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Commercial Demonstration Case Study of a Novel Partial Upgrading Technology using Athabasca Bitumen

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ABSTRACT

A novel partial upgrading technology has been tested and validated at a 1,000 barrel per day Commercial Demonstration Facility in the field in Alberta, Canada. Initially reported in WHOC 16-232. The technology configuration was modified and then further tested over the course of one-year. Updated results will be presented that illustrate that the technology has the ability to significantly reduce the amount of diluent required to meet pipeline specifications by greater than 50%, reduce TAN below 1.0 mg KOH/g of oil while achieving near 100% volumetric yield. Other important product quality data will also be presented including viscosity, density, stability and olefin content. The core technology combines hydrodynamic cavitation and mild thermal cracking, without the formation of coke or by-products, resulting in beneficial product properties. The technology is designed to be applied in the field, close to a production facility or shipping terminal, where extra heavy oil or bitumen is typically blended with diluent for transportation via pipeline or rail.

KEY WORDS

Partial Upgrading, Field Upgrading, Upgrading, Cavitation, Diluent, TAN, Total Acid Number, Sulfur, Viscosity, Bitumen, Pipeline, Stability, P-value.

INTRODUCTION

Exploitation of heavy oil and bitumen resources has historically been challenging due to the high cost to develop, produce, transport and refine into transportation fuels. It is technically difficult and economically challenging to produce due to cost intensive enhanced oil recovery methods often being required. Once produced it is costly to refine into marketable products (i.e. mainly transportation fuels). In addition, it is difficult to transport from remote oil fields to the large, centralized refiners where it is processed into transportation fuels. The reason heavy oils are difficult to transport is primarily due to its high density and highly viscous nature.

Industry experts forecast a large increase in Western Canadian bitumen production over the next 15 years as the oil sands are further developed. Current demand forecasts indicate most of this increase in production will ultimately be transported to refineries in the United States. This will require major expansions of the pipeline and rail infrastructure as the current systems are inadequate to meet the growth in volumes.[1,2,3]

Pipeline tariffs or tolls to transport heavy blends to market are one of the most significant costs that a heavy oil and bitumen producer faces. In addition, the diluent required to meet pipeline specification is purchased at a premium and is subject to a tariff on the volumes sent to the field. Once the blend arrives at the refinery, the diluent content in the blend is sold at a discount, as the diluent is not in demand in most North American refinery markets due to excess supply.

The Canadian Association of Petroleum Producers has forecast that an expansion of the existing transportation infrastructure is required to connect growing crude oil supply from Western Canada to new markets[1].

Pipelines have traditionally been the primary mode of transportation for cost-effective long-term movements of bitumen, but the protracted regulatory process continues to present a number of challenges. This is resulting in higher heavy-to-light discounts due to excess supply, insufficient takeaway capacity and apportionment. Delays in new pipelines is providing the impetus for additional take-away capacity from railways to complement pipeline transport [2].

Another challenge the oil sands are facing is the high carbon content in the bitumen. When bitumen is upgraded at the refinery to produce final products, it undergoes emission-intensive processes. As well, the greenhouse gas (i.e. GHG) impact of diluent production and transportation is significant. Therefore, the industry requires new solutions to improve efficiency and reduce GHGs.

JetShear™, a proprietary, patented-technology developed by Fractal System, Inc., was first tested in a pilot scale facility (e.g. 1 to 30 barrels of oil per day) which successfully demonstrated the potential of the technology using various crudes provided by Alberta bitumen and heavy oil producing companies. In the process demonstration the dilbit was first pressurized and heated, to a certain temperature and pressure, and finally passed through an engineered nozzle or nozzles resulting in a rapid depressurization. The processed fluid was upgraded as evidenced by a reduced viscosity and density.

The company subsequently validated the pilot scale studies in the field by processing heavy oil and bitumen at a 300 barrel per day demonstration facility equipped with two 150 bpd nozzles. The field performance effectively demonstrated that the pilot scale results could be “scaled up” (e.g. 150:1).

