Modern disease and pest management methods highly advise avoiding chemical application in plantations. In particular, the Indonesian Sustainable Palm Oil System (ISPO) insists on opting for natural cultivation remedies to kill pests. Biological control in oil palm plantations suggests introducing predators and parasitoids combined with pheromones and plant-based lures (e.g., fermented castor cake). Some successful cultivation examples are as follows:

- fungi Metarhizium anisopliae with lure eradicate rhinoceros beetles;
- baculoviruses and Bacillus thuringiensis control nettle caterpillars;
- Bacillus thuringiensis combats bagworms and nettle caterpillars.

Efficient pest and disease control in plantations strongly depends on early problem identification and timely response

Oil Palm Plantation Fertilizer Guidelines

Efficient plant cultivation is secured with a sufficient supply of macro and micronutrients, including nitrogen, potassium, phosphorus, magnesium, etc. With a lack of nutrients, adequate growing is impossible.

Fertilization practices for oil palm plantations recommend nutrient applications in equal splits, sourcing from farmyard and green mature, neem cake, and synthetic products. Common ways to provide nutrients in crop cultivation are soil incorporation, scattering, or fertigation. Oil palm plantation fertilizer requirements differ depending on the tree age, with bigger amounts for mature plants.

Nitrogen
N is responsible for overall plant growing and fruit formation, including leaf health and the bunch number and size. Oil palms under nitrogen deficiency reveal chlorotic leaves. However, nitrogen toxicity in cultivation is not beneficial for the plants either since it increases the number of male flowers distorting the inflorescence sex ratio in palms.

Phosphorus
P boosts the number of female flowers and bunch weight. Plant fronds under phosphorus deficiency acquire olive-green hues and premature drying in older foliage. P applications are more favorable for plant cultivation when combined with nitrogen and potassium.

Research on the fertigation effect on palm oil growing on medium black soils in Karnataka in India concluded that NPK applications in oil palm cultivation of 1200:600:1200 vs. 300:150:300 g/plant/year boosted fresh fruit bunch yields (19.11 kg/bunch).

Potassium
K also boosts the formation of female flowers and bunch size and weight. Under potassium deficiency, older foliage of palm plants suffers from chlorosis and necrosis due to nutrient

allocation to newer leaves. The typical signs of P deficiency in plantations are orange spots on plant foliage, starting from pale green to yellow, spreading further on the leaf area and leading to necrosis.

Another prominent symptom to signal a lack of potassium in cultivation is mid-crown chlorosis. As a rule, leaves are green in the midrib area but suffer from marginal necrosis. New leaves grow short. In general, oil palm plantations look unhealthy and wither prematurely.

Magnesium

Mg deficiency in oil palm cultivation is recognizable through leaf discoloration, with bright-orange older leaves and pale green younger ones. In the newest plant foliage, there is no discrepancy in color. Plantation owners can also understand magnesium deficiency in growing by chlorosis in the sun-exposed leaf parts while shaded ones remain deep green.

Micronutrients

The crop doesn't typically suffer from deficiency of Fe, Zn, Mn, or Cu in acid soils. However, a lack of boron may cause foliage malformations, including small, "fish-bone", stiff, and hooked leaves.

Plant nutritional disorders in oil palm cultivation can be corrected with adequate fertilization, depending on the tree age and severity of symptoms. This is why fertilizer inputs on plantations must be estimated with sufficient precision to achieve the highest possible yields from palm growing oil.

Yielding And Harvesting in The Cultivation Method for Oil Palm

Oil palm growers can expect yields after three years of growing. To correctly determine picking time and avoid over-ripening are essential for palm oil quality. Harvesting begins when 5-8 fruits drop loose. Ripe fruit is yellow or orange in color, and orange palm oil seeps outside when pressed with a finger. Fruit bunches are cut manually by knife, chisel, or sickle. When plants grow too tall, fruit gathering is assisted with a hook.

Harvesting machines are a more productive and less labor-consuming option to manual picking in plantations. In fact, complete machine harvesters are attributed to nearly double productivity as compared to manual cutting with buffalo carts for transportation. At the same time, the equipment required for oil palm cultivation and management is more expensive than human labor in terms of maintenance and fuel. However, it will give decent returns in the long run. Harvesting rounds in plantations are repeated about every 10 to 14 days.

Conclusions

Palm oil is an incredibly efficient crop, producing more oil per land area than any other equivalent vegetable oil crop and plantation best practices for growing oil palm offer several extra agricultural benefits:

Growing the crop in plantations, oil palms or any farming cannot be completely environmentally friendly; still, its negative cultivation effects can be minimized. Plantation owners must also contribute to environmental sustainability by improving cultivation practices:

References

K. Kolmetz, Sustainability First Things First, Engineering Practice Magazine, November 2023, Volume 9 Number 41

Saifuddin, N.M. & Salman, Bello & Hussein, Refal & Ong, Mei. (2017). Microwave pyrolysis of lignocellulosic biomass—a contribution to power Africa. Energy, Sustainability and Society.

Hannah Ritchie and Max Roser (2021) - Forests and Deforestation. Published online at OurWorldInData.org.

M. Shahbandeh. Palm oil: global production volume 2012/13-2021/22. statista.com

Oil palm. plantvillage.psu.edu

Paul K. Essandoh, Frederick A. Armah, etc. Floristic composition and abundance of weeds in an oil palm plantation in Ghana. ARPN Journal of Agricultural and Biological Science. Vol. 6, no. 1, January 2011.

Priwiratama, Hari & Susanto, Agus & Prasetyo, Agus. (2018). Biological control of oil palm insect pests in Indonesia.

Reddi, Sanjeevraddi & H.P, Maheswarappa & Chandravathi, B & Patil, D. (2016). Effect of fertigation on yield and economics of oil palm (Elaeis guineensis Jacq.). Karnataka Journal of Agricultural Sciences. 29. 200-202.

Mohd Khalid, Mohd Ramdhan & SHUIB, RAHIM. (2014). Field evaluation of harvesting machines for tall oil palms. Journal of oil palm research. 26. 125 -132.

Sergueueva, K, Palm Oil Plantation, Cultivation and Management, online EOS Data on line

Oil Palm Diseases and Pest, Plant Village on line


TrayHeart
Tower Internals Design
TrayHeart is a professional software that performs hydraulic calculations for all types of tower trays, random and structured packings and liquid distributors. The development of TrayHeart started in 1998 and was continued jointly by universities, companies of the chemical industry and tower internals suppliers. TrayHeart ...
is based on multiple calculation models and large databases of packings, float valves, fixed valves, bubble caps, and liquid distributor templates
is a supplier-independent tool. There are no preferred product placements or promoted designs
considers static dimensions, manways and fastenings
offers an interactive 3D-view for all designs
can be used for single stage, profile and data validation calculations
has a unique, logical and multi-lingual user interface, with multiple input and output options
applies hundreds of online queries to check the feasibility and limits of the calculated designs
is a well introduced software many companies have relied on for more than 20 years
has extensive documentation and is licensed on annual basis
For more information:
www.welchem.com
service@welchem.com
WELCHEM
PROCESS TECHNOLOGY

The Role of High-Severity FCC Technologies in the Future of Downstream Industry

Dr. Marcio Wagner da Silva

Introduction and Context

The current scenario presents great challenges to the crude oil refining industry, prices volatility of raw material, pressure from society to reduce environmental impacts and refining margins increasingly lower. The newest threat to refiners is the reduction of the consumer market, in the last years became common, news about countries that intend to reduce or ban the production of vehicles powered by fossil fuels in the middle term, mainly in the European market. Despite the recent forecasts, the transportation fuels demand is still the main revenues driver to the downstream industry, as presented in Figure 1, based on data from Wood Mackenzie Company.

According to Figure 1, is expected a growing demand by petrochemicals while the transportation fuels tend to present falling consumption. Still according to Wood Mackenzie data, presented in Figure 2, due to the higher added value, the most integrated refiners tend to achieve higher refining margins than the conventional refiners which keep the operations focused on transportation fuels.

NCM = Net Cash Margins

The improvement in fuel efficiency, growing market of electric vehicles tends to decline the participation of transportation fuels in the global crude oil demand. New technologies like additive manufacturing (3D printing) have the potential to produce great impact to the transportation demands, leading to even more impact over the transportation fuels demand. Furthermore, the higher availability of lighter crude oils favors the oversupply of lighter derivatives that facilitate the production of petrochemicals against transportation fuels as well as the higher added value of petrochemicals in comparison with fuels.

As aforementioned, face the current trend of reduction in transportation fuels demand at the global level, the capacity of maximum adding value to crude oil can be a competitive differential to refiners. Due to the high capital investment needed for the implementation that allows the conventional refinery to achieve the maximization of chemicals,

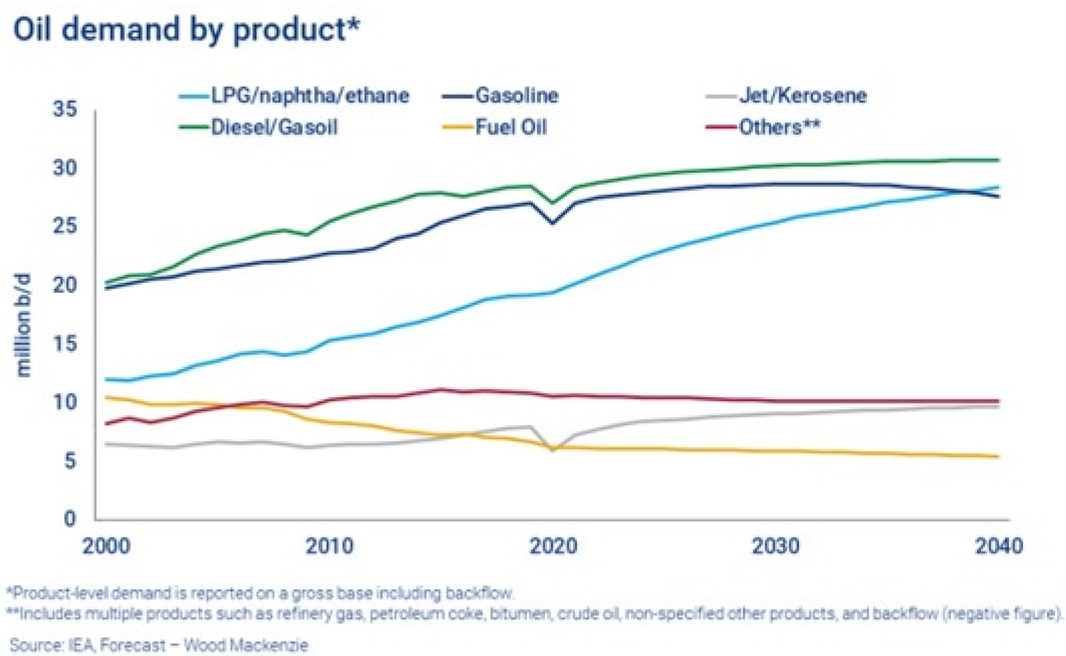


Figure 1 – Global Oil Demand by Derivative (Wood Mackenzie, 2020)

capital efficiency becomes also an extremely important factor in the current competitive scenario as well as the operational flexibility related to the processed crude oil slate. The olefins market will rise in total value of US$ 322 billion dollars in 2026 with a growing rate of 4,0 % in 2022 to 2027 period according to recent forecasts.

Considering exclusively the propylene market, the forecasts are even more encouraging for investments in on purpose propylene production routes. Figure 3 presents the projection to propylene market size for the next years.

According to Figure 3, the propylene market can reach values higher than 150 billion USA dollars in 2032 with an annual rate of 3,76 % with Asia being the bigger market as expected.

Considering the ethylene market, the scenario is even more attractive once is expected an annual growth rate of 5,58 % between 2022 and 2030 and the total size of the ethylene market can reach USD 287 billion in 2030 as presented in Figure 4. Again, the Asian continent is responsible of the major part of this growth.

