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SPECIAL FEATURES

The Relevance of Deep Conversion Refining Hardware in Energy Transition: Directing Fossil Carbon for Noncombustible Purposes

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Introduction and Context

The necessity to reduce the environmental impact and the higher sustainability of the industrial processes normally is translated into stricter regulations and higher control upon the industries activities, mainly to those that have a high environmental footprint as the crude oil production chain. This fact is positive and welcome, in view of the necessity to preserve natural resources and the technological development needed to meet these regulations.

One of the most impacting regulations to the downstream industry is the necessity to reduce the sulfur content in the maritime fuels, known as IMO 2020. This regulation established which from the maximum sulfur content in the maritime transport fuel oil (Bunker) is 0,5 % (m.m) against the previously 3,5 % (m.m). The main objective is to reduce the SOx emissions from the maritime fleet, significantly decreasing the environmental impact of this business.

The marine fuel oil, known as bunker, is a relatively low viscosity fuel oil applied in diesel cycle engines to ship movement. Before 2020, the bunker was produced through the blending of residual streams as vacuum residue and deasphalted oil with dilutants like heavy gasoil and light cycle oil (LCO), due to the new regulation, a major part of the refiners will not be capable of producing low sulfur bunker through simple blend.

Due to being produced from residual streams with high molecular weight, there is a tendency of contaminants accumulation (sulfur, nitrogen, and metals) in the bunker, this fact makes it difficult to meet the new regulation without additional treatment steps, what should lead to increasing the production cost of this derivative and the necessity to modifications in the refining schemes of some refineries. Figure 1 presents a schematic diagram of how the bunker was produced before the IMO 2020.

The drastic reduction of sulfur content in the final product, lead refiners to look for alternatives to reduce the sulfur content in the intermediate streams, and this is a hard task to refiners processing heavy and extra-heavy crudes.

Beyond the necessity to add value to bottom barrel streams in compliance with the IMO 2020, the increasingly restrict environmental regulations require even more capacity to produce cleaner distillates, imposing another challenge to refiners processing extra-heavy crudes. The growing trend of petrochemical integration is another great challenge to refiners with access to extra-heavy crudes once requires more complex and expensive refining hardware, in this sense, the hydrocracking and deep hydrocracking technologies can be a fundamental tool to allow the refiners

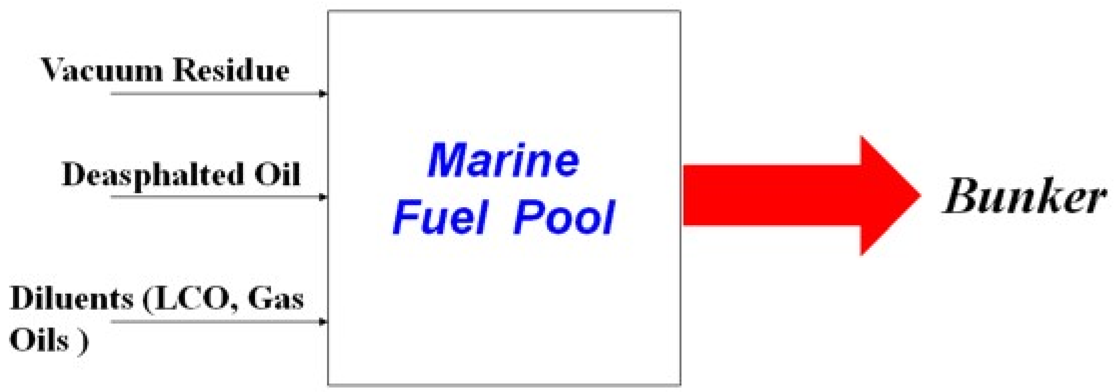

Figure 1 – Bunker Production Process before IMO 2020

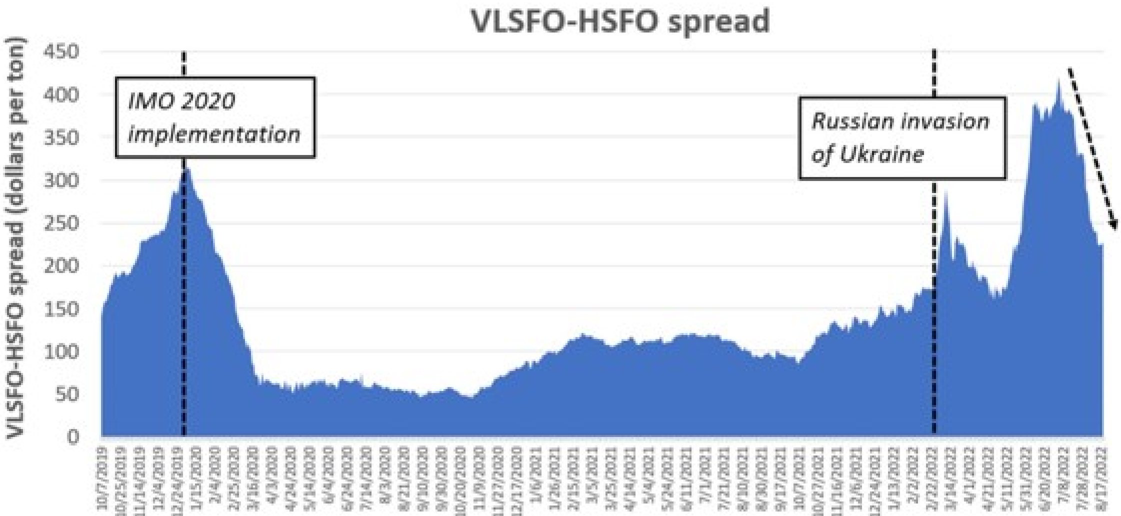

Figure 2 – VLFSO and HSFO Fuel oil Spreads (Ship & Bunker, 2022)

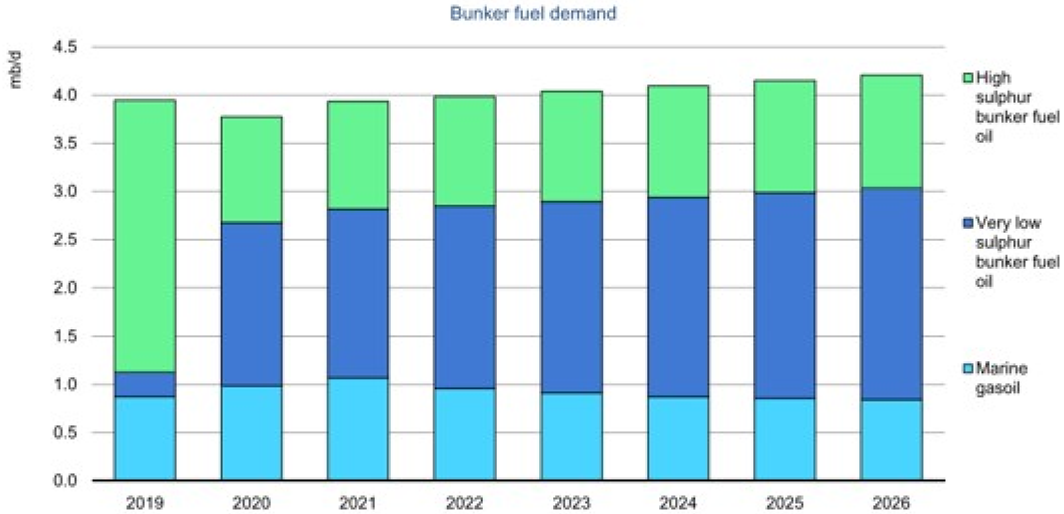

Figure 3 – Growing Participation of VLFSO in the Bunker Market (IEA, 2021)

with high capital investment capacity to reach a highlighted competitive positioning in the downstream market through adequate balance of bottom barrel conversion capacity and petrochemicals maximization.

The war between Russia and Ukraine raised the spread between the 0,5 % sulfur and 3,5 % sulfur marine fuel oil, as presented in Figure 2, becoming even more attractive the production of VLSFO.

Even before the war the spread between VLSFO and HSFO justified investments by refiners to produce low sulfur fuel. Furthermore, it's important to considering the increasingly stricter regulations and the trend of reduction of the HSFO market in the middle term (as presented in Figure 3), this fact plus the trend of reduction in transportation fuels demand and growing demand of petrochemicals at global level tends to favor refiners relying on most processing heavy crude oils and maximize the added value to the processed crude.

Flexible refining hardware in relation to the processed crude slate is an important competitive advantage in the downstream sector, mainly the processing of heavy and extra-heavy crudes due to its lower acquisition cost when compared with the lighter crude oils. The difference in the acquisition cost between these oils is based on in the yield of high added value streams which these oils present in the distillation process, since the lighter crudes normally show higher yields of distillates than the heavier crudes, its market value tends to be higher. As an example, Figure 4 presents the evolution of the discount of WCS (West Canadian Select) crude oil to WTI (West Texas Intermediate) crude oil over the time.

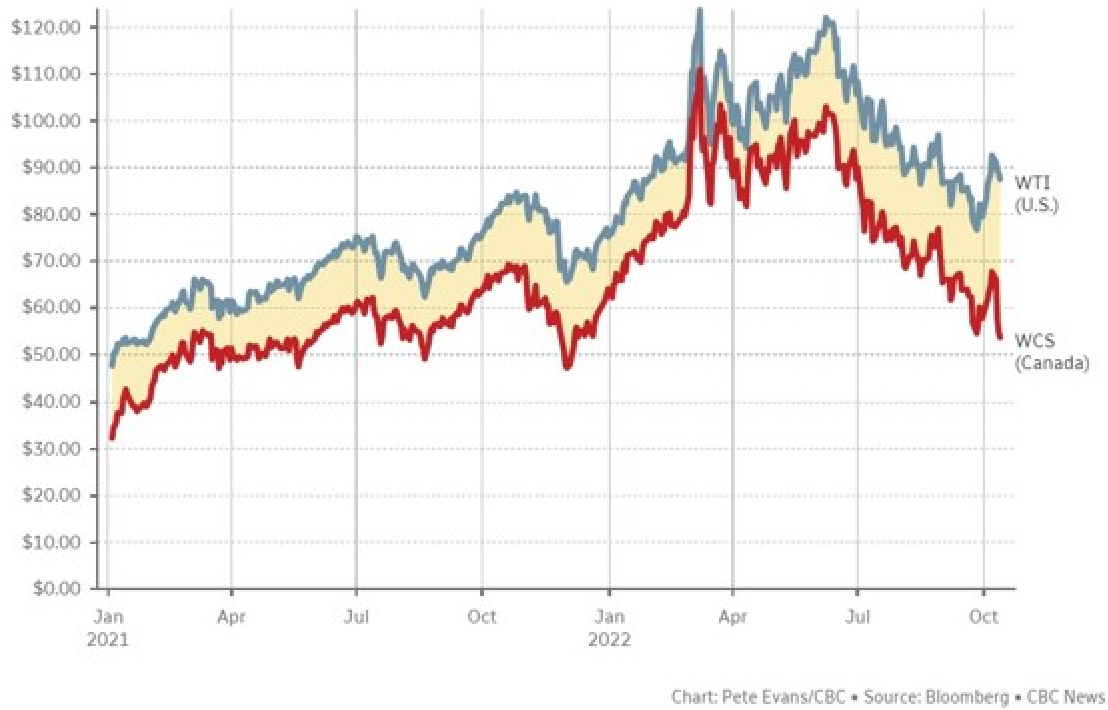

Figure 4 – Price gap between WTI and WCS crude oils (CBC News, 2022)

The WCS is considered a heavy crude (API grade between 19 and 22) with a sulfur content around 3,0 % while the WTI is considered a reference crude with a medium API grade around 40 with very low sulfur content (around 0,3 %), Figure 1 shows a significant price gap between these crudes, leading to a relatively advantage to refiners capable to add value to these crudes, especially considering the IMO 2020 that requires even more refining capacity to add value to the bottom barrel streams. Normally, the valuation of crudes is defined by the quality, the available market in other words it's necessary to find refiners capable of processing this crude oil, and the capacity to transport the crude oil to the consumer market. Heavier crudes tend to present discounts related to lighter crude due to these three variables:

- Quality – Heavier crudes present lower yield of distillates and high added value derivatives like diesel, kerosene, and gasoline than lighter crudes.
- Consumer market – The refiners able to process heavier crudes needs to rely on adequate bottom barrel conversion capacity, in other words, more complex refineries, restricting the consumer market in comparison with lighter crudes.
- Transportation – Heavier crudes present higher logistics costs due to higher energy consumption.

Despite these characteristics, refiners with adequate refining hardware and easy access to heavier crudes can use the price gap between light and heavy crudes as opportunity to improve the refining margins, mainly considering the IMO 2020 that reduced, even more, the acquisition cost of heavier and sourer crudes and due to their characteristics, the hydrocracking technologies broke significative restrictions of the refining hardware to add value to these discounted crudes.

Processing Extra Heavy Crudes – The Hydrocracking Alternative

Refiners processing heavy and extra-heavy (or high sulfur) crudes face a great challenge to meet the IMO 2020 once it is extremely difficult to comply with the new regulation through carbon rejection technologies, in this case, the hydrogen addition technologies are fundamental.

The hydroprocessing of residual streams presents additional challenges when compared with the treating of lighter streams, mainly due to the higher contaminated content and residual carbon (RCR) related with the high concentration of resins and asphaltenes in the bottom barrel streams. Figure 5 shows a schematic diagram of the residue upgrading technologies applied according to the metals and asphaltenes content in the feed stream.