Over the period from 2012-2017 Fractal developed a relationship with a major oil sands producer and expanded the capacity of the 300 bpd Demonstration Facility in phases to a commercial scale demonstration facility (Phase 1) with a throughput capacity of 1,000 bpd. The facility was equipped with two 500 bpd JetShear nozzles which are located inside of the JetShear building and shown in Figure 1.

From April 2014 to April 2015, the Commercial Demonstration facility processed over 110,000 barrels of partially diluted bitumen that was trucked to the site in Provost, Alberta from SAGD projects in the Athabasca region. The partially diluted bitumen blend processed in the JetShear facility was representative of the blend ratio at a typical SAGD Central Processing Facility, upstream of trim blending, where additional diluent is added to meet the pipeline specification.

Building on the successful demonstration of the JetShear™ technology platform that concluded in 2015, Fractal retrofitted the JetShear (JS) facility (Figure 2). The facility included a front-end fractionation unit to distill off the light fraction (i.e. diluent) present in the dilbit blend before entering the reaction zone. In addition, a hydropolishing unit was added to hydrotreat the light fraction produced during the reaction thereby eliminating or reducing the olefins generated during the conversion of the neat bitumen. The new configuration is called Enhanced JetShear (EJS).

EJS was successfully demonstrated in the field over one-year in 2016-2017. During the operating periods, the Facility processed over 110,000 barrels of partially-diluted bitumen. The technology significantly improves the physical properties of bitumen allowing the processed bitumen to move more easily in pipelines. The results achieved indicate that a significant reduction to costs associated with transporting bitumen is possible by avoiding up to 53% of the required diluent for the tested dilbit, reducing the TAN by more than 60% to below industry thresholds and maintaining the olefinic content of the crude below the specification limit (i.e. 1% by weight).

A 3D model presenting the main equipment and layout of the plant is shown in Figure 3. The facility is predominantly comprised of well-known processing equipment. Given that the facility was designed to generate commercial EJS product, heat integration and treatment of by-product gases was not a primary objective, as those technologies are well understood and do not require field-testing.

STATEMENT OF THEORY AND DEFINITIONS

The objective of JetShear™ is to change or modify the structure of bitumen and heavy oils to reduce viscosity, improve density and reduce TAN and thereby improve its value. Viscosity reduction is achieved by targeting modifications of the asphaltene microstructures and its concentration, which comprises the heaviest fraction of heavy oils. Maltenes surround these extremely complex microstructures and the arrangement of these molecules in the maltenes result in the observed high viscosities of heavy oil and bitumen.

JetShear™ uses a low severity hybrid approach relying on hydrodynamic cavitation[4] and the application of heat to structurally modify the asphaltene molecules. Thermal disorder, below incipient cracking temperatures, is first introduced followed by cavitation through a nozzle. Due to the rapid change in pressure, microbubbles form around nucleation sites. Nucleation sites can be suspended submicron particulate matter, colloidal micelles, or pre-existing microbubbles.[5] The forces that hold the liquid together need to adjust to these rapid changes in pressure. The resulting kinetic energy from cavitation is liberated into sufficient chemical energy to modify the microstructure and the state of aggregation of the initial heavy oil components.

The processing of heavy oil with JetShear^{TM} results in a slight reduction of asphaltene and an increase of resins concentration, leading to new and beneficial properties (i.e. decrease in viscosity and lower bulk density) and a stable product with minimal changes in volumetric yield.

There are different ways to measure severity in JetShear^{TM} process, which are all a function of residence time (i.e. average residence time), temperature, and pressure. For our study, pressure was kept constant. Many measures of severity are not practical for experimental purposes due to changes in the composition of the feed and the corresponding impact on residence time.

For example, the feed in the first phase of the commercial demonstration consisted of an under-diluted dilbit with up to 21 vol% of diluent. For the second phase, the diluent was removed before entering the reaction zone which reduced the vapor traffic affecting the flow pattern in the reactor. This made it difficult to compare Phase 1 and Phase 2 (JS vs EJS) on a severity index basis. Also, the reduction of lighter fractions (i.e. diluent) in the head space of the reactor improved operating performance at higher severity conditions. In this paper we compared JS vs. EJS on a diluent displacement basis and believe it to be the most representative way of comparing the Phase 1 and 2 performances.