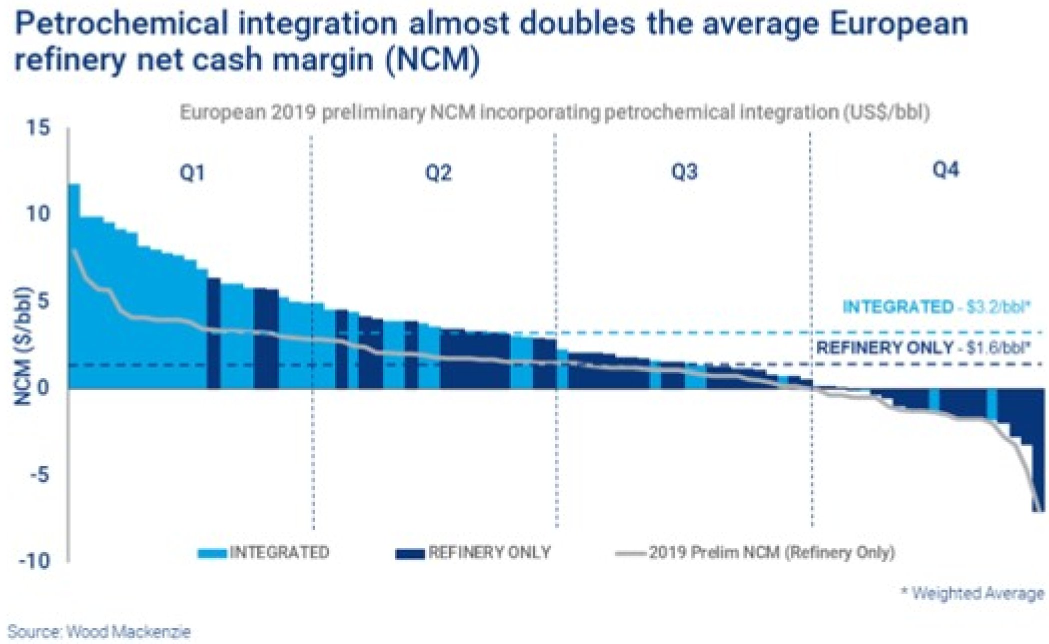


Figure 2 – Refining Margins to Integrated and Non-Integrated Refining Hardware (Wood Mackenzie, 2020)

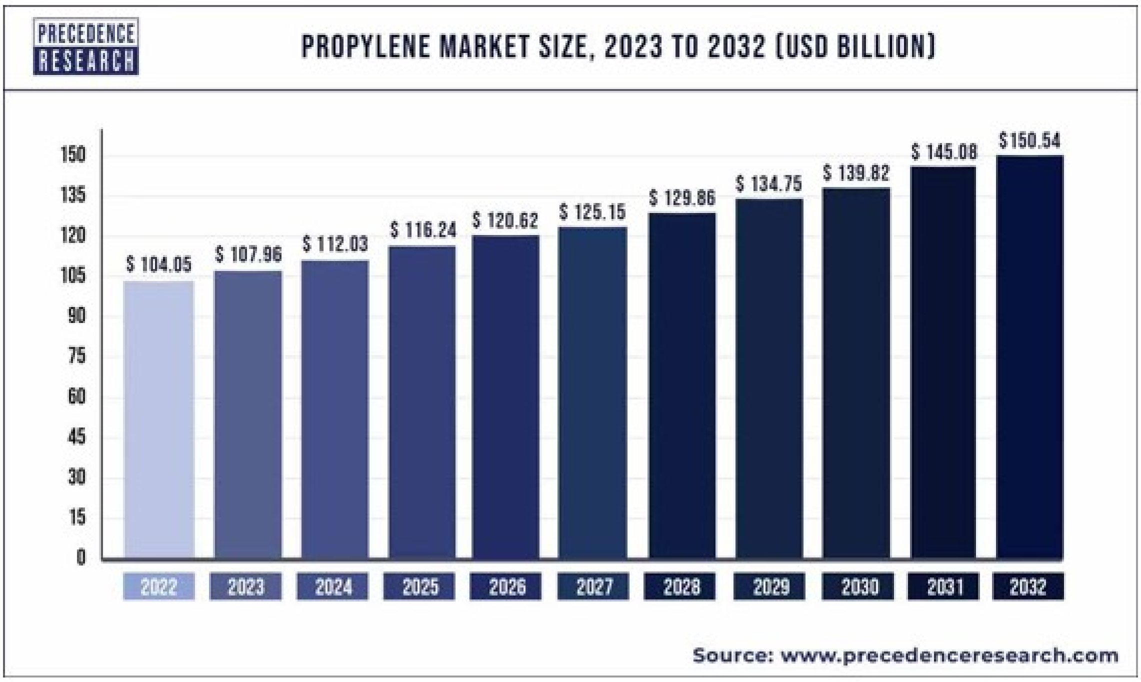


Figure 3 – Evolution of Propylene Market Size for the next years (Precedence Research, 2022)

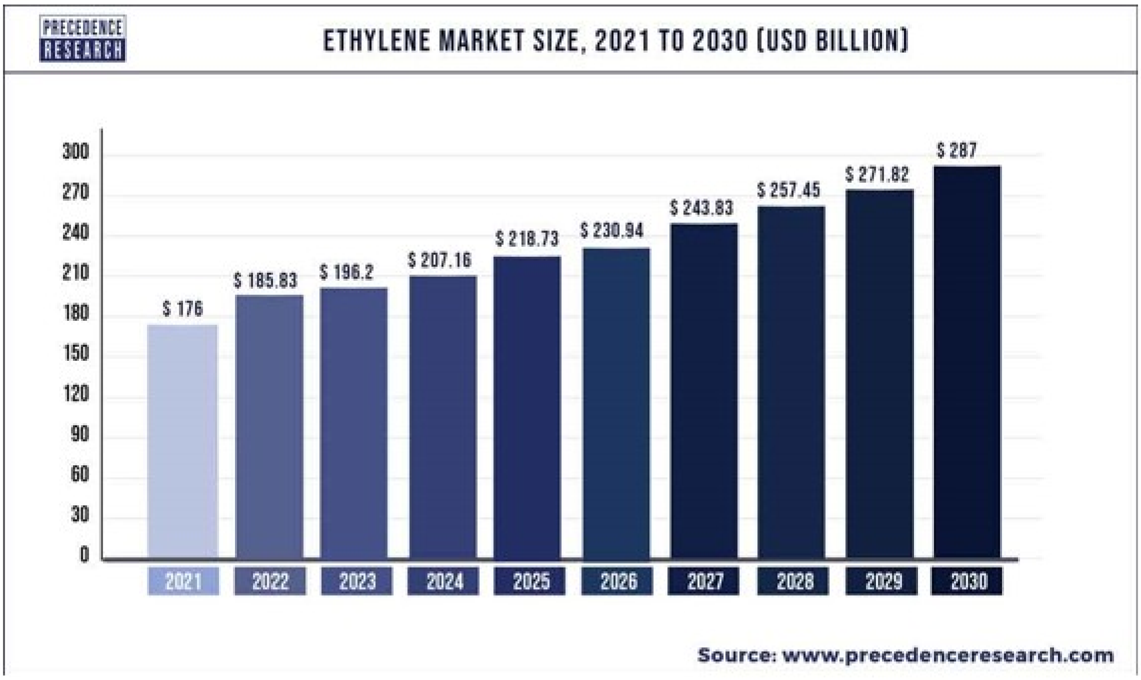


Figure 4 – Evolution of Ethylene Market Size for the next years (Precedence Research, 2022)

Due to his similarities, better integration between refining and petrochemical production processes appears as an attractive alternative to maximize the yield of petrochemicals. Although the advantages, it's important to consider that the integration between refining and petrochemical assets increases complexity, requires capital spending, and affect the interdependency of refineries and petrochemical plants, these facts need to be deeply studied and analyzed case by case.

In this business environment, flexible refining technologies like Fluid Catalytic Cracking (FCC) can ensure high competitiveness to refiners once are capable to produce high quality intermediates both to petrochemicals and transportation fuels, in markets with great demand by petrochemicals, the petrochemical FCC technologies can be an attractive option, despite the high capital spending.

Synergies between Refining and Petrochemical Assets – The Concept of Petrochemical Integration

The focus of the closer integration between refining and petrochemical industries is to promote and seize the synergies existing opportunities between both downstream sectors to generate value to the whole crude oil production chain. Table 1 presents the main characteristics of the refining and petrochemical industry and the synergies potential.

As aforementioned, the petrochemical industry has been growing at considerably higher rates when compared with the transportation fuels market in the last years, additionally, represents a noblest destiny and less environmentally aggressive to crude oil derivatives. The technological bases of the refining and petrochemical industries are similar, which leads to possibilities of synergies capable of reducing operational costs and adding value to derivatives produced in the refineries.

Figure 5 presents a block diagram that shows some integration possibilities between refining processes and the petrochemical industry.

Table 1 – Refining and Petrochemical Industry Characteristics

Refining Industry	Petrochemical Industry
Large Feedstock Flexibility	Raw Material from Naphtha/NGL
High Capacities	Higher Operation Margins
Self Sufficient in Power/Steam	High Electricity Consumption
High Hydrogen Consumption	High Availability of Hydrogen
Streams with low added Value (Unsaturated Gases & C2)	Streams with Low Added Value (Heavy Aromatics, Pyrolysis Gasoline, C4's)
Strict Regulations (Benzene in Gasoline, etc.)	Strict Specifications (Hard Separation Processes)
Transportation Fuels Demand in Declining at Global Level	High Demand Products

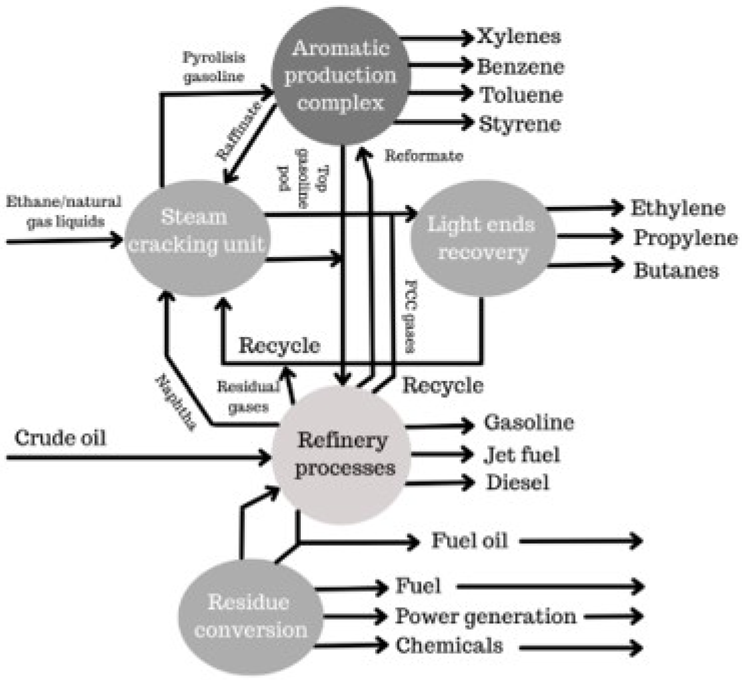


Figure 5 – Synergies between Refining and Petrochemical Processes

Process streams considered with low added value to refiners like fuel gas (C2) are attractive raw materials to the petrochemical industry, as well as streams considered residual to petrochemical industries (butanes, pyrolysis gasoline, and heavy aromatics) can be applied to refiners to produce high quality transportation fuels, this can help the refining industry meet the environmental and quality regulations to derivatives.

The integration potential and the synergy among the processes rely on the refining scheme adopted by the refinery and the consumer market. Process units such as Fluid Catalytic Cracking (FCC) and Catalytic Reforming can be optimized to produce petrochemical intermediates to the detriment of streams that will be incorporated to fuels pool. In the case of FCC, installation of units dedicated to producing petrochemical intermediates, called petrochemical FCC, aims to reduce to the minimum the generation of streams to produce transportation fuels, however, the capital investment is high once the severity of the process requires the use of material with noblest metallurgical characteristics.

The IHS Markit Company proposed a classification of the petrochemical integration grades, as presented in Figure 6.

According to the classification proposed, the crude to chemicals refineries is considered the maximum level of petrochemical integration, where the processed crude is essentially converted into petrochemical intermediates like BTX (Benzene, Toluene, and Xylenes), and Light Olefins (Ethylene, Propylene, C4s).

Fluid Catalytic Cracking Technologies – The Conventional Process x Petrochemical Units

Fluid Catalytic Cracking (FCC) is one of the main processes which give higher operational flexibility and profitability to refiners. The catalytic cracking process was widely studied over the last decades and became the principal and most employed process dedicated to converting heavy oil fractions into higher economic value streams.

The installation of catalytic cracking units allows the refiners to process heavier crude oils and consequently cheaper, raising the refining margin, mainly in higher crude oil prices scenario or in geopolitics crises that can become difficult the access to light oils. The typical Catalytic Cracking Unit feed stream is gas oils from vacuum distillation process. However, some variations are found in some refineries, like sending heavy coke naphtha, coke gas oils and deasphalted oils from deasphalting units to processing in the FCC unit.

The catalyst normally employed in fluid

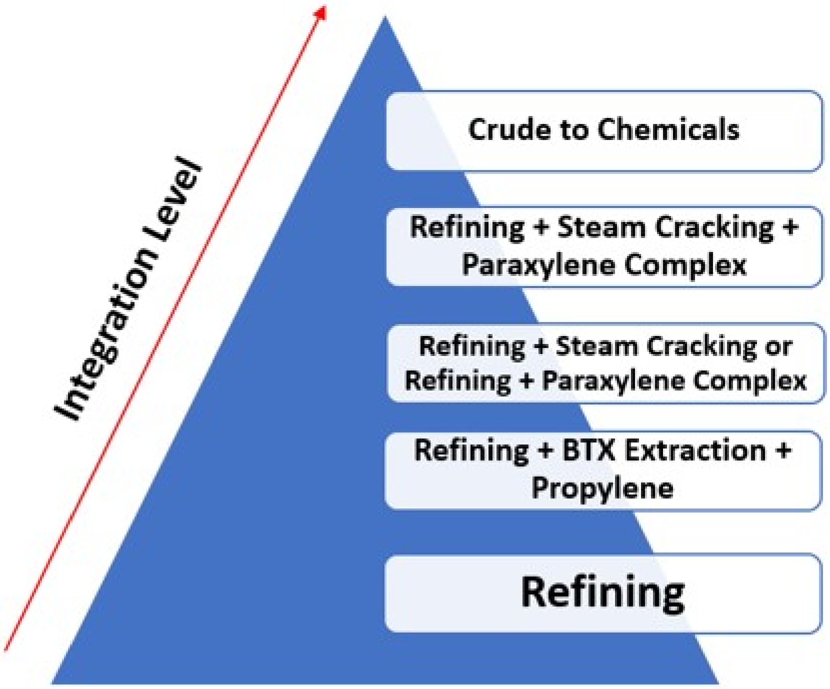


Figure 6 – Petrochemical Integration Levels (IHS Markit, 2018)

catalytic cracking units is a solid constituted by small particles of alumina (Al2O3) and silica (SiO2) (zeolite). By the catalyst characteristics and the operational conditions in the catalytic cracking process (temperature higher than 500 oC), the process is inefficient to cracking aromatic compounds, therefore, how much more paraffinic is the feed stream, the higher is the unit conversion. Figure 7 presents a process scheme for a typical Fluid Catalytic Cracking Unit (FCCU).