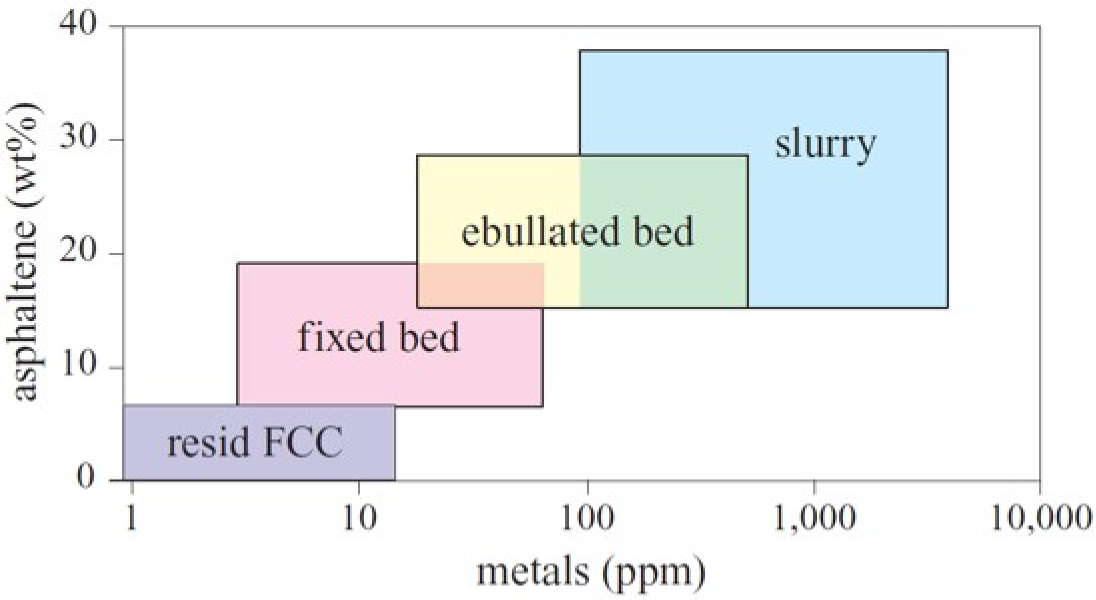

Figure 5 – Residue Upgrading Technologies According to the Contaminants Content (Encyclopedia of Hydrocarbons, 2006)

Higher metals and asphaltenes content led to a quick deactivation of the catalysts through high coke deposition rate, catalytic matrix degradation by metals like nickel and vanadium or even by the plugging of catalyst pores produced by the adsorption of metals and high molecular weight molecules in the catalyst surface. By this reason, according to the content of asphaltenes and metals in the feed stream are adopted more versatile technologies aiming to ensure an adequate operational campaign and an effective treatment.

Catalysts applied in hydrocracking processes can be amorphous (alumina and silica-alumina) and crystalline (zeolites) and have bifunctional characteristics, once the cracking reactions (in the acid sites) and hydrogenation (in the metals sites) occur simultaneously. The active metals used in this process are normally Ni, Co, Mo and W in combination with noble metals like Pt and Pd.

It's necessary to have a synergic effect between the catalyst and the hydrogen because the cracking reactions are endothermic and the hydrogenation reactions are exothermic, so the reaction is conducted under high partial hydrogen pressures and the temperature is controlled in the minimum necessary to convert the feed stream. Despite these characteristics, the hydrocracking global process is highly exothermic, and the reaction temperature control is normally made through cold hydrogen injections between the catalytic beds.

According to the feed stream quality (contaminants content), its necessary hydrotreating reactors installation upstream of the hydrocracking reactors, these reactors act like guard bed to protect the hydrocracking catalyst.

The principal contaminant of hydrocracking catalyst is nitrogen, which can be present in two forms: Ammonia and organic nitrogen.

Ammonia (NH_3), produced during the hydrotreating step, have temporary effects reducing the activity of the acid sites, mainly damaging the cracking reactions. In some cases, the increase of ammonia concentration in the catalytic bed is used like an operational variable to control the hydrocracking catalyst activity. The organic nitrogen has permanent effect blocking the catalytic sites and leading to coke deposits on the catalyst.

As exposed above, extra-heavy crude oils or with high contaminants content can demand deep conversion technologies to meet the new quality requirements to the bunker fuel oil. Hydrocracking technologies are capable to achieve conversions higher than 90% and, despite the high operational costs and installation can be attractive alternatives.

The hydrocracking process is normally conducted under severe reaction conditions with temperatures that vary to 300 to 480 oC and pressures between 35 to 260 bar. Due to process severity, hydrocracking units can process a large variety of feed streams, which can vary from gas oils to residues that can be converted into light and medium derivates, with high value added.

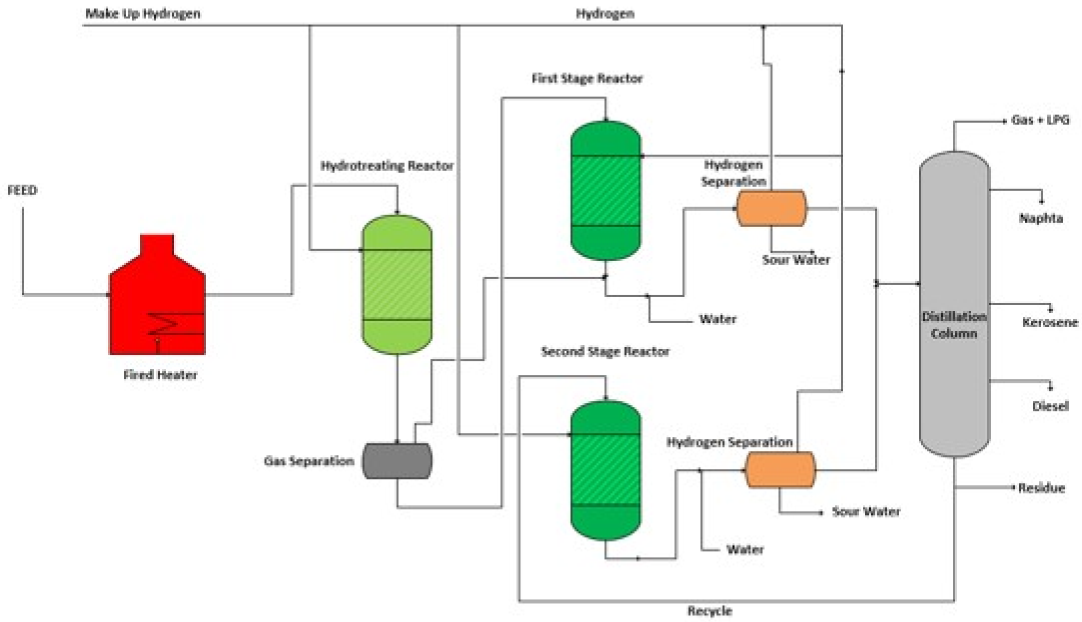

Figure 6 – Typical Arrangement for Two Stage Hydrocracking Units with Intermediate Gas Separation

Figure 6 shows a typical process arrangement to hydrocracking units with two reaction stage and intermediate gas separation, adequate to treat high streams with high contaminants content like nitrogen.

The residue produced by hydrocracking units have low contaminants content, able to be directed to the refinery fuel oil pool aiming to produce low sulfur bunkers, allowing the market supply and the competitiveness of the refiners.

The process shown in Figure 6 presents a fixed bed hydrocracking unit, to heavier crudes. This unit can be inadequate due to the low operating life cycle, in this case the ebulated bed and slurry phase reactors can be more effective, despite the higher capital spending. The capital requirement is one of the most important restrictions to refiners to adopt the hydrocracking technologies both to capital and operating capital due to the necessity of larger hydrogen generation units, catalysts costs, etc. Figure 7 presents a comparison between residue upgrading alternatives related to the capital investment (CAPEX) and effectiveness in the bottom barrel processing.

As presented in Figure 7, the hydrocracking technologies present the higher level of required capital spending, on the other hand offer the higher conversion to bottom barrel streams, a necessity to refiners processing heavy and extra-heavy crudes. According to Figure 3, the other alternatives are not effective to treat residue streams with high carbon residue and metals, common characteristics of extra-heavy crude oils. In this case, the hydrocracking alternative is the most technically adequate solution.

According to data from Global Data Company, the global installed hydrocracking capacity in 2022 was around 12,500 Mbd and will growth under an average annual growth rate of 5,0 % until 2027 and this growth will be headed by USA, China, India, and Saudi Arabia.

Deep Hydrocracking Technologies – Recovering More Added Value from the Crudes

As aforementioned, despite the high performance, the fixed bed hydrocracking technologies can be not economically effective to treat residue from heavy and extra-heavy due to the short operating lifecycle. Technologies that use ebullated bed reactors and continuum catalyst replacement allow higher campaign period and higher conversion rates, among these technologies the most known are the H-Oil and Hyvahl™ technologies developed by Axens Company, the LC-Fining Process by Chevron-Lummus, and the Hycon™ process by Shell Global Solutions. These reactors operate at temperatures above 450 °C and pressures to 250 bars. Figure 8 presents a typical process flow diagram for a LC-Fining™ process unit, developed by Chevron Lummus Company while the H-Oil™ process by Axens Company is presented in Figure 9.

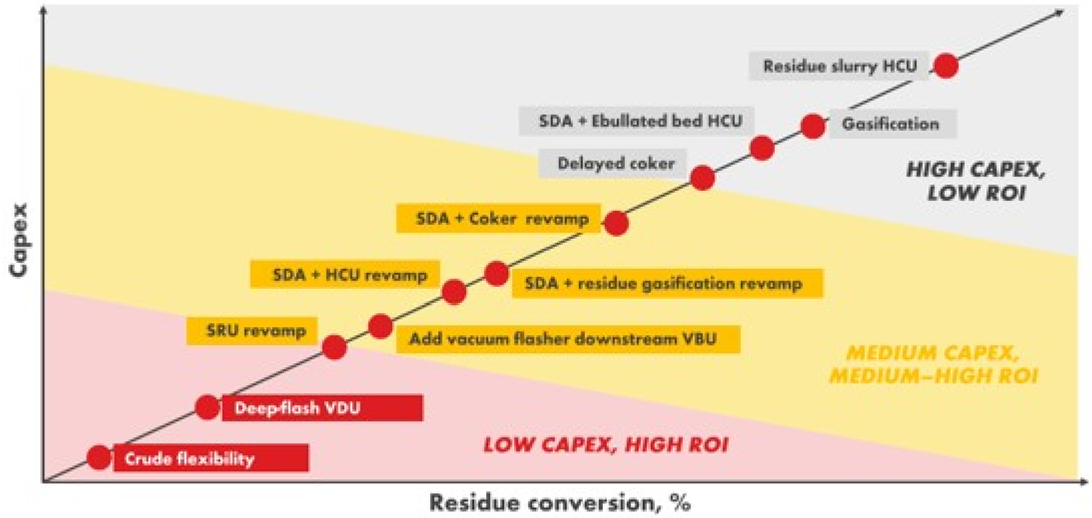

Figure 7 – Capital Spending x Residue Conversion to Residue Upgrading Technologies (Shell Catalysts and Technologies, 2019)

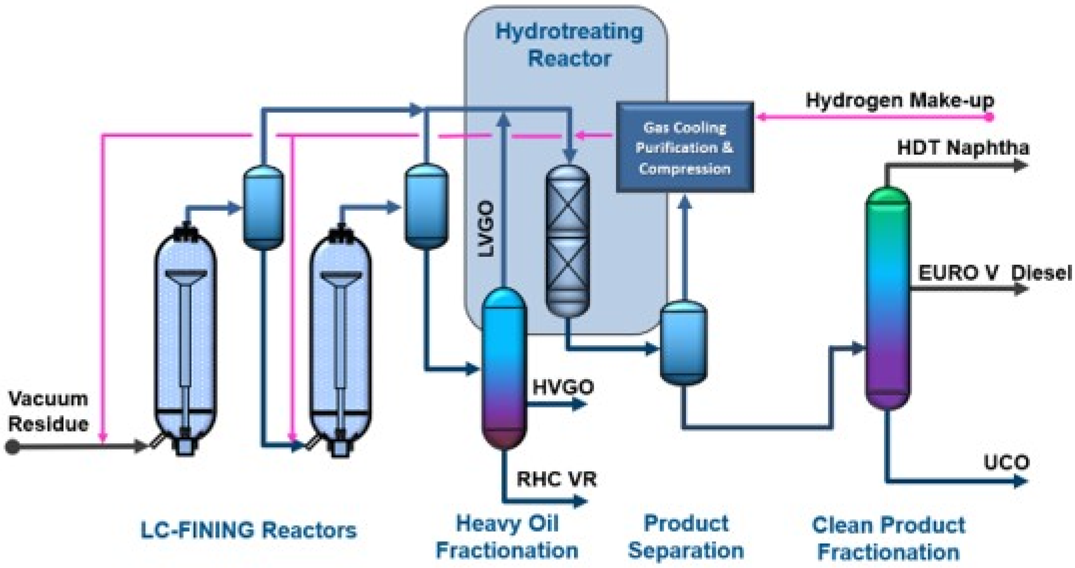

Figure 8 – Process Flow Diagram for LC-Fining™ Technology by CLG Company (Lummus Company, 2022)

Catalysts applied in hydrocracking processes can be amorphous (alumina and silica-alumina) and crystalline (zeolites) and have bifunctional characteristics once the cracking reactions (in the acid sites) and hydrogenation (in the metals sites) occur simultaneously.

