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Ministry of Petroleum & Natural gas
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2nd Edition

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Alok Sharma
Executive Director
CHT

Foreword

It is great pleasure for me to hand out 2nd edition of CHT Oil & Gas Technical Journal.

The Indian refining industry has established itself as a major player globally. The country's refining capacity has increased from a modest 62.00 MMTPA in 1998 to 251.216 MMTPA comprising of 22 refineries – 18 under Public Sector, 3 under Private Sector and 1 in Joint Venture (JV). Indian Refining industry has taken rapid strides and grown significantly to become Asian refining hub and the 4th largest in the world.

Refinery operations are energy intensive and consume nearly 8-10% of crude oil for meeting internal fuel requirement. India now stands committed to reducing the emissions caused by activities for the nation's economic growth by 45% by the year 2030 from 2005 levels, according to the new targets. The nation will also aim to achieve about 50% of its energy requirements from non-fossil fuel-based energy sources by the year 2030.

Increasing renewable energy use across all economic spheres is central to India's Energy Transition. Green Hydrogen is considered a promising alternative for enabling this transition. Hydrogen can be utilized for long-duration storage of renewable energy, replacement of fossil fuels in industry and clean transportation. In 2020, India's hydrogen demand stood at 6 million tonnes (MMT) per year, the demand for hydrogen is expected to see a five-fold jump to 28 million tonnes (MMT) by 2050.The National Hydrogen Mission was approved by the Union Cabinet, chaired by the Hon'ble Prime Minister Shri Narendra Modi. With this approval, the stage is set for India to become a global champion in green hydrogen. Govt of India has taken several steps to incentivize promotion of Green fuels.

Govt of India also targeted blending of 20% ethanol in Petrol by 2025 and 5% biodiesel in diesel by 2030. In order to augment availability of biofuels, GoI is promoting 2G ethanol as well as setting up of 5000 plants for production of 15 MMT of CBG. In today's world, knowledge is treated as the key to success. Knowledge might be power, but it is much more powerful when it is shared.

This edition has been possible due to overwhelming response and contribution by the individuals and organisations. The paper selected in this edition covers broad areas under alternative energy, innovation in operations & trouble shooting and reliability improvement. I hope this edition will help all stakeholders connected with energy sector both in public and private sector to remain abreast with the latest technological developments and formulate their strategies and action plans.

Alok Sharma
ED, CHT

> *When learning is purposeful, creativity blossoms. When creativity blossoms, thinking emanates. When thinking emanates, knowledge is fully lit. When knowledge is lit, economy flourishes.*
>
> - Dr. A.P.J. Abdul Kalam

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Part-1

Alternative Energy and Challenges

> **“We have to make India a Global Hub for Green Hydrogen Production and Export in the Amrit Kaal. This will not only help India to make new progress in the field of energy self-reliance but will also become a new inspiration for clean Energy Transition all over the World.”**
>
> **- Sh. Narendra Modi**

1.1 E- Fuels- Challenges and Opportunities towards Decarbonization

Authors: Kishore Kumar Bhimwal , Brijesh Kumar, P Raman, Alok Sharma
Centre for High Technology

Sh. Kishore Kumar Bhimwal is working as Addl. Director in Centre for high Technology (MoP&NG). He has 19 years of Experience in Process/Heat Transfer (Thermal design specialist) design working with Engineers India Limited. Currently he is associated with Renewable Fuels, Green Hydrogen and Auto Fuel Policy related projects in CHT. He is B. Tech (Chemical) from MNIT, Jaipur.

Sh. Brijesh Kumar is a Chemical Engineer, MBA having long experience in IOC refineries for 17 years with similar tenure of 17 years in R&D Centre of IOCL. He has also served as Executive Director, CHT during Aug 2015-Feb 2019. Currently he is working as a Technical advisor in CHT.

Sh. P Raman started his career in erstwhile CRL and worked in OCC (now PPAC) during the period 1995-2000. He had also Worked in International Trade, Supply Chain Optimisation departments of BPCL. He was involved in Commissioning of Aromatic Recovery units as part of team BPCL's maiden venture into Crude Oil procurement activities, shipping activities like COA with SCI, setting up risk management desk, etc. He had implemented, Selection of crude procurement through the LP Model (PIMS) first oil PSU in India, also implemented Advanced Optimization (AO) in crude selection process facilitated procurement of spot crude oils through M/s Shell trading desk. Currently he is working as Director Technical in CHT.

Sh Alok Sharma Executive Director of CHT has over 31 years of experience at Indian Oil including R&D & Refinery including the areas of Process, Projects and Production. An expert in the Hydro processing, he has excellent knowledge of energy transition aspects. He received World Petroleum Congress Excellence Award 2008 and was selected for Prestigious Endeavour's Awards in 2009 and went to CSIRO, Melbourne on Commonwealth Scholarship. He has over 30 granted patents in his name.

1. Introduction

India is in a unique position to pioneer a new model for low-carbon, inclusive growth as its energy future depends on buildings and factories yet to be built, and vehicles and appliances yet to be bought. India has envisioned cutting its emissions to net zero by 2070. Reduction of carbon footprint shall be achieved through putting electricity at the centre of India's modernisation, efficiency improvement, and increased role of gas and decarbonisation of energy mix with renewable energy – biomass, solar, wind, nuclear and green hydrogen. To support and achieve the net zero target by 2070, India has announced the national hydrogen mission and National Policy on Biofuels, 2018.

Petroleum liquid fuels offer an unequalled combination of qualities i.e. high energy density, easy and safe handling, already existing infrastructure for production, distribution & storage, and low cost compared to the alternatives. About 98% of the fuel requirement in the road transportation sector is currently met by fossil fuels. However, India imports 85% of its oil requirement. Traditional IC engine is quickly becoming out-dated around the world because they are polluting and are being quickly replaced by fully electric vehicles (BEVs). The running cost of an electric vehicle is much lower than an equivalent petrol or diesel vehicle. Electric vehicles have very low maintenance costs because they don't have as many moving parts as an internal combustion vehicle and have zero tailpipe emissions. The figure below shows the battery weight that would be required if electrical power trains were adopted for different transport modes. It can be seen that battery technology will need to achieve at least a 10-fold reduction in weight in order to become a viable substitute for liquid fuels beyond passenger cars and light commercial transport. For low duty vehicle EV is a good option but for marine, aviation and heavy-duty road transport, the energy density of liquid fuels represents a fundamental advantage that will be difficult to overcome even with future battery technology due to charging time and battery weight. This is where e-fuel starts to make more sense. No modifications or updates are required to the vehicles in order to run them on e-fuels. And, there is no change required to be made in the existing fuel supply chain.

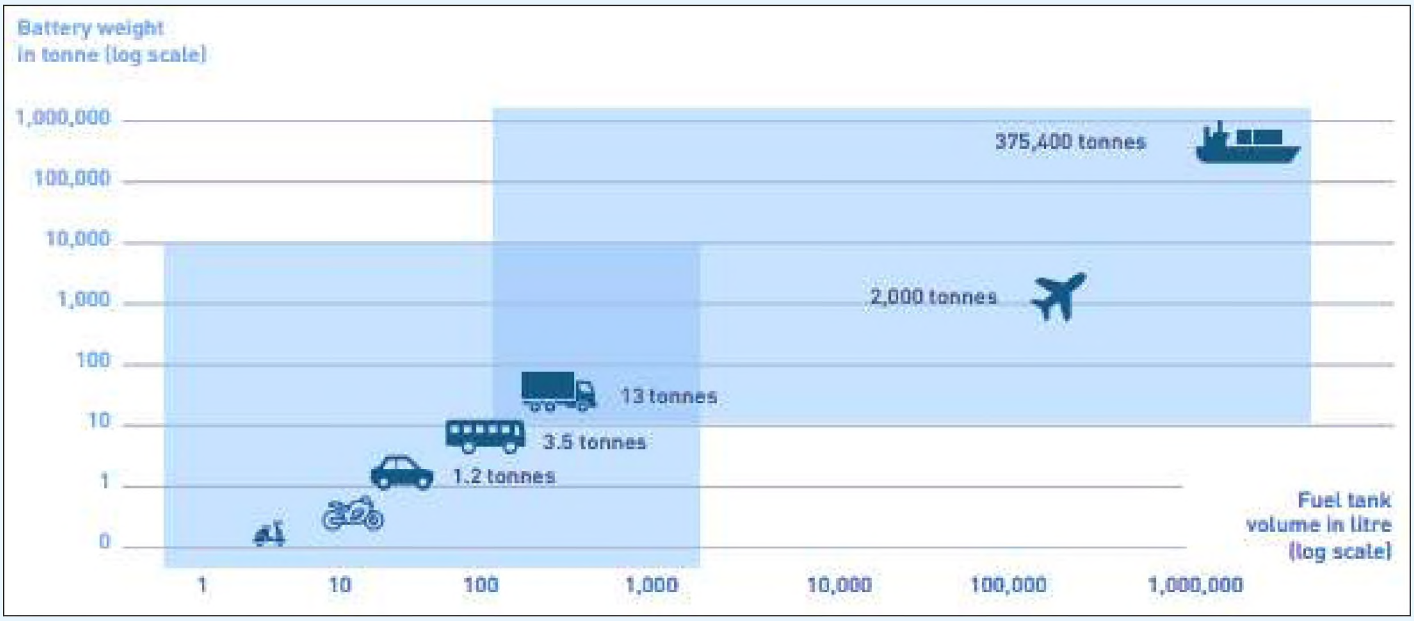


Figure-1: Limited electrification beyond the bus and light truck segment
Source: Fuels Europe Report-Vision 2050

2. e-Fuels

e-fuels are synthetic fuels, resulting from the combination of 'green or e-hydrogen' produced by electrolysis of water with renewable electricity and CO2 captured either from a concentrated source (e.g. flue gases from an industrial site) or from the air (via direct air capture, DAC). E-fuel is nearly carbon neutral in theory. They can be manufactured as 'drop in' replacements for fossil jet fuel, diesel and fuel oil. e-fuels are also referred to as electro-fuels, power-to-X (PtX), power-to-liquids (PtL), power-to-gas (PtG) and synthetic fuels. The most common conversion pathways for liquid fuel synthesis are the Fischer-Tropsch (FT) pathway and the methanol (MeOH) pathway. These technologies are well-known and used at scale. However, these existing processes use fossil carbon sources and new technologies and further innovation will be required to enable non-fossil carbon dioxide sources to be used.

3. Challenges with e-fuels

E-fuel has its fair share of drawbacks and challenges. First, the Production costs for e-fuels are currently more expensive than fossil fuels. The e-fuels production process is inherently inefficient, converting at best half of the energy in the electricity into liquid or gaseous fuels. The energy losses from manufacturing are high due to the many processes involved. However, this might be justified where electrical propulsion is not practical and renewable electricity is cheap and plentiful. Innovation in each process stage has the potential to reduce these costs in the future to enable production and scale up. e-fuel costs are currently relatively high (up to 7 $/ litre) but are expected to decrease over time due to economies of scale, learning effects and an anticipated reduction in the renewable electricity price; this is expected to lead to a cost of 1–3 $/ litre (without taxes) in 2050. The cost of e-fuels could therefore be 1–3 times higher than the cost of fossil fuels at that time.

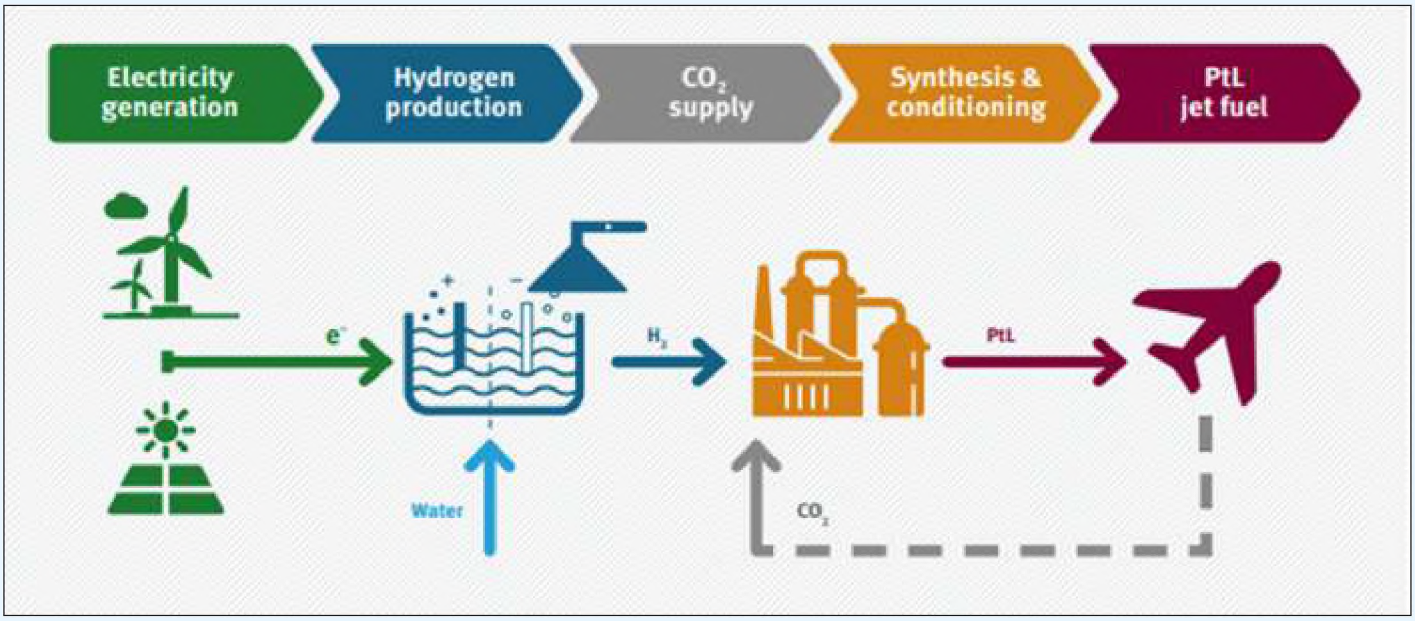


Figure-2: Power-to-liquids production (generic scheme)
Source: power-to-liquids-potentials-perspectives- German Environment Agency

Second, the IC engines are less efficient than electric vehicles. As shown in the Figure-3, about 48% of the energy from renewable electricity is lost in the conversion to liquid fuels, using the average value for drop-in diesel technologies. Then 70% of the energy in those fuels will be lost when they are combusted in internal combustion engines, for a total efficiency of 16% for the e-fuels pathway. In contrast, the majority of energy used by electric vehicles actually goes to powering the wheels, losing only 10% in charging and 20% by the motor and for a total efficiency of 72%.

Source: “E-fuels won’t save the internal combustion engine: by The International Council on Clean Transportation, US (icct)

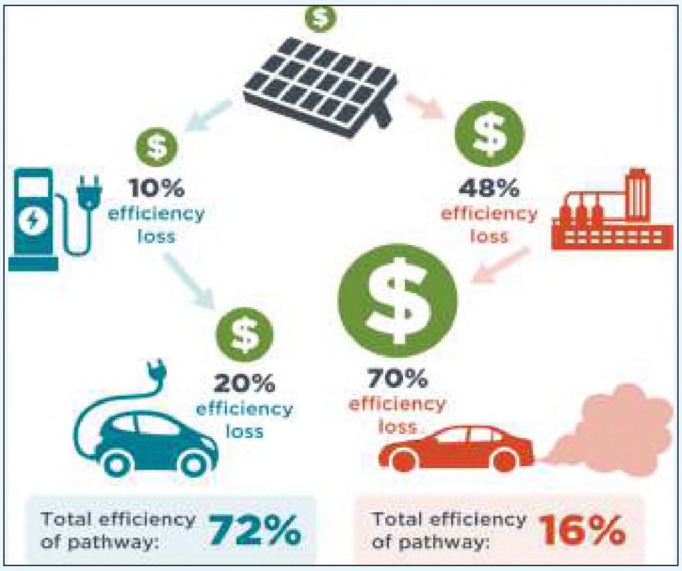


Figure-3: Efficiency pathways

The overall energy efficiency of electricity use in battery electric vehicles (BEVs) is 4–6 times higher than for e-fuels in combustion engines (see Figure-3). The battery electric vehicle has a total overall efficiency (from the power generation point to the final user) of around 69%, while a fuel cell vehicle has an overall efficiency of around 26–35%, and a liquid e-fuel car has an efficiency of around 13–15% (Frontier Economics, 2018).

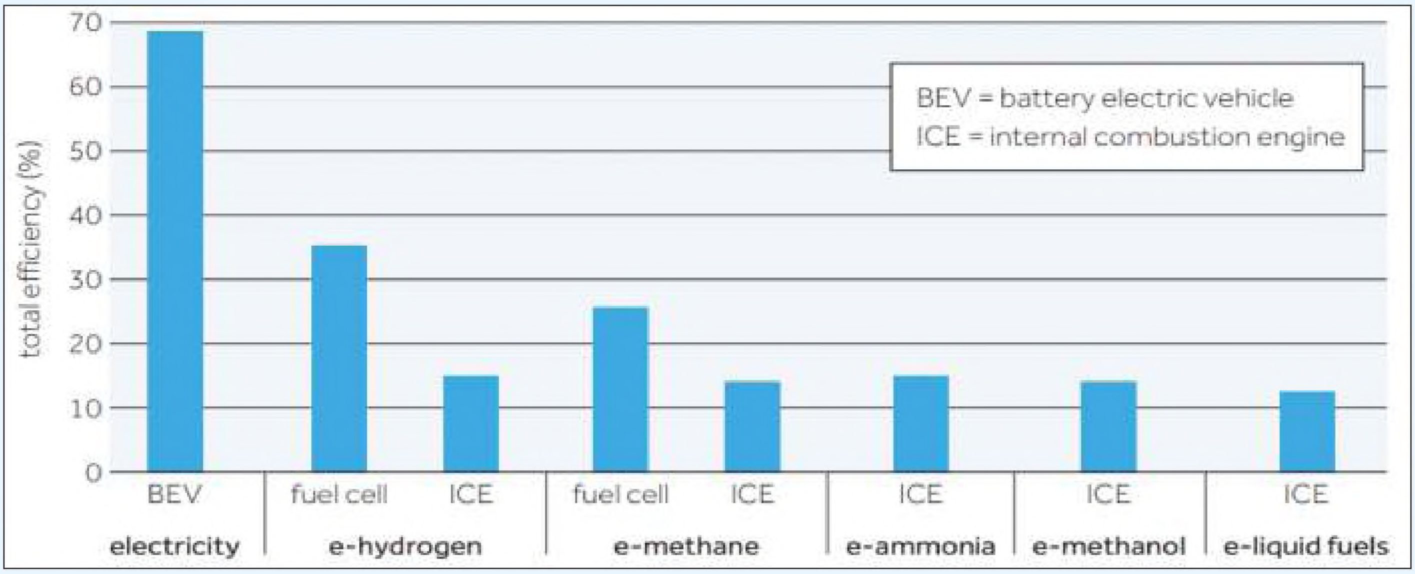


Figure-4: e-fuels final efficiency in engines (WTW approach);
Source: Concawe assessment based on Frontier Economics (2018)

Further, some of challenges associated with hydrogen remain here also, as e-fuels basically require green hydrogen for their production. There also may be synergies between the e-fuels and hydrogen pathway in a way that parts of the process change can later be used for the direct use of hydrogen as well. Finally, e-fuels also emit carbon dioxide when burnt, therefore to fully understand the GHG emission savings a full life cycle assessment of e-fuels has yet to be evaluated in depth.