In a conventional scheme, the catalyst regeneration process consists in the carbon partial burning deposited over the catalyst, according to chemical reaction below:

C + ½ O2 → CO

Carbon monoxide is burned in a boiler capable of generating high pressure steam that supplies others process units in the refinery.

The principal operational variables in a fluid catalytic cracking unit are reaction temperature, normally considered the temperature in the top of the reactor (called riser), feed stream temperature, feed stream quality (mainly carbon residue), feed stream flow rate and catalyst quality. Feedstock quality is especially relevant, but this variable is a function of the crude oil processed by the refinery, so is difficultly can be changed, but for

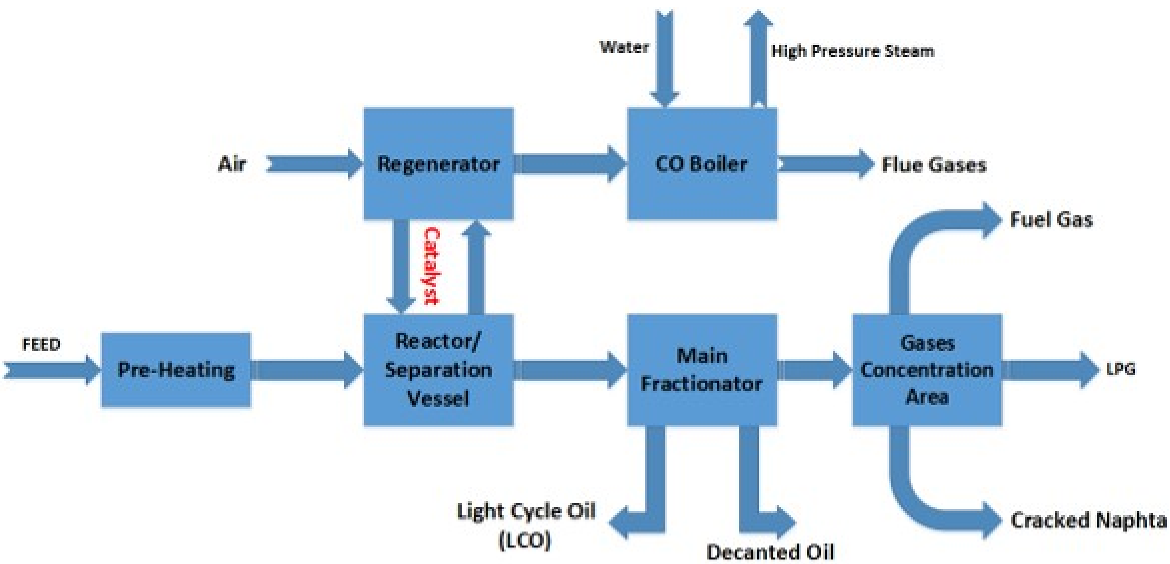


Figure 7 – Schematic Process Flow for a Typical Fluid Catalytic Cracking Process Unit (FCCU)

example, aromatic feedstocks with high metals content are refractory to cracking and conducting to a quick catalyst deactivation.

An important variation of the fluid catalytic cracking technology is the residue fluid catalytic cracking unit (RFCC). In this case, the feedstock to the process is basically residue from atmospheric distillation column, due to the high carbon residue and contaminants (metals, sulfur, nitrogen, etc.) are necessary some adaptations in the unit like catalyst with higher resistance to metals and nitrogen and catalyst coolers furthermore, it's necessary apply materials with most noble metallurgy due the higher temperatures reached in the catalyst regeneration step (due the higher coke quantity deposited on the catalyst), that raises significantly the capital investment to the unit installation. Nitrogen is a strong contaminant to the FCC catalyst because they neutralize the acid sites of the catalyst which are responsible for the cracking reactions.

When the residue has high contaminants content, it is common the feed stream treatment in hydrotreating units to reduce the metals and heteroatoms concentration to protect the FCC catalyst.

Typically, the average yield in fluid catalytic cracking units is 55% in volume in cracked naphtha and 30 % in LPG.

The decanted oil stream contains heavier products and has high aromatic content. It is common that this product is contaminated with catalyst fines and normally this stream is directed to use like fuel oil diluent, but in some refineries, this stream can be used to produce black carbon.

Light Cycle Oil (LCO) has a distillation range close to diesel and normally this stream is directed to treatment in severe hydrotreating units (due to the high aromaticity), after this treatment the LCO is sent to the refinery diesel pool.

Heavy cracked naphtha is normally directed to refinery gasoline pool, however, in scenarios where the objective is to raise the production of middle distillates, this stream can be sent to hydrotreating units for further diesel production.

The overhead products from the main fractionator are still in gaseous phase and are sent to the gas separation section. The fuel gas is sent to the refinery fuel gas ring, after treatment to remove H2S, where it will be burned in fired heaters while the LPG is directed to treatment (MEROX) and further commercialization.

The LPG produced by FCC unit has a high content of light olefins (mainly Propylene) so, in some refineries, the LPG stream is processed in a Propylene separation unit to recovery the propylene that has higher added value than LPG.

Cracked naphtha is usually sent to refinery gasoline pool which is formed by naphtha produced by other process units like straight run naphtha, naphtha from the catalytic reforming unit, etc. Due to the production process (deep conversion of residues), the cracked naphtha has high sulfur content and to attend to the current environmental legislation this stream needs to be processed to reduce the contaminants content, mainly sulfur.

The cracked naphtha sulfur removing represents a great technology challenge because it is necessary to remove the sulfur components without molecules saturation that gives high octane number for gasoline (mainly olefins).

Over the last decades some technology licensers had developed new processes aiming to reduce the sulfur content in the cracked naphtha with minimum octane number loss, some of the main technologies dedicated for this purpose are technology PRIME G+ ™ from Axens, the processes OCTAGAIN ™ and SCANfining ™ from Exxon Mobil, the process S-Zorb™ from ConocoPhillips and ISAL™ technology from UOP.

Usually, catalytic cracking units are optimized to aiming the production of fuels (mainly gasoline), however, some process units are optimized to maximize the light olefins production (propylene and ethylene). Process units dedicated to this purpose have significantly changed his project and operational conditions significantly changed once the process severity is strongly raised in this case.

The reaction temperature reaches 600 oC and higher catalyst circulation rate raises the gases production, which requires a scaling up of gas separation section.

In several cases, due to the higher heat necessity of the unit is advantageous to operate the regenerator with the total combustion of the coke deposited on the catalyst, this arrangement significantly changes the thermal balance of the refinery once it's no longer possible to resort the steam produced by the CO boiler.

Over the last decades, the fluid catalytic cracking technology was intensively studied aiming mainly for the development of units

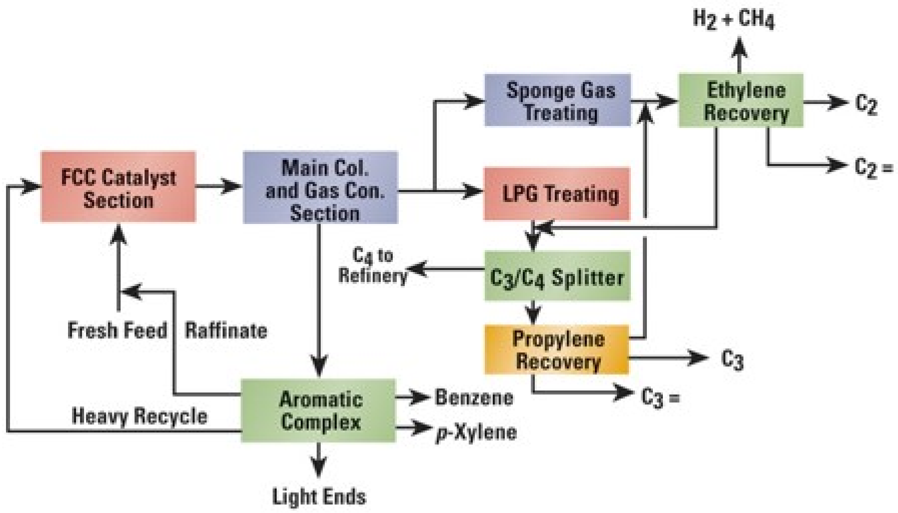


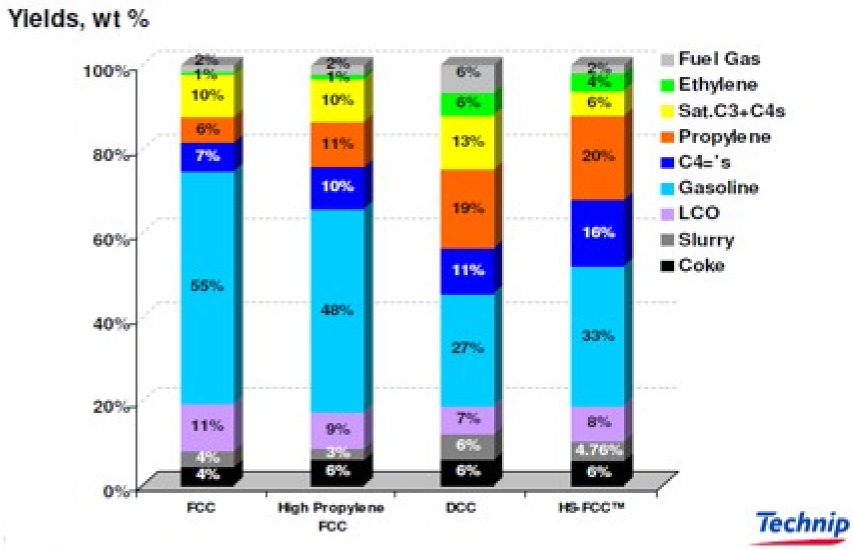
Figure 8 – PetroFCC™ Process Technology by UOP Company.

capable of producing light olefins (Deep Catalytic Cracking) and to process heavier feedstocks. The main licensers for fluid catalytic cracking technology nowadays are the companies KBR, UOP, STONE & WEBSTER, AXENS, and Lummus.

Improving the Yield of Petrochemicals in the Refining Hardware – Some Commercial Petrochemical FCC Technologies

As quoted earlier, in markets with high demand by petrochemicals, the petrochemical FCC can be an attractive alternative to refiners aiming to ensure higher added value to bottom barrel streams. An example of FCC technology developed to maximize the production of petrochemical intermediates is the PetroFCC™ process by UOP Company, this process combines a petrochemical FCC and separation processes optimized to produce raw materials to the petrochemical process plants, as presented in Figure 8. Other available technologies are the HS-FCC™ process commercialized by Axens Company, and INDMAX™ process licensed by Lummus Company.

To petrochemical FCC units, the reaction



	Conv. FCC	HP FCC	DCC	HS-FCC™
ROT	530°C (986°F)	550°C (1022°F)	580°C (1076°F)	600°C+ (1112°F+)
Contact time	2 - 5 s	2 - 5 s	10 s	0.5 - 1 s
C/O	5	10	15	25
Recycle	None	LCN	LCN	None

Figure 9 – Comparative Study between Conventional FCCs and Petrochemical FCC (HS-FCC™)

temperature reaches 600 oC and higher catalyst circulation rate raises the gases production, which requires a scaling up of gas separation section. The higher thermal demand makes advantageous operates the catalyst regenerator advantageous, leading to the necessity of installation a catalyst cooler system.

Figure 9 presents the results of a comparative study, carried out by Technip Company, showing the yields obtained by conventional FCC units, optimized to olefins (FCC to olefins), and the HS-FCC™ designed to maximize the production of petrochemical intermediates.

It's observed a higher reaction temperature (TRX) and a cat/oil ratio five times higher when are compared the conventional process units and the petrochemical FCC (HS-FCC™), leading to a growth of the light olefins yield (Ethylene + Propylene + C4='s) from 14 % to 40%.

The installation of petrochemical catalytic cracking units requires a deep economic study considering the high capital investment and higher operational costs; however, some forecasts indicate growth of 4,0 % per year to the market of petrochemical intermediates until 2025. In this scenario the capital investment aiming to raise the market share in the petrochemical sector can be attractive, allowing then a favorable competitive positioning to the refiner, through the maximization of petrochemical intermediates. Figure 10 presents a block diagram showing a case study demonstrating how the petrochemical FCC unit, in this case the INDMAX™ technology by Lummus Company, can maximize the yield of petrochemicals in the refining hardware. Another FCC technology dedicated to convert residue to olefins is the R2P™ process, developed by Axens Company.

In refining hardware with conventional FCC units, further than the higher temperature and catalyst circulation rates, it's possible to apply the addition of catalysts additives like the zeolitic material ZSM-5 that can raise the olefins yield close to 9,0% in some cases when compared with the original catalyst. This alternative raises the operational costs, however, as aforementioned can be economically attractive considering the petrochemical market forecasts. Figure 11 presents some optimization strategies to improve the petrochemical yield in conventional FCC units.

The use of FCC catalyst additives such as ZSM-5 can increase unit propylene production by up to 8.0%.