An improvement in relation to ebullated bed technologies is the slurry phase reactors, which can achieve conversions higher than 95 %. In this case, the main available technologies are the HDH™ process (Hydrocracking-Distillation-Hydrotreatment), developed by PDVSA-Intevep, VEBA-Combicracking Process (VCC)™ commercialized by KBR Company, the EST™ process (Eni Slurry Technology) developed by Italian state oil company ENI, and the Uniflex™ technology developed by UOP Company. Figure 10 presents a basic process flow diagram for the VCC™ technology by KBR Company.

In the slurry phase hydrocracking units, the catalysts in injected with the feedstock and activated in situ while the reactions are carried out in slurry phase reactors, minimizing the reactivation issue, and ensuring higher conversions and operating lifecycle. Figure 11 presents a basic process flow diagram for the Uniflex™ slurry hydrocracking technology by UOP Company.

Other commercial technologies to slurry hydrocracking process are the LC-Slurry™ technology developed by Chevron Lummus Company and the Microcat-RC™ process by Exxon Mobil Company. Figure 12 presents a basic process flow diagram for the LC-Slurry™ technology developed by Lummus Company.

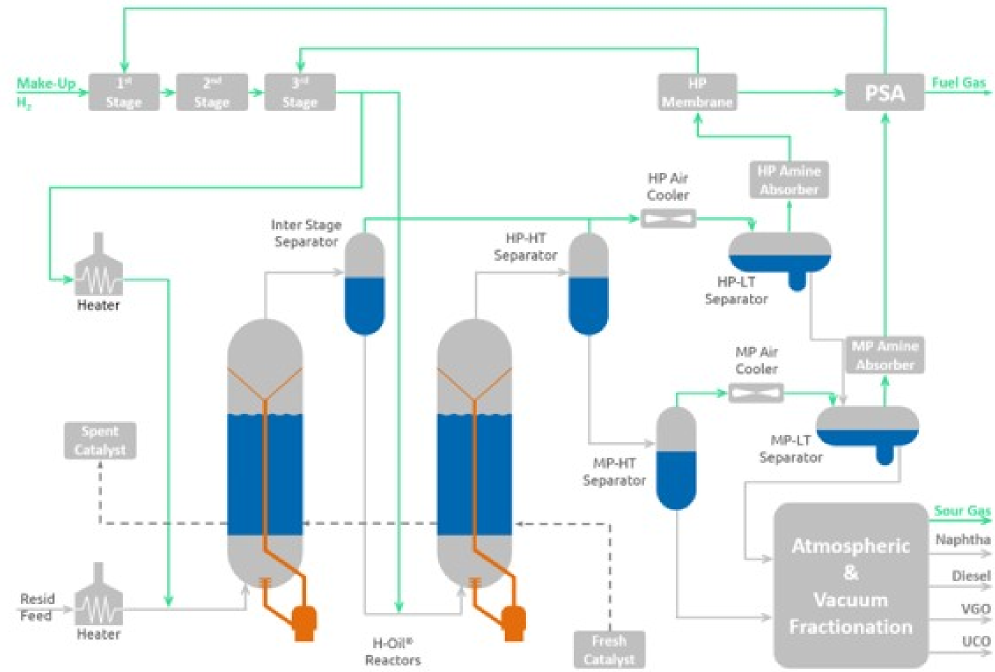

Figure 9 – Process Flow Diagram for H-Oil™ Process by Axens Company (Axens Company, 2022)

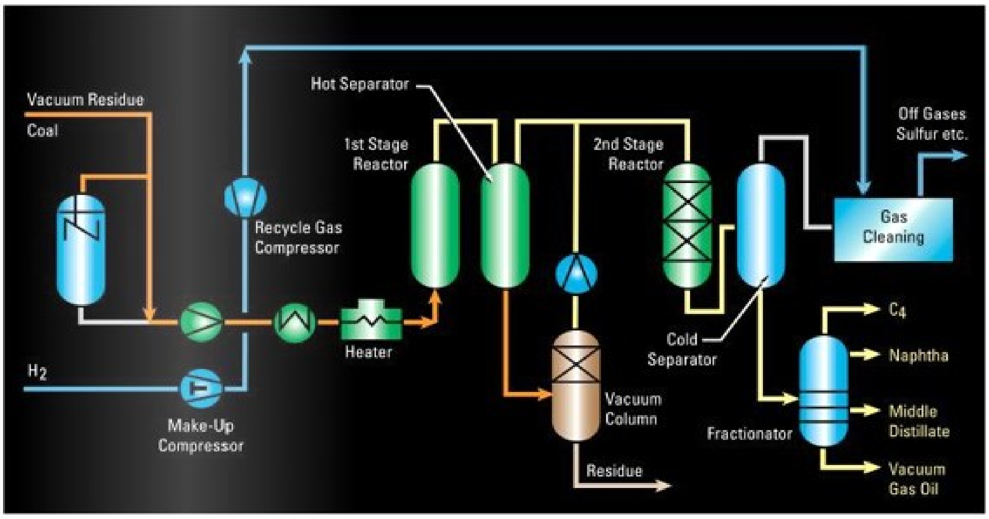

Figure 10 – Basic Process Arrangement for VCC™ Slurry Hydrocracking by KBR Company (KBR Company, 2019)

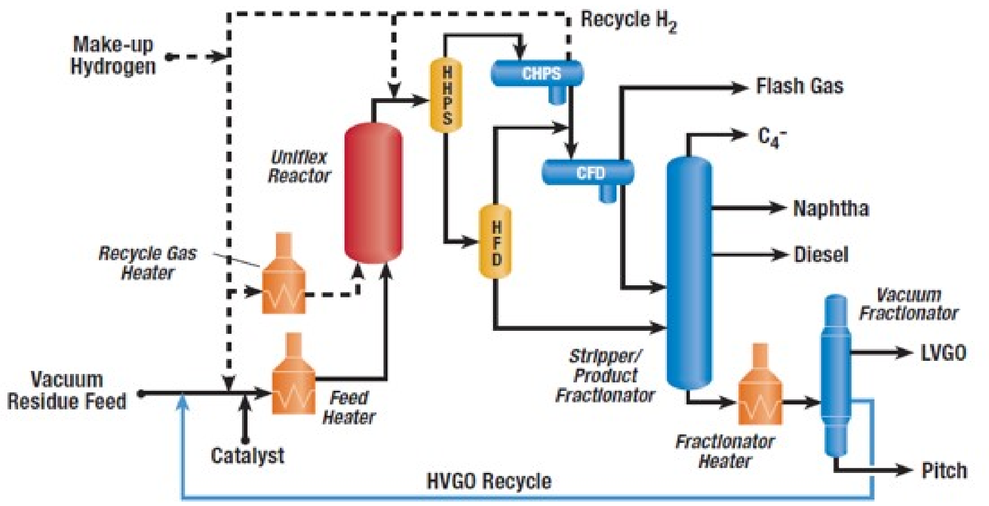

Figure 11 – Process Flow Diagram for Uniflex™ Slurry Phase Hydrocracking Technology by UOP Company (UOP Company, 2019).

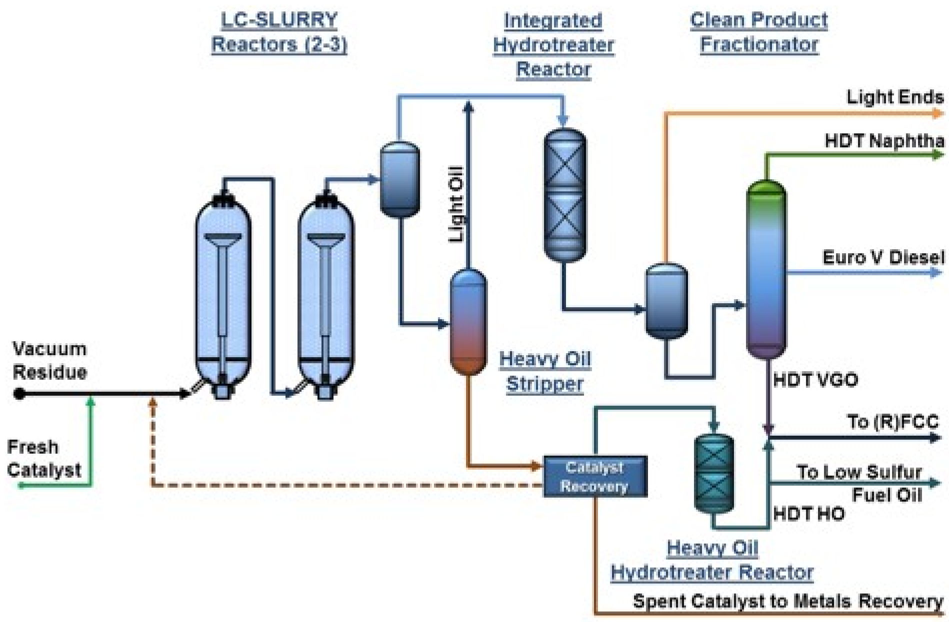

Figure 12 – Basic Process Arrangement for LC-Slurry™ Technology developed by Lummus Company (BISWAS et. al., 2017)

Aiming to meet the new bunker quality requirements, noblest streams, normally directed to produce middle distillates can be applied to produce low sulfur fuel oil, this can lead to a shortage of intermediate streams to produce these derivatives, raising their prices. The market for high sulfur content fuel oil should strongly be reduced, due to the higher prices gap when compared with diesel, its production tends to be economically unattractive.

Deep Conversion Refining Hardware – Petrochemicals from Bottom Barrel Streams

As aforementioned, the residue upgrading units are capable to improve the quality of bottom barrel streams, the main advantage of the integration between residue upgrading and petrochemical units like steam cracking is the higher availability of feeds with better crackability characteristics.

Bottom barrel streams tend to concentrate aromatics and polyaromatics compounds that present uneconomically performance in steam cracking units due to the high yield of fuel oil that presents low added value, furthermore, the aromatics tends to suffer condensation reaction in the steam cracking furnaces, leading to high rates of coke deposition that reduces the operation lifecycle and raises the operating costs. In this case deep conversion units like hydrocracking can offer higher operational flexibility.

Once cracking potential is better to paraffinic molecules, and the hydrocracking technologies can improve the H/C in the molecules converting low added value bottom streams like vacuum gasoil to high quality naphtha, kerosene, and diesel the synergy between hydrocracking and steam cracking units, for example, can improve the yield of petrochemical intermediates in the refining hardware, an example of highly integrated refining configuration relying on hydrocracking is presented in Figure 13.

Considering the recent trend of reduction in transportation fuels demand followed by the growth of petrochemicals market makes the presence of hydrocracking units in the refining hardware raise the availability of high-quality intermediate streams capable of being converted into petrochemicals, an attractive way to maximize the value addition to processed crude oil in the refining hardware. As presented in Figure 13, the synergy between carbon rejection and hydrogen addition technologies like FCC and hydrocracking units can offer an attractive alternative, sometimes the hydrocracking and FCC technologies are faced by competitors technologies in the refining hardware due to the similarities of feed streams that are processed in these units. In some refining schemes, the mild hydrocracking units can be applied as pretreatment step to FCC units, especially to bottom barrel streams with high metals content that are severe poison to FCC catalysts, furthermore the mild hydrocracking process can reduce the residual carbon to FCC feed, raising the performance of FCC unit and improving the yield of light products like naphtha, LPG, and olefins.

Considering the great flexibility of deep hydrocracking technologies that are capable to convert feed streams varying from gas oils to residue, an attractive alternative to improve the bottom barrel conversion capacity is to process in the hydrocracking units the uncracked residue in FCC unit aiming to improve the yield of high added value derivatives in the refining hardware, mainly middle distillates like diesel and kerosene.

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, 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.

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 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 current 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.

The Side Effect of Cracked Feeds – A Special Challenge to Hydrocracking Units

The most common cracked feeds directed to hydrocracking units are residual streams from FCC like Light Cycle (LCO) and Decanted Oil (DO) and Heavy Coker Gasoil (HCGO) from Delayed Coking units. Another less common feed is residue from Visbreaking units.

The main characteristics that influence the hydrocracking performance for each feedstock is presented below:

- FCC Cycle Oils – Present high aromaticity that are normally refractory to cracking reactions as well as refractory sulfur components, raising the sulfur content in the final products and reduction in diesel cetane number, on the other side, normally presents low basic nitrogen content that is a poison to the hydrocracking catalysts.

Thermal Cracking Feeds – Normally presents low aromatics content but concentrate refractory sulfur components.