4. Synthetic Aviation Fuels (SAF)

The global aviation industry contributes ~2.1% of human induced CO2 emission and 12% of total transport related CO2 emission. Air transport is expected to grow at about 4 % p. a. until 2050. However, air transport is more difficult to decarbonize. One option to reduce climate relevant emissions of the sector is an increasing use of SAF. The International Civil Aviation Organization (ICAO) has established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016, with the aim to cap net carbon emissions of international flights at 2020 level by 2027 and by 50% by 2050 relative to 2005 levels. Once CORSIA is in operation, airlines operating on covered routes will be able to meet their emission reduction obligations in two ways. One is to invest in emission reductions in other sectors (offsetting). The second is to reduce emissions directly within the sector, for instance through energy efficiency in design and operation or by burning approved Sustainable Aviation Fuels (SAF) that emit less carbon on a lifecycle basis than conventional jet fuels. If using SAF, airlines could still have to purchase offsets but the amount would be smaller, depending on the lifecycle reduction in emissions achieved by the particular SAF used. These low carbon Sustainable Aviation Fuels (SAF) have the potential to help the aviation sector reduce its carbon footprint significantly, assuming all sustainability criteria are met.

5. Opportunities with e-fuels

e-fuels offer an opportunity for the transport sector to become more sustainable and to deliver its contribution to the climate goals. e-fuels based on energy and feedstock from renewable sources, offer scope to decarbonise the heavy duty and long-distance segments of the transport sector whilst still fulfilling the mobility needs of passenger and freight transport. It will, however, require a drastic transition in fuel production and the effort of all stakeholders.

For fuel producers, e-fuels offer an opportunity to

develop new Product Market Combinations (PMCs) by delivering new products (e-fuels) to the transport market. This role can be fulfilled by current (fossil) fuel producers, by chemical companies or by parties at industrial clusters in new circular business models. Producing 'green' e-fuels can help them achieve their sustainability goals.

Fuel providers have an interest in reusing existing infrastructure to minimise the need for investments in new infrastructure. As infrastructure for diesel and kerosene is already in place, fuel providers could probably favour e-diesel and e-kerosene over other e-fuels. The development of hydrogen infrastructure by third parties will make hydrogen more attractive. Though fuel providers have a large interest in current fossil fuel provisioning, it is inevitable that they become fellow travellers in the transition to sustainable fuels.

For energy suppliers, the production of e-fuels will have a large impact on the demand for electricity from renewable sources. Investments in large-scale renewable energy supplies (e.g. offshore wind parks) are needed. As the supply patterns of renewable sources such as wind and solar are volatile, the energy sector has an interest in flexible demand. Hydrogen production can meet this need for flexibility.

> **"The transport sector is responsible for 23% of global CO_2 emissions."**

6.0 Conclusion

This paper is intended to build a better understanding of the e-fuels especially for Heavy duty vehicle (HDVs), Aviation and Marine sector for achieving net Zero Targets. Though it is not yet clear which e-fuels will become dominant (especially for trucks and ships), it is obvious that such a future requires a large amount of green electricity, hydrogen production, e-fuel production capacity, government stimulation and vehicle development, etc. In order to be ready for this, all stakeholders need to now start preparing themselves and initiate developments. Meanwhile, cost developments for renewable electricity, CO2 and e-fuels production should be monitored in order to be able to make final choices on e-fuels and to take specific actions for the development of these e-fuels. Most importantly, customer acceptance of alternative fuels and vehicle technologies will be the key to achieve sizeable penetration and to have a significant impact on the reduction of fossil fuel imports.

1.2 H2 in SOLID – The "Missing Piece" in the Net-Zero Logistics Ecosystem

Author: James Khong, Co-founder & COO, Galaxy FCT

James Khong is a Co-founder and the Chief Operating Officer of Galaxy FCT, a hydrogen technology company which has a patented process (issued and worldwide pending) which allows rapid and efficient release of H2 gas from solid feedstock - a process which opens the pathway for evolution of a parallel clean energy logistics ecosystem based on "H2 in SOLID". James has extensive work experience in energy and infrastructure project development and project financing in various capacities, having worked as a business development director for the AES Corporation, as an investment banker with Barclays DeZoete Wedd (Corporate & Project Finance), Tokyo Mitsubishi International (Singapore) & CIMB Investment Bank (Equity Capital Markets & Structured Products) as well as legal counsel (Privatization, Infrastructure and Project Financing) with Zaid Ibrahim & Co (ZICO Legal). Apart from working as a professional, he has, over the years, also made direct principal investments in several different businesses/companies including two in the Oil and Gas Support Services Sector/Subsea Services, participated actively with management, and have subsequently exited those investments through trade sale/ IPO. James holds a Master of Laws (LLM, Cambridge, St Johns College), a Bachelor of Laws (LLB, Malaya) and qualified as a CFA (Chartered Financial Analyst) Charter holder in 2001

Abstract

The climate crisis is worsening rapidly and the need for global decarbonization is becoming increasingly urgent. Mankind has made huge strides in clean technology over the past decade, but a couple of "pain points" have remained very persistent, namely:

(1) How to decarbonize where infrastructure simply "doesn't work"; and

(2) Long-duration bulk storage of clean energy without hydrocarbons.

The Solid H2 Logistics Ecosystem may not be a "silver bullet", but it holds immense potential to address these pain points and also to "complement" all other clean-tech solutions that we have today in a way which can truly unleash the full potential of renewable energy to fight against climate change.

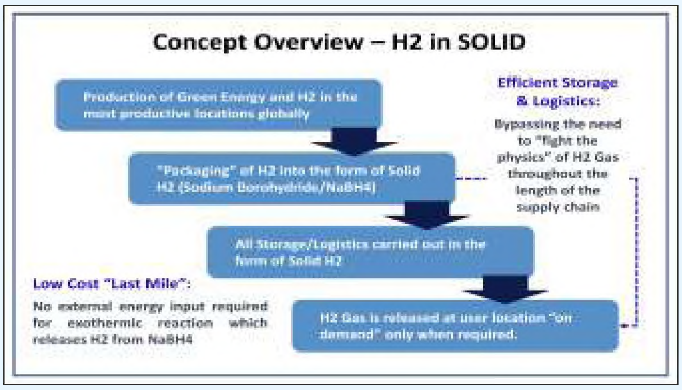
In this paper, we will highlight why the "tipping point" is near for rapid evolution of a Solid H2 Logistics Ecosystem and explain how we can and must accelerate this process to effectively address the climate crisis.

Introduction to Solid H2 Logistics

The concept underpinning Solid H2 Logistics is deceptively simple - bypassing the extremely challenging physics of Hydrogen by carrying out all storage and logistical activities in the form of a solid feedstock … and releasing H2 gas from solid "on demand" at user location when required.

With Solid H2 Logistics, clean energy is converted at the point of production into H2 which is subsequently "packaged" into a solid chemical compound (Sodium Borohydride ($NaBH_4$).

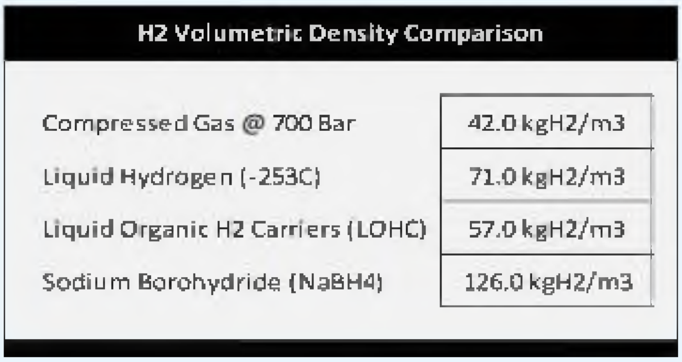
By utilizing $NaBH_4$, an energy-dense compound, which is non-flammable, non-explosive and can be handled at ambient temperature without pressure, storage and logistics across the entire supply chain becomes simple, safe, cost-efficient, and infrastructure-light. H2 gas will be released through a hydrolysis reaction at user location only when needed.



Sodium Borohydride (NaBH4)

The attributes of NaBH4, or Solid H2, make it a form of hydrogen that is "cheap to store, easy to move, and safe to handle, and as such, infrastructure-light across the entire supply chain.

Its logistical efficiency coupled with a high energy density allows for cost-efficient direct shipping from the point of production to end users wherever they may be, eliminating the need for huge investments in transmission infrastructure.



H2 Volumetric Density Comparison	
Compressed Gas @ 700 Bar	42.0 kgH2/m3
Liquid Hydrogen (-253C)	71.0 kgH2/m3
Liquid Organic H2 Carriers (LOHC)	57.0 kgH2/m3
Sodium Borohydride (NaBH4)	126.0 kgH2/m3

Global Net Zero and Green H2

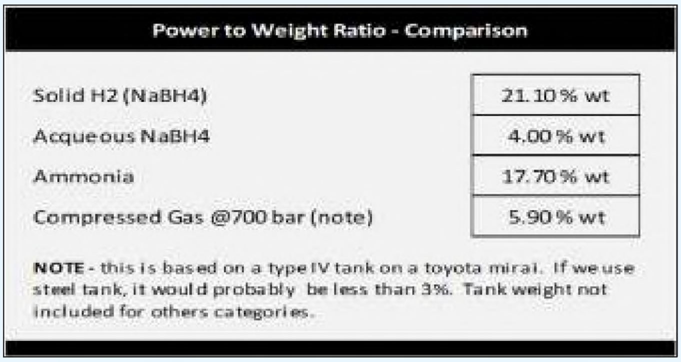
Global decarbonization requires huge quantities of green hydrogen. McKinsey estimates 660 million MT of hydrogen demand annually by 2050 and green hydrogen is projected to account for over 60% by 2035. The lowest cost locations for producing green H2 in bulk are typically remote and far away from main load centers, and over time, it is expected that the bulk of global green hydrogen will be produced in such locations.

As global supply chains inevitably get much longer and more complex, a lot more infrastructure and storage capacity will be required to bridge the gap between variable energy production and increasing fluctuations in demand. Under such conditions, production costs of green hydrogen itself may well be a relatively small portion of "total costs of H2 delivered to the end-user" and the unique advantages of Solid H2 Logistics will become very clear - being able to scale globally with minimal logistical infrastructure and be stored for long durations anywhere at very low cost.

Galaxy FCT & Solid H2

Galaxy FCT's technology breakthrough today allows for the rapid and efficient release of hydrogen gas from solid form NaBH4. IN the form of an aqueous solutions, the NaBH4 content typically ranges between 10% to 20%. This means that lots of water needs to be transported together, resulting in rather poor "power to weight ratio". By using the solid form, this ratio improves significantly as water is readily available in many locations and does not need to be transported in most cases.

Aqueous NaBH4 also requires addition of reaction inhibitors to prevent premature H2 release. This will contaminate the by-product (NaBO2) making recycling of the same much more complex and costly. Galaxy FCT's protocols avoid this completely and the catalysts used can be fully recovered, leaving the by-product uncontaminated and easy to recycle.



Power to Weight Ratio - Comparison	
Solid H2 (NaBH4)	21.10 % wt
Acqueous NaBH4	4.00 % wt
Ammonia	17.70 % wt
Compressed Gas @700 bar (note)	5.90 % wt

NOTE - this is based on a type IV tank on a toyota mirai. If we use steel tank, it would probably be less than 3%. Tank weight not included for others categories.

The "No-Go" Decision from US DOE

It would perhaps be instructive at this juncture to take a deeper dive into the decision of the US Department of Energy in 2007 which decided that NaBH4 was a "No-Go" as On-Board Vehicular Hydrogen Storage.

U. S. Department of Energy Hydrogen Program

Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage

In the early 2000s, there was a surge of interest in NaBH4 as hydrogen carrier when Millennium Cell Inc of the US developed H2 Fuel Cell Car prototypes powered by aqueous (liquid) NaBH4. This "No-Go" decision of the DOE effectively deflated interest in this area as research funds dried up. However, if we looked deeper at the reasons cited and re-considered the same with the lenses of 2023 instead of 2007, we may well come to a different conclusion.

Indeed, mankind's perception of the Climate Crisis has also changed significantly. Back then, many believed it was probably something which would be a problem for future generations, but now in 2023, most people all over the world realize that the crisis is imminent and requires urgent solutions. The immense potential of NaBH4 to address currently unresolved climate "pain points" makes it an extremely compelling proposition.

DOE Perspective 2007	A 2023 Perspective
Aqueous NaBH4 had a very poor "power to weight ratio" and cannot meet the minimum threshold DOE required of 6.0%	Galaxy FCT uses Solid NaBH4 as feedstock and this will make the "power to weight ratio" much higher than the DOE threshold of 6.0%
The On-Board System proposed by Millennium Cell was considered to be too heavy and too big to realistically fit within a car.	We use NaBH4 as clean energy carrier (H2 gas on demand) for many applications. In vehicles, focus will be on heavy vehicles rather than cars.
Economics: DOE doubted the economics which were predicated on availability of cheap energy (USD 3 cents/kWh) which was unrealistic (in 2007)	In April 2021, PPA price for Desert Solar in Saudi signed for record low of USD 1.04 cents/kWh. With greater scale/technology, we believe future prices can go even lower.

A Patented Process

Galaxy FCT's has patents issued in most major countries (worldwide pending).

The hydrolysis process for releasing hydrogen gas is exothermic and does not require external energy input. This makes it highly energy efficient at the user location, where energy may be scarce and expensive. The relative simplicity of this process also makes the last-mile equipment cost-effective once it is produced in large quantities.

Patents Issued (as at Jan 2023):

United States of America, China, India, South Korea, Japan, Saudi Arabia, ARIPO, South Africa & Nigeria, worldwide pending

GFCT's processes provide the foundation for upon which the Solid H2 Logistics Ecosystem can evolve. The conditions are right, and the tipping point is near. The final barrier that now needs to be addressed is scarcity and the high cost of NaBH4. Production needs to be commoditized and prices must be brought down rapidly. Galaxy FCT remains extremely keen to work with potential partners and stakeholders to make this happen as soon as possible so that the ecosystem can evolve rapidly.

Simplified SOLID H2 Generator ("Solid HyGen") Schematic

Solid H2 Applications

Before addressing production costs, let us discuss the applications which are well supported by the Solid H2 Logistics ecosystem. The cost structure of Solid H2 Logistics differs very significantly from conventional clean-tech solutions (which are typically infrastructure intensive).

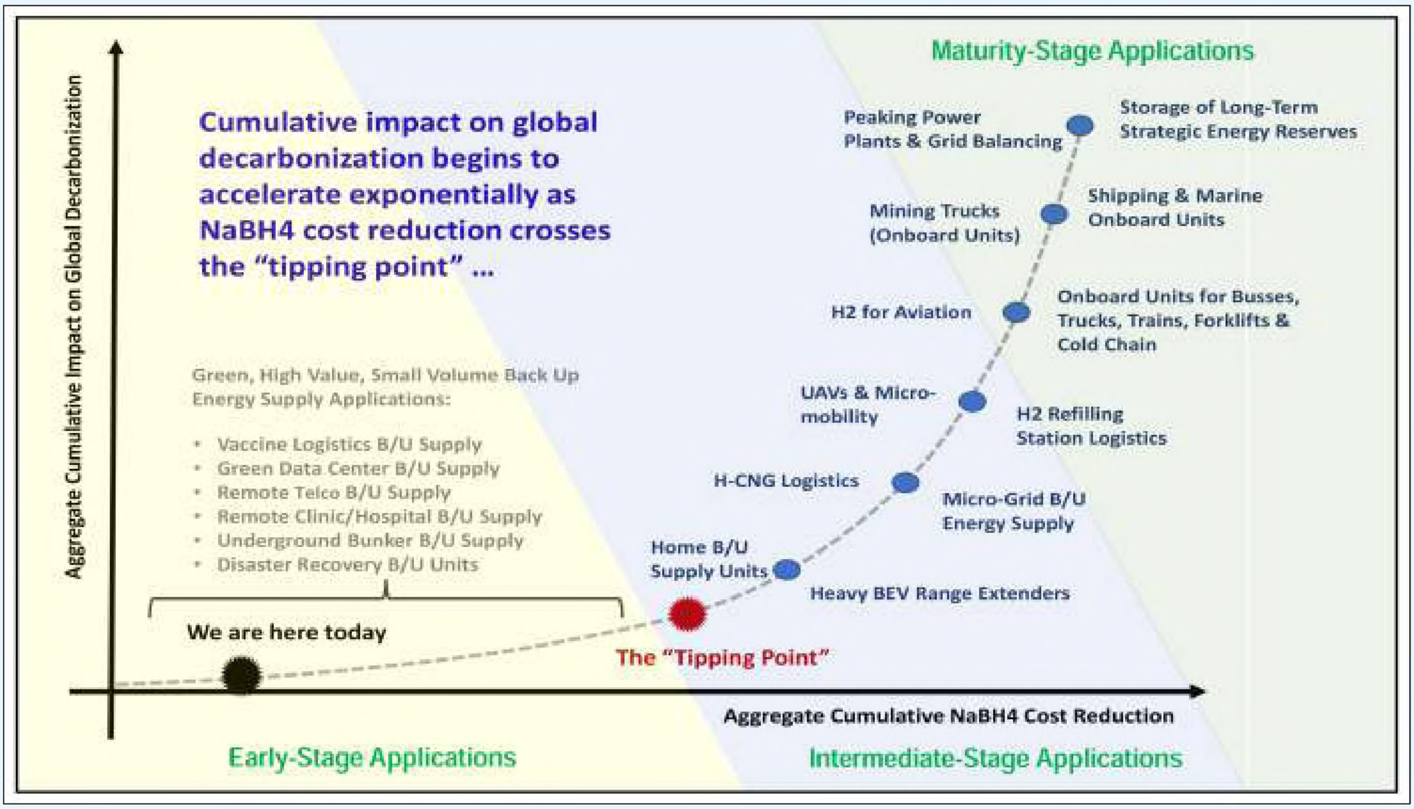
Production costs of Solid H2 take up a substantial portion of overall costs while the production costs of Solid H2 is brought down over time, the number of applications that come into the "sweet spot" will systematically increase as aggregate demand for NaBH4 globally at the same time will tend to rise very sharply.

