SPE-208080-MS

Decarbonization and Improved Energy Efficiency Using a Novel Nanocomposite Surface Treatment

Matthew Nakatsuka, Oceanit; Basile Marco, Eni S.p.A.; Sumil Thapa and Alexander Ventura, Oceanit; Osvaldo Pascolini and Luca Pellicciotta, Eni US Operating Co. Inc; Vinod Veedu, Oceanit

This paper was prepared for presentation at the Abu Dhabi International Petroleum Exhibition & Conference to be held in Abu Dhabi, UAE, 15 – 18 November 2021. The official proceedings were published online on 9 December 2021.

Abstract

Fouling of heat exchanger equipment through the formation and attachment of hard scale, microbially induced corrosion (MIC) products, or particulate erosion is a serious challenge to reliable production in the oil and gas industry. Exchangers which become fouled in this way perform 15-30% worse than their rated ability, requiring either constant intervention to clean away biofilms, continuous injection of biocides and corrosion inhibitors, or the regular plugging of tubes to prevent leaks, representing a significant operating expense and billions of dollars in lost production time.

When an exchanger is unable to provide sufficient heat due to tube fouling, additional sources of heating must be utilized to make up for this deficit and to ensure that facility processes remain within design allowances. This need for supplemental heating is a significant source of carbon emissions in the industry and represents a significant obstacle towards decarbonization efforts. However, it also represents an economically attractive way to simultaneously lower emissions while also lowering a producer's cost per barrel.

This work describes an alternate strategy to control and prevent fouling in heat exchangers, through the one-time application of an omniphobic (water- and oil-repelling) nano-surface treatment. Once applied to a heat exchanger, the extremely smooth and low-surface energy material greatly reduces the ability of MIC-causing bacteria to deposit and adhere to the surface. Because it imparts functionality to the surface itself, rather than simply function as a physical barrier, it enables long lasting protection which was validated under laboratory conditions in a pressurized autoclave, as well as two pilot demonstrations.

Results from both the laboratory and field evaluations of the treatment's promise showed that treated surfaces showed a corrosion rate over 36-times lower when compared to untreated surfaces, while also completely arresting the formation of corrosion pitting, tube fouling, and erosion of the tube interior. These field-validated results were then applied to the observed heating deficit of a proposed deployment site, resulting in calculated carbon emissions savings of up to 17,000 Tons CO_2 per year.

Introduction

The pronounced impact of fouling within heat exchanger systems is well documented and correlates strongly to adverse performance of operations. Within a refinery setting, crude pre-heat trains (PHTs) function as inlet heating systems to heat production fluid as it makes its way to distillation, thus requiring less energy to reach distillation temperatures. Trains consist of various shell and tube heat exchangers transferring energy content from back-end processes that contain heat energy, such as produced water and sales oil, to incoming fluids such as crude; 10 - 60 PHTs can be present based on the size and design of the approximately 750 refineries worldwide (Müller-Steinhagen, 2011). Typical inlet temperature averages approximately 55°F (12.5°C) and outlet temperature exiting the PHT corresponds to approximately 482°F (250°C) (Fraser, 2014) ; this increase in temperature results in the deposition of chemical and physical fouling formation which can reduce heat transfer efficiency for anywhere between 16-30% (Nakao, 2017, Costa, 2011). The key concept regarding PHT and all exchange systems across all industries fundamentally lies within efficiency of transfer. The more heat transferred in the PHTs, the less fuel will be needed to provide supplemental or "make-up" heating after it leaves the PHT, resulting in lowered greenhouse emissions and cost savings. **Current estimations dictate that for every 1.8°F (1°C) loss of heat entering the process heater, a subsequent 2 trillion BTU/year are required for U.S. refineries to make up such losses** that would otherwise be avertable if fouling were mitigated and/or not present (Panchal, 2000).

Currently, the portfolio of technologies, recommendations, and attempts to combat thermal inefficiency due to fouling is exhaustive. Remodeling of design systems to incorporate self-cleaning systems (Klaren, 2000), alterning tube size/orientation (Chambon, 2020), or completely overhauling the geometry of the exchanger itself have been investigated on a pilot/theoretical basis, while efforts to address the fouling issue through optimizing more frequent manual cleaning schedules (NOAA,1999), and enhanced monitoring and optimization of feedstock parameters have also been investigated (Joshi, 2003). However, these major redesigns of facility operations and hardware typically come at significant incurred capital expenditure cost, making adoption slow in the face of economic pressure, while increased frequency of cleaning merely results in swapping one issue (ineffective heat transfer and increased carbon emissions) for another (extra downtime and manhours dedicated to maintenance of each system), with the solution being decidedly temporary in nature.