DATA AND OBSERVATIONS

The goal of the field demonstration project was to achieve 1) Diluent displacement > 50 vol% with stable product properties, 2) TAN lower than 1 mg KOH/gr oil, 3) olefin content below pipeline specification (i.e.1 wt%), and 4) facility operability and throughput expectations with no safety or environmental incidents. All key targets were met or exceeded. Table 1 shows the milestone targets and the field performance achieved.

The following sections describe the main product properties as a function of diluent displacement and a brief discussion of them.

RESULTS AND DISCUSSION

Diluent Displacement

Diluent displacement is a result of the combination of viscosity and density improvements using JetShear^{TM}. It was calculated as the difference between the ratio (diluent/untreated bitumen) required for the untreated bitumen to meet pipeline density and viscosity specifications, and the ratio (diluent/treated bitumen) required for the JetShear^{TM} product to meet pipeline specification.

Using data from the field trials and in-house blending and viscosity correlations, the minimum required diluent addition to raw bitumen to reach viscosity < 350 cSt and density < 940 kg/m^3 at a weighted average yearly reference temperature of 11.9° C were determined. A similar approach was applied to the various JetShear^{TM} products generated at the facility. As shown in Table 1 diluent displacement more than 50% was established as the performance target.

Figure 4 shows the percentage improvement of viscosity measured at 11.9° C as a function of diluent displacement for both Commercial Demonstration phases. It is observed that removal of the diluent upstream of the reaction zone (i.e. JetShear module) results in reduced vapor traffic and improved reaction kinetics, further improving conversion of bitumen, measured as the conversion of the residue. It is postulated that the increase in the concentration of the asphaltenes in the feed to the reaction zone, due to removal of the diluent, plays an important role in the conversion of asphaltenes. Figure 5 shows how Enhanced JetShear distillation profile on an undiluted basis is improved over the tested bitumen: a) Resid decreased by 36%, b) VGO, diesel and naphtha increased by 50% and, c) Improved naphtha/resid ratio in the EJS product (e.g. meeting pipeline specifications) is more attractive to refiners.

During Phase 1 of the technology demonstration the maximum diluent displacement reached was 43% whereas for the second phase was 53%. During the first phase the limiting factor for achieving higher diluent displacement was staying below a maximum olefin content in the pipeline product (i.e. <1.0 wt %). With Enhanced JetShear and the inclusion of a hydropolishing step to address olefins effectively removes olefin content as a constraint. With Enhanced JetShear the limit to achieving higher diluent displacements then becomes product stability.

Among the available methods to measure stability and compatibility is the P-value method (i.e. ASTM D7157). The method is broadly accepted by the industry, is objective, and measures how easily the asphaltenes, in heavy fuel oils and diluted in toluene separate or flocculate with the addition of n-heptane. The test method results in a calculated P-Value. Crudes that show an acceptable P-value number (e.g. >1.25) are deemed stable and are compatible with other crudes.

The principle of the method involves mixing several samples of dilbit with an aromatic solvent (i.e. toluene) at different concentrations. The mixtures are subsequently titrated with a paraffinic solvent (i.e. n-heptane) to cause precipitation of asphaltenes. After each addition of paraffinic solvent, a droplet of the solution is placed on a filter paper for visual detection until appearance of the two dark rings within each other formed in the spot. The determined results of flocculation are used to calculate the stability parameters and subsequently the intrinsic stability from the relative amounts of oil, paraffinic, and aromatic solvents.

At 53% diluent displacement, the product has a P-Value of 1.5, compared with the untreated dilbit, P-value 2.38 (Figure 6). This reduction in stability is normal and is expected in any processing that has a thermal processing component. A thermally processed crude with a P-Value > 1.25 to 1.5 is widely accepted by industry as being stable.