(A) Early-Stage Applications

In early days, as the ecosystem begins to take shape and Solid H2 prices remain elevated, we expect these to revolve on critical (high value) applications which prioritizes safety, availability, flexibility, and resiliency as well as those where long duration storage is required. Examples of such applications would include emergency back-up power supply for remote healthcare, vaccine storage, strategic communication, remote military facilities, underground bunkers, and emergency services. Mainly critical applications which need reliable power in situations when traditional energy sources may be unavailable or impractical.

(B) Intermediate-Stage Applications

As prices are brought lower through large scale production, we expect applications to widen and include more mainstream usage that require greater quantity of energy. Being extremely flexible and resilient, we expect Solid H2 applications to complement other hydrogen carriers, servicing areas where deployment of an extensive infrastructure network is not feasible, where demand is relatively intermittent and/or where there are greater storage needs at various different parts of a complex supply chain. These are circumstances under which infrastructure intensive solutions would be rather uneconomical and impractical and better suited for Solid H2 Logistics.



Maturity Stage Applications

Maturity Stage ApplicationsThis is the stage where there will be very large quantities of Solid H2 being continuously produced at very low cost resulting from a combination between very low cost per kWh of renewable generation, extremely large-scale production in Prime Sites and process improvements from better technology over time. The sooner we reach this stage, the more effectively we will be able to manage the Climate Crisis. Some of the more notable applications would be as follows:

(I) Mining Trucks & Excavators

Mining activities are already responsible for between 4% to 7% of greenhouse gases annually and it is one sector which is extremely difficult to electrify. A lot more critical minerals are needed for the energy transition, and unless this sector is decarbonized, emissions from mining would exacerbate and accelerate the climate crisis. Diesel powered mining trucks and excavators are major sources of carbon emissions. Using Solid H2 onboard units to power mining trucks/excavators will significantly reduce the carbon footprint of mining activities and enable mankind to continue large scale mineral production which is necessary to fast track the energy transition without the massive carbon footprint that could push our planet beyond the climate tipping points.

(ii) Clean Shipping

At the right price point, Solid H2 will emerge as an attractive energy carrier for green shipping. It is safe, simple and cheap to store for long periods with minimal infrastructure anywhere in the world, coupled with high volumetric energy density. Solid form storage also has the added advantage of minimizing leakage, which can be a major issue when shipping fuel is stored in the form of LNG, hydrogen gas/liquid or ammonia. Hydrogen, methane, and nitrous oxide are much more potent as greenhouse gases compared to CO_2 by a factor of 80 times, 11times and 300 times respectively.

(iii) Providing Peak Energy & Grid Stability

As we move towards Net Zero, the electricity grid will have a greater percentage of renewable energy from variable sources which will tend to fluctuate substantially with weather and climate conditions.

With climate change itself progressively causing more severe climate events happening more often than ever, there will be even greater stress on transmission infrastructure and the shortfall between supply and demand of energy when such events occur. As extremes get greater, the quantity of batteries required in any smart grid of the future would be extremely large.

Using Solid H_2 to provide peak energy during these surges would be much more cost effective than deploying batteries for everything. Batteries are most effective when used regularly (time shifting of energy between day and night and to provide additional flexibility on a regular basis), but the peak demand mismatches which happen only occasionally would probably be more efficiently addressed with Solid H_2 in tandem

(iv) Long Duration Strategic Reserves

As the world moves away from hydrocarbons, there will be a critical need for an efficient medium for large scale storage of clean energy for extended periods of time (Strategic Reserves). Currently there are few viable options which depend on specific types of landforms or require construction of very significant fixed infrastructure at specific locations. These tend to lack the flexibility that hydrocarbons provide

Solid H_2 is logistically flexible and efficient and can provide an attractive medium for long duration energy storage. Once production costs come to a reasonable level, it would become an attractive modality for storing long term strategic energy reserves in the post hydrocarbon world.

Commoditizing $NaBH_4$ Production

$NaBH_4$ today is largely produced as a specialty chemical at relatively low annual volume when considered from a global energy perspective. The market is dominated by several large producers within an oligopolistic market structure.

The current production modality starts with the production of Sodium metal using the Down Process which involves electrolysis of molten sodium chloride (NaCl) at high temperatures (circa 650C). Sodium metal being highly explosive needs then transported (mainly from China) submerged in paraffin oil to the $NaBH_4$ plant.The Brown Schlesinger process has been the way $NaBH_4$ has been produced for the past 70 years. Sodium metal is mixed with hydrogen gas at around 300C to form sodium hydride (NaH), which is subsequently reacted with trimethyl borate ($B(OCH_3)_3$) to produce $NaBH_4$. The production processes also include several intermediate stages that involve distillation, separation and drying, as well as wastewater processing.

The key chemical processes are summarized below:

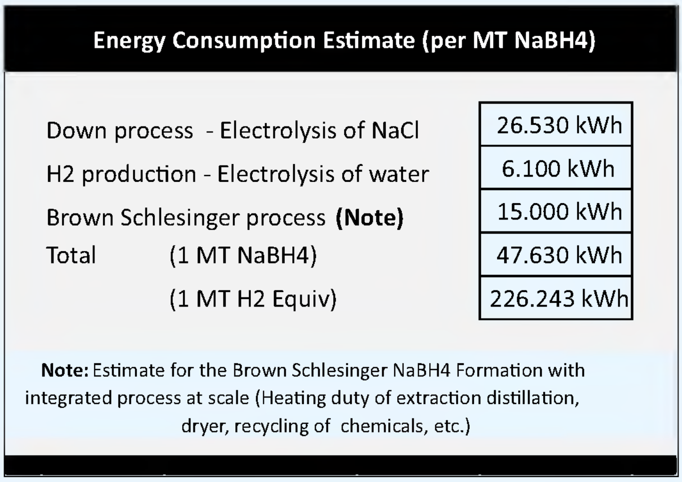
$$\mathbf{Na + H_2 \rightarrow 2NaH} \text{ (200C-350C)}$$

$$\mathbf{4\ NaH + B(OCH_3)_3 \rightarrow NaBH_4 + 3\ NaOCH_3}$$
$$\text{(260C-350C)}$$

It is pertinent to observe that all the core raw materials are either inexpensive or recyclable and the biggest component is energy and process costs.

Key Raw Material (estimates) per MT of $NaBH_4$	
NaCl (to produce Na)	6.157 MT
H_2O (to produce H_2)	0.106 MT
Boric Acid (recyclable)	1.631 MT
Methanol (recyclable)	2.526 MT

This means that there is very significant scope for rapid and meaningful cost reduction that can be garnered from integrated large-scale, continuous production with optimized processes and recycling of intermediate chemicals and waste heat wherever possible.



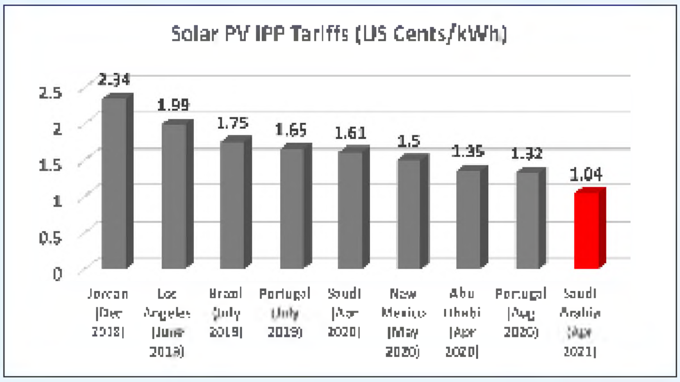
Energy Consumption Estimate (per MT NaBH4)

Down process - Electrolysis of NaCl	26.530 kWh
H2 production - Electrolysis of water	6.100 kWh
Brown Schlesinger process **(Note)**	15.000 kWh
Total (1 MT NaBH4)	47.630 kWh
(1 MT H2 Equiv)	226.243 kWh

Note: Estimate for the Brown Schlesinger NaBH4 Formation with integrated process at scale (Heating duty of extraction distillation, dryer, recycling of chemicals, etc.)

It is pertinent to note that mankind has been making huge strides in bringing down the cost of production for each kWh of renewable energy, especially solar. As we continue to fast-track renewable energy generation globally, the learning curve effect (generally described as Wrights Law) will likely result in a certain percentage reduction for each doubling of aggregate global installed capacity. In the case of Solar PV, this is estimated to be somewhere between 30% to 40% for each doubling of capacity.

See: Wrights Law Points to “Insanely Cheap” Solar Prices (Ramez Naam. 2021)



See: Saudi world record low bid (PV Magazine. Apr 2021)

Desert PPA prices reached a record low in April 2021 with a tariff of USD 1.04 cents per kWh. Although prices had trended up again after that due to trade wars and de-globalization, we believe that the technical trend for prices should go lower. In January this year, prices of solar panels dropped sharply again (27%), reverting back to what we believe to be a reversion to the long-term technology trend.

See: China Solar Panel Price War Driving Renewable Energy Installations Globally (Jan 2023. SCMP)

As renewable energy price per kWh gets lower each passing year, the largest “cost component” of NaBH4 production will continue reducing in dollar terms year after year independently of any process optimization or better technology coming onstream.

Hyper Scaled NaBH4 Production at Prime Sites

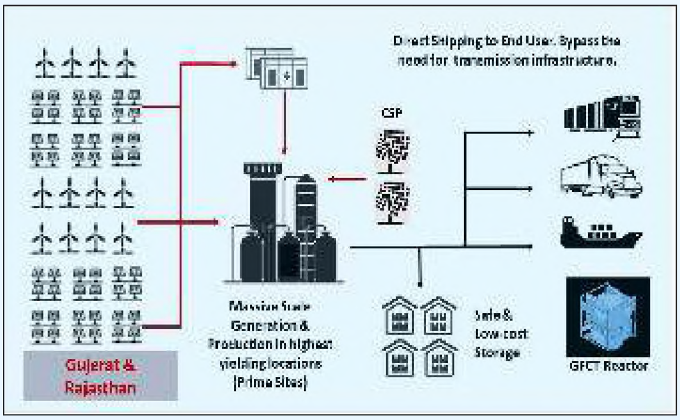
To produce lots of green molecules and to bring prices down rapidly, we need integrate renewable energy production together with NaBH4 production for continuous production at very large scale (“HyperScale”) at the most productive locations on the planet (hereinafter referred to as “Prime Sites”). We expect many Prime Sites to be typically harsh windy deserts which are near the sea.

These places may well be far from transmission infrastructure or load centers, but that would not matter because such production does not rely on the need for transmission.

Projects can be designed such that all energy generated can be used for production of NaBH4 which is then shipped directly from point of production to users anywhere in the world. No special vessels are needed as NaBH4 can be shipped in regular containers.

Removing reliance on transmission will rapidly open up large swathes of previously unused land which are well suited for immediate large-scale production of “green molecules” – something which is desperately needed if we are to mount a rapid response against climate change.

This abundance of vast contiguous lands with little or no competing uses at very low cost will allow for unprecedented scale production that would yield very significant economies of scale.



The same panel (or other capex) deployed in these areas will generate much more kWh of energy and the cost of deployment will also be lower. More importantly, there will not be any need to work out off-take contracts in advance because the final product is an energy commodity (like oil) which is simple and cheap to store for long periods and can easily withstand fluctuations in demand/supply that would derail many other projects, especially those which are much more infrastructure intensive and produce energy which is difficult or costly to store.

The pipeline of projects for low-emission hydrogen production keeps expanding, but few are reaching FID

A significant portion of projects are currently at advanced planning stages, but just a few (4%) are under construction or have reached final investment decision (FID). Among the key reasons are uncertainties about demand, lack of regulatory frameworks and of available infrastructure to deliver hydrogen to end users.

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From an India perspective, the ability to HyperScale production in Prime Sites in say Gujerat/Rajasthan, for example, allow other productive renewable generation sites closer to existing transmission infrastructure to be used for generating green electrons that can be distributed by the electricity grid.

We believe that where the grid has adequate coverage and capacity, it would very often be the clean energy carrier of choice. Green molecules should be focused on supplementing the grid/ batteries where they are inadequate.

An India Centric Perspective to Solid H2 Logistics

India is a unique country which has many key attributes and advantages that enable it to fast-track the Solid H2 Logistics Ecosystem which can in turn bring very significant benefits to India in return as well.

In the next several parts, I will discuss these aspects in greater detail not so much from just a technical perspective but encompassing economic as well as socio-political aspects on the case for accelerating Solid H2 Logistics.

(A) Rapid & Executable Pathway towards Achieving Net Zero Targets

Hyperscaled Prime Site production can provide a rapid and executable pathway for India to achieve its stated Net Zero targets of 500 GW of non-fossil generation by 2030.

- The ability to generate renewable energy at unprecedented scales in remote resource rich locations (Prime Sites) without being constrained by transmission allows immediate deployment at scale with minimal market risk or delay.

- Moving green H2 production to Prime Sites frees up productive renewable locations closer to transmission lines to supply green electrons directly to the grid.

- Solid H2 Logistics complements the Net Zero Grid extremely well as it tends to be efficient and implementable in locations and/or conditions where the Net Zero Grid is weak (i.e., where infrastructure is inadequate or where long duration energy storage is required).

(B) Creating a "Virtuous Cycle" that will Accelerate the Entire Renewable Supply Chain in India

Implementing HyperScaled production of Solid H2 at Prime Sites can create a massive and sustained multi-year demand within Indian borders for all supply chain components associated with the ecosystem.

These would include: (i) Solar PV Panels; (ii) Inverters; (iii) Wind Turbines; (iv) Concentrated Solar Components; (v) Batteries (many different types that would be required, especially large-scale stationary utility scale batteries); (vi) heat exchangers, tubing, and balance of plant; (vii) fuel cells; (viii) electrolysers and many more other associated components (all collectively hereinafter referred to as "Associated Renewables").

This massive, sustained multi-year demand for Associated Renewables which will provide an

extremely conducive environment for rapid and explosive growth of very large-scale production of all Associated Renewables within the country. This would fully leverage India's competitive advantage of having a huge pool of technical talent and its huge young population, making India an extremely competitive producer globally.

The nature of such demand generated from within one's own country is much more secure and resilient against potentially damaging demand fluctuations which can result from extreme global economic cycles, logistical interruptions, trade wars, sanctions as well as unexpected global events like pandemics. From such a large internal and secure base, India would be able to develop an internationally competitive supply chain and fast track its stated ambitions to be a world leader in the production of green Hydrogen.

It is pertinent to note that price reduction of Associated Renewables across the supply chain would also cause production costs of Solid H2 to fall rapidly. This will in turn cause the number of economically viable Solid H2 applications within the "sweet spot" to grow rapidly in number, further causing aggregate demand for Solid H2 (NaBH4) to increase exponentially. This will create the "Virtuous Cycle" that will drive more "HyperScaled" Prime Site Production that will in turn drive greater demand for Associated Renewables, bringing prices even lower … and the cycle continues.

India is one of the few countries in the world which not only has all the right conditions to make this ecosystem happen, but also the market size, material resources and human talent to reap substantial first-mover benefits in the process.

(C) A Pathway towards "Net Zero" which Optimizes Energy Usage

All decarbonization measures tend to fall within one of three categories: (i) reduce consumption; (ii) electrify; or (iii) decarbonize (what cannot be electrified). Of the three, reducing consumption is really the most rapid, direct, and effective way. But it is also the most painful to implement and politically least acceptable.

The flexibility & resilience of Solid H2 logistics allows it to be extremely targeted to meet high value applications and minimize low value (wasteful) applications. An infrastructure- intensive ecosystem, once deployed required high and continuous energy consumption within a relatively small area to ensure efficiency (low average cost per kWh delivered). With low marginal costs per unit energy, high level of consumption is structurally encouraged regardless of the true "value". In this regard, energy (like food) is very much subject to the law of diminishing returns. Deploying infrastructure in certain areas may end up encouraging lots of "low value" applications in these areas, while at the same time, many other areas remain underserved and high value applications there cannot be met. In a large country like India where there are infrastructure shortages in many areas, developing Solid H2 logistics will enable a more efficient way of distributing clean energy across various locations without "distortion" of the pricing mechanism. This allows for more high value applications to be met while encouraging users to refrain from low value (wasteful) applications because any energy which is not used (saved) can be easily stored and used another time, another day at minimal cost.