In this work, a novel fouling resistance solution was demonstrated and evaluated in an extreme weather environment notorious for heavy fouling and microbially-induced corrosion (MIC) attack. The solution consists of a nanocomposite material previously qualified for use in seawater-fed heat exchangers to reduce biofouling (Nakatsuka, 2021). The water based, environmentally friendly, and non-toxic "nano-surface treatment" (NST) is capable of being applied extremely thinly on the interior diameter (ID) of shell-and-tube exchangers, providing unrivaled surface protection through the extremely low surface energy and low surface roughness, allowing for active repulsion of scale-forming compounds, while further improving fluid flow, allowing for the removal of deposited, but not adhered scale. Most importantly, the NST, trade name HeatX does not have an adverse effect on actual heat transfer as many traditional thick polymer coatings such as glass-flake epoxies or flexible siloxanes exhibit.

A multi-stage, phased deployment effort was utilized to evaluate the NST at four key stages to de-risk the technology, as well as determine the economic and environmental value of the proposed solution. These stages include: (1) Laboratory validation of MIC protection, (2) Fluid compatibility testing and pilot scale application with produced water spools, (3) Deployment and evaluation on representative shell-and-tube exchanger, and (4) Economic modeling of decarbonization effects on representative facility.

The Data and Results presented in this paper are referred to the Nikaitchuq upstream plant in the USA Alaska North Slope, owned and operated by Eni US since First Oil on 2011. Nikaitchuq experienced MIC situations in the past few years. Studies and remediate actions to troubleshoot the above events have been

performed and to some extent they are still on going. A significant step change occurred on 2020 with the application of the referred innovative technology.

The treatment was planned in two phases to get enough elements required to define technology risks and raccomandations to follow to. At first, a discontinuous service, off line the main production line, was selected and its batch service rappresented the most adequate choice. Following to the positive results the second phase was to apply the nanocomposite to the bundle of one exchanger inside the train 1 of the main production stream. Results are dscribed on § 4.

Description and Application of Equipment and Processes

Laboratory Validation of MIC Protection

Circular coupons, of diameter 1.18″ and .187″ depth, were machined from 1018 low carbon steel, and subjected to the nano-surface treatment. Three different conditions were investigated: Uncoated control samples, Coated Samples, and "Damaged" Coated Samples with an X-Mark. These coupons were subsequently weighed, and the surface was scanned with a 3D optical profilometer to create a pre-test baseline for comparison.

For exposure, the coupons were mounted into a polyetheretherketone (PEEK) cage, which allowed for only a single side of the coupon to be exposed at any given time. This cage was the lowered into a 1 gallon (3.78L) autoclave for testing, and 0.66 gallon (2.5L) of a pH 7 sodium chloride (16.488 g/L) and sodium sulfate (0.2958 g/L) brine was used to fill the remainder of the autoclave. Of this brine solution, 250 mL consisted of a "Desulfovibro Vulgaris" American Type Culture Collection (ATCC) 7757 strain that had been carefully incubated for 5 days at 37°C until maximum growth was achieved. The autoclave was subsequently pressurized to 1000 psi at 37°C, and the pressure was maintained for 1068 hours. After testing was completed, coupons were weighed first, then cleaned via ultrasonic bath for 360 seconds until any adhered bacteria scale had been removed. The treatment was then removed from the surface utilizing a common chemical cleaner, and the substrate below the NST was scanned utilizing the 3D profilometer for the formation of any pits greater than 10µm in depth. Finally, all coupons were weighed and compared to the baseline measurements of the coupons taken prior to any treatment. This autoclave setup and subsequent mounted cage setup can be seen in Figure 1 below.

Figure 1—Autoclave used for MIC testing of NST (Left). Test Coupons mounted in Peek cage (Center). SRB culture after conclusion of test (Right).

Fluid compatibility testing and pilot scale application with produced water spools

A short spool of 4″ ID which was typically utilized in the loading of traditional cleaning and inspection pigs into a produced water line was selected as a candidate for test deployment of the treatment. While this section had no significant issues with fouling or reduced heat transfer, these spools were particularly susceptible to the formation of aggressive microbially-induced corrosion (MIC) within the line. MIC within the line would cause wall thinning and visible material loss in as little as 2-3 months under normal operation, necessitating either repair or replacement, and causing a significant delay in operations. Material was applied

to the interior of the spool on-site in an extremely challenging weather environment and was required to cure and be stored in temperatures well below the freezing point of water.

Over the course of approximately six months, the treated test spools were used in the same way they had been done previously, with no changes in normal operation. No additional preventative measures were utilized to control MIC, such as the introduction of other treatment chemicals or nitrogen purging of residuals when not in use. After six months, the line was taken out of service and inspected by a third-party inspector. A VT-1 visual inspection according to the ASME Section V code was completed to detect discontinuities and corrosion pitting within the pipeline interior. Pictures were taken from inside of the pipe utilizing artificial light and a GoPro camera. Furthermore, a UT-2A ultrasonic spot check for corrosion was performed utilizing a 10MHz Olympus Epoch 600 single transducer operating in longitudinal mode.