Installation of catalyst cooler system raises the process unit profitability through the total conversion enhancement and selectivity to noblest products as propylene and naphtha against gases and coke production. The catalyst cooler is necessary when the unit is designed to operate under total combustion mode due to the higher heat release rate as presented below.

$C + \frac{1}{2} O_2 \rightarrow CO$ (Partial Combustion) ΔH = - 27 kcal/mol

$C + O_2 \rightarrow CO_2$ (Total Combustion) ΔH = - 94 kcal/mol

In this case, the temperature of the regeneration vessel can reach values close to 760 oC, leading to higher risks of catalyst damage which is minimized through catalyst cooler

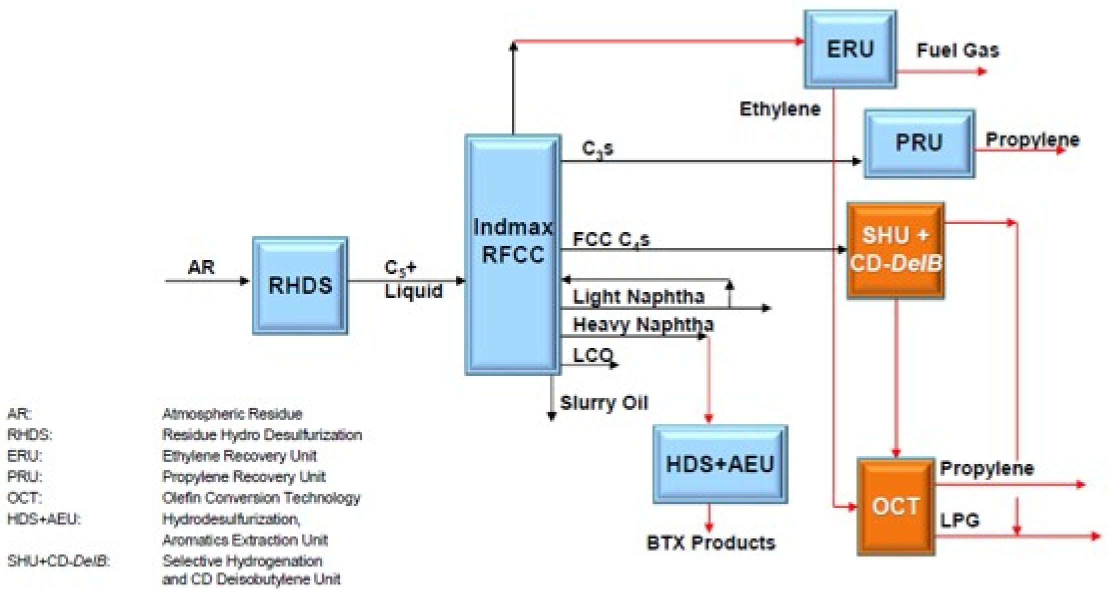


Figure 10 – Olefins Maximization in the Refining Hardware with INDMAX™ FCC Technology by Lummus (SANIN, A.K., 2017)

installation. The option by the total combustion mode needs to consider the refinery thermal balance, once, in this case, will not have the possibility to produce steam in the CO boiler, furthermore, the higher temperature in the regenerator requires materials with noblest metallurgy, this significantly raises the installation costs of these units which can be prohibitive to some refiners with restricted capital access.

Among another petrochemical FCC technologies, it's possible to quote the Maxofin™ and K-COT™ processes developed by KBR Company and the SCC™ technology developed by Lummus Company. Figure 12 presents a basic process arrangement for the K-COT™ technology developed by KBR Company.

Due to the higher production of light olefins, mainly ethylene, another important difference between conventional and petrochemical FCC units is related to the gas recovery section, while in conventional FCC is applied absorber columns, in petrochemical units is applied cryogenic processes though refrigeration cycles in similar conditions which are applied in steam cracking units.

The cryogenic processes applied to olefins recovery raises, even more, the capital requirement to petrochemical FCC units when compared with conventional FCCs, despite this, the growing market for petrochemicals and falling demand for transportation fuels, tends to compensate the higher investment.

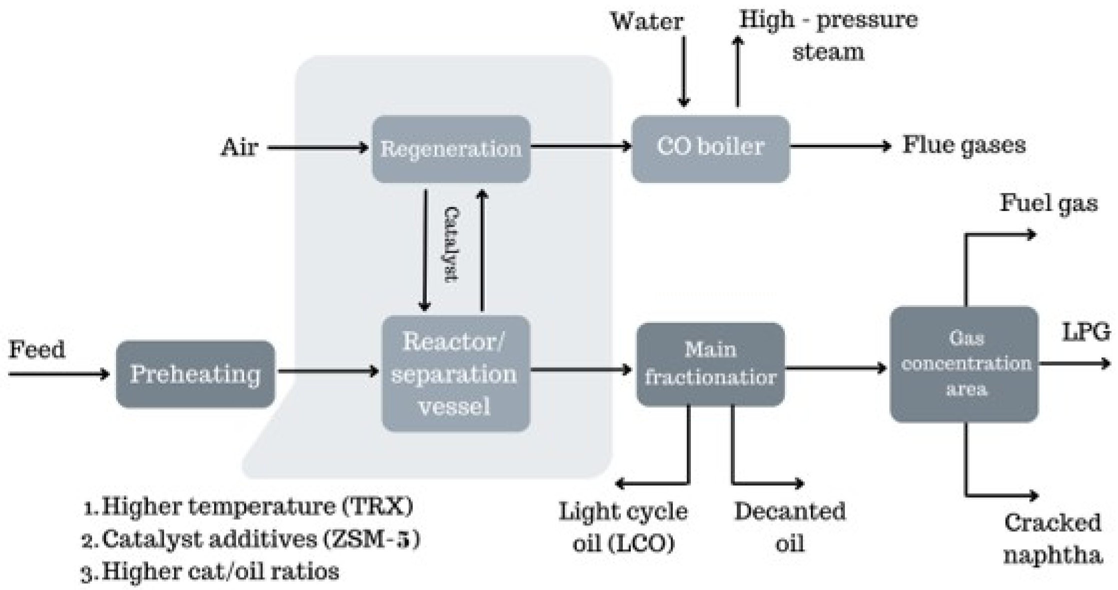


Figure 11 - Optimization of Process Variables in FCC Units to Improve the Yield of Petrochemicals Intermediates

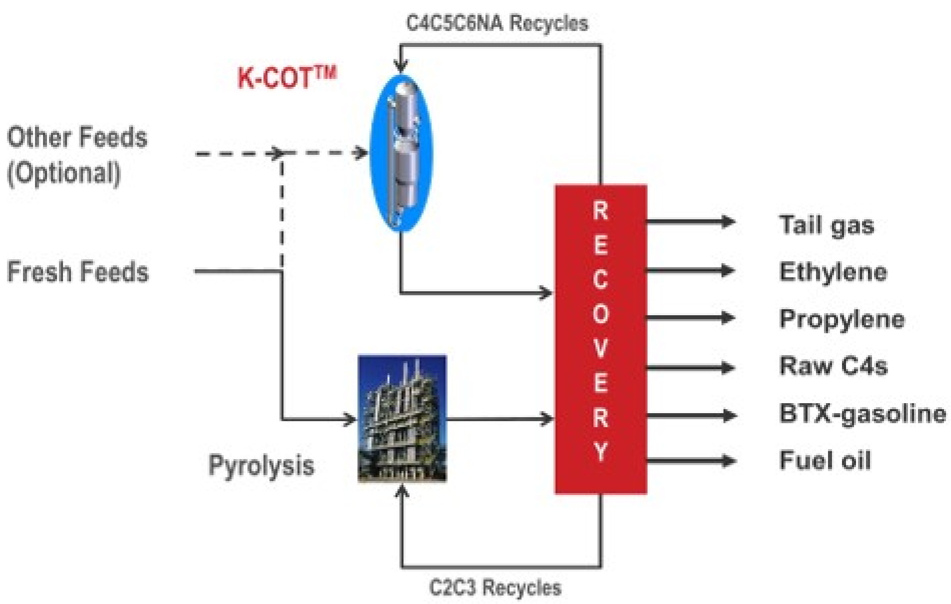


Figure 12 – Process Concept for the K-COT™ FCC Technology Developed by KBR Company (SINGH, 2018)

The FCC Catalyst – Making the Miracle Possible

A key factor in the FCC operation is the catalyst applied in the process. The catalyst normally employed in fluid catalytic cracking units is a solid constituted by small particles of alumina (Al2O3) and silica (SiO2) (zeolite). By the catalyst characteristics and the operational conditions in the catalytic cracking process (temperature higher than 500 oC), the process is inefficient to cracking aromatic compounds, therefore, how much more paraffinic is the feed stream, the higher is the unit conversion.

The active phase in the FCC catalyst is composed of the zeolite that is responsible by the catalytic activity and selectivity of the catalyst and by the alumina that is responsible by the cracking of heavier molecules allowing these molecules to reach the access to the zeolitic phase. The other components of the FCC catalysts are the inert (kaolim) and synthetic matrixes that are responsible to the mechanical resistance, hardness, and act as binder agent between the active phases and the matrix.

According to the process conditions, some compounds can be added to the catalyst with specific purpose. In refineries that process feed streams with high amount of nickel it's common to add antimony as that act as passivator agent, another deleterious metal is the vanadium, in this case is applied some trap agent to minimize his effects. Figure 13 presents an arrangement of a typical design of FCC catalyst.

As aforementioned, the processing of heavier crude oils leads to a more challenging feedstocks to FCC units due to the higher concentration of residual carbon and mainly contaminants such as Nickel and Vanadium. The nickel acts as dehydrogenation agent leading to the coke deposition over the catalyst and raises the hydrogen production, normally the refiners used to process heavier feeds apply metals passivators as boron to keep under control the deleterious effect of metals, the most common form to control the nickel effects is to inject Antimony in the FCC feed.

The vanadium effect over the FCC catalyst involves the degradation of the zeolite matrix leading to the reduction in the catalytic activity and his action is kept under control through vanadium traps. In the last years some catalyst developers are focusing his research to study the effects of iron in the FCC catalyst, the high concentration of iron is a characteristic of the shale oils produced in the North America and the availability of these crudes raises significantly in the last years, especially after 2015, when the United States starts to export his internal production. The iron is not catalytically active, but this compound can accumulate over the catalyst surface reducing the porosity reducing the activity and leading to dehydrogenation reactions as well as carbon monoxide (CO) promoter, furthermore the high concentration of Iron can raise the SOx emissions in the catalyst regenerator.

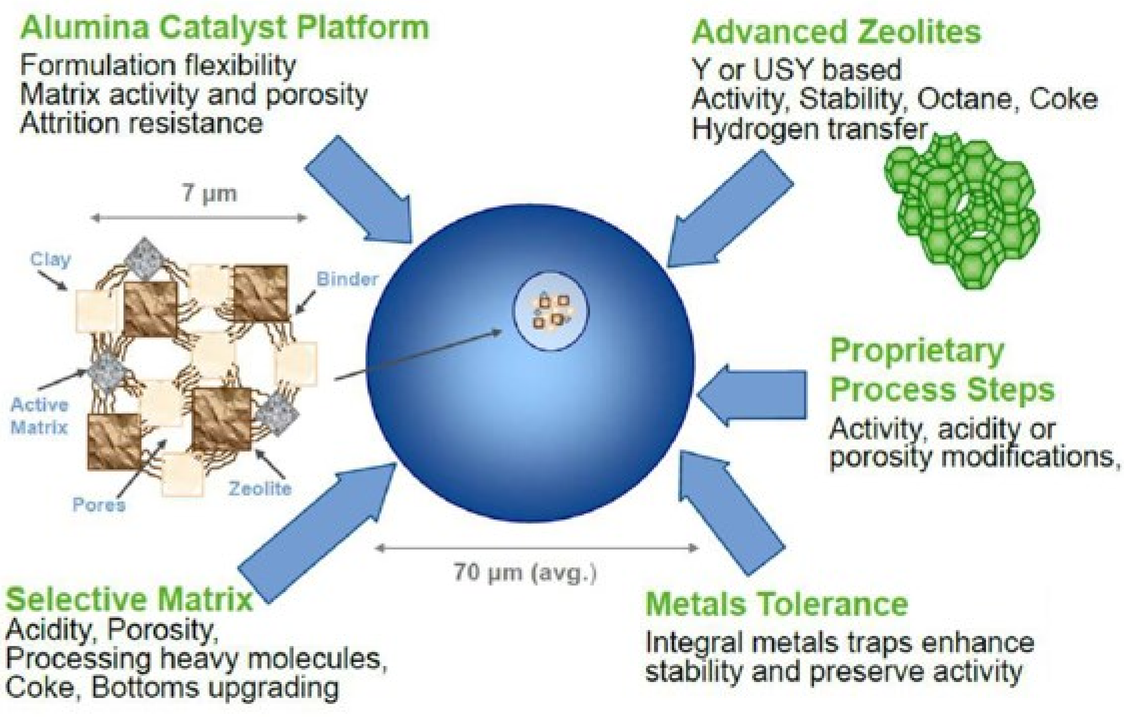


Figure 13 – Typical Design of FCC Catalyst (Grace Company, 2015)

Another dangerous contaminant of FCC catalyst is sodium, this compound promotes an irreversible deactivation of the catalyst through the chemical degradation of the zeolitic matrix. By this reason, an adequate control of the crude oil desalting process is fundamental to control the sodium content in the FCC feeds, preserving the catalyst lifecycle. Nowadays, some refiners are injected with caustic soda in the crude to improve the desalting characteristics, and stricter control is required in these cases. A less common contaminant found in some crude oils is copper, its effect is the promotion of dehydrogenation reactions, raising the yield of hydrogen and coke. The copper is present in some NOx reducing agents.