(D) Integrating Symbiotic Clusters – De-salination & Agrivoltaics

Green H2 production requires lots of water. Most Prime Sites are dry desert locations and those most suitable for HyperScaled production are located close to the sea. This facilitates shipping of the product to end users and allows for production of freshwater from desalination.
Given these dynamics, it would be highly symbiotic to integrate Solid H2 production with De-salination and Agrivoltaics:

- Agrivoltaics, the practice of planting crops under the many square miles of solar panels will not only improve land use and enhance food security, but it will also cool the panels and increase the energy generation efficiency of the panels;

- Crops planted under solar panels will result in much less water loss and be better protected against extreme weather events;

- The Desalination plants will enjoy very low energy costs and the concentrated brine produced (which is an environmental problem) can be dried with waste heat from production processes and NaCl can be used as raw material for NaBH4 production.

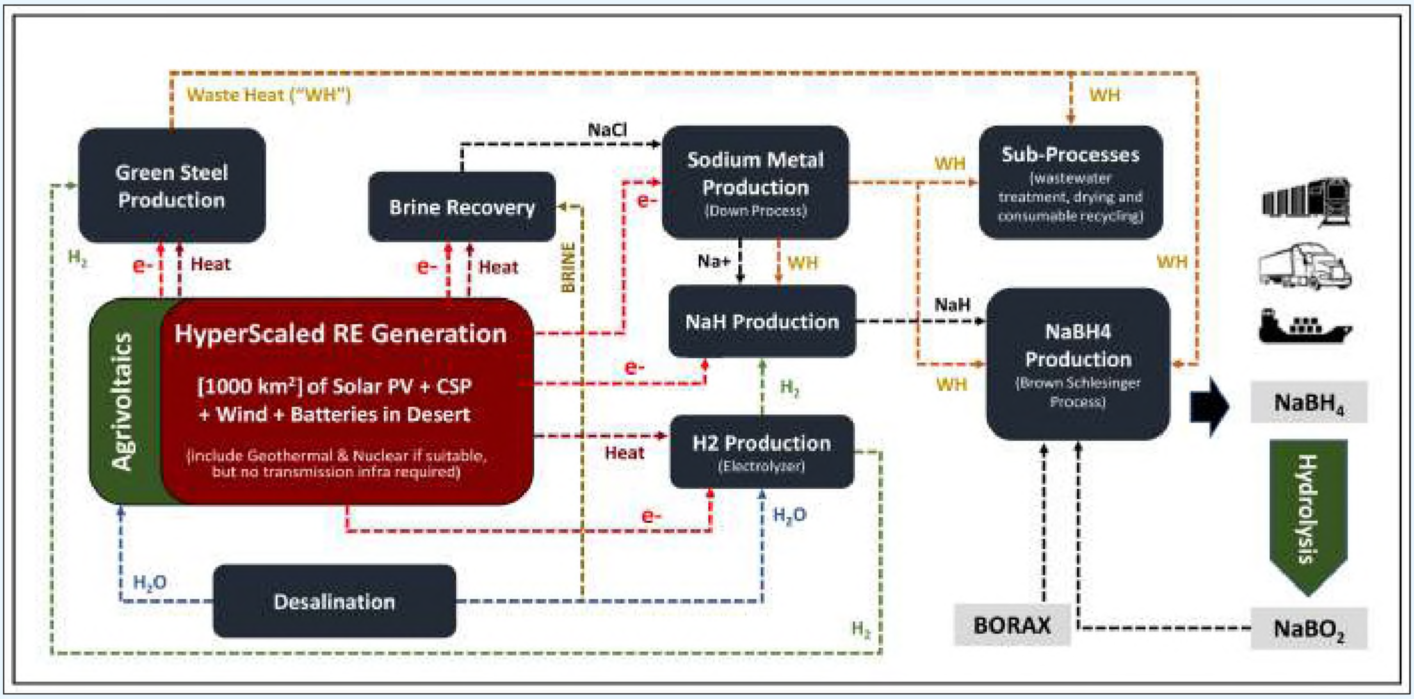
Integration of such clusters will enable further optimization of processes in a way that would improve total productivity overall.

(E) Integrating Symbiotic Clusters – Green Steel & Aluminum Production

India currently has very ambitious plans to increase production of green steel and green aluminum. These production facilities require lots of clean energy, requires lots of green hydrogen as feedstock and generates lots of waste heat. Integrating them with Solid H2 production at Prime Sites will allow for even further symbiotic process optimization.

- Production plants will have access to very low-cost green energy and reliable low-cost supply of green H2.
- Waste heat generated from the production plants can be recycled for many of the processes involved with NaBH4 production (especially, distillation & drying processes, wastewater processes and crystallization of desalination brine).

The diagram below illustrates how "Hyper-Scaling" at Prime Sites can be taken to the next level by integrating these Symbiotic Clusters as well.



Global Climate Collaboration

Solid H2 Logistics can also provide a very pragmatic sub-ecosystem for nations to start rekindling some desperately needed climate collaboration between nations which has, in recent years, been made much more difficult and complicated by sharply increased geopolitical tension as it transitions towards a multipolar world.

Under such circumstances the difficulties and risks associated with large-scale and costly long-term infrastructure projects are massively increased. When it comes to developing countries and interdependent cross-border projects, the risks and difficulties are further compounded.

All countries understand and accept that climate collaboration is critical if mankind is to navigate the Climate Crisis successfully. But reaching agreement on the terms of such collaboration has been extremely difficult. Despite 27 years of COP (Conference of Parties), very little has been achieved.

We believe that Solid H2 Logistics can potentially offer the world a very timely and interesting opportunity to meaningfully kick-start large-scale climate collaboration in a very tangible and mutually beneficial way. What if nations can come together under a multilateral treaty umbrella and designate several resource-rich locations (Prime Sites) which

can be leveraged for joint HyperScaled Solid H2 production. Each nation will be entitled to their share of production which can be shipped back to their own countries (similar to concept of "farming-in" arrangements in Oil & Gas Concessions).

- Scale of production would be a lot larger with pooling of capital resources, capturing greater economies of scale. Such scale will also fast forward the production of huge quantities of green molecules that the world needs to decarbonize the "hard to abate" segments which electricity grids and batteries cannot adequately serve.

- Capex deployed at Prime Sites will be more productive, rollout costs per unit will be cheaper and land costs will be low. Host countries, typically poorer developing countries, can benefit from the carried interests they will receive in return, making decarbonization more equitable.

- Cost of capital will be much lower because political risk is largely mitigated by security arrangements under multilateral treaty. Today where global interest rates are all trending upwards, this will make a huge difference to final production costs.

- Solid H2 can scale in all countries in the world regardless of pre-existing infrastructure or their ability to afford and deploy clean energy infrastructure in their country. In many developing countries which cannot afford massive infrastructure deployment, this ecosystem can effectively complement stand-alone microgrids that can be rapidly rolled out.

- Rich countries can subsidize poor countries in part from the extra value/efficiencies which is created from through collaboration instead of having to fund expensive infrastructure in poor countries where the economic and socio-political factors for infrastructure development are far from satisfactory. Rich countries will also be assured that assistance rendered in this way will result in direct positive impact on decarbonization in the recipient countries.

Most importantly, Solid H2 Logistics allows immediate collaboration (which is extremely urgent) without waiting to untie the Gordion Knot in figuring how the world can fund massive global infrastructure networks in many countries and/or locations where it not viable economically nor politically, and to overcome the many complications arising from geo-political issues.

Time is quickly running out, and resources are finite. Infrastructure should be judiciously deployed where it is most productive and pragmatic. Fast tracking the maturity of Solid H2 logistics through global collaboration provides the world with a viable alternative to fill the gaps.

Solid H2 Logistics provides a framework or platform where nations can start meaningful collaboration in a limited area and in a way which does not prejudice existing geopolitical differences in any material way. India, being a large country and a rising economic power, has the capacity and resources to optimize and refine the technologies that make this ecosystem work. More importantly, as a country which is, and has been consistently neutral politically, India is also very well placed to take the lead in encouraging the world to meaningfully collaborate within this ecosystem.

Some Final Thoughts

Many scientists (See: UNEP Report "The Production Gap" 2021) have opined that a huge portion of the known reserves of hydrocarbon must be left in the ground if mankind is to avert the worst consequences of the Climate Crisis. But which country will make the sacrifice? Will solutions only be possible by use of force? Perhaps … we can fast track the maturity of Solid H2 Logistics together and unleash the full potential of renewable energy globally so that Solid H2 can produced in huge quantities at a price point that can out-compete fossil fuels … then, market forces can probably do the rest.

As a final observation, we would like to reiterate that India has all the necessary conditions and resources to make this ecosystem work in very large scale. Successful execution would enable India to benefit immensely as "first mover" in many ways:

- Effective decarbonization, especially in the many areas in India where infrastructure deployment is not possible or pragmatic.

- Development of the entire renewables supply chain from the sustained "multi-year" demand generated by hyper-scaled production of Solid H2 at Prime Sites

- Enhanced energy security from ability to harness energy which is "cheap to store, easy to move and safe to handle, infrastructure LIGHT" within own borders.

- Long term clean energy storage, especially in the post-hydrocarbon era.

- Establishing an environment that would foster technology innovation and development throughout the Solid H2 Logistics Ecosystem While there is much to be done to make this ecosystem work, it's pertinent to note that the base scenario for success relies principally on existing technologies and processes which have been proven scalable and there is no reliance on new technology breakthroughs that have yet to happen. When these happen, they will only enhance the ecosystem, but are not necessary.

The circumstantial evidence that we see today points to the conclusion that the potential benefits of this ecosystem are immense. Probably one of those situations that goes "beyond Pareto" - where 10% of the efforts may well produce 90% of the results and as such, we believe that no effort should be spared in accelerating this exciting ecosystem and no stone should be left unturned.

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1.3 Strengthening India's Energy Security with Green Hydrogen Integration to Fertilizer Plants

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Abstract. /Back Ground

The world is currently seized with the problem of establishing a balance between environment friendly technologies to minimize the impact of fossil fuel-based processes on the environment. In this context the role of hydrogen has emerged as very significant. One, hydrogen is required in enormous quantities in Refineries to meet the distillate quality to meet the environmental specifications, second Hydrogen is one of the essential ingredients in the Ammonia Urea production process. Exhibit 1 provides an overview of the requirements of hydrogen in the Refinery and Fertilizer segment and its anticipated trend over the following decades. This study therefore aims at establishing green hydrogen integration to fertilizer plants and thereby strengthening India's energy security.

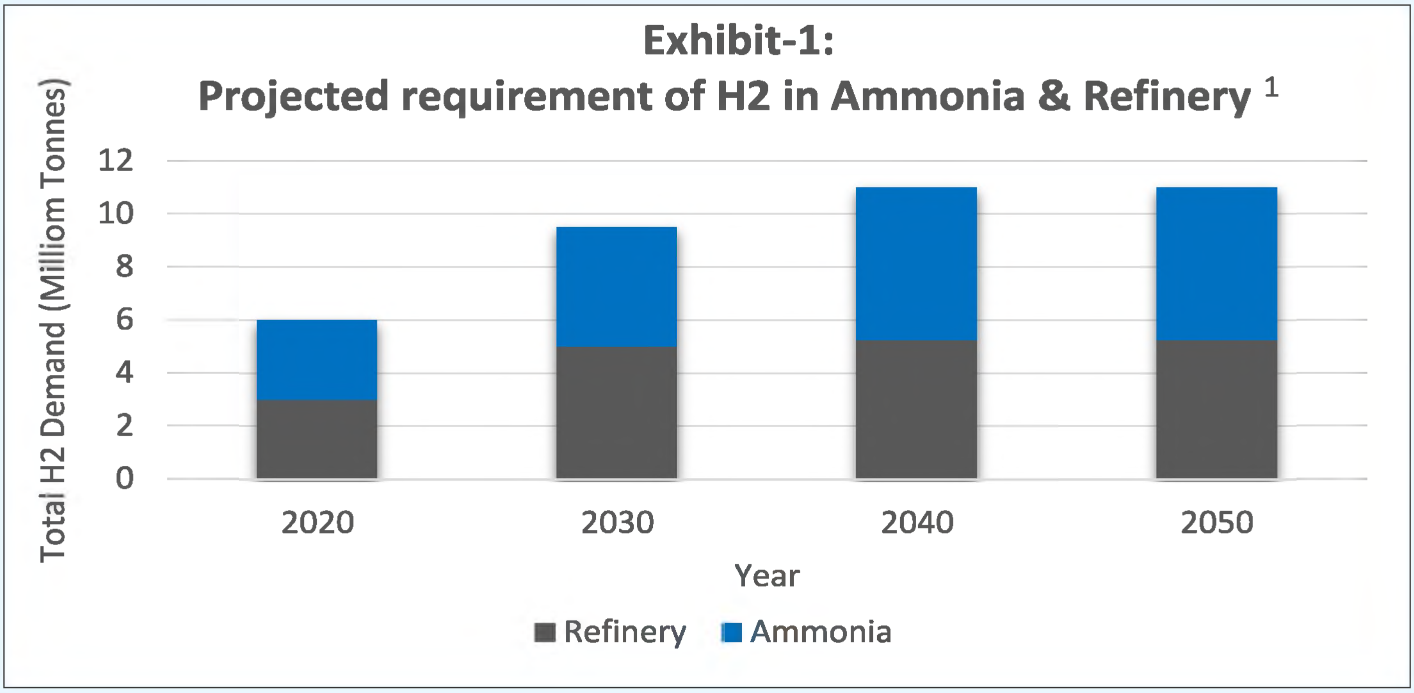

Exhibit-1:

Projected requirement of H2 in Ammonia & Refinery [1]

Figure : 1 Prepared based on NITI Aayog, Report June 2022

Introduction:

Globally, hydrogen is primarily produced by steam reforming or Steam Methane Reforming (SMR) process, in which natural gas is used to produce hydrogen to meet the requirements of the Fertilizer and the Refineries. The Country, being deficient is gas production, has to primarily resort to importing the same. The process of production of Hydrogen through the steam reforming emits a substantial amount of CO2. Also, both gas and crude are imported in the country which accounts for a significant import bill. Import forecast of natural gas and oil are indicated in Exhibit 2a and 2b against two scenarios; namely, Maximum Energy Security (Heroic Effort in Demand Sectors) (Import-M, Cost-M) and Least Effort Scenario (Import-L, Cost-L); starting from the year 2022 up to the year 2047. Total import bill of natural gas and oil for this period can go as high as INR 60 trillion and INR 605 Trillion respectively, against Least Effort Scenario. However, total import bill for both of natural gas and oil can be limited to INR 22.5 Trillion and INR 275 Trillion respectively against Maximum Energy Security (Heroic Effort in Demand Sectors).

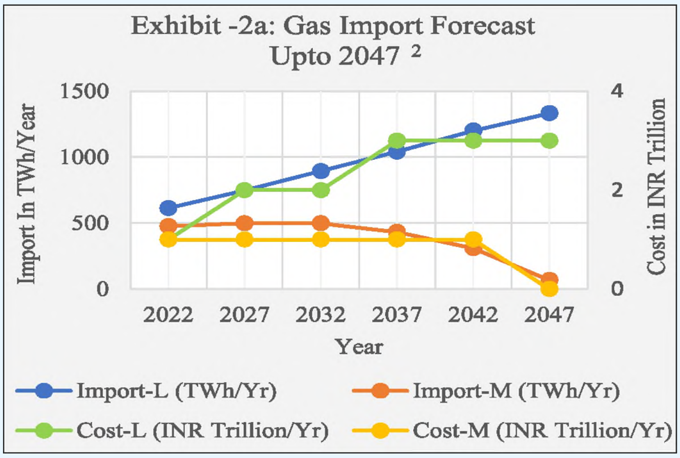

Figure :2 Prepared based on India Energy Security Scenario 2047

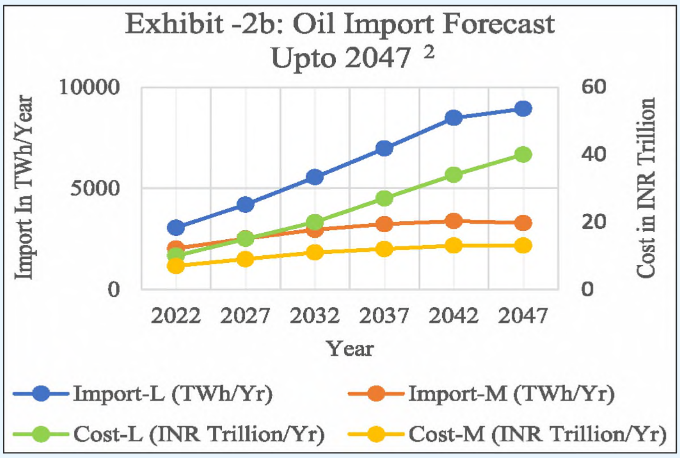

Figure :2 Prepared based on India Energy Security Scenario 2047

Towards the journey of sustainable development across the globe, Green Hydrogen has emerged as a potential solution for reduction of carbon footprint. India's distinct advantage in terms of low-cost solar energy has provided further boost towards this technology shift and compensated the huge cost incurred in import of electrolysers. However, with the successful strategic partnership between international electrolyser manufacturers and big domestic players and indigenization of electrolysers thereof, cost of green hydrogen is bound to reduce drastically. Levelised Cost of Hydrogen, LCOH in US$/Kg of green H2, forecasted for a period of 2022-2047 is indicated in Exhibit-3.

Nitrogen extracted through air separation, while reacting with this green hydrogen can be utilised to produce green ammonia, which can replace the requirements of natural gas in the fertilizers, and correspondingly therefore reduce the import bill. Further, this green ammonia along with CO2, captured from refinery emission can produce urea and will also be beneficial for the environment by means of reduction in carbon footprint in the Refineries in particular. Transportation of CO2 is a difficult as well as costly affair, so this substitution needs to be started with the fertilizers which are in the neighborhood of refineries, or else new fertilizer plants can be planned to be set up near existing and new refineries.