Deployment and evaluation on representative shell-and-tube exchanger

A representative shell-and-tube heat exchanger bundle designed for heat exchange between production fluid (tube side) and produced water (shell side) had the NST applied to the ID of each tube. The entire exchanger was fabricated from carbon steel and had 1607 tubes of 0.75″ OD by 22’ in length. The entire exchanger was configured in a straight-tube, 2-pass setup, and was put into service for approximately one year before the bundles were taken offline and inspected through visual analysis. Standard practice of draining and flushing the bundles was followed in this regard prior to borescoping of representative tubes; with a comparison of hard deposit build-up being compared in real time to a sister unit exposed to the same product on the tube side. Final judgement as to the operability, acceptability, and survival of the coating under these harsh operating conditions was left up to an independent third-party inspector.

Light shine inspection looks at the quality of light that can shine through the full length of a tube when looking along the tube axis from one end. This method provides a quick qualitative assessment of degree of tube obstruction/fouling by evaluating both the amount and the outline shape of light passing through tubes. Clean tubes with light to no fouling or obstruction allow light to shine bright and in a clear circle, reflecting the tube shape. Hard fouled or obstructed tubes either do not allow light to pass through or create an outline that is no longer circular.

Economic Modeling of Decarbonization Effects on Upstream and Facility Applications

Projection of the NST economic benefit was based off a model PHT where input and output temperatures, mass flow rate, and fouling factor had been previously determined through historical data analysis. Three different fouling rate reductions were considered here and could be considered the conservative/median/optimistic projections for the treatment: (1) 15% reduction in overall fouling, (2) 50% reduction in overall fouling, and (3) 100% reduction in overall fouling. The decrease in thermal efficiency due to fouling was assumed as 16% based off the comparative heat transfer values of hard mineral scales and that of the treatment material when applied at the suggested 1 mil final thickness. These are shown in below.

Table 1—Heat Balance and Heat Transfer Comparison Due to Fouling Reduction

	Units	Baseline	Conservative (15%)	Median(50%)	Optimistic (100%)
Mass Flow	[lb/hr]	1,000,000	1,000,000	1,000,000	1,000,000
Crude Heat Capacity	[Btu/lb/°*R*]	0.48	0.48	0.48	0.48
Inlet Temp	[°F]	55	55	55	55
Theoretical Input	[MMBTU/hr]	214	214	214	214
Desired Temp.	[°F]	500	500	500	500
Fouling Factor	[%]	16%	13.6%	8%	0%
Fouling Transfer Loss	[MMBTU/hr]	34	29	17	0

	Units	Baseline	Conservative (15%)	Median(50%)	Optimistic (100%)
Actual Transfer	[MMBTU/hr]	179	185	197	214
Actual Temp	[°F]	429	439	464	500

Presentation of Data and Results

Laboratory Validation of MIC Protection

Images of the coupons immediately after removal from the autoclave, prior to any rinsing or attempted removal of formed iron scale (Fe_2S), can be seen in Figure 2 below. The dark black scale seen predominantly on the untreated coupons was then removed utilizing ultrasound cleaning for 6 minutes in PBS buffer, and coupons were re-imaged for the presence of pitting and surface deformation. These images are shown in Figure 2 below. Quite surprisingly, the "damaged" coupon with intentionally added scribe marks showed no signs of penetration in the induced cracks, and no formation of underfilm corrosion or delamination.

Figure 2—Images of coupons before and after ultrasonic cleaning and PBS buffer rinsing. Uncoated coupons show significant bacteria colony growth which causes scarring and pitting of the substrate. NST coupons show minimal bacteria colony growth, and no signs of substrate scarring after cleaning.

After initial surface cleaning, the coupons were then further prepared for analysis by exposing the underlying substrate to determine if any pitting had developed deep on the face of the coupons. Adhered iron scale was removed from the uncoated coupons through gentle bead blasting, while the coating was removed through a 24-hour soak in a mutual solvent, upon which the dissolved coating remnants could be removed using gentle mechanical abrasion. 3D profilometry determining the coupon surface roughness and the number of pits greater than 10µm in depth were numerated and marked for further analysis; the actual topographic maps and pit detection can be seen in Figure 3 below.