Aiming to improve catalytic activity, some developers apply rare earth compounds to the FCC catalyst such as Lanthanum and Cerium. These compounds raise significantly the activity and selectivity of the final catalyst, but his high cost made the refiners avoid his application, furthermore, the presence of rare earth in the catalyst improve yield of gasoline and reduces the light olefins production in FCC units, in the current scenario this is exactly the inverse that the refiners are looking for.

The trend of reduction in transportation fuels demand is making refiners optimize his FCC units to maximize petrochemical intermediates against transportation fuels. To achieve this goal, normally the refiners are applying the most severe conditions as higher catalyst/oil ratios, higher reaction temperature (TRX), and the use of ZSM-5 as additive to the catalyst.

The presence of ZSM-5 in the catalyst is capable to improve the yield of light olefins in the FCC unit by up to 8,0 %. One of the most important roles of the refinery's optimization teams is to analyze the FCC equilibrium catalysts to find the improvement alternatives based on the contaminants content and the reached conversion of the unit as well as the degradation observed on the equilibrium catalysts. The volumetric conversion of an FCC unit is defined as Equation (1).

(1) Volumetric Conversion (%) = [Feed – (LCO + Decanted Oil)]/ Feed x 100

The fraction LCO and Decanted Oil (DO) is considered non converted fractions.

The main FCC catalyst developers present in the market nowadays are BASF Catalysts Company, Albermarle, and W. R. Grace Company.

Propylene Recovery Section

The growing demand by petrochemicals lead some refiners to install propylene recovery units aiming to allow the maximization of light olefins yield in his refining hardware. Among the light olefins, the propylene is one of the most relevant petrochemical intermediate due to the high demand and added value.

The propylene can be applied as intermediate to the production of some fundamental products, for example:

- Acrylonitrile;
- Propylene Oxide;
- Cumene;
- Acrylic Acid;
- Polypropylene;

Propylene can be produced through conventional processes like Steam Cracking and Fluid Catalytic Cracking (FCC) or through directed processes like metathesis of ethylene and butane, propane dehydrogenation, olefins cracking, Methanol to Olefins processes (MTO), among others. Currently a major part of the propylene market is supplied by steam cracking units, but close to 28 % of the global propylene demand is from the separation of LPG produced in Fluid Catalytic Cracking Units (FCC).

Normally, the LPG produced in FCC units contains close to 30 % of propylene and the added value of the propylene is close to 2,5 times of the LPG. According to the local market, the installation of propylene separation units presents an attractive return over investment. Despite the advantage, a side effect of the propylene separation from LPG is that the fuel stays heavier leading to specifications issues, mainly in colder regions, in these cases alternatives are to segregate the butanes and send this stream to gasoline pool, add propane to the LPG or add LPG from natural gas. It's important to consider that some of these alternatives reduce the LPG offer, which can be a severe restriction according to the market demand.

A great challenge in the propylene production process is the propane and propylene separation step. The separation is generally hard by simple distillation because the relative volatility between propylene and propane is close to 1.1. This fact generally leads to distillation columns with many equilibrium stages and high internal reflux flow rates.

There are two technologies normally employed in propylene-propane separation towers that are known as Heat-Pump and High-Pressure configurations.

The high-pressure technology applies a traditional separation process that uses a condenser with cooling water to promotes the condensation of top products, in this case, it's necessary to apply sufficient pressure to promote the condensation of products in the ambient temperature. Furthermore, the reboiler uses steam or another available hot source. The adoption of high-pressure separation route requires a great availability of low-pressure steam in the refining hardware, in some cases this can be a restrictive characteristic and the heat pump configuration is more attractive, despite the higher capital requirements.

The application of heat pump technology allows decrease the operating pressure by close of 20 bar to 10 bar, this fact increases the relative volatility propylene-propane, making the separation process easier and, consequently, reducing the number of equilibrium stages and internal reflux flow rate required for the separation.

Normally, when the separation process by distillation is hard (with relative volatilities lower than 1.5) the uses of heat pump technology are more attractive.

Furthermore, some variables need to be considered during the choice of the best technology for the propylene separation process like availability of utilities, temperature gap in the column and installation cost.

Normally, the propylene is produced in the refineries with specifications. The polymer grade that is most common and has higher added value with a purity of 99,5 % (minimum) this grade is directed to polypropylene market. The chemical grade where the purity varies between 90 to 95% is normally directed to other uses. A complete process flow diagram for a typical propylene separation unit applying heat pump configuration is presented in Figure 14.

The LPG from FCC unit is pumped to a depropanizer column where the light fraction (essentially a mixture of propane and propylene) is recovered in the top of the column and sent to a deethanizer column while the bottom (butanes) is pumped to LPG or gasoline pool, according to the refining configuration. The top stream of the deethanizer column (lighter fraction) is sent back to FCC where is incorporated to refinery fuel gas pool, or in some cases can be directed to petrochemical plants to recover the light olefins (mainly ethylene) present in the stream while the bottom of the deethanizer column is pumped to the C3 splitter column, where the separation of propane x propylene is carried out. The propane recovered at the bottom of the C3 splitter is sent to LPG pool where the propylene is sent to propylene storage park. The feed stream passes through a caustic wash treating aiming to remove some contaminants that can lead to deleterious effects to petrochemical processes, an example is the carbonyl sulfide (COS) that can be produced in the FCC (through the reaction between CO and S in the Riser).

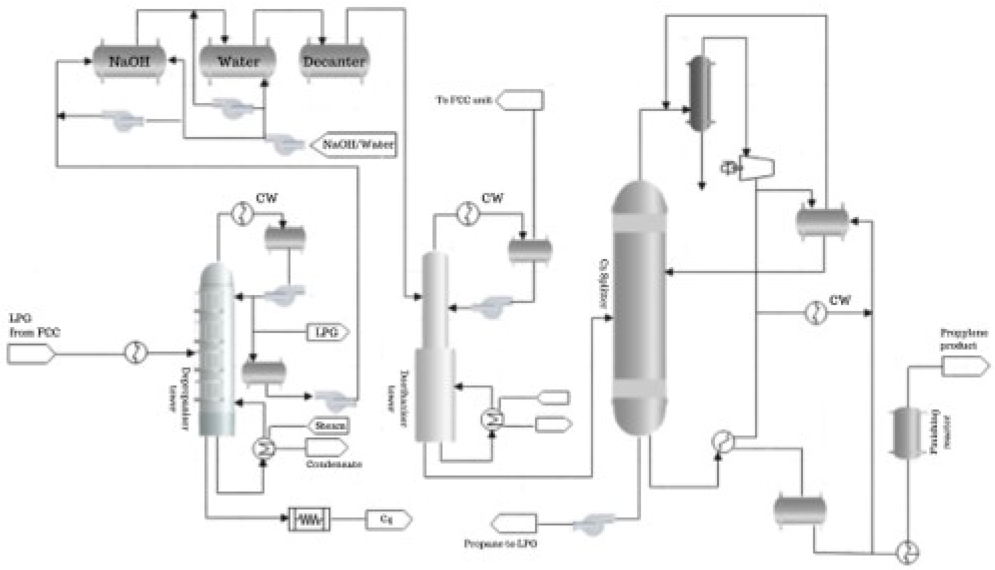


Figure 14 – Typical Process Flow Diagram for an FCC Propylene Separation Unit Applying Heat Pump Configuration

Integrated Refining Schemes – Closer Integration with Petrochemical Assets

Historically, the refining industry growth was sustained and focused on transportation fuels, this can explain the profile of the traditional refining schemes shown above. Nowadays, the downstream industry is facing a trend of reduction in transportation fuels demand, followed by a growing demand for petrochemicals. This fact is the main driving force to promote the change of focus in downstream industry.

The growing market of petrochemicals has led some refiners to look for a closer integration between refining and petrochemicals assets aiming to reach more adherence with the market demand, improve revenues, and reduce operation costs. To reach this goal, the refiners are implementing the most integrated refining schemes as presented in Figure 15.

As presented in Figure 15, the integrated refining scheme relies on flexible refining technologies such as catalytic reforming and fluid catalytic cracking (FCC) that are capable to reach the production of high-quality petrochemicals and transportation fuels, according to the market demand. Another significant characteristic of the integrated refining schemes is the strong synergy between deep conversion technologies like hydrogracking and fluid catalytic cracking units and processing units capable of producing high added value petrochemicals like steam cracking and catalytic reforming units.

A more integrated refining configuration allows the maximization of petrochemicals, raising the refining margins and ensuring higher value addition to the processed crude oils. Another fundamental competitive advantage is the operational flexibility reached through the integrated refining configurations, allowing the processing of discounted and cheaper crude oils, raising even more the refining margins.

The Role of Petrochemical FCC Technologies in the Crude Oil to Chemicals Strategy

Due to the increasing market and higher added value as well as the trend of reduction in transportation fuels demand, some refiners and technology developers has dedicated his efforts to develop crude to chemicals refining assets. One of the big players that have been invested in this alternative is the Saudi Aramco Company, the concept is based on the direct conversion of crude oil to petrochemical intermediates as presented in Figure 16.

The process presented in Figure 16 is based on the quality of crude oil and deep conversion technologies like High Severity or petrochemical FCC units and deep hydrocracking technologies. The processed crude oil is light with low residual carbon that is a common characteristic in the Middle East crude oils, the processing scheme involves deep

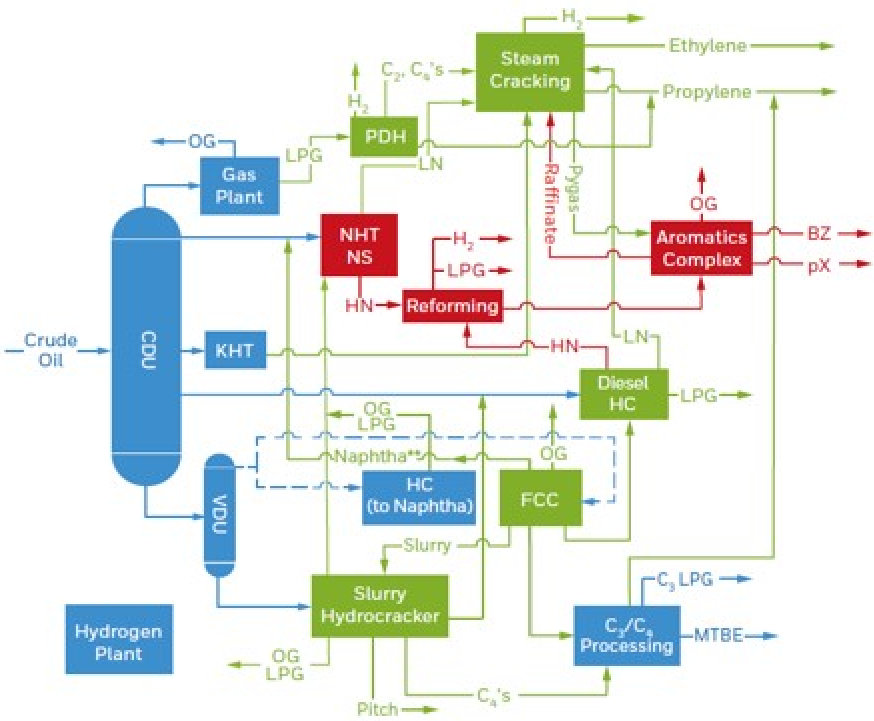


Figure 15 – Example of an Integrated Refining Focusing on Petrochemicals Scheme by UOP Company

catalytic conversion aiming to reach maximum conversion to light olefins. In this refining configuration, the petrochemical FCC units have a key role to ensure high added value to the processed crude oil.

Figure 17 presents a comparison between the petrochemicals yields of traditional refineries, a benchmark integrated refinery and Hengli crude to chemicals complex, according to data from IHS markit.

Analyzing Figure 17 it's possible to note the higher added value reached in crude to chemicals refineries when compared even with highly integrated refineries.

As aforementioned, face the current trend of reduction in transportation fuels demand at the global level, the capacity of maximum adding value to crude oil can be a competitive years. differential to refiners. Due to the high capital investment needed for the implementation that allows the conventional refinery to achieve the maximization of chemicals, capital efficiency becomes also an extremely important factor in the current competitive scenario as well as the operational flexibility related to the processed crude oil slate.