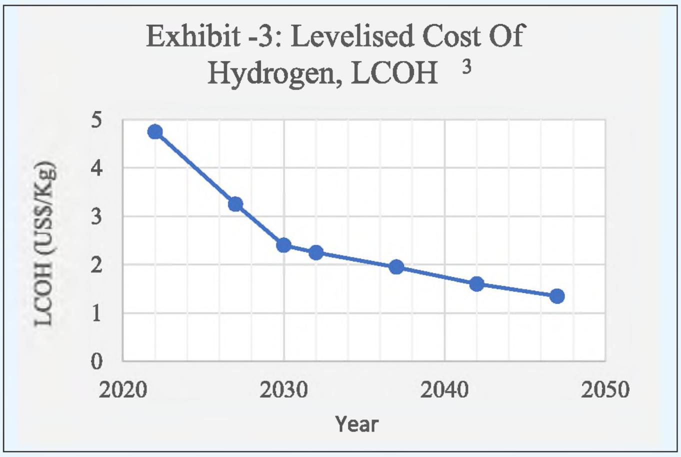

Exhibit-3 Prepared based on NITI Aayog, Report June 202

To gain the full advantage of this substitution, other major sources of carbon emissions in the fertilizers, such as fuel burning in the captive power plant (CPP), which in itself is a potential source of CO2 emission, needs to be eliminated, thus initially energy requirement may be fulfilled from grid power, till the time solar energy network is available. To begin with, this proposal will be a motivator towards sustainability goals, at a later date when green ammonia cost will be offsetted by the cost of natural gas import bill, the system will start gaining economy. In the next phase, green hydrogen can be planned to substitute the requirement of naphtha in refineries, which is presently used to produce hydrogen. The displaced naphtha from the Hydrogen plants of the refineries, may be suitably utilised as a feedstock for petrochemicals to provide better economy or alternatively can be blended to gasoline.

Since the production of green hydrogen warrants a very large power requirement, when the same is sourced from the solar energy, will require vast tracts of land and water as well. All these would imply a very high capital expenditure, given additionally the fact that, significant costs towards sourcing licensed technology, import cost of electrolysers, would also be involved. It would therefore be advisable to plan the installation of large green hydrogen plants in a phased manner; initially, to meet the requirements of the fertilizer plants and subsequently for the refineries, as the technology for production of Green hydrogen matures and the hardware is manufactured indigenously at large scale.

Project Details/ Paper Details:

Based on an assumptive analysis of a typical fertilizer plant in India (2200 TPD of Ammonia and 3850 TPD of Urea) considering gas price as $8 /MMBTU, urea price as $300/ton and the operating cost considered as 25% of the gas price the typical payback period (<3years) against a variable receding price of green hydrogen to ascertain the breakeven point emerges as indicated in Exhibit-4.

Exhibit-4: Economy of the Business Proposal considering Normal Condition

Green Hydrogen cost $/kg	CAPEX of Green H2 Plant (in Crores)	Gas import price per annum (in Crores)	Revenue from Urea per Annum (in Crores)	Operating Cost Green H2 Plant (in Crores)	Operating Margin per Annum (in Crores)	Payback period
6	6200	1390	3050	347.5	1312.5	4.72
5	5120	1390	3050	347.5	1312.5	3.90
4	4096	1390	3050	347.5	1312.5	3.12
3	3072	1390	3050	347.5	1312.5	2.34

Due to the geopolitical crisis in the Western Europe, gas price has increased asymptotically from $6-$8/MMBTU to > $12/MMBTU, urea price has also shoot up from $300/ton to > $850/ton. Considering gas price as $12 /MMBTU, urea price as $850/ton, ceteris paribus, the abovementioned figures come out as indicated in Exhibit-5.

Exhibit-5: Economy of the Business Proposal considering Exigency Condition

Green Hydrogen cost $/kg	CAPEX of Green H2 Plant (in Crores)	Gas import price per annum (in Crores)	Revenue from Urea per Annum (in Crores)	Operating Cost Green H2 Plant (in Crores)	Operating Margin per Annum (in Crores)	Payback period
6	6200	2090	8650	522.5	6037.5	1.03
5	5120	2090	8650	522.5	6037.5	0.85
4	4100	2090	8650	522.5	6037.5	0.68
3	3080	2090	8650	522.5	6037.5	0.51

Conclusion:

From Exhibit-4 it may be inferred that upon availability of green hydrogen for displacement of natural gas as feedstock to the fertilizer plant net annual saving of Rs. 1390 Crores for a typical ammonia urea complex as derived above would result as a net saving for Govt. of India. Additionally, sample calculation considering fixed price of urea and gas as mentioned above green hydrogen @$3/kg begins to show attractive returns. However, from Exhibit-5 it is evident that, in an emergency situation such as geopolitical crisis of western Europe, when gas price shoots up inordinately, net annual savings increases as Rs. 2090 Crores with payback period as low as a year even for green hydrogen @$6/kg, and thereby green hydrogen plants should be pushed through at a blistering pace.

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1.4 Infrastructure for Green Hydrogen production and its challenges

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Mr. Debashis Thakur is currently working as Senior Manager (Technical Service) at Numaligarh Refinery Limited. He is a chemical engineer & MBA with over 15 years of experience in the fields of Refinery Operations, Technical Services for different hydro-processing process units. As a process engineer, he was involved in study of making design changes to process units and their trouble-shooting having skills in simulation and design tools. He is a key member of NRL's initiative towards green hydrogen and in alternate energy horizon

Introduction & Future growth Projection of Green H2:

Green hydrogen becomes one of the important tool for India towards achieving decarbonisation or net zero target, which was set during COP26. SMR based hydrogen (Grey H2) which consists of 96-98% of H2 produced today in the world is derived from natural gas or naphtha via the steam methane reforming (SMR) process. The SMR is very CO2 intensive and generates 10 kg of CO2 for each kg of H2 produced in this process. Hence to achieve net zero by 2070 (India context), switching from grey to green hydrogen is an imperative step.

Adoption of green hydrogen can enable India to abate 3.6 gigatonnes of CO2 emissions cumulatively between now and 2050. This can be a significant lever for the nation to contribute towards its recently announced climate targets and net-zero vision. Hydrogen, as an energy carrier, is becoming crucial for achieving decarbonisation of hard-to-abate sectors. Many sectors such as iron ore and steel, fertilizers, refining, methanol, and maritime shipping emit major amounts of CO2, and carbon-free hydrogen will play a critical role in enabling deep decarbonisation.

According to the IEA's **Net Zero by 2050 Roadmap**, the size of the H_2 economy could be as large as 300 MTA (see Figure 1), including about 200 MTA of blue H_2 (IEA, 2021), in which Green Hydrogen share will be 45%. Also the recently published report on **"Harnessing Green Hydrogen"** NITI Ayog, the total Hydrogen demand in India could grow more than fourfold by 2050, representing almost 10% of global hydrogen demand , giving a push towards attaining net zero target (Figure:2)

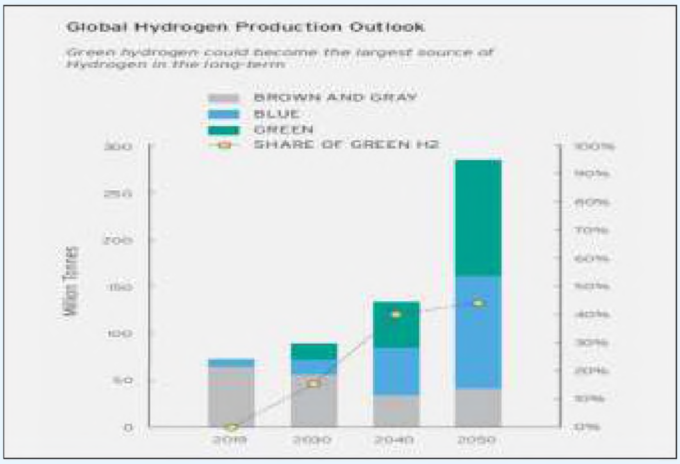


Fig: 1 (IEA, NITI Ayog report)

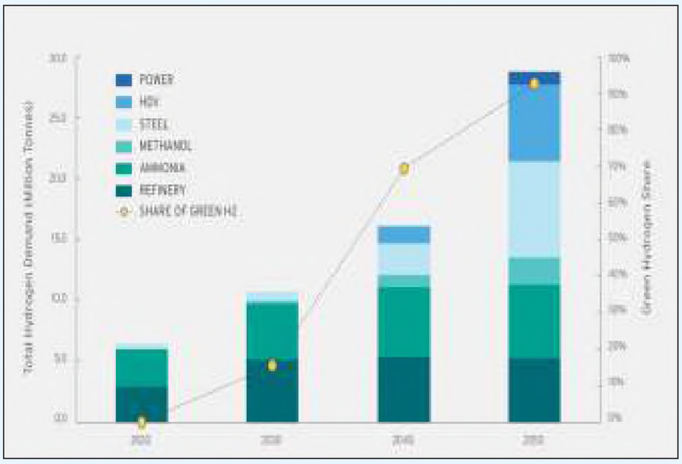
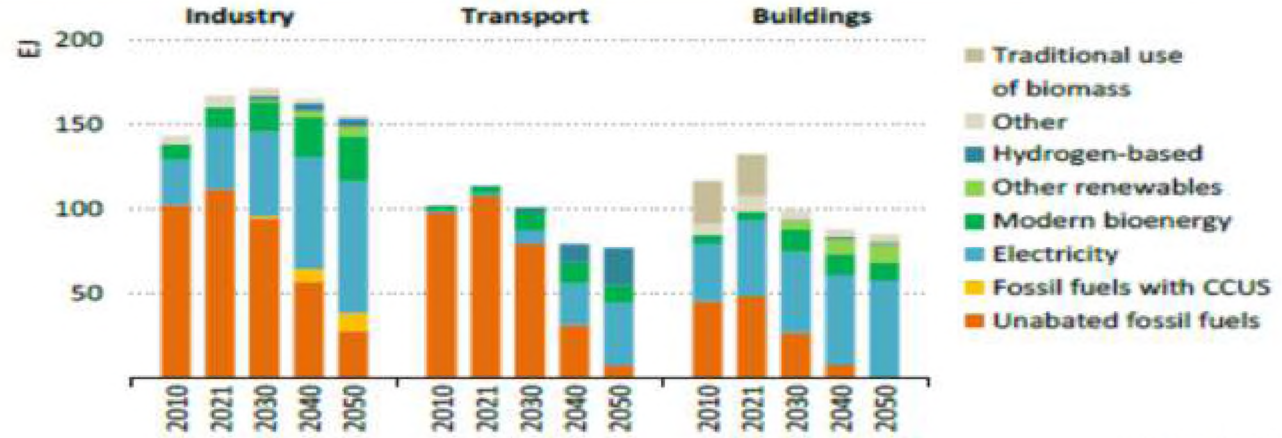


Fig: 2 (NITI Ayog report-2022)

As per the World energy outlook 2022 by IEA, the unabated fossil fuels directly provided nearly 60% of total final consumption in 2021, excluding fossil fuel use for non-energy purposes such as chemical feedstock's. In the NZE Scenario, this falls to around 45% in 2030, and to only 5% by 2050. Electricity becomes the “new oil” in terms of its dominance of final consumption; unlike oil, however, it plays a key role in all end-use sectors. The share of electricity in total final consumption rises from 20% today to slightly less than 30% by 2030 and more than 50% by 2050. Hydrogen and hydrogen-based fuels take off after 2030 and account for 10% of total final consumption by 2050



IEA. CC BY 4.0.

End-use sectors come to be dominated by electricity, which provides more than half of total final consumption by 2050

This could result in the mitigation of 1.6-3.5 gigatonnes of greenhouse gas emissions annually by 2050. Given the projected growth in green hydrogen, there is consequent expectation for an exponential growth in electrolyser capacity. The electrolyser market is expected to reach gigawatt-scale in 2022 spurred by increasing installation in China.

The emerging opportunity for hydrogen in India rests in the ability to produce price-competitive green hydrogen and enabling market creation for that hydrogen.

Technologies for production of Green Hydrogen:

The technologies available for production of green hydrogen are not new, but the maturity level in higher commercial and industrial scale is yet to be proven. The most abundant technology for production of green hydrogen is water electrolysis. **Water electrolysis** is the process of splitting of water to produce hydrogen at cathode and oxygen and anode. There are basically four types of electrolysers namely; alkaline water electrolysers (AEL), Proton Exchange membrane Electrolysers (PEM), Anion Exchange Membrane Electrolysers (AEM) and Solid Oxide Electrolyser. The minimum voltage required (electrical work without loss) to split the water molecule is 1.229 Volt which is known as reversible voltage. However for continuous reaction without external heat, the minimum electrical work required is 1.281Volt which is known as thermo-neutral voltage.

Alkaline Electrolyzer:

Alkaline electrolyzer use an aqueous caustic solution of 20%–30% KOH as electrolyte. The cell is composed of two electrodes separated by a porous diaphragm used to avoid the recombination of hydrogen and oxygen produced as shown in the Figure: 1. Hydrogen is produced at cathode and Oxygen is produced at anode.

$$2\ OH \rightarrow \frac{1}{2} O_2 + H_2O + 2e^- \quad \text{(anode)}$$
$$2H_2O + 2e \rightarrow H_2 + 2OH^- \quad \text{(cathode)}$$

There are two cell structures of alkaline electrolysis on market, unipolar and bipolar. In the mono-polar configuration, the cells are connected in parallel and the electrodes are connected to the corresponding DC power supply. The total voltage applied to the stack is the same of that applied to an individual cell, and the electrodes have a single polarity. In the bipolar configuration, each electrode has two polarities and the cells are connected in series. The voltage applied to the stack is the sum of single-cell voltage. The current that flows through the stack is the same for cells. The detailed of the technical properties are mentioned in the **Table: 1**

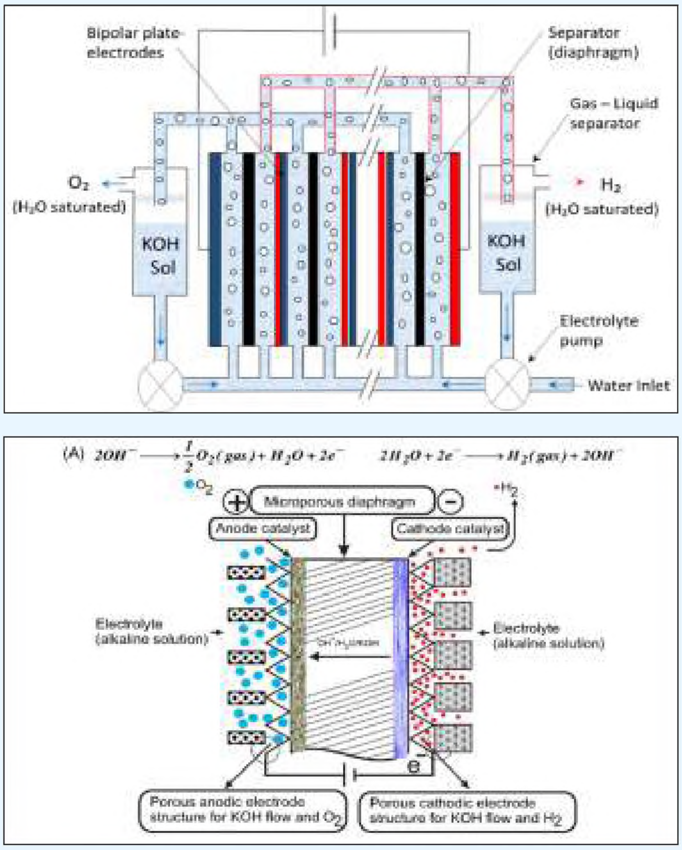


Fig: 1 Alkaline water Electrolyser

Proton Exchange Membrane Electrolyser:

PEM water electrolyzer use a polymer electrolyte membrane (or proton exchange membrane) as ionic conductor. The Water is oxidized at the anode to produce oxygen and hydrogen evolves at the cathode. The most commonly used membrane material is Nafion from DuPont.

$$H2O \rightarrow \tfrac{1}{2}\, O2 + 2H+ + 2e^{-} \quad \text{(anode)}$$
$$2H^{+} + 2e \rightarrow H2 \quad \text{(cathode)}$$

The MEA is the key device for proton exchange membrane water electrolysis (PEMWE), which is of a sandwich structure containing a solid electrolyte membrane, catalyst layer (CL), and gas diffusion layer (GDL) as shown in Fig:2. The current collectors enable an electric current to flow from the bipolar plates to the electrodes and, simultaneously, the supply of reactant water and the removal of the generated gas bubbles from the electrodes. The detail technical specification is mentioned in Table: 1

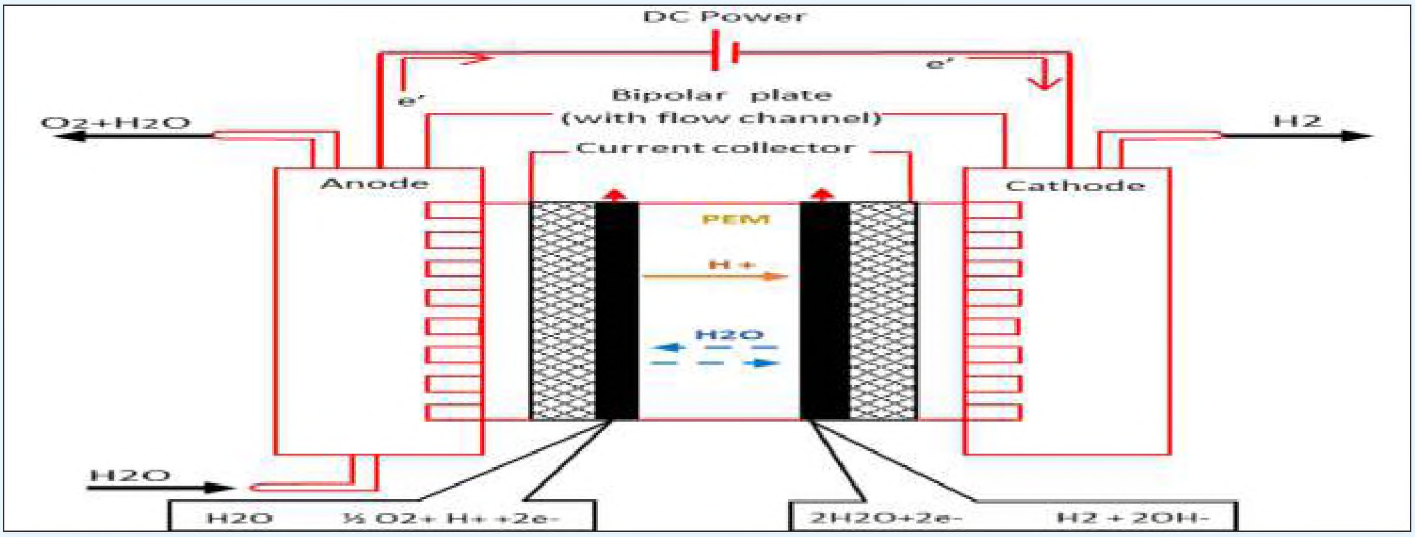


Fig: 2 Proton Exchange Membrane Electrolyser

Anion Exchange Membrane (AEM):

The working principal is similar to AEL, however instead of porous diaphragm, cathode and anode (PGM or Non PGM) is separated by AEM.