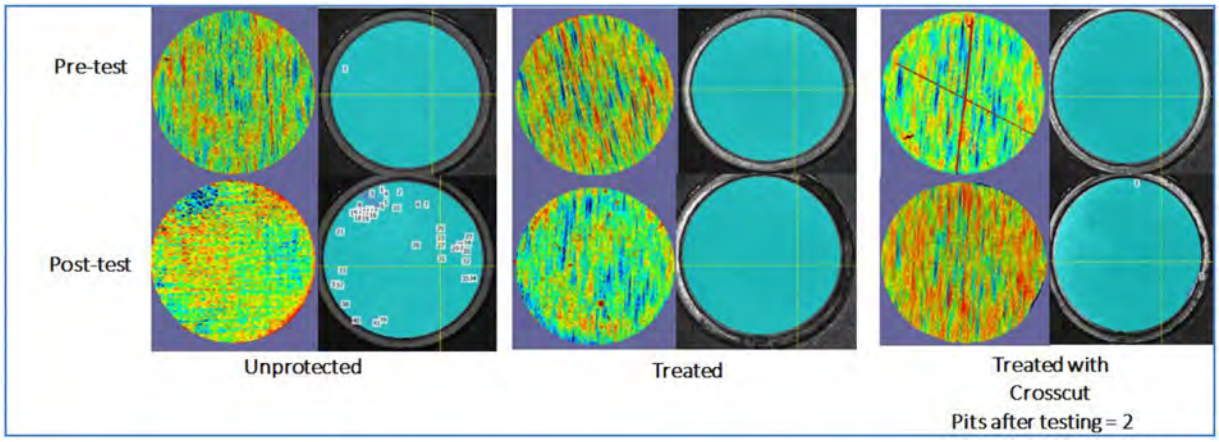

Figure 3—3D profilometry of untreated, treated, and "damaged" treated coupons.

Summarized results for the testing can be seen in Table 2 below. Nearly 41 pits of maximum depth ~ 30μm were found on the unprotected and uncoated coupon, while only 2 pits, both on the extreme edges of the coupon (and one along the path of the intentional damage), were found on the X-cut treated coupon. Zero instances of pitting were observed on the intact coated coupon. Surface roughness measurements taken on the coupons generally ranged between 1.8-2.2μm prior to coating for all coupons (RMS 63 smooth machined finish). After testing had been completed, and excess scale and coating had been removed, coated coupons retained the same machined finish, increasing by only approximately 5%, more than likely a result of the coating application and removal. In contrast, unprotected coupons saw their surface roughness increase closer to 3.2μm, nearly doubling, as a result of the pit formation and material losses. Finally, based on weight loss during the test, a generalized corrosion rate of 23.39 mils per year (mpy) was calculated for the uncoated coupons. With almost no weight loss during the test, NST coupons displayed a corrosion rate of only 0.65 mpy, and the damaged coupons showed only slightly worse performance at a calculated rate of 2.13 mpy.

Table 2—Summarized Results for MIC testing

	Untreated	Treated	Treated with X-Cut
Number of Pits Found	41	0	2
% Increase in Surface Roughness	134	5%	5.4%
Generalized Corrosion Rate (mpy)	23.39	0.65	2.18%

Fluid compatibility testing and pilot scale application with produced water spools

As can be seen in Figure 4 below, visual inspection of the treated line showed no signs of pitting or corrosion during the testing. Some disbonded material was observed, however it is important to note that the removal and or flaking of the treatment from the surface had no effect on corrosion; areas where the topcoat of the surface treatment material had become disbonded were still protected from corrosion, indicating that the treatment most strongly bonded to the surface remains in place.

Figure 4—Comparison of the typical damage seen in kicker line, with wall losses up to 85% in some areas (Left), and spool line after treatment, showing no visible signs of corrosion or pitting (right).

It is illustrative to note here that the NST does not rely entirely on forming an impermeable barrier on the pipeline interior, but to affect a permanent, chemically bonded change on the prepared pipeline surface, with additional material only serving as a secondary guard against abrasive wear of this treated surface. In this application, treatment was applied to a final thickness of 2.5 mil over five cycles of treatment, to make the treatment more durable to the mechanical forces created during pigging operations. However, the outcome of this inspection would suggest that the addition of this excess material may have instead left the entire treatment susceptible to flaking and debonding. To prevent this from occurring, Oceanit would recommend scaling back the overall applied thickness by 50% or more, as the corrosion protection enhancement clearly does not rely on the physical barrier nature of the treatment.

Visual inspection was confirmed through additional UT testing of the pipeline wall. Prior to application, straight pipe sections were manufactured with a specification of 0.337″ thickness, while elbow joints were slightly thicker at 0.370″ wall thickness. Performing this testing on the existing kicker spool line, for comparison purposes revealed significant wall loss, generally in the 50-66% range, with the very deepest corrosion pits demonstrating wall loss of up to 85%. In contrast, the treated line showed no pitting or wall loss, with all inspected pieces being accepted for service according to the ASME B31.3 standard.