SARA Analysis

The major reactions during thermal upgrading of heavy oils and bitumen can be summarized as follows:

Thermal Chemistry*:*

- Cleavage of C-S. S-S, S-H and C-H bonds
- Cleavage of C-C bonds - side chain fragmentation
- Hydrogen shuttling
- Ring hydrogenation/dehydrogenation
- Ring growth – leading to coke formation
- Ring opening
- Formation of olefins and diolefins

The cleavage of relatively weak bonds such as S-S and C-S during thermal reaction results in a significant reduction in viscosity but the cleavage of C-C bonds which are the most prominent bond in heavy oils and bitumen is most effective to reduce the molecular weight and produce distillate products.

Product analysis indicates that during thermal reactions, dehydrogenation of hydrocarbons, as well as disproportionation of bond-cleavage generated radicals, can result in formation of unsaturated compounds such as olefins, which may be undesirable products in refinery feedstock. Side chain fragmentation, from mono-di aromatics, polyaromatics and polar bonds can also lead to lighter hydrocarbons. While these types of reactions also produce paraffinic compounds, which may be desirable (e.g. saturates increase), they are non-solvents and can precipitate asphaltenes. Further, in the absence of hydrogen, as the reaction severity is increased, aromatization and dehydrogenation of aromatic cores in asphaltene molecules makes these relatively large molecular structures less soluble in the reaction products, lowering e the P-value of the product.

In thermal-cracking-only processes the hydrocarbon free radicals that are produced combine with other free radicals and create multi-aromatic rings. These condensation reactions eventually produce highly condensed asphaltenic structures.

The tendency of thermal-cracking-only processes to produce asphaltenes and lighter non-solvent paraffins results in a conversion limit beyond which product instability can occur. Higher thermal severity increases the rate of condensation reactions, resulting in the creation of additional asphaltenes[6].

Mild thermal cracking in combination with cavitation, however, results in asphaltene conversion. SARA analysis performed on the untreated and treated product are shown in Table 2. A 10% reduction of asphaltene concentration is observed in the pipeline spec EJS product vs. the pipeline spec dilbit feed, despite the lower diluent content in the EJS product. This result is not common in thermal-cracking-only processes. Also observed is an increase of the resin content which could contribute to the stability of the product. Asphaltene conversion is further evidenced by examining the C5 Insoluble wt% of the undiluted bitumen and undiluted EJS product as shown in Table 3. The treated bitumen clearly has a significant reduction in asphaltene content due to the combination of cavitation and mild thermal cracking.

Density

The observed density improvement shown in Figure 7 was relatively minor for the Jetshear trials but is still important with respect to volumetric yield. Density was improved even further in the second Enhanced Jetshear trials at higher severities and hydrogen addition (i.e. hydropolishing of the light fraction produced).

The tested generic bitumen required ~31 vol% diluent to meet both viscosity and density specifications for a reference pipeline temperature of 11.9° C. Normally, the untreated bitumen blended with diluent is viscosity limited. This means that additional diluent is required to reach the viscosity specification over and above that required to meet the density specification.

For the conditions investigated in the second phase, the diluent avoidance ranges from 43% to 53%. After JetShear™ processing the partially upgraded bitumen becomes density limited and requires additional diluent, over and above that required to meet the viscosity specification, to meet the average pipeline density specification of <940 kg/m^3.

Yield

Over the course of the field trials, material balance closure was generally greater than 98% and typically 99%. There are small amounts of losses due to by-product gas generation in the JetShear process that averaged between 0.3 and 0.4 wt %. Offsetting this loss was an average density improvement greater than 1% (see Figure 7) resulting in an average volumetric yield of 99.3 vol% during the Phase 2 trials.

TAN

TAN, an acronym for Total Acid Number, is an indicator of the acidity present mainly in the alkylated naphthenes contained in heavy oils and bitumen. Naphthenes are cyclic compounds with no double bonds between carbon atoms. The latter are therefore saturated with hydrogen. Acid groups in organic molecules are essentially carboxylic groups [R-COOH] and are normally located at the end of the alkyl group attached to the cyclic naphthenic core. Such carboxylic groups are associated with corrosion when at high temperatures and, consequently, refiners discount crudes due to TAN beyond a certain level of acidity. TAN is determined via a neutralization test using potassium hydroxide (KOH) where the number of mg of KOH needed to neutralize 1 g of crude represents the Total Acid Number or TAN (i.e. ASTM D664).