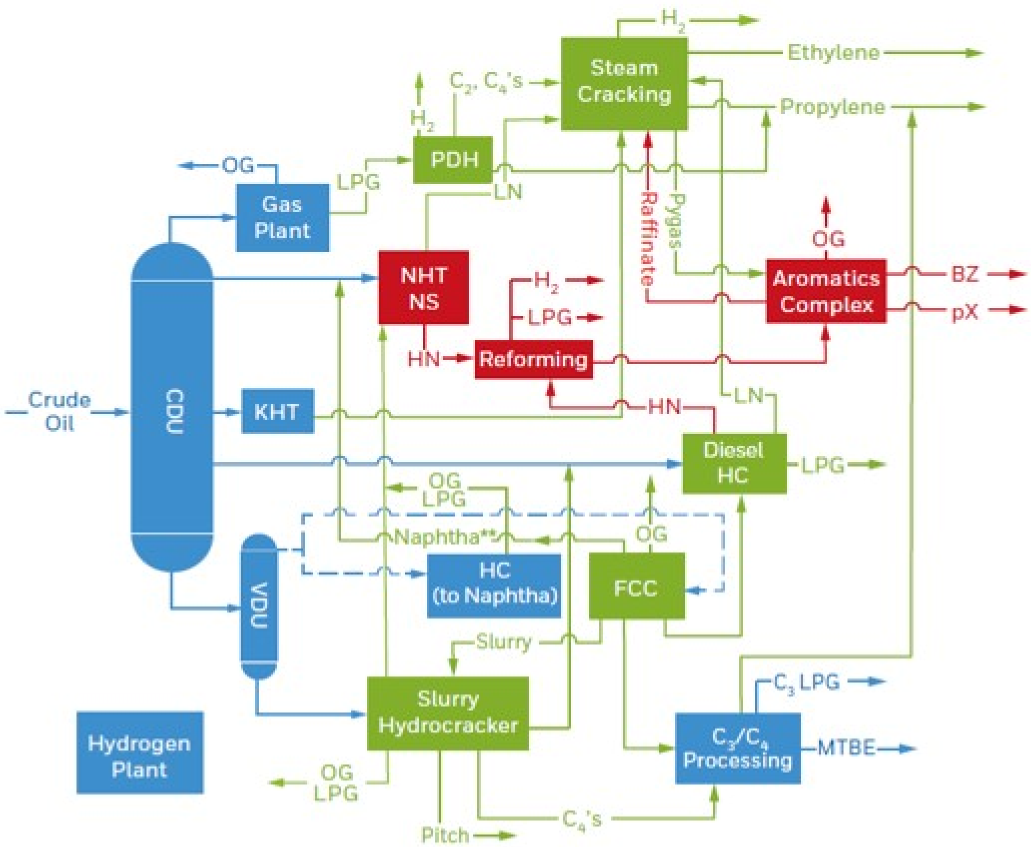

Figure 13 – Integrated Refining Scheme Relying on Residue Upgrading and Petrochemical Maximization Technologies (UOP, 2019)

The Heavy Coker Gasoil (HCGO) is an interesting case study as a feed to hycrocracking unit. Refiners with high complexity refining hardware can rely on the synergy between delayed coking and hydrocracking technologies to ensure added value to bottom barrel streams.

The quality of the HCGO relies on the quality of the feed to the delayed coking unit as well as the operating mode of the unit, mainly the recycling ratio. Higher recycling ratios produces better quality HCGO once reduces Conradson Carbon Residue (CCR), reducing the contaminants content like metals, sulfur, and nitrogen.

Despite this advantage, the delayed coking operators normally minimize the recycle ratio to minimum as possible aiming to raise the fresh feed processing capacity and the quality of HCGO is not an optimization focus of the refinery. For this reason, normally HCGO is a hard feed to hydrocracking units due to the high content of refractory sulfur components, high CCR, high nitrogen content, and aromatics concentration.

The sulfur and nitrogen content raises the heat release in the first bed (Higher exothermal profile) that can produce damage to the catalysts, the nitrogen tends to inhibit the cracking reaction leading to lower conversion in the unit. Hydrocracker's processing feeds with high nitrogen content tend to apply processing configuration with intermediate gas separation to control the catalyst activity. The higher production of H2S and NH3 due to the higher concentration of sulfur and nitrogen reduces the hydrogen partial pressure, raises the necessity of washing water to the units, and can raise the corrosion rate in the processing unit.

Aromatics compounds tend to raise the hydrogen consumption, the heat release in the catalyst bed, and are precursors of coking deposition that deactivate the catalyst. Other side effects of the cracked feeds to hydrocracking units are the impact over the quality of the final products like lower cetane number of diesels, higher smoke point of kerosene, lower viscosity index in the lubricating oils and higher sulfur content.

As described above, processing cracked feeds in hydrocracking units present some additional challenges to refiners related to hydrogen consumption, better quench design of the catalyst bed due to the higher exothermic profile of the reactions, and lower global activity of the catalyst due to the higher poison content, like basic nitrogen. These characteristics lead the refiners processing cracked feeds in hydrocracking units to invest more capital in feed treating systems like filtering and guarding beds. Despite this apparent disadvantage, refiners able to add value to bottom barrel streams can enjoy highly competitive advantage considering the downstream market post IMO 2020. For refiners processing extra-heavy bottom barrel streams, the deep hydrocracking technologies like slurry phase hydrocracking can be an interesting option, despite the high capital and operating costs.

The Lubricating Market – Short Lifetime to Solvent Route

According to recent forecasts, the global market of automotive lubricants will grow under annual rates around 6,3 % between 2022 and 2030 reaching a total market size of USD 120 billion in 2030. Figure 14 presents the growing trend for the automotive lubricants market. The high added value of lubricants in comparison with the transportation fuels accompanied by the trend of reduction in transportation fuels demand indicates an attractive alternative to refiners with adequate refining hardware to improve their revenues and competitiveness in the downstream market.

Like others crude oil derivatives, economic and technology development have been required the production of lubricating oils with higher quality and performance, moreover with lower contaminants content.

The main quality requirements for lubricating oils are viscosity, flash point, viscosity index (viscosity change with temperature), fluidity point, chemical stability, and volatility.

According to the American Petroleum Institute (API), the lubricating base oils can be classified as described in Table 1.

The lube oils from groups II, III and IV have higher quality than base oils from group I, the content of contaminants like sulfur and unsaturated compounds are significantly reduced, moreover, the viscosity index are superior for groups II, III, and IV.

The main disadvantage of the solvent route, when compared with the hydrorefining route, is that the solvent route can produce only Group I lubricating oil, this can limit its application to restricted consumer markets, which can reflect in the economic viability. Figure 15 presents a forecast for the market share evolution of different kinds of base oils in the market.

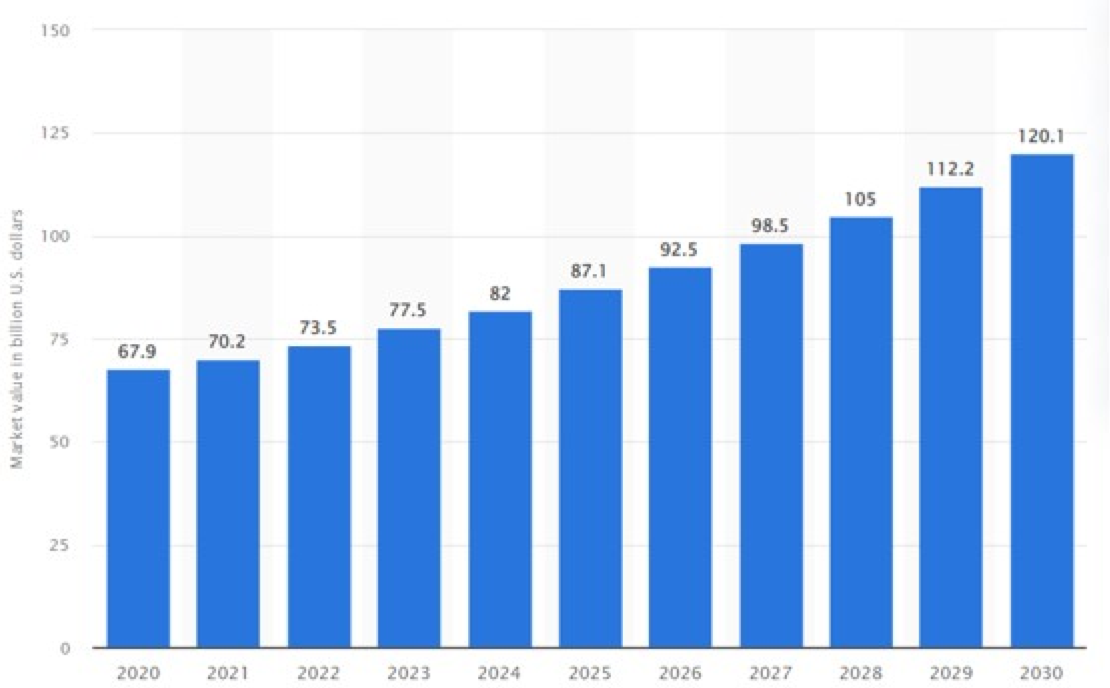

Figure 14 – Growing Trend in the Demand by Automotive Lubricants (STATISTA, 2022)

Table 1 – Lubricating Base Oils Classification

Group	Typical Production Process
I	Solvent Extraction
II	Hydrocracking/Hydrotreating or Hydrocracking + Solvent Extraction
III	Hydrocracking/Hydrotreating
IV	Synthetic

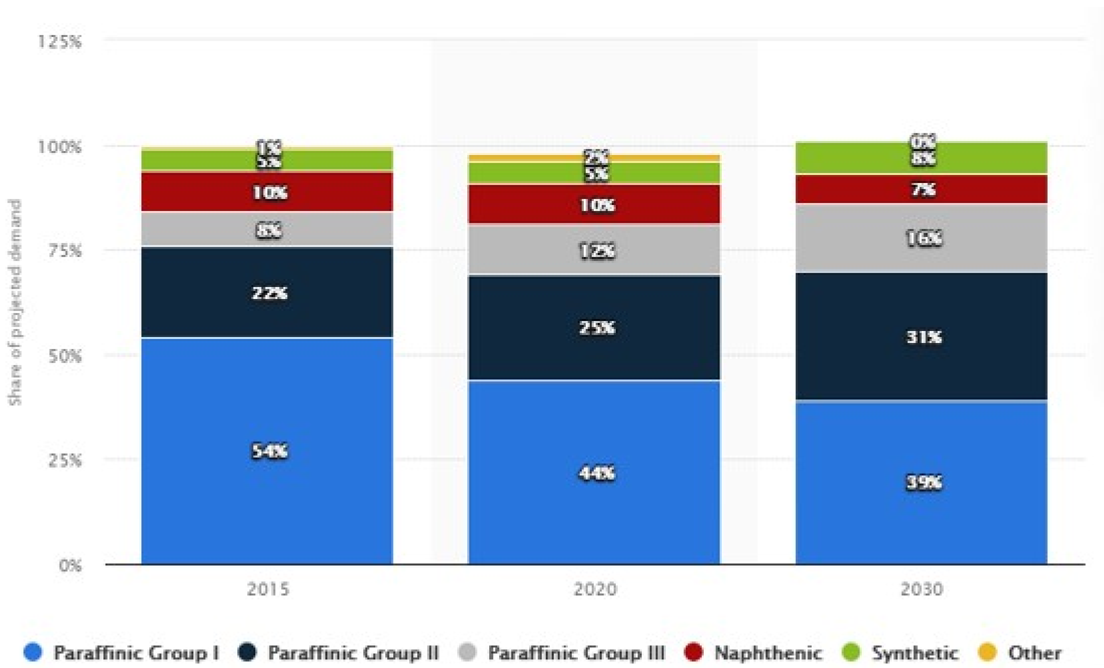

Figure 15 – Base Oil Demand Distribution (STATISTA, 2020)

According to the data from Figure 15, a significant reduction in the demand for Group I base oil is expected, leading to a great competitive loss for refiners relying on base oil production exclusively through solvent routes.

Another solvent route disadvantage is the solvents applying which can cause environmental damage and needs specials security requirements during the processing, production of low value-added streams like aromatic extract is another disadvantage. In this sense, refiners relying on solvent routes tend to lose market in the next years and face difficulties finding markets for their products, reducing in a significant manner their competitiveness in the downstream market.

Producing High Quality Lubricating Oils – The Hydroprocessing Route

In the lubricating oil production by hydrorefining, the physical processes of the solvent route are substituted by catalytic processes, basically hydrotreating processes. Figure 16 shows a block diagram of the processing sequence to produce base lube oils through hydrorefining route.

In this case the fractionating in the vacuum distillation step has more flexibility than in the solvent route, once that the streams will be cracked in the hydrocracking unit, so another distillation step is necessary.

After the vacuum distillation and propane deasphalting steps, the process streams are sent to a hydrotreating unit. This step seeks to saturate polyaromatic compounds and remove contaminants like sulfur and mainly nitrogen which is a strong deactivation agent for the hydrocracking catalyst.

In the hydrocracking step, the feed stream is cracked under control conditions and chemical reactions like dehydrocyclization, and aromatics saturation occurs which give to the process stream the adequate characteristics to the application as lubricants.

The following step, hydroisomerization, seeks to promote the isomerization of linear paraffins (which can reduce de viscosity index) producing branched paraffins.

After the hydroisomerization the process stream is pumped to hydrofinishing units to saturate remaining polyaromatic compounds and to remove heteroatoms, in the hydrofinishing step the water content in the lube oil is controlled to avoid turbidity in the final product.

In hydrotreating units dedicated to producing lubricants, one of the focuses of the hydrotreating process is to reduce the concentration of long chain paraffin, to achieve this goal is applied a specific catalyst bed containing dewaxing catalysts (ZSM-5). One of the most known hydrodewaxing technology in the market is the MSDW™ process, commercialized by ExxonMobil Company. A basic process flow diagram for MSDW™ process is shown in Figure 17.