Deployment and evaluation on representative shell-and-tube exchanger

The treated exchanger, referred to here as the produced-water exchanger (PWX), was opened and compared to an untreated, nearby sales-oil production exchanger (SOPX). It is noteworthy that while both exchangers were contained within the same process train, the treated PWX exchanger is exposed to crude product coming from a manifold, on the way to separation, while the SOPX sees oil that has already gone through separation and has had most of the water cut, sand, and excess gas already removed prior to export. As such, one would expect the PWX to show significantly more signs of fouling even if they had undergone the same length of service. For both the PWX and SOPX, logistical constraints required the bundles to remain installed in shell with channel heads in place during inspection. Prior to assessing the appearance of the tube sheets and tube ends, both bundles were pressure washed with hot water to remove residual product, but no further cleaning was undertaken. Comparison photos can be seen in Figure 5 below.

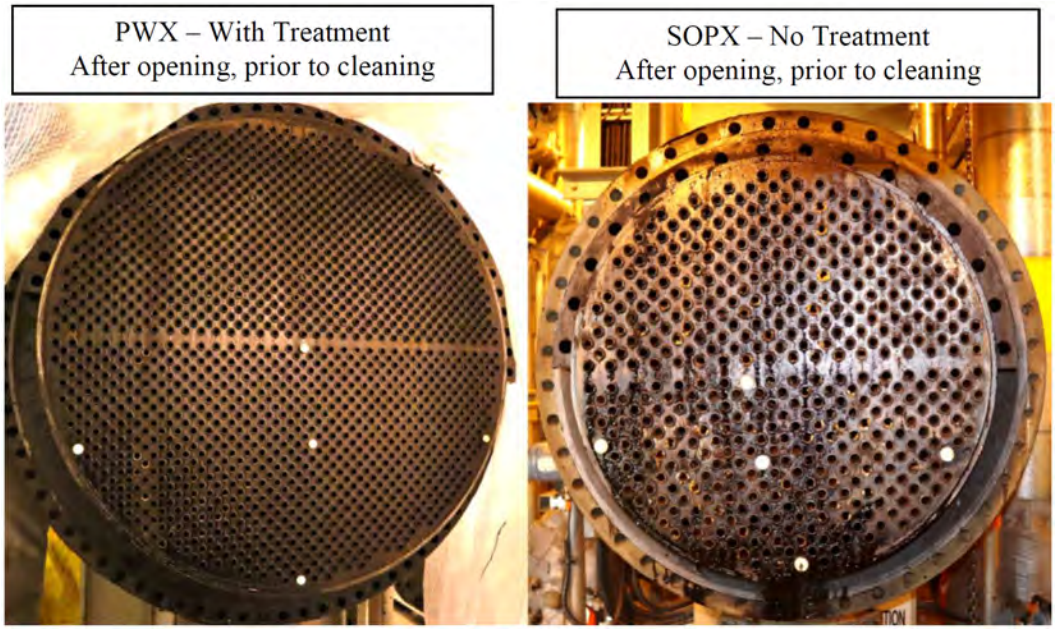

Figure 5—Visual inspection of treated (PWX) and untreated bundles (SOPX) after approximately 1 year of continuous service. Treated exchanger shows virtually no signs of scale deposition, while the scale and fouling is so severe in the untreated exchanger that that tubes have begun to become constricted.

Borescope inspection was done using standard video borescope. The treated PWX tubes, were clean and free of hard crude build up, with the grey metal finish of the tubes clearly visible on in almost all of the tubes, with a small minority of areas having soft residue from crude residue appearing orange-brown. The comparison SOPX tubes are entirely covered in black hard deposits from the crude, and the the early onset of pitting due to erosion and MIC is beginning to form. This comparison can be seen in Figure 6 below.