As described above, the fluid catalytic cracking units can ensure operational flexibility and higher refining margins for the downstream players under the challengeful scenario imposed on fossil fuels and is expected to grow investments in FCC installations for the next years. Based on data from GlobalData Company, the global installed fluid catalytic cracking capacity will rise from 14,4 million barrels per day (MMbpd) in 2022 to

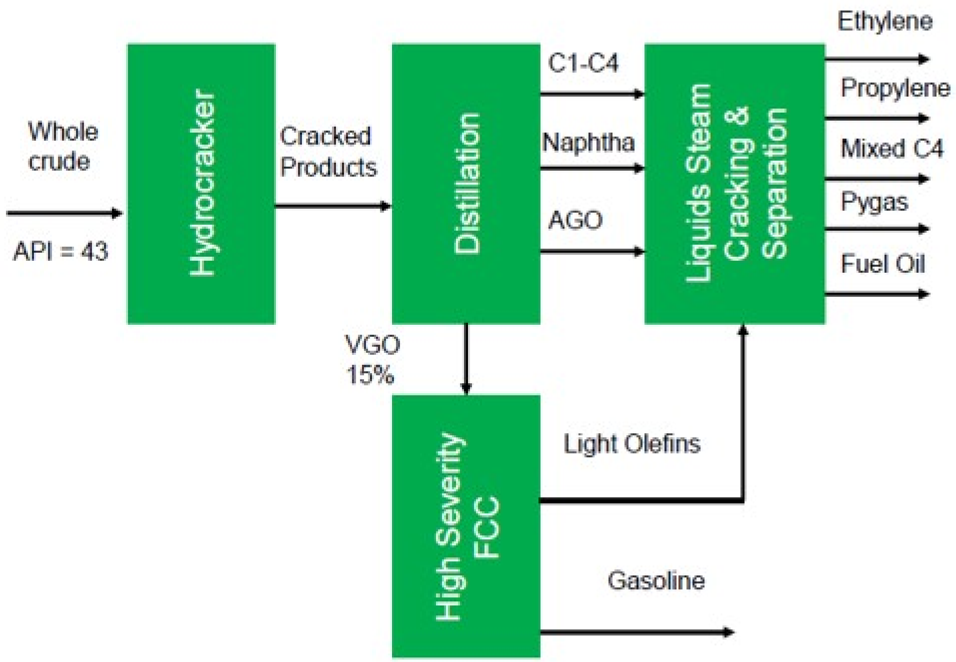


Figure 16 – Saudi Aramco Crude Oil to Chemicals Concept (IHS Markit, 2017)

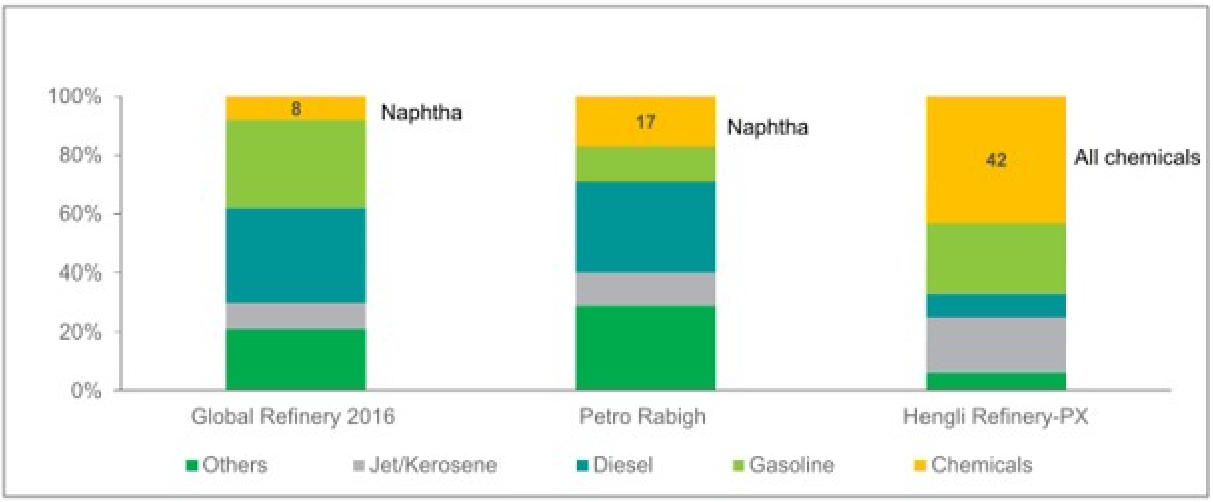


Figure 17 – Petrochemicals Yield Comparison (IHS Markit, 2018)

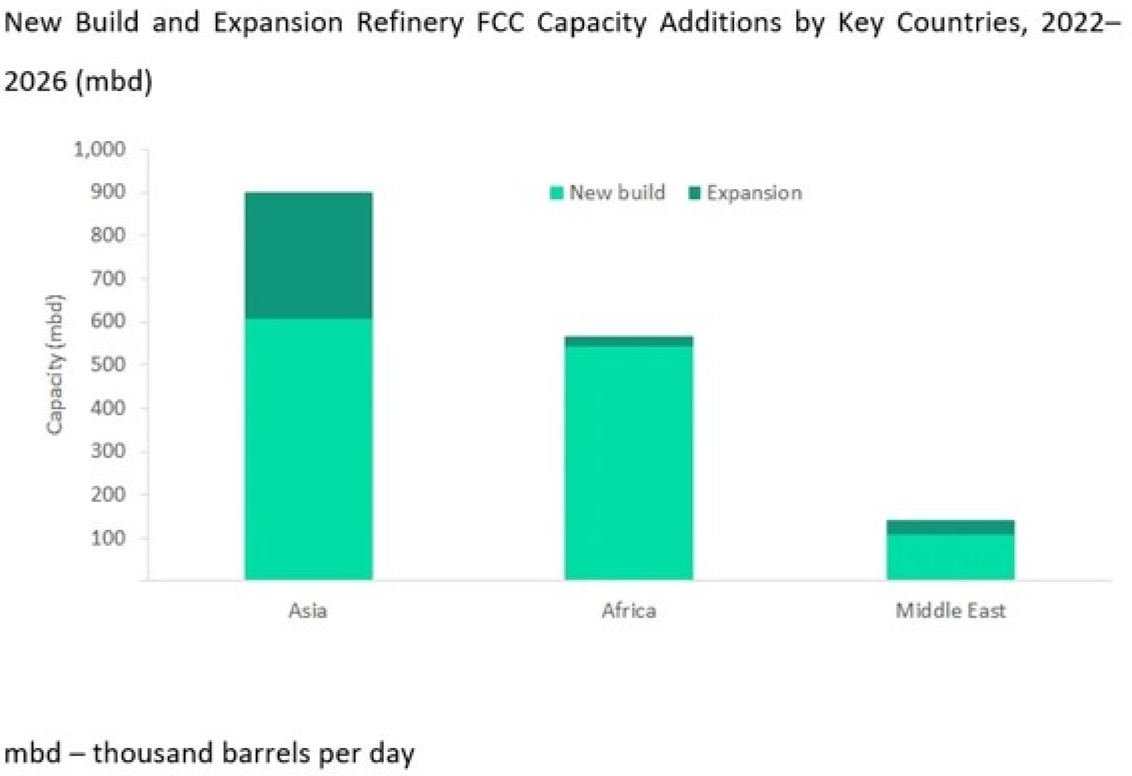


Figure 18 – Growth of Global FCC Installed Capacity 2022 to 2026 (GlobalData Company, 2022)

15,8 MMbpd in 2026, a growth of 9,3 % in four years. Figure 18 presents an overview of the growth of FCC installed capacity for the next years.

As expected, the growth of FCC capacity will lead by the Asian players which presents highest integration capacity among the downstream players and have been investing heavily to maximize the petrochemicals yield in their refining assets, including crude to chemicals refineries. The Asian players will add close to 900 thousand barrels per day (Mbd) to the global FCC processing capacity until 2026 followed by the African players, which have been invested in FCC as part of their strategy to reduce the external dependence from high quality gasoline, in other words, differently of Asian players the addition of global FCC capacity produced by African players tends to be related to conventional and low severity FCC units with the gasoline production focus especially leaded by the new Dangote refinery in Nigeria, the Africans players will add close to 570 Mbd to the global FCC processing capacity until 2026.

Although the advantages presented by closer integration between refining and petrochemical assets, it's important to understand that the players of downstream industry are facing a transitive period where, as presented in Figure 1, the transportation fuels are responsible for a great part of the revenues. In this business scenario, it's necessary to define a transition strategy where the economic sustainability achieved by the status (transportation fuels) needs to be invested to build the future (maximize petrochemicals). Keeping the eyes only in the future or only in the present can be a competitive mistake.

Closing the Sustainability Cycle – Plastics Recycling Technologies

As described above, we are facing a continuous growth of petrochemicals demand, and a great part of these crude oil derivatives have been applied to produce common use plastics. Despite the higher added value and significant economic advantages in comparison with transportation fuels, the main side effect of the growth of plastics consumption is the growth of plastic waste.

Despite the efforts related to the mechanic recycling of plastics, the increasing volumes of plastics waste demand most effective recycling routes to ensure the sustainability of the petrochemical industry through the regeneration of the raw material, in this sense, some technology developers have been dedicated investments and efforts to develop competitive and efficient chemical recycling technologies of plastics.

One of the most applied technologies for plastics recycling is in the catalytic pyrolysis where the long chain polymeric are converted into smaller hydrocarbon molecules which can be fed to steam cracking units to reach a real circular petrochemical industry. Another route is the thermal pyrolysis of plastics, is this case, it's possible to quote the Rewind™ Mix technology developed by Axens Company.

Another promising chemical recycling route for plastics in the hydrocracking of plastics waste, in this case the chemical principle involves the cracking of carbon-carbon bonds of the polymer under high hydrogen pressure which lead to the production of stable low boiling point hydrocarbons. The hydrocracking route presents some advantages in comparison with thermal or catalytic pyrolysis, since the number of aromatic or unsaturated molecules is lower than the achieved in the pyrolysis processes, leading to a most stable feedstock to steam cracking or another downstream processes as well as is more selective, producing gasoline range hydrocarbons which can be easily applied in the highly integrated refining hardware.

The chemical recycling of plastics is a great opportunity for technology developers and scientists, especially related to the development of effective catalysts to promote depolymerization reactions which can ensure the recovery of high added value molecules like BTX. More than that, the chemical recycling of plastics is an urgent necessity to close the sustainability cycle of an essential industry to our society.

Conclusion

The synergy between refining and petrochemical processes raises the availability of raw material to petrochemical plants and makes the supply of energy to these processes more reliable at the same time ensures better refining margin to refiners due to the high added value of petrochemical intermediates when compared with transportation fuels. Another advantage is the reduction of risks of transportation fuels oversupply, facing the current scenario of demand reduction and restriction of fossil fuels. It's important to consider that integrated processes lead to higher operational complexity, however, given current and middle term scenarios to the refining industry, better integration between refining and petrochemical processes is fundamental to the economic sustainability of the downstream industry. In this scenario, Petrochemical FCC units can ensure a significant competitive advantage to refiners inserted in markets with high demand by petrochemicals, despite the higher capital spending in comparison with conventional FCC units. Again, it's important to understand the transitive period faced by the downstream industry and maintain competitive operations with the current focus in transportation fuels while the transition to petrochemicals is prepared in a sustainable manner aiming to keep economic sustainability and competitiveness in the downstream market.

As presented above, the FCC technologies have a fundamental role in the new downstream industry and is expected capital investment from refiners in the next years to revamp their FCC units to maximize olefins as well as to install petrochemical FCC units to achieve higher level of petrochemical yield in the refining hardware, especially in the Asian market with present a more integrated refining park and higher demand of petrochemical intermediates. In summary, we can say that the petrochemical FCC is a relevant competitive advantage in the current scenario of the downstream industry and are expected to invest in capital investments to install new units or revamp the existing FCC units to ensure higher added value to the processed crude through petrochemicals maximization.

References

Advances in Catalysis for Plastic Conversion to Hydrocarbons – The Catalyst Group (TCGR), 2021.

CHANG, R.J. – Crude Oil to Chemicals – Industry Developments and Strategic Implications – Presented at Global Refining & Petrochemicals Congress (Houston, USA), 2018.

GARY, J. H.; HANDWERK, G. E. Petroleum Refining – Technology and Economics.4th ed. Marcel Dekker., 2001.

Global Capacity and Capital Expenditure Outlook for Refineries – Global Data Company, 2022.

LAMBERT, N.; OGASAWARA, I.; ABBA, I.; REDHWI, H.; SANTNER, C. HS-FCC for Propylene: Concept to Commercial Operation. PTQ Magazine, 2014.

MALLER, A.; GBORDZOE, E. High Severity Fluidized Catalytic Cracking (HS-FCC™): From concept to commercialization – Technip Stone & Webster Technical Presentation to REFCOMM™, 2016.

Refinery-Petrochemical Integration (Downstream SME Knowledge Share). Wood Mackenzie Presentation, 2019.

ROBINSON, P.R.; HSU, C.S. Handbook of Petroleum Technology. 1st ed. Springer, 2017.

SALGADO, H. Controlling the metals content of FCC equilibrium catalyst. PTQ Magazine, Q3 2018.

SARIN, A.K. – Integrating Refinery with Petrochemicals: Advanced Technological Solutions for Synergy and Improved Profitability – Presented at Global Refining & Petrochemicals Congress (Mumbai, India), 2017.

SILVA, M. W. – More Petrochemicals with Less Capital Spending. PTQ Magazine, 2020.

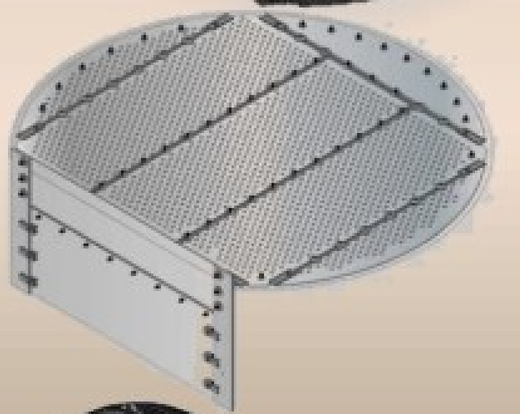
SINGH, V.P. – KBR Olefins Technology Solutions- The Key is Flexibility. Technical Presentation KBR Company, 2018.