For most heavy oils and bitumen blends refiners desire crudes with TAN less than 1. Beyond this level, a penalty in pricing is applied by refiners and is a function of the level of TAN.

Under typical operating conditions for JetShear™ (i.e. severities), naphthenic acids with lower bonding energies are destroyed through decarboxylation reactions leading to reduced TAN in the treated products. Figure 8 shows a TAN reduction higher than 60% with Enhanced JetShear, due to higher severities and improved reaction zone kinetics compared to Base JetShear. Also, hydropolishing (i.e. hydrogen addition) of the lighter fractions contribute to reduce TAN even more, via hydrogen incorporation.

Olefins

As explained before, during thermal reactions, dehydrogenation of hydrocarbons can result in formation of unsaturated compounds such as olefins, which has a specification limit for the upgraded product to be sent via pipeline. The olefin content increases with the severity of the process, limiting the diluent displacement for JetShear with no hydrotreating (Phase 1). The olefin content in the product before hydropolishing does not meet the specification.

Olefin content in the Enhanced JetShear product, after hydropolishing does meet the pipeline specification for 53% diluent displacement. Olefin content in the final product, blended to pipeline spec, was lower than 1 wt% for all the cases and was below the detection limit (i.e NMR) on a number of samples analyzed.[7]

Net Value Addition

As previously discussed the Enhanced JetShear product (i.e. EJS) has an improved viscosity and density, lower TAN and lower residue fraction, is considered stable and has olefin content below accepted pipeline specifications. However, EJS product also has higher residue Concarbon compared to the untreated dilbit residue as a result of residue conversion.

Based on the various bitumen feedstocks tested and assays from products generated at the commercial demonstration facility a large third-party market consulting firm estimated that the bitumen netback improvement (i.e. diluent avoidance plus delta refining value) due to the reduction in viscosity and slight improvement in density results in a value uplift that ranged from C$3.50 to C$9.00 per barrel of bitumen over the next 10 years, depending on the process severity. In addition, the potential transportation savings (i.e. using publicly available pipeline tariff information) were determined based on the reduced volume of blend and diluent shipped per barrel of bitumen. When accounting for the transportation savings the overall benefit to a producer of the EJS product is estimated to be in a range of C$7.50 to

C$12.50 per bbl bitumen over the next ten years.

The range of values are primarily driven by the heavy oil differential and the diluent price relative to light oil. Over the next ten years significant volatility in these commodity metrics are expected to occur as a result of constrained take-away capacity in the Canadian pipeline system. Reducing the diluent content in the pipeline system via partial upgrading technologies, like Enhanced JetShear is therefore critically important in reducing heavy oil and bitumen price volatility, especially given the challenges associated with the regulatory process and building new pipelines.

CONCLUSION

- Enhanced JetShear improves the conversion of bitumen beyond Base JetShear performance
- Commercial field demonstration of Enhanced JetShear met all milestones:
- Processed over 100 K bbls using 500 bpd nozzles using Enhanced JetShear (>225,000 bbls in total).
- Improved distillation profile through partial upgrading.
- Diluent used to meet pipeline spec was reduced more than 50%, due to viscosity and density upgrade
- Olefins content below pipeline spec.
- Produced a stable partially upgraded product with P-value > 1.5.
- Reduced TAN (lower than 1 mg KOH/gr oil) thereby removing high-TAN discounts.
- Enhanced JetShear can lower transportation costs and increase infrastructure utilization.
- The combination of cavitation with mild thermal cracking extends the performance (i.e. asphaltene conversion) of thermal cracking only processes.