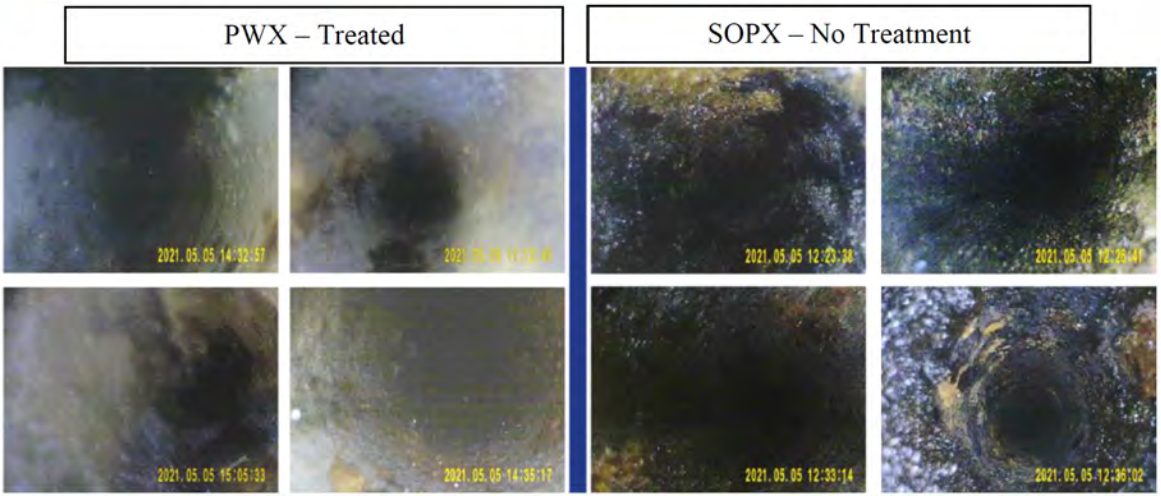

Figure 6—Borescope images of tube interiors.

Every tube inspected for the treated PWX bundle showed no constriction or limitation of light shone through and with clearly defined circular shape; therefore, the PWX was deemed clear and free of obstruction and build up. For the comparison SOPX bundle without treatment, many tubes did not allow the light to shine through and for tubes that did, the **shape of light through the tubes were clearly distorted; therefore, it can be determined that fouling and obstructions are present within the tubes of the SOPX bundle that had no treatment**. This can be seen in Figure 7 below.

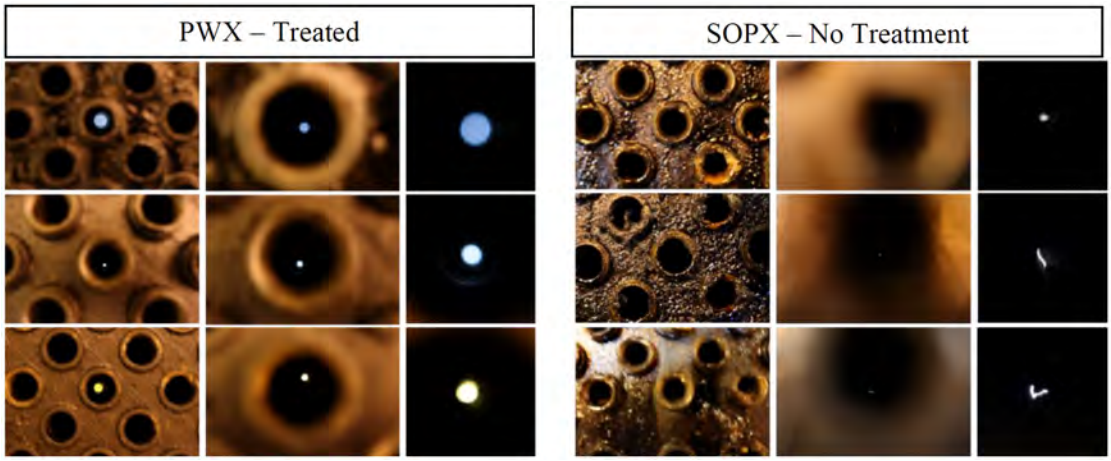

Figure 7—Images of tube blockages because of scale adhesion.

The following observations were drawn from this field trial:

- No buildup of hard deposits from product fluid on treated surfaces. Comparable SOPX unit had hard product build up and significant tube obstruction under similar operating conditions.
- Treatment material survived extreme E&P Flow entering Train 1 PWX unit (note that before application this unit was already 10 years old but held in storage) after 1 year of service.
- Treated treated surfaces deemed acceptable for continued service in PWX unit.
- In follow up vacuum test all tubes passed test (Note: <40 tubes had poor sealing around ferrule inserts and required follow up testing or removal of ferrule before passing).

Comparison of the treated PWX to the SOPX bundle without treatment show a stark contrast. The SOPX bundle that was not treated shows notable amounts of hard deposits and fouling on both the tube sheet and inside tubes. This is visible from both pictures of the tube sheet and borescope imaging inside of the tubes. Treated surfaces show no hard buildup of solids and after light cleaning revealed the presence of the treated surface, which appears as grey metal finish. Furthermore, the light shine test quickly demonstrated that the treated tubes retain a clear flow path throughout the length of the tube, whereas the untreated tubes appeared to be at least partially obstructed by fouling buildup.

Economic Modeling of Decarbonization effects on Upstream and Facility Applications

It is noted that corrective maintenance composed a significant part of the yearly budget required to face costs that are mandatory. The Nikaitchuq plant Train 1 and 2 exchangers rappresents the process core step to ensure a quality product and in similar plants exchangers rappresent key elements composing the Energy Intensity which is characterizing the plant efficiency and part of the relevant carbon foot print.