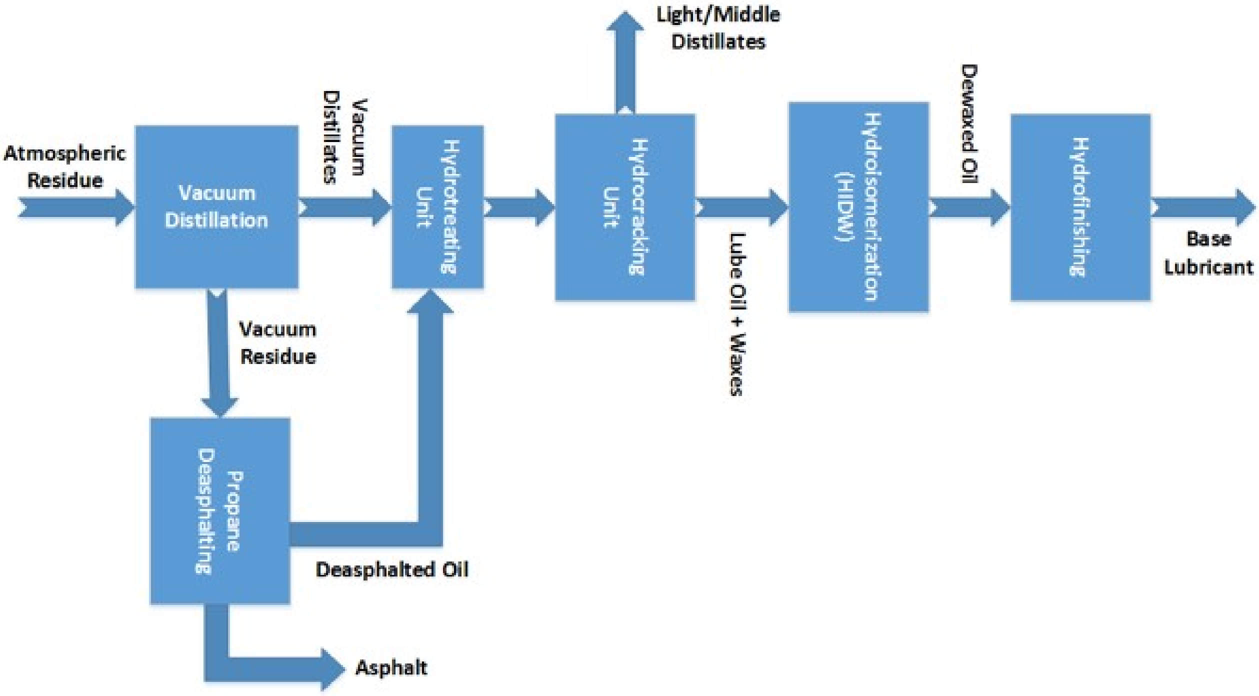

Figure 16 - Processing Scheme for Base Lubricating Oil Production through Hydrorefining Route

HDF = Hydrofininshing

Another available hydrodewaxing technology is the Isodewaxing™ process, developed by Lummus Company, this process is shown in Figure 18.

At this point it is important to quote that the main quality requirements of the lubricating oil are put under control through the following processes:

- Viscosity – The viscosity of the lubricating oil is controlled in the distillation step, managing the cuts in the crude distillation units or in the distillation columns after hydrocracking units.
- Viscosity Index (VI) – This variable is controlled in the hydrocracking step through the reduction in the aromatics content.
- Saturates – Another parameter that is adjusted in the hydrocracking step, through reduction of aromatics.
- Pour Point – This quality requirement is controlled in the hydrodewaxing step, through the reduction of waxes content.

As an example, Figure 19 presents a refining configuration capable of producing high quality lubricating oils based on hydrorefining route.

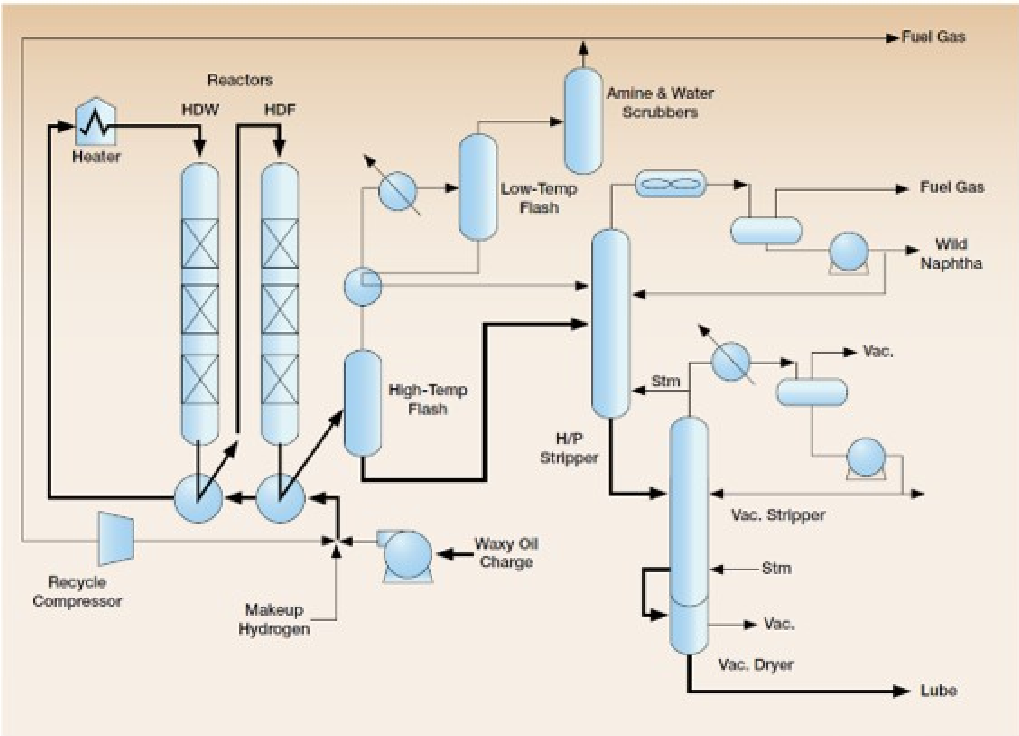

Figure 17 – Basic Process Flow Diagram for MSDW™ Dewaxing Technology by ExxonMobil Company (ExxonMobil Website).

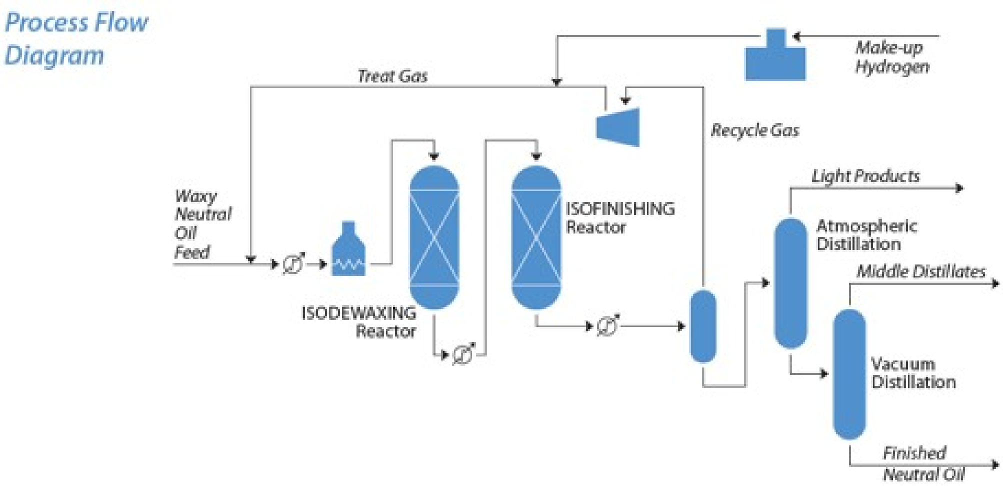

Figure 18 – Basic Process Flow Diagram for the Isodewaxing™ technology by Lummus Company.

Despite the high capital spending involved in the hydroprocessing route, it's possible to achieve better quality, higher added value, and products with growing demand against the production of Group I lube that presents contraction demands. In this scenario, it is expected which refiners, relying on exclusively solvent routes, lose market share forcing revamps of the existing lubricating production units or the exit from the market.

As discussed above is expected a significant growth of the global hydrocracking installed capacity for the next years. As expected, this growth will be headed by the Asian refiners as presented in Figure 20.

The headed by Asian players is expected once these players present high integration level between refining and petrochemical assets, requiring high bottom barrel conversion capacity to maximize the yield of petrochemicals, again this shows the competitive advantage for the Asian players due to the highest flexibility and profitability of their refining hardware.

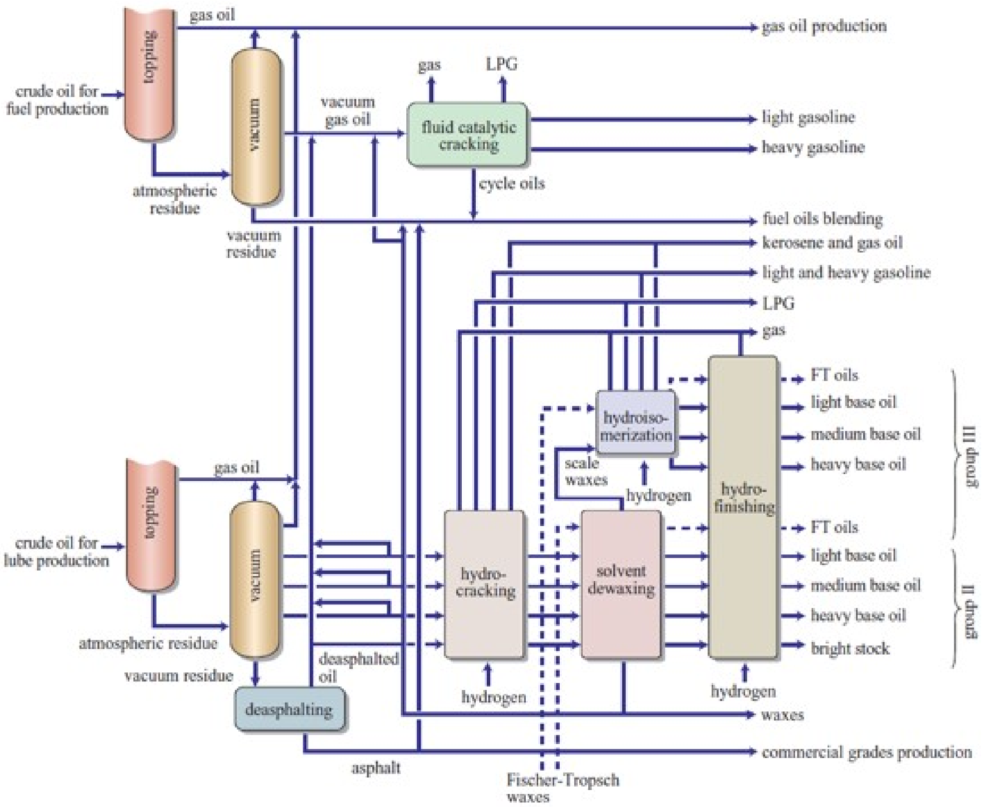

Figure 19 – Lubricating Oil Production Based on Hydrorefining Route (Encyclopedia of Hydrocarbons, 2006)

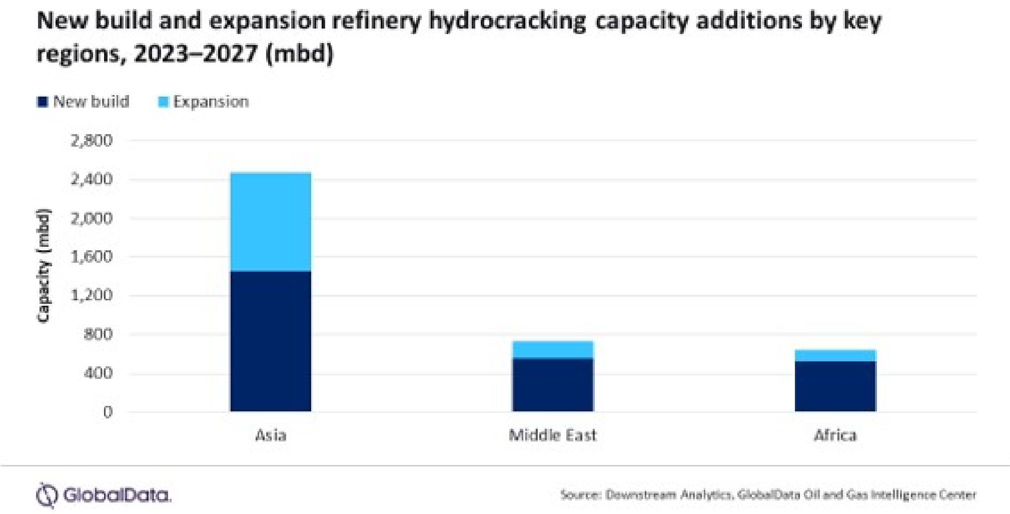

Figure 20 – Participation in the Global Growth of Hydrocracking Capacity by Region (Global Data Company, 2023)

Conclusion

Comply with IMO 2020 put under pressure the refining margins of low complexity refineries and reduced conversion capacity, once there is the tendency to raise the prices of low sulfur crude oils, furthermore, the higher operational costs depending on the technological or optimization solution adopted by the refiner. The challenge is even harder to refiners processing heavy and extra-heavy crudes, in this case, despite the high capital spending the hydrocracking technologies can offer an attractive alternative, beyond this, hydrocracking technologies appear like a fundamental enabler to ensure high conversion of bottom barrel streams, especially considering the growing trend of integration between refining and petrochemical assets. For refiners processing low sulfur crudes, the solvent deasphalting technologies can be an attractive way to comply with IMO 2020.