ACKNOWLEDGMENT

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NOMENCLATURE

- Diesel – hydrocarbon fractions that boil between 428-650º F (220-343º C).
- GHG- Greenhouse gas represented as kg CO_2e/bbl of SAGD bitumen
- Naphtha – hydrocarbon fractions that boil between IBP and 360º F (IBP-182º C). Includes straight run and heavy naphtha.
- The test method to determine the presence of olefinic material is the Proton Nuclear Magnetic. Resonance Spectroscopy (HNMR) test. The results of the test procedure are reported in terms of mass % olefin as a 1-decene equivalent.
- P-Value –ASTM D7157. This test method describes a sensitive method for estimating the intrinsic stability of an oil. This test method can be used by petroleum refiners to control and optimize the refinery processes and by blenders and marketers to assess the intrinsic stability of blended asphaltene-containing heavy fuel oils. It is based on titration and visual detection of peptized or precipitated asphaltenes.
- Resid (residue) – hydrocarbon fractions with boiling points greater than 981º F (527º C).
- SAGD – Steam Assisted Gravity Drainage.
- TAN – Total acid number determined from ASTM D664 - 11a, “Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration”.
- VGO – Vacuum Gas-Oil are eh hydrocarbon fractions that boil between 650-981º F (343 - 527º C).

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TABLES

Category	Measure	Enhanced JetShear Target	Results to date August 2017	
HSE	Lost time injuries	0	0	☑
Performance	Yield (wt%/vol%)	≥ 98 wt% / 99 vol%	98wt% / 99.3vol%	☑
	Material balance closure	< 1%	< 1%	☑
	Throughput	500	~ 500 bpd	☑
Product quality	Diluent displacement	≥ 50%	≥ 50%	☑
	TAN reduction	≥ 30% or ≤ 1 mg KOH/g	0.54 mg KOH/g	☑
	Stability (P-Value)	≥ 1.5	≥ 1.5 at 53% DD	☑
	Olefins	On spec < 1%	On Spec < 1%	☑

Table 1 - Commercial Demonstration Facility milestones for EJS

	Saturates, wt%	Aromatics, wt%	Resinas, wt%	Asphaltenes, wt%
Delta change, wt%	4.8	-3.3	5.3	-10.8