The Water is oxidized at the anode to produce oxygen and hydrogen evolves at the cathode. An anion exchange membrane (AEM) is a semi-permeable membrane generally made from ionomers (as shown in Figr: 3.)

$$2\ OH^- \rightarrow \tfrac{1}{2}\ O_2 + H_2O + 2e^-\quad \text{(anode)}$$
$$2H_2O + 2e^- \rightarrow\ H_2\ + 2OH^-\quad \text{(cathode)}$$

An anion exchange membrane (AEM) is a semipermeable membrane generally made from ionomers and designed to conduct anions while being impermeable to gases such as oxygen or hydrogen.

There three categories of membranes available, first category is Heterogeneous membrane made of NRL exchange material embedment in inert compound. Second category is interpenetrating polymer network which is basically combination of two polymer networks without any covalent bonds.

Third category is homogeneous membrane with an anionic exchange material covalently bound with in a chemically inert structure.Poly-vinyl alcohol (PVA) and LDPE are commonly used poly-hydroxyl polymer as a backboned in a fabrication of an efficient stable AEM

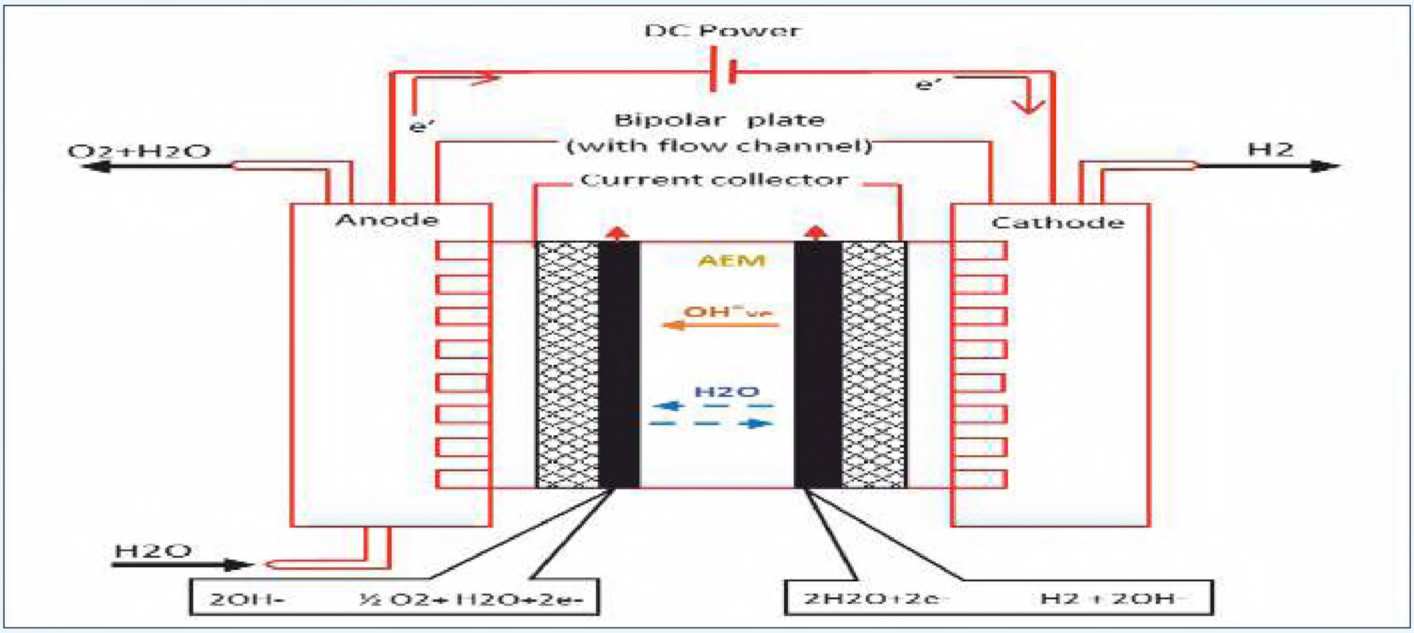


Fig: 3 Anion exchange membrane electrolyzer

Solid Oxide Electrolyser Cell:

Materials and technology used in SOE are based on that of solid oxide fuel cells. The most common electrolyte material is stabilized zirconia. This material shows high ionic conductivity, chemical, and thermal stability at working temperature (800–1000°C). The basic reaction are as follows:

$$2\ OH^- \rightarrow\ \tfrac{1}{2}\ O_2 + H_2O + 2e^-\quad \text{(anode)}$$
$$2H_2O^+ \rightarrow 2e^-\ \ H_2\ + 2OH^-\quad \text{(cathode)}$$

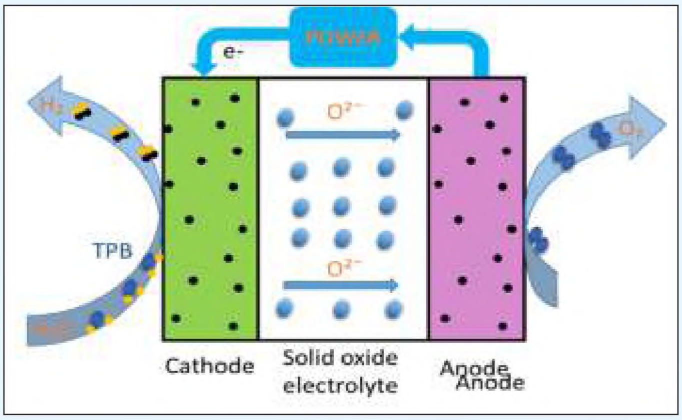


Fig: 4 Solid oxide electrolyzer

Table: 1 Comparison of Technology

Parameters	Alkaline Electrolyser	PEM Electrolyser	AEM	Solid Oxide Electrolyser
Electrolyte/ Membrane	KOH(30%) , Porous membrane (Asbestos/ Zirfon)	Solid electrolyte/membrane :Per-fluorosulphonic Acid /Nafion	Ionomers (Poly-vinyl alcohol (PVA) and LDPE are commonly used poly-hydroxyl polymer as a backbone for AEM	Zirconia Ceramics/YSZ
Electrodes/ Catalyst	Anode: Ni/Ni Alloys Cathode: Steel+ Ni-Co	Anode: Graphite/PTFE+ IrO2/RuO2 Cathode: Graphite+ Pt/Pd.	Anode: Graphite/PTFE+ IrO2/RuO2/Ni Cathode: Graphite+ Pt/Pd/Ni-Co	Anode: Ceramics (Mn, La, Cr)/Ni. Cathode: Ni &Zr Cermet
Charge carriers	OH-	H+	OH-	O2-
Cell Temperature	50-100	80-100	50-100	800-1000
Max Pressure (barg)	Up to 30	8-85		-
Sp. Energy Cosn. (kW/Nm3)	5.8-7.3	4.5-7.5		~4
Capacity(Nm3/h)	10-700	0.01-30		0.01-30
Water quality	1-2 Bs/cm	<0.1Bs/cm	<20Bs/cm	-

Table: 2- Advantages & Disadvantages of different Technology

	Alkaline Electrolyser	PEM Electrolyser	Solid Oxide Electrolyser	Anion Exchange Membrane Electrolyser
Advantage	• Most matured & proven technology • Low CAPEX • High production rate	• Less area required for installation. • higher current density and low ohmic losses • Safe and reliable with no corrosive environment. • Can operate at high DP across membrane/ electrodes to avoid oxygen compression • High H2 purity >99.999	• Low power consumption due to high cell temp.(>800 deg.C)	• Low CAPEX for non-utilization of PGM Group Electrode / Electrode catalyst due to its basic nature of electrolytic environment • Less possibility of diffusion of oxygen into hydrogen chamber due to presence of ionomer membrane
Disadvantage/challenges	• Larger Foot Print • Corrosive environment (KOH) • Low current density • Higher ohmic losses • May require additional purification section	• High CAPEX due to noble bases catalyst/ electrodes (Pt/Ir.) • Water quality (conductivity) is critical to maintain good performance • Drawback of Nafion is that the conductivity decreases at temperature above 100°C because of membrane dehydration. • Solid membrane is prone to incorporate cationic species found in feed water resulted to use only de-aerated /deionized water of high purity (<0.1µs/cm).	• Technology is not yet matured and commercialised. • Degradation problem in cell/electrodes due to void formation, grain boundary coarsening, and inter-granular fracture at the oxygen electrode/electrolyte interface and hydrogen side degradation may be due to nickel-agglomeration, interface fracture, and carbon deposition	• Technology is not matured in MW scale. • Conductivity of AEM is less than that of PEM electrolysers due to its lower mobility of hydroxide ion (approximately 15 times) • Membrane suffer lack of chemical stability at high pH , necessary for good ionic conductivity

Challenges for Refineries/ end users:

- For utilising green Hydrogen in refineries and other industries as utility or fuel its cost should be at par to the present grey hydrogen.

- The cost of electrolyser at present is quite high (PEM' cost \$1000-1250/kW, AEL's cost \$850-950/kW). To make green Hydrogen cost \$1/kg, cost of electrolyser should be reduced by 80%.

- Moreover renewable electricity cost should be Rs.1-2/kwh, life of electrolyser should be increased to 20 years and efficiency should be increased by 76-80% to make Green H2 price competitive.
- Availability & reliability of RE power is a paramount important for green H2 production.

- The biggest challenges lies on the round the clock (RERTC) power availability for production of green H2 through power storage (battery or pump storage) and banking facility.

- The low CUF of solar and wind (20-22 % & 29-33%) requires higher installed capacity of RE power and that additionally impact the cost of RE power.

- Challenges pertaining to electrolyser technology need to be addressed to increase the service life of the electrolyser and also to reduce the CAPEX.

NRL's initiative toward Green H2 production:

NRL has taken ardent role for production green Hydrogen in line with Govt. of India's intention to meet the GHCO target. A domestic tender with detail scope of work and responsibility was floated on open tender basis on 3rd April 2022 for Design , Engg, supply , installation of Green Hydrogen plant of capacity 300 Kg/hr. (2.4 KTPA) of on EPC basis , at Numaligarh. The Green hydrogen produced shall be used in the Hydro-processing units like WHFU, HCU, DHDT of the refinery and thus replace 5% of the present grey hydrogen. Accordingly, there will be reduction of 24000 Tons of CO2/yr.

Summary:

To meet the target of net zero by 2070, Green Hydrogen is an important tool for India, and refineries need to play a pioneering role in this aspect. However to achieve the economy of scale when compared to grey hydrogen, technological improvement is imperative to make electrolyser cheaper for the end user. Also affordability of RERTC is one of the paramount requirement to make Green hydrogen cost at per with Grey hydrogen

* * *

Part-2

Operations and Trouble Shootings

> **The energy transition will be more of a wave of managed change in the global energy portfolio versus an event, ensuring energy access and security, whilst progressing to net-zero. Achieving the net-zero goal requires global coordination and access to skills, technology, and global financing.**
>
> **- Minister of Petroleum & Natural Gas and Housing & Urban Affairs, Sh. Hardeep Singh Puri**

2.1 Safe and Reliable Fired Heater Operation:

Best practices for safe operation during low-capacity run

Authors: Navneet Agarwal, Mohtsim Anwar, Kapil Batra, Engineers India Limited

Mr. Navneet Agarwal working as DGM in EIL, He having More than 24 years of work experience in the field of Fired Heater design, revamp & troubleshooting for the hydrocarbon industry. Manages a team of engineers working on Fired Heaters and Combustion System. Holds a B.Tech degree in Chemical Engineering from Indian Institute of technology, BHU.

Mr. Mohtsim Anwar working as Manager in EIL, he having More than 10 years of work Experience in Thermal & Hydraulic Design / Rating, engineering, Revamp and Troubleshooting of API 560 Fired Heaters & combustion systems for the Refining and Petrochemical Industries including exposure of conducting Performance Guarantee Test Run for HRSG. Holds a Bachelor degree in Chemical Engineering from Moradabad Institute of Technology, Moradabad.

Mr. kapil Batra working as deputy Manager in EIL, He having more than 9 years of work experience in thermal design, engineering and troubleshooting of fired heaters. Interested in developing tools for increasing productivity and reliability though digitization. Holds a Bachelors degree in Chemical Engineering from Laxminarayan Institute of Technology, Nagpur.

Introduction:

Fired heaters operate under extremely harsh conditions. Hence, safe and reliable fired heater operation is of paramount importance during any operating scenario of a fired heater in refinery or petrochemical industry. As per reliability engineering, the biggest risk in fired heaters arises during start-up and operation at lower capacities or turndown. A lot of impetus is given to the operation during start-up of Fired Heaters as a specialized team leads the task with an appropriate plan for the job. However, turndown operation is often unprecedented. This is mostly led by the plant operators who may have limited knowledge of the safe operating window for fired heater operation. Any negligence could not only lead to temporary shutdown but also cause major damage to Fired Heater system. Based on the occurrence of situations during start-up and turndown scenarios, loci are plotted on Failure Rate v/s Time and a phenomenon with close resemblance to Bathtub curve is obtained.

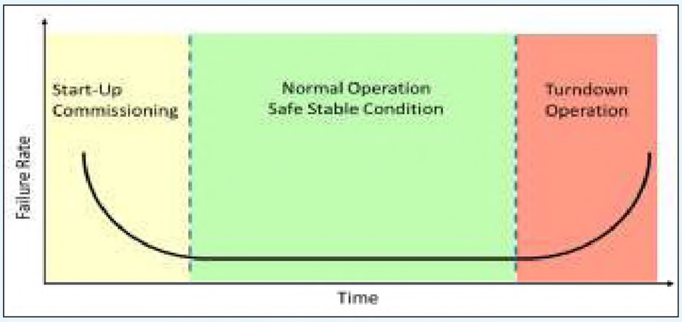


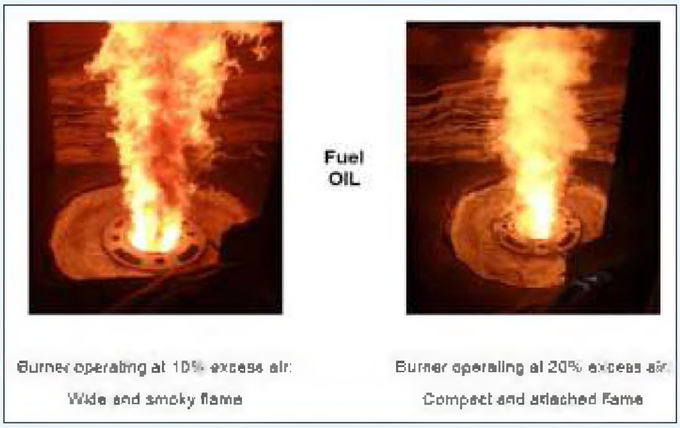
Figure 1: Bathtub Curve

back to the drawing board and prepare oneself for heater operation during low-capacity condition. At low capacity, a fired heater could face multiple issues such as unstable burner flames, tube vibration, high Tube Metal Temperatures (TMTs), lower efficiency etc. Good planning and readiness to operate the heater at lower loads could greatly reduce the losses and protect the equipment. A Fired Heater specialist can have a finger in the pie for carrying out an explicit study for evaluating the heater's performance at low capacity, establishing integrated operating windows (IOW), drawing operating procedures, and training operators for optimal, safe, and reliable heater operation.

1.0 Challenges with Low-Capacity Operation

1.1Poor Combustion:

At lower throughput, burners may be operated at duties well below their optimal design point. The reduction in burner heat liberation creates a soft and lazy flame with a tendency to roll over towards coils. This is due to the reduced air side pressure drop required for good fuel to air mixing. To overcome this scenario, the operator must operate at higher excess air levels to increase the mixing rate and to create a more compact flame. However, using high levels of excess air (above 50%) may impact the stability of combustion flame, leading to flame failures and losses.



Burner operating at 10% excess air:
Wide and smoky flame

Burner operating at 20% excess air:
Compact and attached Fame

Figure 2: Flame picture – Incomplete combustion Vs Complete Combustion

During turndown operation, the air flowrate even with >50% excess air can be significantly lower than that for the design case. Lower air flowrate could lead to maldistribution of air in burner ducts. Insufficient air or excess fuel gas could result in incomplete combustion and accumulation of unburned hydrocarbons also known as "CO bogging". This could be an extremely dangerous situation which can quickly escalate into an explosion. This is indicated by high CO/combustibles at arch (>1500 ppm). A burner devoid of sufficient air would produce "huffing/puffing" flames. Hence, operating personnel should be vigilant and observe the individual burner flames.

A change in fuel composition and operating conditions can alter the burner performance curve. For example, Hydrogen has a flame speed 10 times that of methane, which means chance of flashback of hydrogen at lower loads is much higher than that for methane. Operators must be aware and vigilant to avoid such problems as flame flashback, flame lift off etc. The changes in fuel composition could also necessitate new settings for trips and alarms to avoid nuisance trips and losses.