Corrective maintenance used to occure frequently, before applying the treatment, and now all the associated costs of the corrective maintence on the referred exchangers, including refurbishment and the stand by make way to preventive maintence only. The saving, associated to that, is quantified equal to around 15% of annual maintence operation costs. The above does not consider indirect costs as of HSE and the risks strictly related to corrective maintence activities in harsh environment that are therefore eliminated in the moment in time that the corrective maintenance on the referred exchangers is required no more by using the nanocomposite. Among advantages there is also the inventory, since the extended life time of the equipment reduces the spare parts replacements need.

It is noted that a limited or extensive use of the technology proveds different results and therefore any projection of savings on varios assets and contribution the decarbonization needs to be evalutated and customized on case by case basis, as per what would it be the constest, plant to plant.

The following considerations are of course a projection based upon the results obtained so far.

So, according to, ideal temperatures at the mode fall shy of a 71°*F* interval from the desired 500°F mark. For the total heat balance, we can note that the additional heat required to reach such a mark would approximately equate to 34 MMBtu/hr. **Another, and maybe a more optimistic way of phrasing this would be that the facility is losing the 34 MMBtu/hr. during the pre-heat process thus suggesting that this 34 MMBtu/hr. is capable of recovery given precise and innovative engineering solutions**. Furthermore, additional heat input is required to reach what was already the optimal input temperature. The lack of recovery of this thermal energy dictates that additional heating must take place to compel separation and distillation processes. Table 3 estimates the associated carbon footprint for both baseline process streams versus those utilizing the surface treatment in conservative, median, and optimistic projections. The assumption is made that this heat loss must be made up through the utilization of a process heater operating on natural gas. Any fuel source other than natural gas will likely increase these numbers.

Table 3—Equivalent Carbon Footprint from Heat Recovery Loss

	Units	Baseline	Conservative (15%)	Median(50%)	Optimistic (100%)
Additional Heat Required	[MMBTU/hr]	34	29	17	0
NG Emmissions	[lb. CO_2 /MMBTU]	117	117	117	117
Additional Emmissions	[lb. CO_2/hr]	3999	3399	1999	0
Annual Emmissions	**[TCO_2/year]**	**17514**	**14887**	**8757**	**0**

This analysis shows that a complete removal of fouling would reduce annual emissions by 17,514 tons of CO_2 annually. **To put this in perspective, this would amount to the same carbon sequestration of 19,500 acres of forest annually or 17.5 million pounds of coal burned**. Staggering enough, this amounts to only the front-end heat recovery regarding PHT systems. Thus far, investigation into a simple heat balance and overall heat recovery loss produces a strong stance on emissions, though, the complexity and severity go beyond limited understanding of its impacts (Macchietto, 2011, Müller-Steinhagen, 2009), however, the decarbonization effects of complete elimination of fouling and the associated fouling factor could potentially result in the total transformation of the sector.

According to the U.S. Energy Information Administration (EIA), in the year 2020 refineries consumed 44,027 million kWh of U.S purchased electricity. Furthermore, the EIA as of Dec. 2020 reports that the U.S. gross input of crude oil to distillation units equates to 14,539 thousand BPD which assuming a year-round process would produce 5.3 billion barrels annually. Mathematically, the potential BTU required to refine one barrel of crude oil would produce a figure of 565,000 BTU/bbl. Cross referencing this data with total capacity in BPD and previously reported figures of 5.5 billion BTU/day lost per 1.8°F (1°C) loss of heat transfer, and a 15% fouling factor, shows that the overall effect of the treatment on redcuing energy requirements grows significantly as the scope of deployment and size of the facilty grows over time. This can be seen in Figure 8 below.