Table 2 – SARA Analysis of diluted untreated and treated dilbit, delta change

	Untreated bitumen	Treated bitumen
Asphaltene, C5 Insoluble, wt%	17.64	12.15

Table 3 – Untreated and treated bitumen asphaltene content

FIGURES

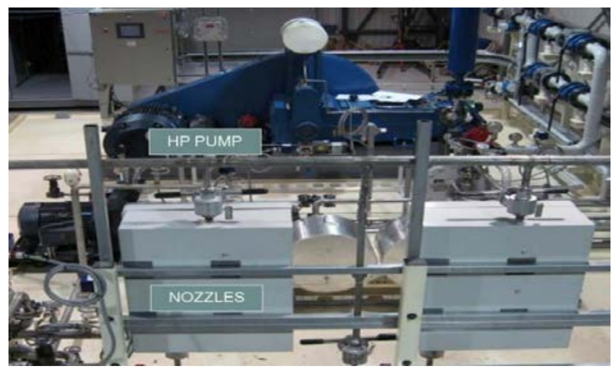

Figure 1 - JetShear nozzles and high-pressure pump

Figure 2 - JetShear Commercial Demonstration Facility located near Provost, AB

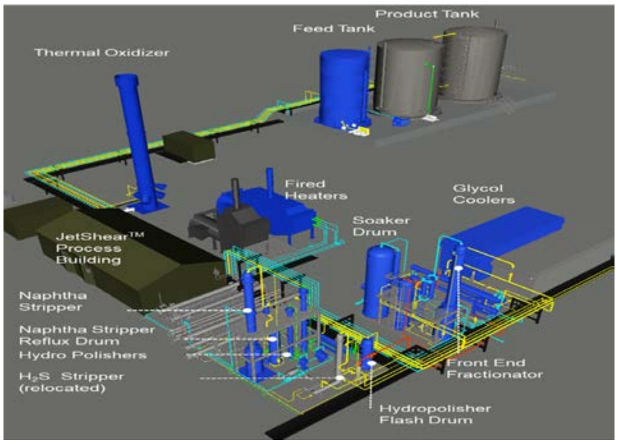

Figure 3 - JetShear 3D model

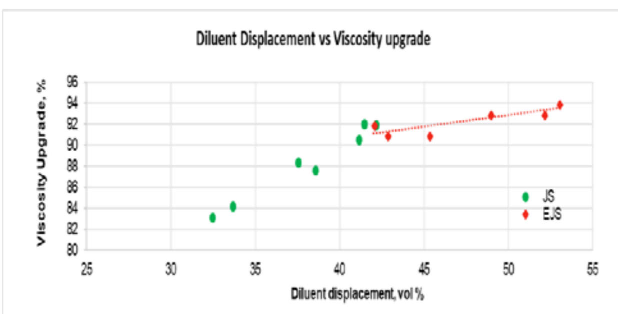

Figure 4 – Diluent Displacement vs Viscosity Upgrade

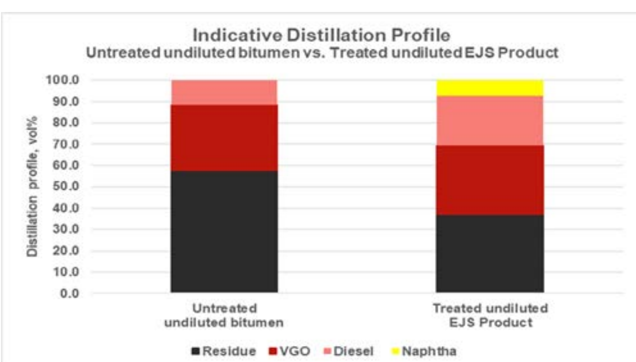

Figure 5 – Indicative distillation profile

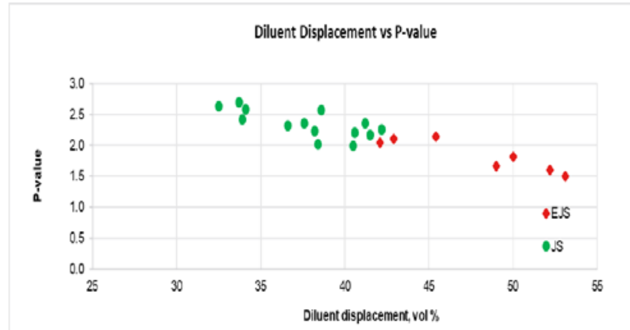

Figure 6 – Diluent Displacement vs P-value

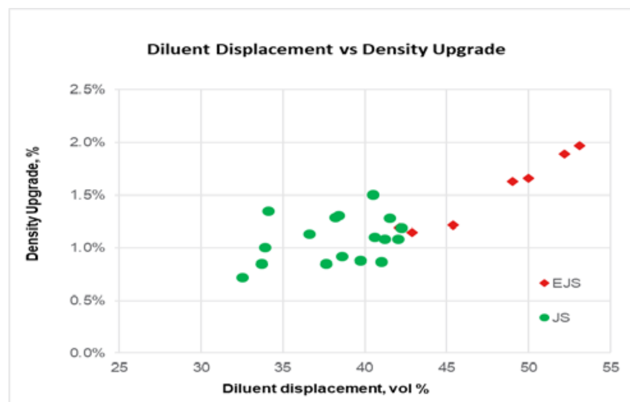

Figure 7 – Diluent Displacement vs Density Upgrade

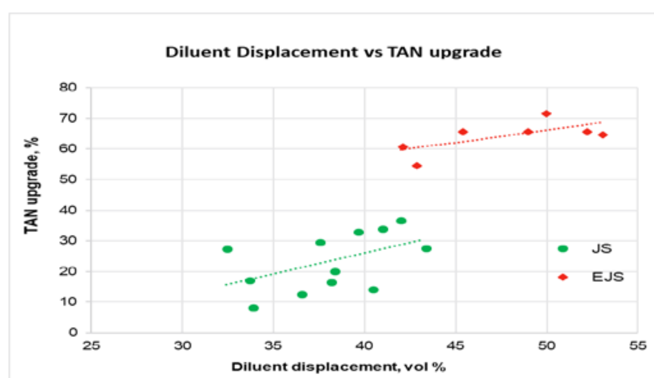

Figure 8 – Diluent Displacement vs TAN