The downstream industry faces a transitive period with deep changes in the consumer market where the necessity to decarbonize the energy matrix requires a increasing participation of renewables in the crude oil refineries and the technological development like electric vehicles and 3 D printing have great potential to destroy transportation fuels demand, leading to deep changes in the production profile of crude oil refineries. Stricter regulations like IMO 2020 raise, even more, the relevance of the residue upgrading capacity to the competitiveness in the downstream industry, creating pressure over the refiners with low complexity refining hardware, in this sense, refiners with high capital investment capacity are looking for closer integration with petrochemical assets as a strategy to reduce costs and improve revenues.

Regarding the lubricating market, due to accelerated technological development, especially in the automotive market, the Group I lubricating oil tend to lose market in the next years this fact tends to lead the refiners to look for capital investment aiming to sustain their competitiveness in the lubricating market.

As aforementioned, despite the high capital investment of the hydroprocessing units, the higher added value of the Groups II and III lubricants and the growing market can justify the investment mainly considering the trend of reduction in transportation fuels demand at a global level in the middle term that has been leading the refiners to look ways to ensure market share and revenues in the downstream industry through the maximization of high added value derivatives with the growing market as petrochemicals and lubricating oils.

Another side effect for lubricating producers based on solvent routes due to the loss of competitiveness is raising the imports to supply the internal market, leading to an external dependence on critical production input as well as negative effects on the balance of payments. This reinforces the relevance of capital investments in hydrocracking processing units as a strategy to maximize the added value to crude oil reserves, especially considering the transition period faced by the downstream market where petrochemicals tend to overpass transportation fuels as main driver of crude oil demand at global level.

Again, it's important to understand the transitive period faced by the downstream industry and maintain competitive operations with the current focus on transportation fuels while the transition to petrochemicals is prepared in a sustainable manner aiming to keep economic sustainability and competitiveness in the downstream market, in other words, our current operations will sustain our desired future.

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Author

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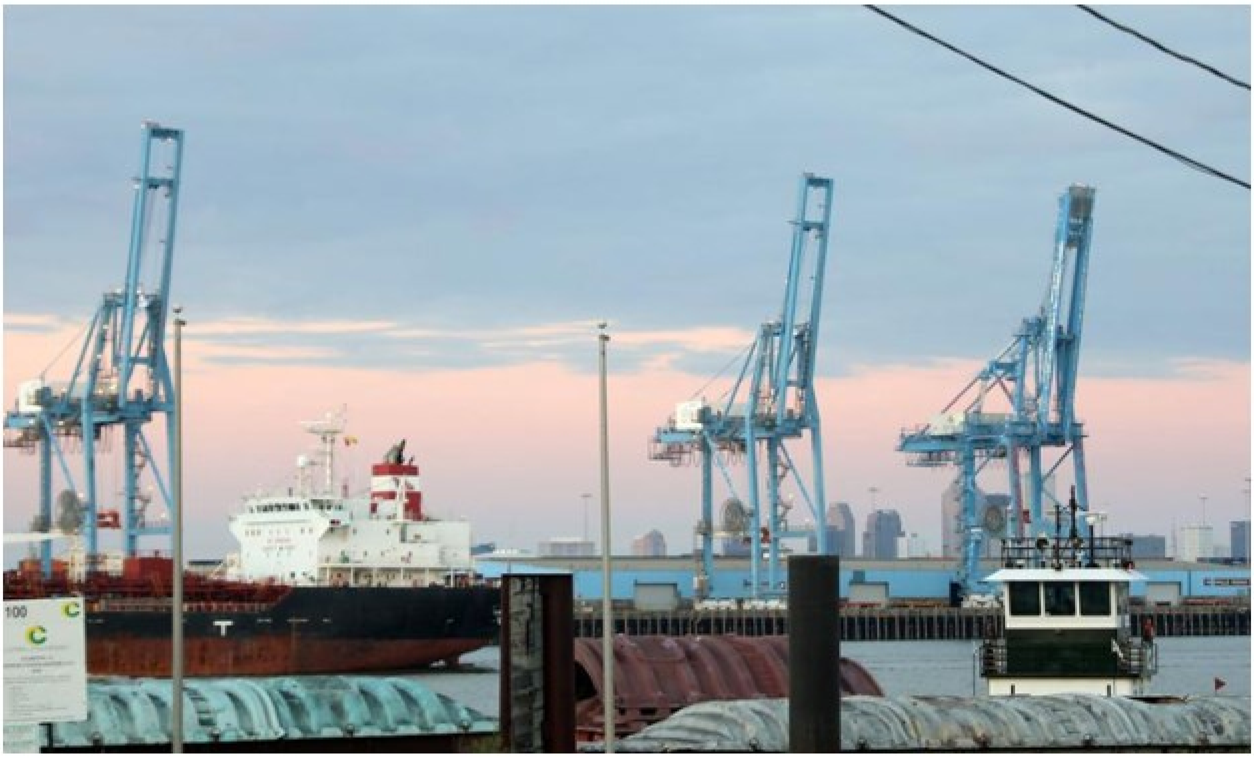
The View from Rock Bottom: Look Past the Tariffs….Its About the Shipping, Stupid…

Ron Cormier



Courtesy China's COSCO Shipping Corporation Limited.

Welcome back to the March edition of TVFRB! I am traveling this month and into April as well, including a trip from my home in temperate Mexico, to Houston and then on to the UK. I am looking forward to the UK's still-cooler weather next week, since in Houston, air conditioning compressors are already whirring away at homes and businesses all around town. Humidity has already condensed on my iced tea glass at this moment! Such is typical of life most of the year in Houston though.

Since our last thought exchange back in December, the US federal government has changed reigns, with the beginning of the second Trump administration. As he promised during his campaign, the president instantly introduced frustrating trade tariffs causing mass uncertainly in most all commodity markets; associated stock market upsets have already taken place commensurately, as well.

Whether are not you are a supporter of such frustrating trade tactics (causing multi-trillion-dollar losses in stock market equity, currently too), we business folk must now deal with, and navigate our businesses through, yet one more significant liability for profitability. While oil/gas products surcharges are most likely to apply as well, we may more specifically study those early commodities which have already been affected.

Among a long list of isolationist trade controls meant to return manufacturing to the USA, the administration has proposed US port fees on ships made in China. Surcharges on these ships are already hitting agricultural, metals, and coal exports, as examples.

Reuters' reported Wednesday that "President Donald Trump's plan to revive U.S. shipbuilding using massive fees on China-linked ship visits to American ports is causing U.S. inventories to swell and is already stoking uncertainty in embattled agriculture and coal markets, as exporters struggle to find ships to send goods abroad.”

The United States Trade Representative is holding a public hearing regarding proposed Section 301 port call fees, which could range from $500,000 to $1.5 million per port call for vessels with Chinese-built connections.

“Trump is drafting an executive order that would rely on funding from a U.S. Trade Representative proposal to levy fines on China-made ships or vessels from fleets port fees have limited the availability of ships needed to move agriculture, energy, chemicals, mining, construction and manufactured goods to international buyers, according to major U.S. exporters and transportation providers in interviews with Reuters, letters to U.S. officials, and comments ahead of USTR hearings late month.”

Troutman Pepper Locke reported that the Trump administration’s proposal includes “a service fee (that) will be imposed on vessel operators from China, requiring payment of up to $1 million per entry into a U.S. port or up to $1,000 per net ton of the vessel’s capacity. In practice, most ships are expected to incur the maximum $1 million fee per port call. If a vessel makes multiple stops at U.S. ports, the operator will be required to pay this fee for each entry.”

In addition, “a service fee of up to $1.5 million per port call will apply to any operator with a vessel constructed in China or a fleet that includes such vessels, regardless of their flag or operator nationality,” Troutman Pepper Locke reported. “Even if a specific ship was not built in China, its operator may still be subject to the fee based on the overall composition of their fleet.”

Gao Lingyun, an expert at the Chinese Academy of Social Sciences in Beijing, said that the strong backlash from US industries shows that the US government's policy will ultimately result in American businesses and consumers paying higher prices. "The US is essentially lifting a rock only to drop it on its own foot," Gao told the Global Times. Apart from the shipbuilding and shipping industries, other US industries, especially exporters, also raised concerns and objections.

"We are extremely concerned that if this proposal goes into effect, US soybeans will be effectively shut out from our global export markets," Mike Koehne, an Indiana soybean farmer and director of the American Soybean Association, said in a document submitted to the USTR Office before the Monday hearing.

Koehne noted that the US does not have the domestic flag capacity to handle its export market at the rate proposed by the USTR. "Our industry is reliant upon ocean-going vessels to export our crop to customers around the world in a cost-effective and efficient manner."

"The USTR's proposed remedies targeting China's maritime, logistics and shipbuilding sectors could have severe unintended consequences for the US mining industry, which relies heavily on global shipping networks," Veronika Shime, vice president of International Policy and Sustainability at the National Mining Association, said in a statement submitted to the USTR.

Increased costs, supply chain disruptions, and even the outright inability to import or export critical materials could bring the industry to a standstill - threatening US manufacturing, energy production and national security. "We are already hearing reports of company transportation contracts being canceled, signaling immediate and serious disruptions," said Shime.

"We urge the USTR to consider the ripple effects beyond shipbuilding and engage with stakeholders to develop targeted solutions that do not inadvertently weaken American mining, manufacturing, and energy security," said Shime.

"This action will slam the brakes on oil and gas production as the fees are onerous and make the US immediately uncompetitive," Enterprise Products Partners, a Houston-based energy infrastructure company, stated in a document submitted to the USTR.

The company stated that "every time our people travel internationally to promote US energy exports, they get the same question - can we depend on the US. This action tells the world that they cannot."

The company also quoted Lars Jensen, CEO of Vespucci Maritime, a shipping expert, as saying "if the intention is to drastically increase costs for US importers and make US exports uncompetitive, this proposal is likely to do the job."

Global Time "Vessel owners have already refused to provide offers for future U.S. coal shipments due to the proposed USTR fees, Xcoal Energy & Resources CEO Ernie Thrasher said in a letter to U.S. Department of Commerce Secretary Howard Lutnick dated March 12 and seen by Reuters," Baertlein, Plume and Gardner reported. "…The letter from Pennsylvania-based coal marketer Xcoal (a MetCoal Exporter) and comments from agriculture representatives showing tangible impacts from the proposed fees have not previously been reported."

How the Proposed Fees Could Impact U.S. Agriculture

Baertlein, Plume and Gardner reported that "U.S. farmers, who are already getting pummeled by retaliatory tariffs from China, Mexico and Canada, also are caught in the crossfire of the Chinese ship fee fight, the American Farm Bureau Federation said."

"The inability to secure ocean freight transportation from May and beyond has restricted their ability to sell bulk U.S. agricultural products like corn, soybeans and wheat because exporters are unsure what the final cost would be, three U.S. grain export traders told Reuters," Baertlein, Plume and Gardner reported. "…Bulk agricultural exporters could face an additional $372 million to $930 million in annual transportation costs from the fees, the Farm Bureau said. That would represent substantial margin loss in global markets where competitiveness is often determined by mere pennies per bushel."

These proposed fees are expected to significantly increase shipping costs, potentially diverting traffic to non-US ports and leading to longer inland transportation routes, which could further accelerate costs for consumers.
While the proposal aims to strengthen the US maritime sector by encouraging the use of US-flagged and US-built vessels, the immediate benefits are expected to go to South Korean and Japanese shipyards, with long-term revitalization of the domestic industry taking years to materialize.

Importers and consumers of products containing imported components should stay alert regarding the latest logistics news, as the United States Trade Representative (USTR) plans to hold a public hearing on March 24, 2025, regarding proposed Section 301 port call fees.

Major Logistics News Going Underreported

If implemented, this measure could reshape global shipping dynamics and have far-reaching consequences for international trade with the United States. While the maritime industry and logistics news sources are paying close attention to this issue, metal buyers and energy traders are understandably focused on product tariffs. As such, the upcoming fees aren't getting the attention they deserve in the media. If you're worried about how the latest logistics news might affect your bottom line, pay close attention to these still-unfolding moves.

The proposed new fees would require significant operational changes for shipping companies, who would likely avoid smaller ports where they would need to spread the proposed fees across fewer containers. Instead, they would favor high-volume ports like Los Angeles, Long Beach, New York and Savannah.

Meanwhile, lower-volume ports like Oakland, Tacoma and Seattle could suffer sharp declines in traffic. For consumers, the impact wouldn't just come from the 301 fees, either. Longer inland transportation routes could drive up costs by more than $1,000 per 20-foot container.

The proposed fees range from $500,000 to $1.5 million per port call for vessels with Chinese-built connections. Most analysts expect the new fees to significantly increase shipping costs and reduce services for fleets that include Chinese-built ships.

Benefits of the Policy Could Be Years Away
Another major concern involves traffic diversion. For instance, shipping companies may choose to reroute cargo through non-U.S. ports, such as those in Mexico or Canada, to avoid the fees.

Although this strategy would sidestep the 301 charges, it could lead to delays, higher domestic delivery costs and potential product shortages. Even when vessels continue to use major U.S. ports, the added costs will likely pass on to consumers, just as tariff costs have in the past.

One of the primary goals behind the proposal is to strengthen the U.S. maritime sector by encouraging the use of U.S.-flagged and U.S.-built vessels. While this could eventually serve to revitalize the domestic shipbuilding industry and reduce reliance on foreign-built ships, any significant investment in U.S. shipyards will take years to materialize. In the short term, South Korean and Japanese shipyards will likely see the biggest benefits.