1.2 Draft Fluctuation:

Draft in fired heaters is controlled either through stack damper (for natural draft operation) or through Induced Draft fans (for induced or balanced draft operation). For natural draft operation, as per API 560 stacks are to be sized for 120% of design load. Hence, when operating at lower loads the stacks become significantly overdesigned, providing high available draft in fired heaters. This high draft needs to be compensated by closing the stack damper for increased pressure drop.

Operating Case	Available P Across Damper
Design (100%)	0.125
Normal (80%)	0.230
Turndown (50%)	0.310

Figure 3: Available Pressure Drop across Damper

From figure 3, we can infer that closing the damper to meet the turndown requires almost double pressure drop compared with design case. This coupled with non-linear characteristics of damper operation makes it challenging to operate the damper. Hence, in practice, most times the stack damper is left unregulated because of the fear that it will get completely closed or stuck. Similarly, at low-capacity operation, ID fan may be operating at its stall point wherein no further reduction in draft would be achievable. Such factors could lead to high draft operation in fired heaters.

High draft can affect flame patterns, leading to a potential flame out situation. High draft can also lead to air ingress from openings such as peep doors, tube penetrations etc. This air also known as tramp air does not mix with the fuel and shows up in O2 analyzers. It also absorbs the heat that should be transferred to the heater tubes leading to less efficient fired heater operation.

Figure 4: Tramp Air Leakage a) Tube Penetrations b) Open Sight Port

1.3 Emissions:

Operating the furnace at lower throughput could have an all-round impact- financial & environmental. Emissions from fired heaters during turndown operation are often neglected. Licensors overindulge in specifying extra design margins as a safeguard to meet the performance guarantees. This could result in excessive burner overdesign which could limit heater turndown operation. Below bridgewall (BWT) temperatures of 1300°F, typical during turndown, heaters can encounter increased CO and volatile organic compound (VOC) emissions. Hence it is important to contemplate the entire spectrum of heater operation at design stage itself to meet the emission requirements at lower loads. Burner vendors must be consulted for guaranteed CO& VOC emissions at lower loads.

During turndown, the flue gases exiting from the stack also have less buoyant force which could ultimately results in the increased ground level concentration. Therefore, the GLC dispersion analysis shall also consider the heater turndown scenario and accordingly height of stack & highest working platform should be finalized.

1.4 Lower Efficiency:

To ensure proper air/fuel mixing, fired heaters are operated at significantly high excess air during turndown operation. However, when firebox operates at higher excess air level, not only does the extra air reduces the adiabatic flame temperature but also the conc. of H2O & CO2 is diluted which lowers the effective emissivity of flue gas, reducing the firebox efficiency. As a result, the heater needs to be fired harder to compensate and is less energy efficient which in turn proportionally increases the fuel cost and greenhouse gas emissions. In countries where CO2 penalties / credits are considered, this would lead to an additional cost of operation.

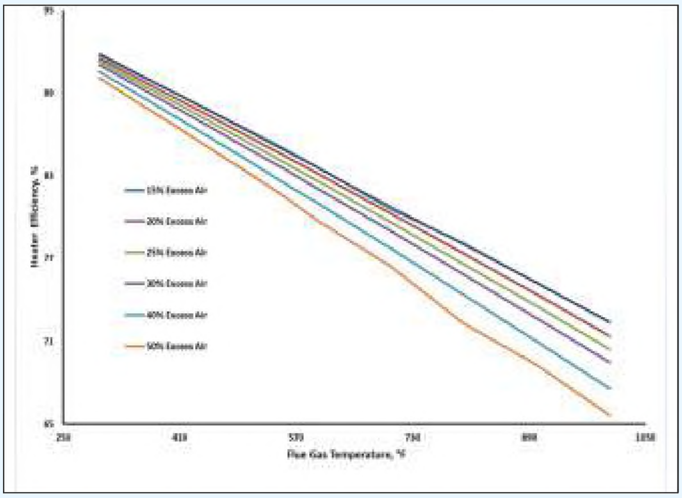


Figure 5: Heater Efficiency Vs Flue Gas Stack Exit Temperature for varying excess air %

1.5 Cold Firebox/High CO Levels:

One must operate the fired heater above the cold firebox conditions to ensure flame stability, no CO breakthrough & safe operating conditions for the field personnel. As per API 535 3rd edition, “High CO levels can occur when firebox temperatures are below 705°C (1300°F). Flame instability and flameout can occur when firebox temperatures are below 648°C (1200°F) and at low oxygen or floor temperature is less than 540°C (1000°F)”. In next generation burners such as Ultra low NOx burners, flue gas recirculation is used to quench the flame and under high turndown the recirculation of the flue gas will further exacerbate flame inerting and CO emission generation.

1.6 Heat Flux Mal-distribution:

Ideally at lower throughput, all burners must be in service. However, sometimes it becomes difficult to operate all burners because of constraints such as low fuel gas pressure etc. Proper selection of burners to be taken out of service is important to avoid heat flux maldistribution which could lead to issues such as high TMT's, tube fouling etc.

Further, for combination fuel firing, burners must be operated on both the fuels simultaneously, this allows the air to be controlled equally to all the burners. Firing individual fuels on alternate burners will require the air to be controlled individually (controlling air globally for all burners may lead to the worst performance). It also creates different heat flux profiles within the firebox as the heat flux from the oil flame is greater than a gas flame.

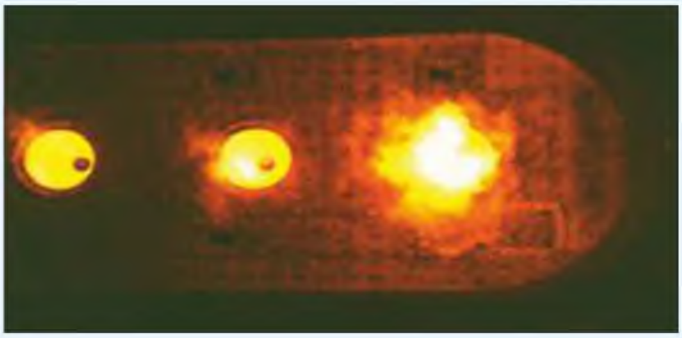


Figure 6: Improper Burner operation leading to flux maldistribution

1.7 Process Control:

Low process fluid flowrate during turndown operation is accompanied with reduced flow mass velocity and reduced pressure drop, possibly leading to mal-distribution in process coils. During turndown, the inlet control valve may also go out of its controllability range, if not sized accordingly. It is also important to monitor the APC-pass COT balance control (if any) as it may not operate effectively at lower throughput. For heaters with two phase flow, reduced flowrate may lead to unwarranted flow regime such as annular or slug flow, leading to vibrations.

On the process side, it is also important to monitor the TMTs. Due to reduced flow rate, the reduction in inside flow co-efficient and reduced process fluid mass velocity could increase the chances of coking and fouling. TMTs can also increase due to increased probability of uneven heat flux distribution and flame impingement. Heater firing rate is generally controlled based on COT of primary service. Hence, during turndown operation it is inevitable that the secondary service used for heat recovery will have reduced absorbed duty as less energy is available for recovery.

Figure 7: Accelerated fouling at reduced load

1.8 Auxiliary Equipment Operation:

Cast Air Preheaters are used to increase efficiency by extracting heat from flue gases leaving the convection section and preheating the air used for combustion. However, at low air and flue gas flow rates, if not operated correctly, flue gases could be cooled below flue gas acid dew point leading to corrosion and tube rupture in cold end of APH.

The low air or flue gas flowrate during turndown operation could lead to operating fans (ID or FD) in stall region. Fans should be carefully designed taking care of heater turndown operation. Inlet box dampers could be very unreliable during low-capacity operation due to non-linear flow/control characteristics.

2.0 Recommended Practices for Safe & Reliable Operation

2.1 Burner Operation:

Being the heart of Fired Equipment, burner operation is directly linked with safe &reliable Fired Heater operation. In most fired heaters, to maintain a stable process output, control by regulating fuel flow to the burner along with appropriate control over excess air is implemented over the entire operating range. The output of the process controller should be cascaded to the main fuel controller and the minimum burner load should be ensured by adopting either of the following:

1. Providing a minimum opening on the fuel control valve or

2. A dedicated minimum pressure controller, which guarantees a minimum burner load. If based on the process load, master signal (Coil Outlet TIC) would drive the required fuel flow down to threshold limit of flame stability, the active minimum pressure controller shall take over.

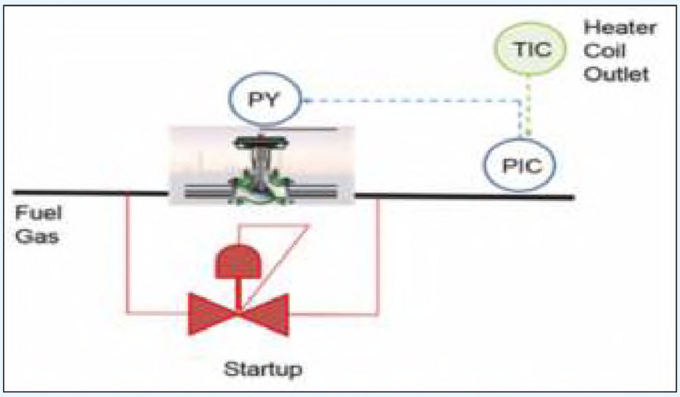


Figure 8: Example of Fuel Flow Control

In some cases, to achieve lower throughput, some burners may be required to be shutdown to ensure that the burners in operation are under the contour of their operating envelope. It is important to close the air registers of burners which are not in operation to avoid tramp air ingress. Also, for such scenarios operated burners must be rotated periodically, so that all tubes are equally heated.

Care should be taken while operating combination fired burners (since combination burners are commonly designed to operate on both fuels simultaneously or any combination of both, this allows the air to be controlled individually to all the burners). To ensure proper atomization, in case of oil / combination fuel fired burners, wet steam should be avoided to prevent water droplets forming in the piping or burner gun as the heat to vaporize the water will absorb much of the necessary heat for ignition & complete combustion. Wet steam also causes a considerable wear on the atomizer tip, which has a detrimental effect on the atomization and therefore the quality of flame.

In addition to above, operators must be sensitized to carry out periodic checks at lower capacity for flame surveillance through peep / sight doors to observe flame color, shape and any pulsation and install thermal sensors (as applicable).

2.2 Emission Control:

At heater turndown operation, proper tuning of combustion parameters is key to reduce the emissions. Heater turndown operation may result in high CO formation due to improper air and fuel mixture at the burners:

- In addition to CO measurement at arch level, provision shall also be kept to measure CO content at various location(s) through portable analyzer(s)
- Shutting one or several burners may help due to a better combustion on the remainder burners.
- Be sure to close air register of the OFF burners (except for very high temperature services),but keep the pilots on in order to ensure the ON burners have proper air in fuel mixture.

2.3 Burner Air Duct Design:

Burner air manifolds must be carefully designed to allow for proper distribution of air to all the burners present in multiple rows. During the design stage, CFD modelling must be mandatorily carried out from venturi flow meter outlet to the last burner at both design case and turndown case. This ensures that variation of air between different burners is <3%.

2.4 Draft And ID /FD Fan Control:

Arch of the heater is the point of highest pressure inside the heater and is commonly used as point of control. As discussed, at turndown, flue gas flowrate is greatly reduced which requires the stack damper or ID fan to operate at below normal operating range. Hence, it is important to check the stack damper at every shutdown to ensure it is working properly and carryout repairs or modifications as needed. A good stack damper design can help elevate the operators concern of damper getting completely shut or stuck during turndown operation. ID fans must be fitted with VFD as they provide more reliable control than inlet box damper during low-capacity condition. Many times, resistance is introduced to operate the ID fan above its stallregion. During turndown operation, it may be required to increase draft set-point due to flame stability, here the first step is to have the burners checked to ensure that they were designed, tested or operated properly.

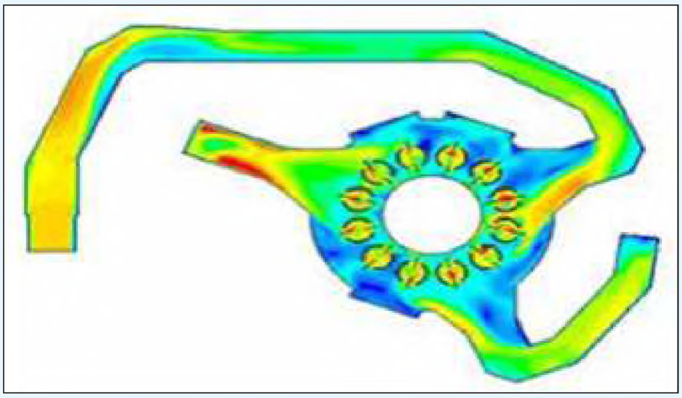


Figure 9: Example of CFD Modelling in Air Distribution Duct

2.5 Instruments/Alarms/Set Points:

It is necessary to verify that the existing instruments can perform accurately during the turndown conditions. It is recommended to have checks in place for fuel pressure element & control valve(s).Flow transmitters must be corrected for molecular weight with changes in fuel gas composition. It is also important to adjust the alarm settings on various instruments based on new fuel composition. For heaters provided with automatic lead lag control system changes in fuel composition may also necessitate manual correction in fuel LHV or Wobbe index to calculate the fuel flow demand and combustion air flow demand correctly. In some cases, the instruments may be required to be changed to ensure proper operation and accuracy in measurement at low-capacity operation. Some instruments may require recalibration to obtain accurate readings at low-capacity operation. Incorrect readings could present potential hazardous situation for heaters such as CO flooding, high draft etc. Hence, both the designer and operators play a key role during turndown operation.

2.6 Air Preheater Operation:

Many Licensors provide an air bypass controller which operates air bypass in cascade control with flue gas outlet temperature. It ensures flue gases are not cooled below the flue gas acid dew point. This a good engineering practice as it avoids manual operation and ensures against cold end corrosion.

3.0 Role of Licensor/Heater Contractor

3.1 Thermal Rerating:

Refineries can leverage Fired Heater Consultant's expertise to identify and establish safe boundary conditions for achieving superlative and reliable heater performance at turndown operation. Armed with knowledge and tools, Consultants employ techniques such as modelling the Fired Heater for existing geometry and benchmark the existing operating performance. The fired equipment is then re-rated for the process fluid and fuel conditions expected at low-capacity operation. This exercise provides the requisite information to identify the boundary condition for heater operation. Based on the data obtained, Consultants can pick out the shortfalls with equipment and auxiliary to extend the turndown limit and improve reliability. Engineering calculations are performed to review the performance of auxiliary equipment such as Fans, Air Preheater, burners etc.

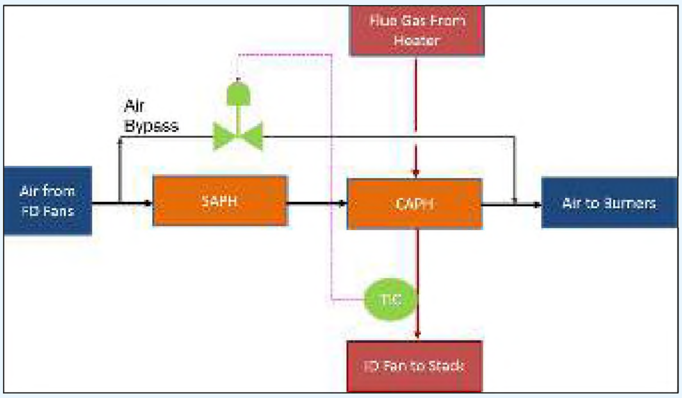


Figure 10: Air bypass controller to avoid flue gas acid dew point condensation.

3.2 Liaison With Suppliers:

Consultants can also liaison with Burner Suppliers to set optimum excess air operating limits for efficient and safe combustion at turndown. Burner suppliers can also help with providing information on emissions details which are expected to increase during low-capacity operation.

3.3 Operator Training:

Meeting fired heater reliability together with optimum heater performance can be a challenging accomplishment. Specialized training of the operating personnel can be master stroke in achieving this feat. Operators need the know-how to operate and control the equipment as well as how to troubleshoot and solve the problems that may arise. Heater Consultant can provide advanced training to operating personnel and develop monitoring programs during such operations. This program will involve identifying and monitoring critical operating parameters such as tube metal temperature, CO emission, excess O2 etc. Consultant can set reliability limits (i.e. integrity operating windows (IOWs)), for the key parameters. The performance measurements during actual operation are compared to these limits to identify potential failures and operating risks. Heater Contractor can help with setting up alarms and trip points according to the low-capacity operation to avoid frequent trips and smooth operation of fired heater.

3.4 Field Survey

A Fired Heater consultant can help with field surveys to assess the condition of Fired Heaters. It can help with identification of leaks or holes in the heater which can cause increased tramp air leakage during turndown operation due to higher available draft. Consultants can also provide on the job training in adjusting the excess air and heater draft, flame visualization and setting up/identifying the burners to be operated during turndown. Identification of physical defects can help prolong heater life and improve heater performance.

Case Study I:

Turndown duty optimization of Charge Heater in DHDT unit during design stage

- Significant variation was observed in the Design case heater absorbed duty and Normal case duty for a Reactor Charge Heater in DHDT Unit.
  - Design Absorbed duty: 24MMkcal/hr
  - SOR Case Duty: 4 MMkcal/hr
- Based on initial estimation of combustion parameters, it was discovered:
  - Design case BWT: ~875°C (1610°F)
  - SOR case BWT :<540°C (1,000°F)
    BWT= 1000°F is typically considered as threshold firebox temperature to meet CO emissions.
- After deliberations, Licensor reduced the overdesign margins considered for design duty case
- Revised Heater Design Duty= 21 MMkcal/hr.
- Reduction in heater design duty enabled the heater to be designed to meet CO emission guarantees for SOR case operation.