TALLMAN, M. J.; ENG, C.; SUN, C.; PARK, D. S. - Naphtha Cracking for Light Olefins Production. PTQ Magazine, 2010.

ZHANG, Z. Crude oil to chemicals: Challenges and Opportunities in a Sustainable World - Wood Company Presentation at METECH 2024, 2024.

Author

Dr. Marcio Wagner da Silva is Process Engineering Manager at a crude oil refinery based in São José dos Campos, Brazil. Bachelor's in chemical engineering from University of Maringa (UEM), Brazil and PhD. in Chemical Engineering from University of Campinas (UNICAMP), Brazil. Has extensive experience in research, design and construction to oil and gas industry including developing and coordinating projects to operational improvements and debottlenecking to bottom barrel units, moreover Dr. Marcio Wagner have MBA in Project Management from Federal University of Rio de Janeiro (UFRJ), in Digital Transformation at PUC/RS, and is certified in Business from Getulio Vargas Foundation (FGV).



SIL Verification for High Integrity Pressure Protection System

Jayanthi Vijay Sarathy

Flammable and toxic gas release to the flare during an unplanned event is not uncommon in process industries. However, flaring can be minimized since the inventory is commercially valuable. Towards this, safety instrumented systems (SIS) such as a High Integrity Pressure Protection system (HIPPS) can be installed which shuts off the source of the high-pressure gas rather than release it and burnt off at the flare. This way the HIPPS system acts as a risk reduction measure rather than risk mitigation measure.

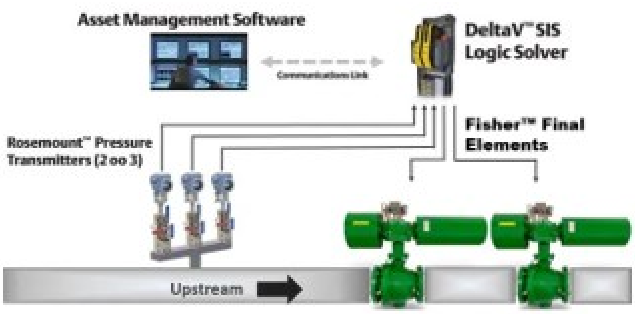


Figure 1. HIPPS Schematic [1]

A typical HIPPS System consists of three pressure sensors which follows a 2oo3 voting philosophy to detect the over pressure in the line, a logic solver which processes the sensor signals, and transmits it to the solenoid valve and an actuated shutdown valve (acting as the final element) which shuts down the line in the event of an over pressure.

Pressure vessels that operate above atmospheric conditions of 15 psig are designed as per Code ASME Section VIII Division 1 and to cover matters of overpressure protection, UG-125 to UG 140 of the said code provides basic requirements. The ASME UG-140 requirements and procedures are commonly known as Code Case 2211. Additionally, SIS systems need to comply with international codes such as IEC 61508, IEC 61511, API 520 / 521 / 526. SIS systems also need to be independently verified and certified to meet Safety Integrity Level (SIL) ratings.

The following article demonstrates a SIL verification study for HIPPS system using one of the various verification methods to estimate the PFD_{avg}.

General Notes

1. In the hierarchy of process safety protection layers, an SIS begins to function, after the Basic process control system (BCPS), Alarms & Operator intervention, fail. An SIS moves the process from a state of risk to a safe state through a Safety Instrumented function (SIF). To measure the effectiveness of a SIF, it is quantified using SIL rating. A given SIS can have multiple SIFs also. To arrive at the SIL rating, it is based on the average probability of failure on low demand (PFD_{avg}).
2. The recommended standard for HIPPS is either a SIL 3 or SIL 4, based on the risk reduction factor (RRF) and the PFD_{avg} on Low Demand (shown in below table). If the failure is expected to be more frequent, the probability of failure on High demand (PFH_{avg}) is used.

Table 1. RRF and PFD for SIL Rating

SIL Rating	RRF	PFDavg	PFHavg
1	100 to 10	$\geq 10^{-2}$ to $<10^{-1}$	$\geq 10^{-9}$ to $<10^{-8}$
2	1000 to 100	$\geq 10^{-3}$ to $<10^{-2}$	$\geq 10^{-8}$ to $<10^{-7}$
3	10,000 to 1000	$\geq 10^{-4}$ to $<10^{-3}$	$\geq 10^{-7}$ to $<10^{-6}$
4	100,000 to 10,000	$\geq 10^{-5}$ to $<10^{-4}$	$\geq 10^{-6}$ to $<10^{-5}$

The procedure to perform a SIL verification study consists of A) Identifying SIL capability printed on the certificate of the component B) Calculate PFD_{avg} for the sensor, logic solver, final element and sum them up C) Check the architectural constraints of the subsystems.

4. The hardware fault tolerance (HFT) can be defined as the maximum number of hardware failures that can be tolerated by the SIS. It can be computed as (N-M) in the "MooN" voting philosophy, where M is the number of sensors getting activated out of the N number of sensors. Applying this to some common voting philosophies, we get

Table 2. HFT for various voting configurations

System [MooN]	HFT [M-N]
1oo1	0
1oo2	1
1oo3	2
2oo2	0
2oo3	1

From the HFT table, it is seen that a 1oo2 voting configuration can tolerate 1 hardware fault, but a 1oo1 voting configuration has zero hardware fault tolerance [HFT]. Failures can be systematic or random failures.

5. The Safe failure fraction (SFF) can be defined as the fraction of all failures that are safe. However, the term SFF has to be elaborated further to consider which types of failures can be considered to be safe. To expound, the failure rate is expressed as 'l', and its units as 1/ hr. The failure rate can be further classified based on the diagnostics of the fault, i.e., Safe, dangerous, detected and undetected failure, i.e.,

l_{DD} = Dangerous / Detected

l_{DU} = Dangerous / Undetected

l_{SU} = Safe / Undetected

l_{SD} = Safe / Detected

Of the 4 classifications, l_{DU} is considered to be the worst failure since the fault can render a dangerous hazard which is not detected. All the other three, l_{DU}, l_{SU}, l_{SD} though are not desirable, but can be either detected to be fixed or allows the component to continue functioning safely. The SFF is calculated as,

$$SFF = \frac{\lambda_{DD}+\lambda_{SD}+\lambda_{SU}}{\lambda_{DD}+\lambda_{DU}+\lambda_{SU}+\lambda_{SD}} \quad (1)$$

6. Further to SFF, as per IEC 61508, a component can be either Type A or Type B. Type A are components with well-defined failure modes, well known failure rates, and behaviour under fault conditions that can be completely determined. Whereas Type B are components which do not have well defined failure modes and sufficient field data is not available to classify the failure rates. Microprocessors used in the safety function can be termed as Type B. Based on SFF and HFT, the target SIL rating [Route 1H] can be determined from table 3

Table 3. Target SIL [IEC 61508, Route 1H]

	Type A			Type B		
SFF	HFT=0	HFT=1	HFT=2	HFT=0	HFT=1	HFT=2
< 60%	SIL 1	SIL 2	SIL 3	N.A.	SIL 1	SIL 2
60% to < 90%	SIL 2	SIL 3	SIL 4	SIL 1	SIL 2	SIL 3
90% to < 99%	SIL 3	SIL 4	SIL 4	SIL 2	SIL 3	SIL 4
> 99%	SIL 3	SIL 4	SIL 4	SIL 3	SIL 4	SIL 4

7. To perform a SIL verification study, the integrity of the SIL safeguard is compared with the required level of SIL integrity. To estimate the PFD_{avg}, the mathematical modelling includes,

    A. Reliability Block Diagrams [RBD]

    B. Cause Consequence Analysis [CCA]

    C. Fault Tree Analysis [FTA]

    D. Markov Models

    E. Petri nets models

   The choice of modelling depends on the prevailing circumstances and is up to the analyst to choose the appropriate method.

8. The PFD_{avg} calculated depends on,

    A. Dangerous detected and undetected failure rates [l_{DD}, l_{DU}]

    B. Redundancy configuration [e.g., 1oo2]

    C. Common cause b-factor

    D. Proof Test interval

    E. Lifetime of SIF

    F. Mean time to restore [MTTR]

    G. Proof Test Coverage

9. The dangerous undetected [l_{DU}] type of failure plays a significant role in estimating PFD_{avg} calculations, while the dangerous detected type of failure [l_{DD}] although can alter the PFD_{avg}, but is omitted since its impact is very small. The rate of dangerous undetected failure can be expressed in FIT, where 1 FIT = 1 × 10^{9}. Therefore if l_{DU} = 7 × 10^{-7}, then it is expressed as 700 FIT.

10. The common cause of failure is quantified by the b-factor, which represents the fraction of failure where two or more failures will occur due to a common cause. Typical values of b-factor are 5% for the sensor, 2% for the logic solver and 10% for the final element.

11. Proof test interval [T_i] relates to how often tests are carried out to check for system integrity and is directly tied to the plant maintenance schedules. Each SIF subsystem can have different proof testing frequency. For e.g., sensors can have proof testing between 1 to 4 years, logic solvers tested between 2 to 5 years and final element can be tested between 1 to 2 years.

12. Lifetime of SIF [LT] represents the total duration, a particular SIF would remain in service. This should not be confused with how long a SIF functions before failing. LT can vary between 10 to 20 years.

13. Mean Time to Restore [MTTR] represents the sum of mean detection time [MDT] of a dangerous failure and the mean repair time [MRT]. Typical values of MDT and MRT are 8 hours and 72 hours respectively.

14. Proof Test Coverage [PTC] quantifies what percentage of dangerous undetected failures were able to be detected during proof testing. A PTC of 100% indicates all dangerous undetected failures were discovered. However, this is not always the case. Therefore, for sensor and logic solvers, PTC range would be typically between 90% and 95%, while final elements would have a PTC range between 70% and 90%, depending on the type of proof testing performed.

15. The PFD_{avg} depending on the voting / redundancy configuration and common cause failure as per IEC 61508-6:2010, can be computed as follows,

$$PFD_{avg}(1oo1) = \frac{PTC \times \lambda_{DU} \times T_i}{2} + \frac{[1-PTC] \times \lambda_{DU} \times T_i}{2} + [\lambda_{DD} \times MTTR_{DD}] \quad (2)$$

$$PFD_{avg}(1oo2) = \frac{[[1-\beta] \times PTC \times \lambda_{DU} \times T_i]^2}{3} + \frac{[[1-\beta] \times [1-PTC] \times \lambda_{DU} \times LT]^2}{3} + \left|\frac{\beta \times PTC \times \lambda_{DU} \times T_i}{2}\right| + \frac{[\beta \times [1-PTC] \times \lambda_{DU} \times LT]}{2} \quad (3)$$

$$PFD_{avg}(2oo3) = [[1-\beta] \times PTC \times \lambda_{DU} \times T_i]^2 + [[1-\beta] \times [1-PTC] \times \lambda_{DU} \times LT]^2 + \left|\frac{\beta \times PTC \times \lambda_{DU} \times T_i}{2}\right| + \frac{[\beta \times [1-PTC] \times \lambda_{DU} \times LT]}{2} \quad (4)$$

16. The risk reduction factor (RRF) is estimated as a reciprocal of the PFD_{avg}, i.e.,

$$RRF = \frac{1}{PFD_{avg}} \quad (5)$$

17. When applying the b-factor to account for common cause failure, IEC 61508:2010, table D-5 suggests modifying the b-factor by a factor depending on the redundancy.

Table 4. β Correction factors

MooN		N		
		2	3	4
M	1	β	0.5 x β	0.3 x β
	2	-	1.5 x β	0.6 x β
	3	-	-	1.75 x β

18. Systematic capability (SC) is a measure of confidence that the systematic safety integrity meets the specified SIL requirements, i.e., Systematic capability acts as a defence against systematic failures or errors due to quality, design, processes and procedures. A systematic capability of SC 2 would mean the product meets the requirements of SIL 1 as well as SIL 2.

An example is, when a manufacturer issues a product with an IEC 61508 certificate for the product with a systematic capability of SC 3, it indicates the product is SIL 3 capable under the condition that the PFDavg and architectural constraints are verified for each application, the product is used for. The certificate will also include random capability with details such as whether the device is Type A or Type B and if Route 1H or 2H. When checking for systematic capability of the entire assembly, say the sensor and the logic solver are certified to SC 3, but the final element is proven to be only upto SIL 2, then the overall SIL to qualify per systematic capability is allowed only upto SIL 2.

19. Route 1H refers to failure rates determined by lab testing, whereas Route 2H is based on failure rates determined by actual field data, which is obtained from suppliers who have received validation from independent global safety certification sources. Route 1H exhibits upto 70% confidence levels, whereas Route 2H exhibits confidence levels upto 90%, i.e., 90% certainty that the predicted failures will occur as expected.

Route 1H uses the SFF and HFT table (Type A and B) to determine the SIL rating, whereas Route 2H avoids using SFF, but instead uses the HFT for determining SIL rating. For programmable systems and complex devices with diagnostic facilities, Route 1H can be used, while for simple mechanical devices like valves and final elements, Route 2H can be used. For Route 2H, the HFT requirements as per IEC61508,

Table 5. Route 2H HFT Requirements

SIL	Mode	Min. HFT
1	Low/High/Continuous	0
2	Low Demand	0
3	Low/High/Continuous	1
4	Low/High/Continuous	2

Case Study

A HIPPS System consisting of shutdown valves with actuator, pressure transmitters with interlocking manifold, field mounted control panel, a solid-state logic solver in the HIPPS cabinet, and a fibre optic link in the HIPPS cabinet connecting to the instrument equipment room, is to be installed at a gas gathering station. The HIPPS system located upstream of the pipeline pig launcher, upon detecting a pressure rise in the line, over and above a predetermined set point, initiates a shutdown of the ESDV. The subcomponents of the SIS have been certified individually by the vendor for their SIL compatibility and systematic capability (SC).