Although the USTR will make its determination soon, the final decision rests with the U.S. President. Moreover, there is no set timeline for the decision, thus leaving the industry in a state of uncertainty.

With that, if your business has not already placed these “trade war” issues on your business strategy and directional radar, then hopefully our March TVFRB piece will inspire further study, research, and most importantly, communication with your elected US Congress representatives. Until May, please remain healthy and happy.

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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
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Stages of Happiness

Karl Kolmetz

Happiness

Happiness is the combination of at least three parts, enjoyment, satisfaction and meaning.

Enjoyment is not pleasure, that is an animal concept. Human enjoyment involves people and memories to make something lasting, and this is uniquely human.

Satisfaction is the joy that comes from accomplishing something hard with struggle, this is a human concept.

Meaning is the significant that your life matters.

Research that looks at identical twins separated at birth and are tested forty years later shows that 50% of their happiness is genetic, so your mother did make you unhappy. This is important to understand because the same studies show 50% of your tendency to abuse alcohol is also genetic, but you can change that proclivity to zero by not drinking. Habits are important if you know yourself.

The next 25% of happiness is circumstances, life's ups and downs will affect your happiness, and many people think this is everything. The job, the family, the vacation but this is transitory. This will change as you go through life.

The next 25% of happiness is good habits. This is 25% of your happiness that is under your direct control. You can improve your circumstances and control your genetic proclivities. There are four things that can control your habits: Faith, Family, Friends, and Work.

Faith

For happiness faith is a path that will transcend yourself, to pay attention to things larger than yourself. We need perspective for each of us to get small and the universe to get large. We need something to get small and not let the narcissistic world think of ourselves as large and take over your soul.

Family Life

Families have been under attack for several generations. Long term studies show the happiest people are in long term relationships. Many people sacrifice long term happiness for short term pleasure. The failure of relationships are affairs, selfishness and pride. Easy to let short term issues result in long term unhappiness.

Friends

There are many types of friends. There are real friends, deal friends and worthless friends which everyone has.

Real friends are people that you have long term connections with. They have been honest with you, kept their word and not taken advantage of situations. It is very hard to find real friends and you are lucky to have very many.

Deal Friends are people that you deal with in your life. Your work acquaintances and people that you have business dealing with.

Work

Only two things that predict happiness in your profession, earning your success and serving other people. Earning your success means that you are creating value in your life, and value in the life of other people. That means you are being rewarded and acknowledged for merit, hard work and personal responsibility. The only economic system that brings joy to work is the free enterprise system, even with all its flaws.

The essence of dignity is to be needed as a person. The essence of despair is to be managed like a liability, instead of assets to be developed. That is why government assistance programs fail because they treat people like liability instead of assets to be developed. You need to serve in your work and see how you are helping other people live better lives.

Declining Happiness

Since 1990 there has been a continually decline of happiness in every survey. There is a lack of the four things of happiness. There is a decline in faith, they are not building relationships, they are not building friendships, and they do not have a vocational since of their work.

Also contributing to the declining happiness is the social order change. Our current social order now values where you obtained your education, more than your knowledge, more than your values, more than your work ethic. Over fifty percent of the people in the elite workplaces went to the same 34 elite colleges. Many organizations only hire their managers from the same elite college that have very liberal values.

So hard work, knowledge and values no longer will get you the best jobs in many organizations, leading to many people rejecting the new social order because it is based on connections instead of merit. There is general unhappiness with the new social order.

Stage One – Selfishness Equals Unhappiness

The default state of humanity is me first and every child is born with this trait. The innate tendency of humans is self-interest. They must be taught to share as part of their development. This is where we all start. An infant only wants immediate gratification, and this is not a sustainable lifestyle. The long term of me first is failure. Sustained self-centeredness ultimately leads to failure.

Many members of my family are still in stage one.

Stage Two - Family Sharing and Some Happiness

Family sharing is essential. We learn to share with our family knowing that they are some of the only people that will support us in hard times. They can depend on our help, and we can depend on theirs. This is a very important theme in Asia, but we seem to have lost this in the USA, we now depend on the government, to the detriment of our family units.

Again, many family members look for help but provide very little in return when needed.

Stage Three – Sacrifice for the greater good

Sacrifice is fundamentally essential to the foundation of civilization. Civilization, being inherently social and future-oriented, necessitates individuals to forgo their immediate personal interests for the benefit of the community. Maturity and wisdom involve the ability to prioritize long-term goals over present demands. This entails the sacrifice of self for the future and for the greater good of the community. Such sacrifices have historically contributed to the abundance of wealth and freedom observed in Western Civilization.

When a child makes a friend, they learn to share. I have a turn, then you have a turn – the sacrifice there is that it is not always my turn.

Western Civilization was fundamentally organized around a sacrificial altar within the church. The church served as the focal point of the town, and the town, in turn, was central to the state. Sacrifice played a crucial role in the development of Western Civilization. It is voluntary self-sacrifice towards the highest possible end that is the foundation of civilization.

Today many organizations are teaching that individual identity is more important than the greater good, which is leading to social fragmentation and ultimately leading to less abundance of wealth and freedom.

Very few people reach stage three and those that do are highly respected and despised at the same time.

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Process Design of Industrial Deaerators

Jayanthi Vijay Sarathy

The primary purpose of an industrial deaerator is to purge feed water in process facilities of any oxygen (as air). Oxygen in feedwater is a common cause for corrosion in industrial equipment. The presence of any carbon dioxide in feed water exacerbates corrosion by forming carbonic acid which lowers the pH of the water. With time, pitting corrosion sets in & perforates the equipment.

To attend to the issue of oxygen in feedwater, a deaerator collects the returning feedwater containing non-condensables (including air) and is stripped out using steam. The following article explains the process design steps for a deaerator.

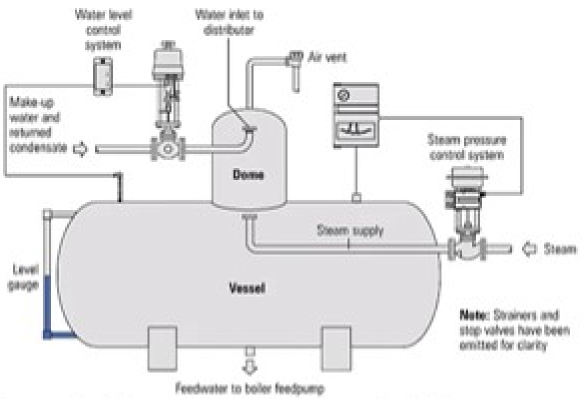

Figure 1. Deaerator Schematic [4]

General Notes

1. The solubility of gas in a solvent depends on its pressure and temperature and is governed by Henry's Law. At higher temperatures, the solubility of gas decreases. However, at higher pressures, solubility increases which dictates the necessity to operate a deaerator at lower pressures.

2. In actual practice, feedwater is both chemically (such as sodium sulphite) and thermally treated to expunge any dissolved gases to maintain a pH between 8 and 9 to avoid corrosion.

3. The saturation temperature, (i.e., boiling) of water is 100^0C at 1 atm. When feed water comes into contact with the stripping steam, chances are that the feedwater can vaporize and would be vented with the steam. Therefore, to prevent loss of feedwater through venting, it is imperative to supply feedwater below its saturation temperature, say between 80^0C to 90^0C. Typically, the feedwater must be deaerated up to 0.02 mg/litre (ppm)

4. Deaerators can operate under pressurized or vacuum conditions. For pressurized deaerators, typical operating conditions would be between 0.2 to 0.5 barg. The deaerated water collection vessel would have a holdup time of 10 to 15 minutes or higher depending on the process requirements. Since the steam is suppled via a control valve, steam pressures can range from 5 barg to 10 barg. The returning feedwater supply pressure must be at least 2 barg to ensure sufficient atomization occurs and the water droplets come into contact with the steam inflow.

5. To minimize steam consumption and increase efficiency, the feed water must be hot as possible, but below saturation temperature. However, since this is not possible during a plant start-up, the feedwater tank must be provided with heating coils for plant start-up purposes.

6. The deaerator can also be insulated to minimize heat losses. During venting, along with air / non-condensables, some amount of water is also expected to be lost due to entrainment. Turndown ratios are typically around 5:1. The control system must include steam control, water level control and manual venting provisions.

Problem Statement

A deaerator operates at 0.2 barg with feed water supplied at 80^{0}C from condensate tank in a process facility. The non-condensables is taken to be only air. It is assumed that the deaerator is insulated well with no heat losses and the air is assumed to be completely carried by the steam to the vent. The Air % in total volume of air-steam mixture a.k.a., volume of air to steam in mixture at 0.2 barg is taken to be 16.408% from figure 2. Alternatively, the online calculator from Ref [6], can be used to determine the Air% in total volume of air-steam mixture. The boiler supplying steam operates at 5 barg with a supply flow of 5 tonnes/hr.

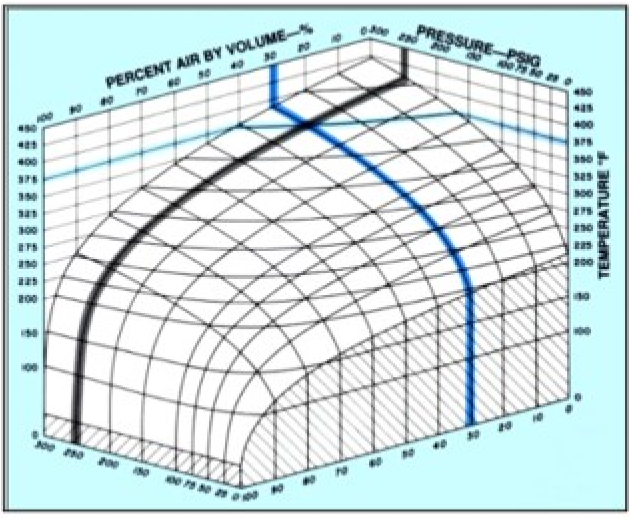

Figure 2. Volume of Air to steam in mixture [7]

From the data given, the venting rates can be calculated as,

$$Steam\ Saturated\ T\ at\ 0.2barg = 105.101°C \quad (1)$$

The partial pressure [PP_{air}] of air in steam is,

$$PP_{air} = P_{Deaerator} - \left[\frac{Air\ \%}{100} \times P_{Deaerator}\right] \quad (2)$$

$$PP_{air} = 1.21325 - \left[\frac{16.408}{100} \times 1.21325\right] \quad (3)$$

$$PP_{air} = 1.01418\ bara \quad (4)$$

$$Air\ Saturated\ T\ at\ 1.0142\ bara = 100°C \quad (5)$$

With the presence of air in steam, there would be a reduction in the saturation temperature of steam since air is a poor conductor of heat. As a result, the deaerator operating temperature would be lower than 105.101^{0}C at 0.2 barg, i.e., 100^{0}C. Therefore, the reduction in steam temperature in the deaerator is,

$$\Delta T = T_{steam} - T_{Air-Steam\ mixture} \quad (6)$$

$$\Delta T = 105.101 - 100 = 5.101°C \quad (7)$$

The steam released with per litre of air is,

$$m_{steam/air} = \frac{100-Air\%}{Air\%} \quad (8)$$

$$m_{steam/air} = \frac{100-16.408}{16.408} = 5.095\ litres \quad (9)$$

The density of air is calculated using Ideal gas equation. Considering the operating pressures are low at 0.2 barg, the compressibility factor [Z] is taken to be 1.0.

$$\rho_{air} = \frac{PP_{air}[bara] \times MW[\frac{kg}{kmol}]}{Z \times \left(0.08314\frac{m^3.bar}{kmol.K}\right) \times T[K]} \quad (10)$$

$$\rho_{air} = \frac{1.01418 \times 28.96}{1 \times 0.08314 \times (100+273.15)} = 0.947 kg/m^3 \quad (11)$$

From steam tables [8], the specific volume [v_{steam}] of steam at 100^{0}C is 1.41385 m^3/kg from which the steam density is calculated as,

$$\rho_{steam} = \frac{1}{v_{steam}} = \frac{1}{1.41385} = 0.7073\frac{kg}{m^3}\ or \left[\frac{gm}{L}\right] \quad (12)$$

Therefore, the steam released by 0.9467 gms of air is,

$$m_{steam\ release} = m_{steam/air} \times \rho_{steam} \quad (13)$$

$$m_{steam\ release} = 5.095 \times 0.7073 = 3.6\ gms \quad (14)$$

The solubility at 0.2 barg and 80^{0}C is,

$$S_{80°C} = 0.0002024 \times 28.96 = 0.00702\frac{gm}{lit} \quad (17)$$

Therefore, the total air and steam vented per 1000 kg of deaerator capacity is,

$$m_{T,steam/air\ mix} = 7.02 + 26.71 = 33.73\ gm \quad (20)$$

In practice, the flow rate of the order of 30 or 40 gms of steam-air mixture is very low to be vented / regulated and must be purged to avoid re-entrainment. For this reason, manufacturers recommend a venting rate between 0.5 to 2.0 kg of steam-air mixture per 1000 kg of feed water [3].