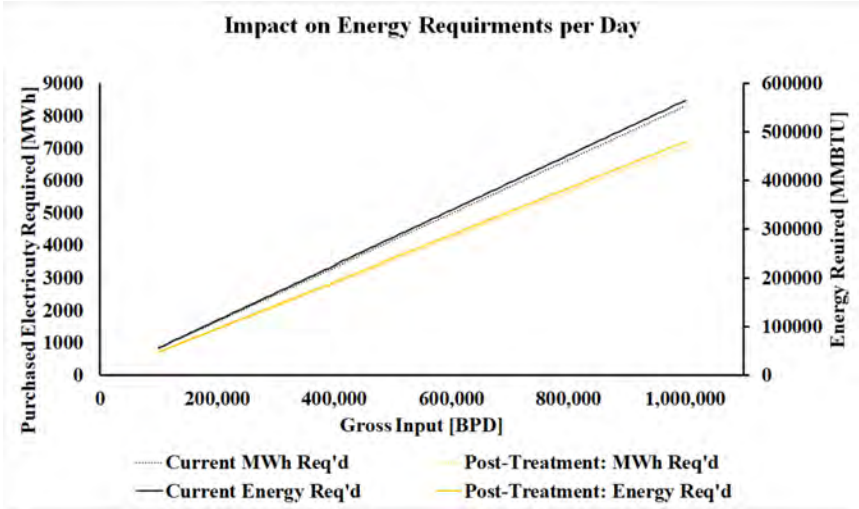

Figure 8—Effect of the Treatment on Energy Requirements

Utilizing the reported global estimate of 87 million barrels per day and 88 million tons of additional CO_2 produced per year due to fouling (Müller-Steinhagen, 2009), we can estimate the total tons of CO_2 from fouling per barrel produced. In 1992, it was estimated that in the U.S. the cost of such fouling represented $1.2 billion annually, noting that at the time, no cost penalty was associated with emissions. Today, factoring in annual inflation of 2.14% brings the estimated costs to approximately $2 billion. Previous studies (Macchietto 2011, Costa, 2011) have quantified the additional costs of fouling to range from $0.12 to $0.20 per barrel produced on facilities below 160,000 BPD; with larger facilities to be even more inefficient. Our analysis conservatively estimated costs at $0.10 per barrel based off the projected facility size. A larger projection for the gross effects of treatment across multiple facilities can be seen in Figure 9 below. The treatment offers as a cost-effective solution to mitigating such impact with no added infrastructure, thus paving the way toward redefining the industry in terms of the carbon footprint alongside an economic standpoint.

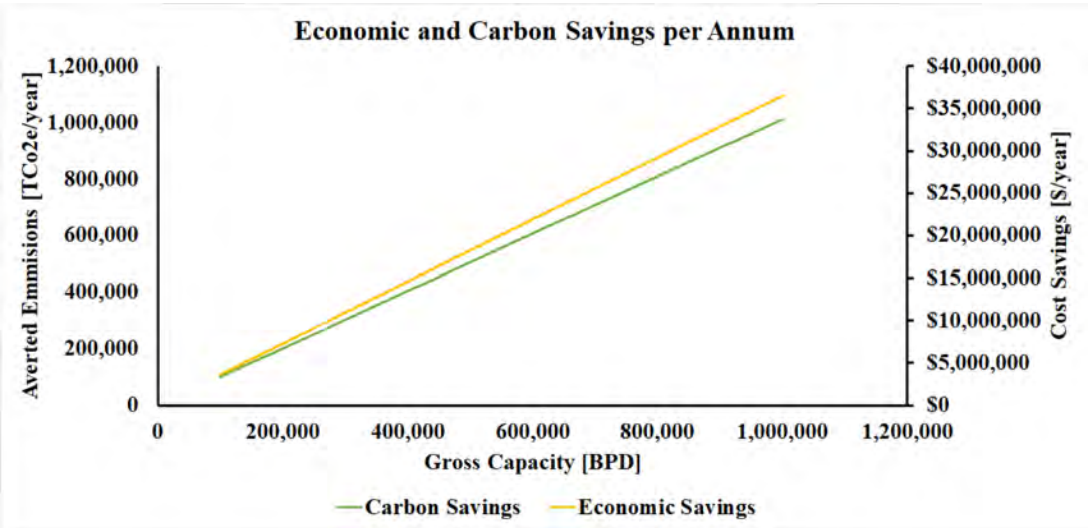

Figure 9—Effect of Treatment in Reducing Emissions and Operational Fuel Costs

Conclusions

In this work, a novel method effectivelly contributing to the decarbonization through the improvement of the pre-heat train at a certain oil production facility owned by the authors was explored. Laboratory evaluation of

this new scale-and-fouling repellent surface treatment revealed that it was highly resistant to both corrosion and scale formation due to microbial activity, reducing the rate of corrosion by over 97%, and completely arresting the formation of pits on low-carbon steel substrates. The subsequent pilot test where the treatment was field-applied demonstrated high effectiveness against corrosion by MIC, scale adhesion, and erosion. After exposure to real-world environments, the treatment showed both durability and compatibility with produced water and sales oil products, and greatly curtailed the effects of MIC. By eliminating the effect of fouling within exchangers, the need for supplemental heating to maintain the design temperatures of the facility could be all but eliminated, providing annual emissions savings of over 17,000 tons of CO_2 from the target facility alone. With the technology already having been substantially derisked in an extreme environment, and the immediate benefit of avoiding corrective and preventative maintenance costs has already been realized, it is expected that an extended deployment of the system will occur in the near future based on facility schedule and availability. Further analysis of the benefits gained through improving heat rate can then be compared to the projected benefits included in the work here.

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