The systematic capability as per manufacturer's certificate for the pressure transmitters, logic solver, SDV SOV and actuator is certified to SC 3 (SIL 3 capable) for HFT = 1. The pressure transmitter (sensor) and generic PLC (logic solver) are identified as Type B devices following Route 1H to determine SIL capability. The SDV, SOV and SDV actuator are identified as Type A devices following Route 2H to determine SIL capability. The case considered for this article is the SIF is operating on low demand.

To perform a SIL verification study, the architectural compatibility and PFD_{avg} of all the components with the dangerous-undetected failure rate $[\lambda_{DU}]$ needs to be estimated.

The failure rates of the components from various manufacturers are as follows,

Table 6. Failure Rates

Component	Failure rate [λ] [1/hr]			
	λ_{DD}	λ_{DU}	λ_{SD}	λ_{SU}
Pressure Transmitters [PT]	0	4.40E-08	3.01E-07	1.74E-07
Generic PLC	3.97E-06	2.50E-07	1.19E-05	1.36E-07
Shutdown Valve [SDV]	8.74E-08	8.95E-08	1.81E-08	9.74E-10
3 Way Solenoid Valve [SOV]	1.43E-07	2.00E-09	0	3.36E-07
SDV Actuator	0	4.95E-08	0	8.86E-08

In the above table,

- Pressure Transmitter is the Sensor
- Generic PLC is the logic Solver
- SDV + SOV + Actuator is the final element

The proof test details are as follows,

Table 7. Proof Test Details

Component	Op hours per year	Life Time [LT]	Proof Test Interval [T_i]	Proof Test Coverage [PTC]	Mean Time to Restore [$MTTR_{DD}$]	β-Factor
	[hrs]	[years]	[years]	[%]	[hours]	[%]
Sensor	8760	20	3	90	72	5
Logic Solver	8760	20	5	90	72	2
Final Element	8760	20	1	70	72	10

Assumptions

Prior to verifying the SIL ratings, the following assumptions are made.

1. Failure rates [l] are assumed to be constant during the usable life of the subcomponents.
2. Non-interfering components such as communication module, fuse module, bypass module, etc are not included in the verifications, since they do not impact the performance of SIS.
3. The total number of operational hours of all the components in a single year is 8,760 hrs.
4. The Lifetime of the facility is 20 years. The b-factor is 5% for the sensor, 2% for the logic solver and 10% for the final element.

Methodology

To verify the SIL rating, the steps taken are,

1. The SFF for Type B components is estimated first, followed by considering the architectural constraints (HFT) of each subsystem to meet the target SIL. The failure rate and type (A/B) of each component is compared with Table 3 for the target SIL with a HFT of 0. If the type and SFF indicate the target SIL is achieved, then no redundancy for that element is required. If it is not achieved, then redundancy of the element will be needed (HFT = 1 or 2 columns apply).
2. The systematic compatibility is then checked for each component, to see if it is atleast the same as that of the target SIL. If this cannot be achieved, then revisit the redundancy again to ensure SC does not suffer from common cause failure.
3. PFD_{avg} estimation of individual subsystems (sensor, logic solver and final element) using RBD method and adding them.
4. Assign overall / Total SIL compatibility rating for the HIPPS assembly based on systematic capability (SC), architectural constraints and PFD_{avg}.

From the inputs available, the SFF can be calculated based on Eq. 1 as,

For the pressure transmitter [sensor],

$$SFF = \frac{0+3.01\times10^{-7}+1.74\times10^{-7}}{0+4.4\times10^{-8}+3.01\times10^{-7}+1.74\times10^{-7}} = 91\% \qquad (6)$$

Performing similar SFF calculations for other components, and taking HFT = 0 and 1, the architectural constraints are retrieved from Table 3 for the sensor and logic solver [Type B]. For Type A components [SDV+SOV+Actuator], based on Route 2H [Table 5], the SIL rating is taken for HFT = 1, (manufacturer's data). This is summarized as,

Table 8. Calculated SFF and SIL Rating

Component	SFF [%] [For Route 1H]	Type B [Route 1H]		Type A [Route 2H]	
		HFT = 0	HFT = 1	HFT = 0	HFT = 1
Pressure Transmitters [PT]	91	SIL 2	SIL 3	-	-
Generic PLC	98	SIL 2	SIL 3	-	-
Shutdown Valve [SDV]	54	-	-	SIL 2	SIL 3
3 Way Solenoid Valve [SOV]	99	-	-	SIL 2	SIL 3
SDV Actuator	64	-	-	SIL 2	SIL 3

From the above table, based on the type and HFT, the SIL rating and redundancy is chosen,

Table 9. Chosen SIL Rating and Redundancy

Component	HFT = 1 [Type B]	HFT = 1 [Type A]	SIL Rating	Redundancy
Pressure Transmitters [PT]	SIL 3	-	SIL 3	2oo3
Generic PLC	SIL 3	-	SIL 3	1oo2
Shutdown Valve [SDV]	-	SIL 3	SIL 3	1oo2
3 Way Solenoid Valve [SOV]	-	SIL 3	SIL 3	1oo2
SDV Actuator	-	SIL 3	SIL 3	1oo2

The PFD_{avg} is now estimated based on the redundancy chosen, from eq. 2 to eq. 5 and b correction factor from Table 4. For the sensor operating on a 2oo3 voting philosophy,

$$PFD_{avg}(2oo3) = [[1-(1.5\times0.05)]\times0.9\times4.4\times10^{-8}\times(3\times8760)]^2 + [[1-(1.5\times0.05)]\times[1-0.9]\times4.4\times10^{-8}\times(20\times8760)]^2 + \left[\frac{(1.5\times0.05)\times0.9\times4.4\times10^{-8}\times(3\times8760)}{2}\right] + \frac{[(1.5\times0.05)\times[1-0.9]\times4.4\times10^{-8}\times(20\times8760)]}{2} \qquad (7)$$

Or $PFD_{avg}(2oo3) = 6.94\times10^{-5}$ (8)

The risk reduction factor [RRF] is,

$$RRF = \frac{1}{PFD_{avg}(2oo3)} = \frac{1}{6.94\times10^{-5}} = 14{,}416 \qquad (9)$$

Performing similarly for the logic solver on a 1oo2 voting philosophy,

$$PFD_{avg}(1oo2) = \frac{[[1-0.02]\times0.9\times2.5\times10^{-7}\times(5\times8760)]^2}{3} + \frac{[[1-0.02]\times[1-0.9]\times2.5\times10^{-7}\times(20\times8760)]^2}{3} + \left[\frac{0.02\times0.9\times2.5\times10^{-7}\times(5\times8760)}{2}\right] + \frac{[0.02\times[1-0.9]\times2.5\times10^{-7}\times(20\times8760)]}{2} = 1.8\times10^{-4} \qquad (10)$$

The risk reduction factor [RRF] is,

$$RRF = \frac{1}{PFD_{avg}(1oo2)} = \frac{1}{1.8\times10^{-4}} = 5{,}586 \qquad (11)$$

Performing similarly for the final element with SDV, SOV and SDV Actuator's redundancy / voting philosophy of 1oo2, the individual PFD_{avg} and RRF is summarized as follows,

Table 10. Calculated PFD_{avg} and RRF

Component	Redundancy	PFD_{avg}	RRF [-]
Pressure Transmitters [PT]	2oo3	6.94E-05	14416
Generic PLC	1oo2	1.80E-04	5568
Shutdown Valve [SDV]	1oo2	2.69E-04	2371
3 Way Solenoid Valve [SOV]	1oo2	5.87E-06	
SDV Actuator	1oo2	1.47E-04	

It is to be noted that in the above table, the RRF value (RRF = 2,371) for the final element components [SDV + SOV + SDV Actuator] is computed by summing up the individual component's PFD_{avg} and taking its inverse.

To estimate the overall / total PFD_{avg}, all the individual component PFD_{avg} values in Table 10 are added, and the inverse of its sum is taken. Therefore,

$$Overall\ PFD_{avg} = [6.94 \times 10^{-5}] + [1.8 \times 10^{-4}] + [2.69 \times 10^{-4}] + [5.87 \times 10^{-5}] + [1.47 \times 10^{-4}] \quad (12)$$

Or $$Overall\ PFD_{avg} = 6.71 \times 10^{-4} \quad (13)$$

The overall RRF is computed as,

$$RRF_{Overall} = \frac{1}{Overall\ PFD_{avg}} \quad (14)$$

Or $$RRF_{Overall} = \frac{1}{6.71 \times 10^{-4}} = 1{,}491 \quad (15)$$

Verification Results

From Systematic Capability,

Sensor, logic solver and final element are certified to SC 3 (SIL 3 capable), as per the individual component manufacturer's certificate. Therefore, the overall SIL qualifies up to SIL 3 as per systematic capability.

From Architectural Constraints,

1. The sensor element with HFT = 1, Route 1H and Type B qualifies for SIL 3 in the SIF.
2. The logic solver with HFT = 1, Route 1 and Type B qualifies for SIL 3 in the SIF.
3. The final element with HFT = 1, Route 2H and Type A qualifies for SIL 3 in the SIF.

From PFD_{avg},

For an RRF of 1,491, the HIPPS assembly corresponds and meets SIL 3 criteria. The risk reduction achieved for the overall HIPPS assembly with a SIL 3 rating is 1,491 times.

Conclusion

Considering meeting all the three criteria of systematic capability of SIL 3, architectural constraints of SIL 3 and PFD_{avg} of SIL 3, the HIPPS system meets the overall target of SIL 3.

References & Further Reading

https://www.emersonautomationexperts.com/wp-content/uploads/2018/08/Emerson-HIPPS-Solution.jpg

IEC61508:2010 Edition

https://www.consiltant.com/en/tool/pfd-calculator/

https://safetyandsis.com

https://www.lntvalves.com/media/34900/c2-sil-verification.pdf

https://www.exida.com/articles/Three-Barriers.pdf

https://www.exida.com/Blog/Back-to-Basics-14-Systematic-Capability

https://www.miinet.com/images/pdf/whitepapers/Logic_Solver_for_Overpressure_Protection_White_Paper_Moore_Industries.pdf

Author

Vijay Sarathy holds a Master's Degree in Chemical Engineering from Birla Institute of Technology & Science (BITS), Pilani, India and is a Chartered Engineer from the Institution of Chemical Engineers, UK. His expertise over 10 years of professional experience covers Front End Engineering, Process Dynamic Simulation and Subsea/Onshore pipeline flow assurance in the Oil and Gas industry. Vijay has worked as an Upstream Process Engineer with major conglomerates of General Electric, ENI Saipem and Shell.

Appendix A

SIL Verification Study for High Integrity Pressure Protection System [HIPPS]

Sr. No	Component	Op hours per year	Life Time [LT]	Proof Test Interval [T_i]	Proof Test Coverage [PTC]	Mean Time to Restore [$MTTR_{DD}$]	β-Factor
-	-	[hrs]	[years]	[years]	[%]	[hours]	[%]
1	Sensor	8760	20	3	90	72	5
2	Logic Solver	8760	20	5	90	72	2
3	Final Element	8760	20	1	70	72	10

Component		Failure rate [λ] [1/hr]				SFF [%] [For Route 1H]	Type B [Route 1H]		Type A [Route 2H]	
		λ_{DD}	λ_{DU}	λ_{SD}	λ_{SU}		HFT = 0	HFT = 1	HFT = 0	HFT = 1
Sensor	Pressure Transmitters [PT]	0	4.40E-08	3.01E-07	1.74E-07	91	SIL 2	SIL 3	-	-
Logic Solver	Generic PLC	3.97E-06	2.50E-07	1.19E-05	1.36E-07	98	SIL 2	SIL 3	-	-
Final Element	Shutdown Valve [SDV]	8.74E-08	8.95E-08	1.81E-08	9.74E-10	54	-	-	SIL 2	SIL 3
	3 Way Solenoid Valve [SOV]	1.43E-07	2.00E-09	0	3.36E-07	99	-	-	SIL 2	SIL 3
	SDV Actuator	0	4.95E-08	0	8.86E-08	64	-	-	SIL 2	SIL 3

Component		HFT = 1 [Type B]	HFT = 1 [Type A]	SIL Rating	Redundancy	PFD_{avg}	RRF [-]
Sensor	Pressure Transmitters [PT]	SIL 3	-	SIL 3	2oo3	6.94E-05	14416
Logic Solver	Generic PLC	SIL 3	-	SIL 3	1oo2	1.80E-04	5568
Final Element	Shutdown Valve [SDV]	-	SIL 3	SIL 3	1oo2	2.69E-04	2371
	3 Way Solenoid Valve [SOV]	-	SIL 3	SIL 3	1oo2	5.87E-06	
	SDV Actuator	-	SIL 3	SIL 3	1oo2	1.47E-04	
		SIL Based on Architectural Constraints = Lowest SIL rating in SIL Rating list = SIL 3			Total PFD_{avg}	6.71E-04	1,491
					SIL Rating Achieved		SIL 3

IACPE

INTERNATIONAL ASSOCIATION OF

CERTIFIED PRACTICING ENGINEERS

IACPE.COM