Steam Requirements

To estimate the steam requirements for the deaerator, it can be made based on the boiler's capacity and feedwater requirements. For this, the boiler's maximum useful steaming rate must be determined which depends on the initial feedwater temperature. The maximum boiler output [m_{boiler}] is estimated as,

$$m_{boiler} = \frac{\lambda_{1\,atm} \times Boiler\ Capacity}{H_{Boiler\ Pressure} - H_{feedwater\ Temperature}} \quad (21)$$

Where,

$\lambda_{1\,atm}$ = Latent heat of vaporization [kJ/kg]

$H_{boiler\ Pressure}$ = Specific Enthalpy at Boiler Pressure [kJ/kg]

$H_{feedwater\ Temperature}$ = Specific Enthalpy at feedwater temperature [kJ/kg]

For a boiler pressure of 5 barg at the inlet of the steam control valve and 5,000 kg/h of steam, the latent heat of vaporization [□] at 1 atm is 2,258 kJ/kg [9]. The specific enthalpy at the inlet of the steam control valve [$H_{boiler\ P}$] is 2,756.23 kJ/kg for 5 barg. The initial feedwater specific enthalpy [$H_{feedwater\ T}$] at 80^{0}C is 334.501 kJ/kg. Therefore, the maximum or effective boiler output [m_{boiler}] is,

$$m_{boiler} = \frac{2258 \times 5000}{2756.23 - 334.501} = 4{,}662\ kg/h \quad (22)$$

To estimate the steam requirements, an energy balance is made such that the initial amount of heat in the feedwater and heat added by the injected steam is equal to the final amount of heat in the feedwater and condensed steam. The energy balance is,

$$(m_{boiler} h_1) + (m_s h_g) = (m_{boiler} + m_s) h_2 \quad (23)$$

Where,

m_{boiler} = Max boiler output at initial T [kg/h]

h_1 = Enthalpy of feedwater at supply T [kJ/kg]

m_s = Steam flow rate [kg/h]

h_g = Enthalpy of steam supplied [kJ/kg]

h_2 = Enthalpy of feedwater at final T [kJ/kg]

Re-arranging the energy balance equation,

$$m_s = m_{boiler} \times \frac{[h_2 - h_1]}{[h_g - h_2]} \quad (24)$$

Therefore, for an effective/max boiler capacity [m_{boiler}] of 4,662 kg/h, the enthalpy of the returning feedwater supply [h_1] at 80^{0}C is 334.501 kJ/kg. The enthalpy of steam supplied at the upstream of the control valve [h_g] at 5 barg is 2756.23 kJ/kg. The enthalpy of feedwater at a final temperature [h_2] of 105.101^{0}C is 440.19 kJ/kg.

$$m_s = 4{,}662 \times \frac{[440.19 - 334.501]}{[2756.23 - 440.19]} = 213\ kg/h \quad (25)$$

Therefore, the steam flow required at 5 barg at the steam control valve upstream is 213 kg/h, and a downstream pressure of 0.2 barg, i.e., the operating pressure of the deaerator. The saturation temperature of air-steam mixture in the deaerator operating at 0.2 barg is 105.101^{0}C, which reduces to 100^{0}C due to the presence of 16.408% Air in the steam.

Steam Control Valve Size

To regulate steam into the deaerator, a steam control valve is placed in the line from the boiler to the deaerator. The boiler generates steam at 5 barg which is reduced to 0.2 barg at the downstream of the control valve (assuming line losses are neglected). For a steam flow rate of 213 kg/h, the control valve coefficient [C_v] is calculated as,

$$C_v = \frac{m}{94.8 \times F_P \times P_1 \times Y} \sqrt{\frac{T_1 Z_1}{x \times MW}} \quad (26)$$

Rearranging to calculate mass flow rate 'm',

$$m_s = C_v \times 94.8 \times F_P \times P_1 \times Y \sqrt{\frac{x \times MW}{T_1 Z_1}} \quad (27)$$

Where,

$$Y = 1 - \frac{x}{3\,F_K\,X_T} \quad (28)$$

$$F_K = \frac{k}{1.4} \quad (29)$$

$$x = (P_1 - P_2)/P_1 \quad (30)$$

m_s = Steam Mass flowrate [kg/h]

C_V = Flow rate coefficient at rated capacity [-]

P_1 = Upstream absolute pressure [bara]

P_2 = Downstream absolute pressure [bara]

MW = Gas molecular weight [kg/kmol]

T_1 = Control valve inlet temperature [K]

k = specific heats factor [C_p/C_v]

Z = gas compressibility factor [-]

ΔP = Pressure drop at rated flow [bar]

F_p = Piping geometry factor ($F_p = 1$)

F_K = Ratio of specific heats factor [=k/1.4] [-]

x = Pressure drop ratio [-]

X_T = Choked flow ΔP factor (Ref 12) [-]

Y = Gas expansion factor [-]

$$If\ \frac{\Delta P}{P_1} > F_k x_T\ then\ x = F_k x_T \quad (31)$$

$$If\ \frac{\Delta P}{P_1} < F_k x_T\ then\ x = \frac{\Delta P}{P_1} \quad (32)$$

$$If\ \frac{\Delta P}{P_1} > F_k x_T\ then\ Crictical\ Flow \quad (33)$$

$$If\ \frac{\Delta P}{P_1} < F_k x_T\ then\ Sub\ crictical\ Flow \quad (34)$$

Table 1. Steam Control Valve Sizing

Parameter	Value	Units
Inlet Pressure [P_1]	5.0	barg
Outlet Pressure [P_2]	0.2	barg
Inlet Temperature [T_1]	3.60	^{0}C
Steam MW	18.02	kg/kmol
Ratio of Specific Heats [$k = C_P/C_V$]	1.2986	-
Gas Compressibility Factor [Z]	0.9497	-
Piping Geometry Factor [F_p]	1.0	-
Control Valve Characteristics	Eq %	-
Control Valve Size Chosen	6	inch
Rated ΔP Factor [x_T]	0.78	-

Based on ANSI/ISA S75.01 method, for a piping geometry factor (F_p) of 1.0, i.e., no pipe fittings, 6" control valve size, equal percentage characteristics and a steam flow of 213 kg/h, the control valve C_v is estimated to be 3.14.

Appendix A

Air Solubility in Water

The solubility of air in water [S] can be estimated based on Henry's Law [1] which is calculated as,

$$S = K \times P \qquad (35)$$

Where,

S = Solubility [g/L]

K = Henry's constant [mol/lit/atm] or [M/atm]

P = Partial pressure of the gas in solvent [atm]

Henry's constant is dependent on temperature and can be adjusted to the de-aerator feed water temperature using the correlation like Van't Hoff equation [1] as follows,

$$K[T] = K^0 \times e^{\left[\frac{-\Delta_{sol}H}{R}\left(\frac{1}{T}-\frac{1}{T^0}\right)\right]} \qquad (36)$$

Where,

K^0 = Henry's constant at reference temperature of 293.15 K [M/atm]

T = Feedwater Temperature [K]

T^0 = Reference Temperature of 293.15 [K]

$-\Delta_{sol}H / R$ = Enthalpy of Dissolution [M/atm]

Considering air consists of oxygen and nitrogen predominantly, the enthalpy of dissolution [$-\Delta_{sol}H/R$] can be calculated from known data [2], i.e., the solubility of air [K^0] in water is ~7.9 x 10^{-4} at 20^0C and 1 atm and a rejection rate of 5.9 grams of air per 1000 kg of water [0.0002024 mol/litre] at 80^0C [353.15 K] and 1 atm. Therefore, for a de-aerator feedwater pressure of 1 atm and 20^0C,

$$7.9 \times 10^{-4} = K^0 \times 1 \xrightarrow{yields} K^0 = 7.9 \times 10^{-4} \qquad (37)$$

And Henry's Constant [K] at 80^0C and 1 atm,

$$K[T] = \frac{S_{80^0C}}{P_{atm}} = \frac{0.0002024}{1} = 0.0002024\ M/atm \qquad (38)$$

Re-writing the temperature dependent Henry's constant equation, the enthalpy of dissolution of air in water is,

$$\frac{-\Delta_{sol}H}{R} = \frac{ln\left[\frac{K[T]}{K^0}\right]}{\left[\frac{1}{T}-\frac{1}{T^0}\right]} = \frac{ln\left[\frac{0.0002024}{0.00079}\right]}{\left[\frac{1}{353.15}-\frac{1}{298.15}\right]} = \sim 2350 \qquad (39)$$

The Van't Hoff equation in the above form though is valid for a limited range, but the value of $-\Delta_{sol}/H$ does not vary change much with temperature variation of the order of around 20K [1]. Therefore, for the low operating temperature of the deaerator [0.2 barg] and feed water temperature in the range of 80^0C to 90^0C, the enthalpy of dissolution [$-\Delta_{sol}H/R$] can be taken as 2350.

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Appendix B: MS-Excel Spreadsheet

Process Design of Industrial Deaerator

Air in water - Reference Data		
Molar Mass of Air	28.96	g/mol
Density of Water	1000	kg/m^3
Mole Fraction of Air	1.0	-
Partial Pressure [$P_{air\ in\ Water}$]	1.0	atm
Henry's Law Contant at 20°C, 1 atm [H°] - AiW	0.00079	M/atm
Solubility of Air in Water at 1 atm, 20°C	0.0229	gm/litre
	22.88	mg/l
Henry's Law Contant at 80°C, 1 atm [H°] - AiW	0.00020	M/atm
Solubility of Air in Water at 1 atm, 80°C	0.0059	gm/litre
Solubility of Air in Water at 1 atm, 80°C for 1000L [= 1000 kg]	5.86	gms
Enthalpy of Dissolution [$-\Delta_{sol}$ x H / T] of Air in Water	2,350	K
Deaerator Operating Conditions		
Henry's Law Contant at Deaerator T - AiW	0.0002024	M/atm
Solubility of AiW at Deaerator 0.2 barg, 80 degC 1000L [= 1000 kg	0.0002424	mol/lit
	0.00702	gm/litre
	7.02	gms
Venting Requirements		
Feed Water Temperature [T]	80	°C
Deaerator Operating Pressure	0.2	barg
	1.213	bara
Saturated T of Steam at 0.2 barg	105.101	°C
Air % in total volume of air-steam mixture	16.408	%
Partial Pressure of Air	1.01418	bara
Saturated T of Steam-Air Mix at 1.0142 bara (or) Dearator Op T	100	°C
Fall in Steam Temperature due to Air in Steam [ΔT]	5.101	°C
Steam Released per litre of Air [$m_{steam/air}$]	5.095	litres
Density of Air at 100 degC [ρ_air] [kg/m3 = gm/L]	0.9467	gm/litre
Specific Volume of Steam at 100 degC [v_steam]	1.41385	litre/gm
Density of Steam at 100 degC [ρ_steam]	0.7073	gm/litre
Steam Released by 0.9467 gms of Air	3.60	gms
Air Released from 7.02 gms of feedwater	26.71	gms
Total Air & Steam Vented per 1000 kg of Deareator Capacity	**33.73**	**gms**

Steam Requirements		
Boiler Capacity	5,000	kg/h
Boiler Pressure at Inlet of Steam Control Valve	5	barg
Saturated Temperature of Steam at 5 barg	158.919	°C
Specfic Heat Ratio of Steam at 5 barg [k =Cp/Cv]	1.2986	-
Gas Compressibility Factor [Z] of Saturated Steam at 5 barg	0.9497	-
Latent Heat of Vapourization [1 atm] [λ]	2258	kJ/kg
Specific Enthalpy of Steam at Boiler P [5 barg] [H_Boiler_P]	2756.23	kJ/kg
Initial Feedwater Specific Enthalpy [80 degC] [H_feedwater_T	334.501	kJ/kg
Max Boiler Output [m_{boiler}]	4,662	kg/h
Enthalpy of Feedwater at 105.101 degC [h2]	440.19	kJ/kg
Enthalpy of Steam supplying at Control Valve [5 barg] [hg]	2756.23	kJ/kg
Enthalpy of Feedwater at 80 degC [h1]	334.501	kJ/kg
Steam Flow Rate Required [ms] [5 barg]	212.74	kg/h

Steam Control Valve Requirements		
Control Valve Inlet Pressure [P1]	5.00	barg
Control Valve Outlet Pressure [P2]	0.20	barg
Control Valve Inlet Temperature [T1]	158.919	°C
Steam Molecular Weight [MW]	18.02	kg/kmol
Rated Pressure Drop Factor [xT]	0.78	-
Flow Behaviour across Control Valve	CRITICAL	-
Steam Control Valve Flow Characteristics	Equal %	-
Steam Control Valve Size	6"	-
Steam Control Valve C_v	**3.14**	-

Steam Control Valve Sizing		
CONTROL VALVE INPUT		
Parameter	**Value**	**Unit**
Control Valve Inlet Pressure [P_1]	**5.00**	barg
	87	psia
Control Valve Outlet Pressure [P_2]	**0.20**	barg
	18	psia
Control Valve Inlet Temperature [T_1]	**158.92**	°C
Steam Molecular Weight [MW]	**18.02**	kg/kmol
Ratio of Specific Heats [$k = C_P/C_V$]	**1.2986**	-
Control Valve C_v	**3.14**	-
Gas Compressibility Factor [Z]	**0.9497**	-
CALCULATIONS		
Parameter	**Value**	**Unit**
Pressure Drop [ΔP]	70	psia
Pressure Drop Ratio [x]	0.72	-
Piping Geometry Factor [F_p]	**1.00**	-
Ratio of Specific Heat Factor [F_k]	0.93	-
Control Valve Flow Characteristics	**Equal %**	-
Control Valve Size	**6"**	-
Rated Pressure Drop Factor [x_T]	**0.78**	-
Expansion Factor [Y]	0.667	-
Flow Behaviour across Control Valve	**CRITICAL**	-
Mass Flow through Control Valve	**212.7**	kg/h

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