Case Study II:

Comparison of performance for an Oil Feed heater in Resid Hydrocracking Unit for design and turndown operation:

From the above parameters, it can be observed that the turndown case specified by Licensor necessitates a burner turndown ratio of 1:6. Also, the BWT for turndown case is ~487°C even though the design case BWT is 831°C. For such cases, the burner vendors need to be consulted to meet flame stability and CO emissions which are evaluated on a case-case basis. Also, it will be pertinent to note that Licensor had specifically advised to keep the process fluid velocity >1 m/sec at turndown to prevent coking/fouling in the fired heater during turndown operation.

Parameters	Design Case	Turndown Case
Total Absorbed Duty, MMKcal/hr	19.38	3.82
Process Duty, MMkcal/hr	16.5	3.25
Waste Heat Recovery, MMkcal/hr	2.88	0.57
Flowrate, kg/hr	321,500	157,500
Pressure Drop, kg/cm2	4.5	0.80
Avg. Rad. Heat Flux, kcal/h-m2	31,000	7,400
Peak Rad. Heat Flux, kcal/h-m2	37,800	9,000
Velocity, m/sec	2.5	1.2
Film temperature, ®C	400	365
Excess Air, %	15	50
Fired Duty, MMkcal/hr	22.17	4.43
Efficiency	87.4	86.3
BWT, ®C	831	487
Burner Design Heat Release, MMkcal/hr	2.54	0.42

4.0 Precis

It is important to consider the risks and impacts when running below defined operating envelopes on minimum throughput. Unit adjustments require a more detailed, facilitated discussion with experts to ensure safe operation.

Risk	Symptom(s)	Consequence(s)
Poor combustion / Process heat integration	Local hot or cold spots/ Flame stability issues	Possibility of fuel rich environment which ma resultingin uncontrolled combustion, leading to equipment damage / fire
	Poor flame pattern / burner performance	Low oxygen conditions at burners, flame blow out, uncontrolled combustion, equipment damage / fire
	High draft / tramp oxygen biasing true excess oxygen at burners	Unreliable O2 analyzer readings and loss of efficiency
	Issues lighting burners / maintaining burners	Burners unavailable when needed
	Convection tube failure	Afterburning, damage / fire
Low tube velocity	Rapid internal coking of tubes	Exceeding tube mechanical design temperature, loss of containment / fire
	Unexpected locations of tube coking	Decreased cycle between spall / decoke, loss of operating flexibility
	Radiant/shock tube failure	Unexpected loss of throughput when units return to high rates
Operation near operating envelopes Ь SIS trips, min/max burner pressure, etc	Operating in or very near alarm(s)	Accidental heater trips, increased risk recovering from trips and operational upsets
	Issues with flame stability	
Corrosion in steam generators and air preheaters (APH)	Steam Ь unstable level/pressure	Furnace trips via level instability
	APH Ь operating at or past dew point	Damage/plugging to bundles

It is critical to ensure stable flame pattern, optimized heat flux, and keeping equipment biased towards safe operating modes

Low tube velocity can lead to exponentially faster coking rates or a change in location of coke formation. Operators must ensure that operating limits are maintained by monitoring processes continuously.

5.0 Conclusion

As discussed in various sections of this paper, this guideline provides a roadmap on high risk, high impact concerns, symptoms, and consequences for unit turndown conditions. Operators must be aware and cautious of normalization of deviation, if running in or near alarm points confirm validity of the alarm points. Accidental trips can result in higher risk activities like lighting a heater or restarting a unit.
Additional risks should be considered before proceeding into a planned shutdown or mothball. For further guidance on these issues, we welcome you to reach out to Engineers India Limited. We are here to help you succeed in safe and reliable fired heater operation.

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(1) API-560 : Fired Heaters for General Refinery Services, Fifth Edition, February 2016
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(3) SR.11.11950 : Control System & Instrumented Protected Functions for Forced Equipment system for a multi burner heater or boiler by Stefan Ehrenreich (PTS/EUHT)
(4) The keys to successfully revamping a fired heater : how to maximize value, by XRG Technologies, May 2022
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(6) “Q&A” form www.heurtey.net/news-events
(7) Rethink fired heater design for emissions by Malhotra, K., S & B Engineers and Constructors Ltd.
“Fired Heater Health Monitoring and Reliability Management” by Quest Integrity, February 15, 2023

2.2 Optimization of Isomerization reactor temperatures

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Abstract. /Back Ground

Isomerization reactions are equilibrium limited unlike reactions involved in other secondary processing units of refineries and therefore needs special treatment with respect to optimization of Reactor temperatures. Further lead/lag configuration of reactors in a typical isomerization unit makes it more complex for day to day optimization of reactor temperatures and therefore concept of operating curves is generally used for that purpose. However, these operating curves are dependent on many parameters that vary dynamically and pose a challenge for temperature optimization. Current work focuses on developing an approach for optimization of isomerization reactor temperatures specific to Penex unit of IOCL's Panipat Refinery based on operating experience and licensor guidelines.

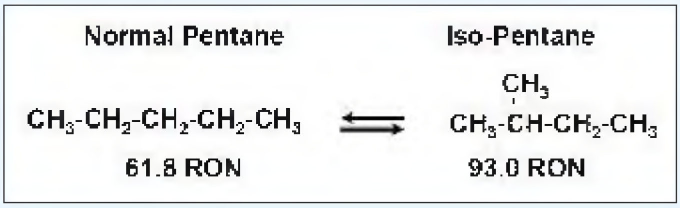
Introduction

Typical Isomerization unit feed consists of straight run light naphtha from atmospheric and vacuum distillation unit and contains C5/C6 compounds and some amounts of C7+ components. Typical configuration consists of De-isoPentanizer(DIP)/ De-isoHexanizer (DIH) column placed either in the upstream or downstream of the reactor and stabilization section depending on design intent of the unit. Isomerization unit of Panipat Refinery is called as Penex unit (licensed by UOP Honeywell). It is of the configuration, DIP column followed by Reactor and stabilization section followed by DIH Column. Intermediates and unreacted components are separated as side draw in DIH column and are recycled back to reactor. Isopentanes are separated as top draw in DIP column and DIP bottoms along with DIH side draw are fed to reactor along with Hydrogen. Stabilizer downstream of reactor separates lighters, excess Hydrogen and HCl as off gas and stabilizer bottom is fed to DIH column. The reactor employs Catalyst (Pt on Chlorinated Alumina) for the purpose of isomerization of C5 and C6 hydrocarbons in the feed into branched components. Other reactions include Benzene saturation, Ring opening of cyclic compounds, C7+ Cracking etc. Isomerization reactions are equilibrium limited which do not achieve complete conversion due to thermodynamic limitations and therefore the conversion in a typical reactor is governed by equilibrium ratios which indicate maximum achievable ratio (product/reactant) for a given reactor outlet temperature. Operating curves indicate product ratios as a function of reactor outlet temperature for a given feed quality and residence time. Pressure and Hydrogen/Hydrocarbon ratio are generally fixed and do not impact operating curves. However, feed quality and thruput (residence time) typically vary on week to week basis based on crude quality. Also these operating curves vary depending on the extent of catalyst deactivation which is time dependent. This requires continuous optimization based on operating curves generated from lab data and plant data. Figure 1 shows schematic of Penex isomerization unit process flow.

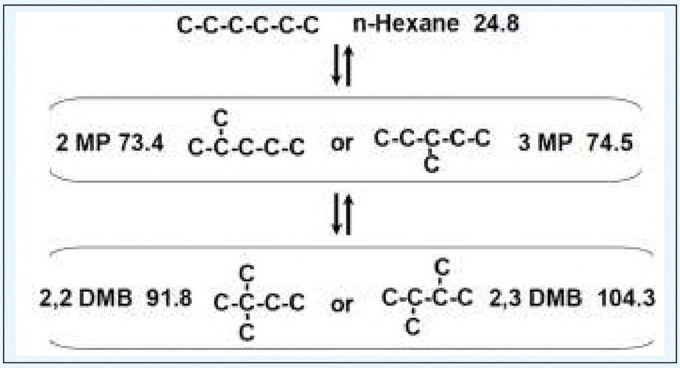
Isomerization reaction chemistry

Isomerization reactors often run below their maximum achievable octane potential due to lack of understanding of complex reactor kinetics and their dynamic behavior to varying feed composition and thruput. Factors affecting the reactions are analyzed and practically implementable methodology to optimize reactor parameters to achieve maximum possible octane of isomerate is recommended accordingly.

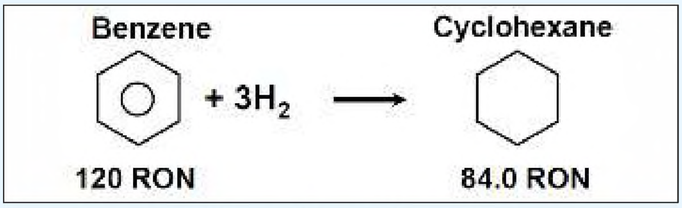
Following are the Isomerization reactions taking placing in Penex reactor



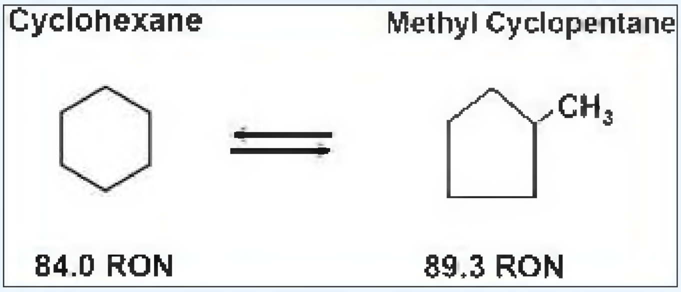
1.Isomerization of n-Pentanes



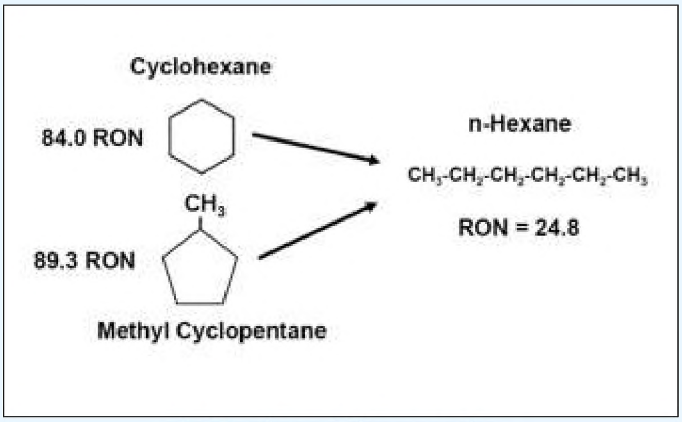
2.Isomerization of n-Hexanes



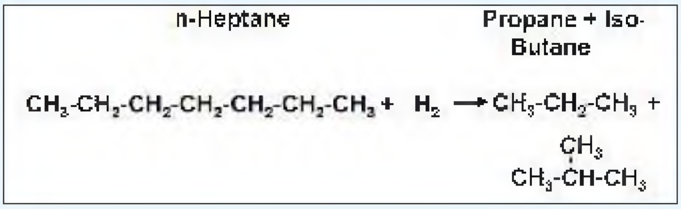
3.Saturation of Benzenes



4.Napthene Isomerization



5. Napthene Ring opening



6. Hydrocracking

7. Formation of Heavies

Some amount of lighters (Propane and Butane) combine to form heavies depending on amount of C6 Cyclics in the feed.

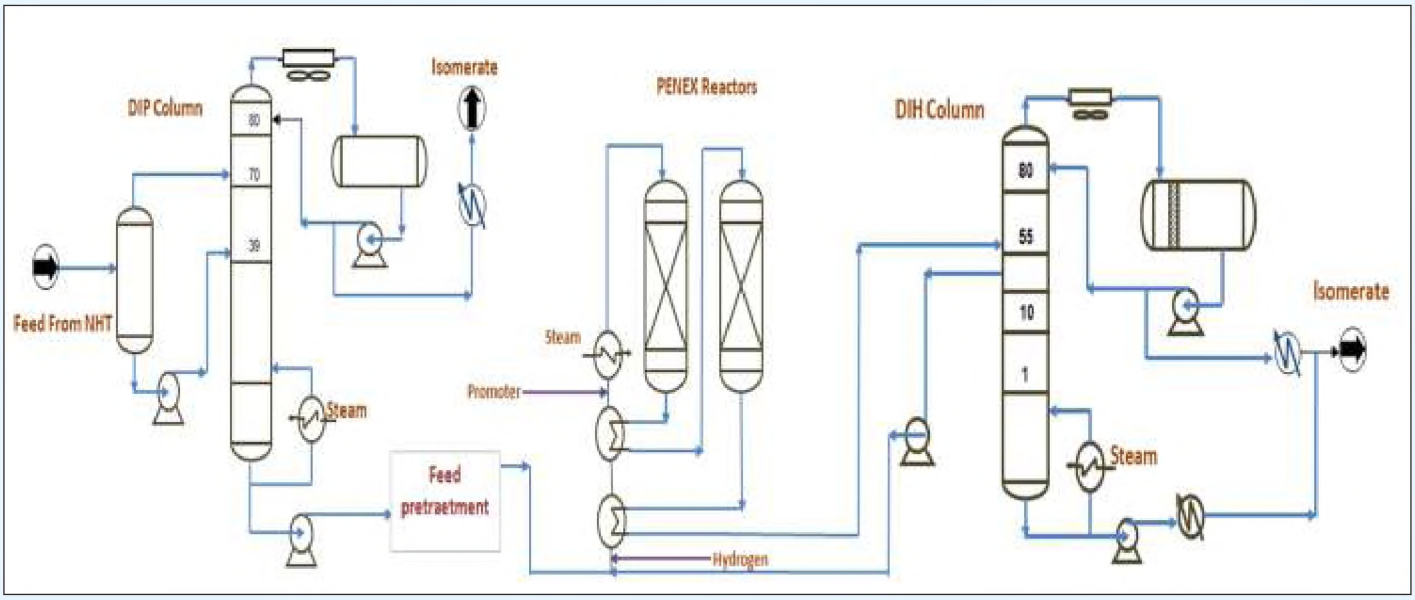


Figure 1: Schematic of Penex Isomerization unit flow

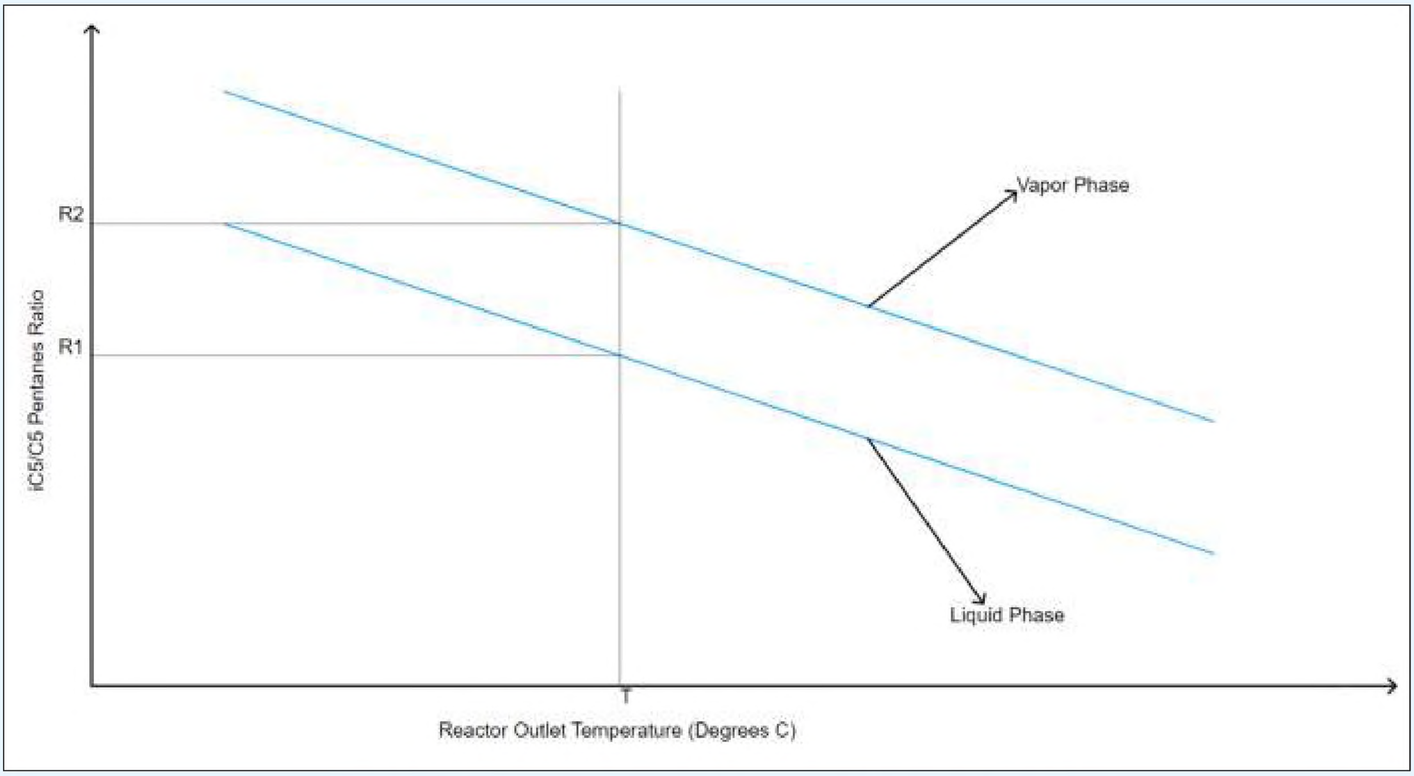


Figure 2: Equilibrium curve for iso-pentane product ratio

While Isomerization reactions are equilibrium limited, other reactions can go to completion depending on residence time and bed temperatures. Equilibrium limited reactions cannot achieve 100% conversion and are limited by thermodynamics as governed equilibrium iso-ratios/ product ratios. Main isomerization products, iso Pentane (iC5), 2, 2- Di Methyl Butane (2, 2-DMB), 2, 3-Di Methyl Butane (2, 3-DMB) determine the final product octane and therefore temperature optimization is done to maximize these components in isomerate.

Figure 2 shows equilibrium curve for iC5/C5 Pentanes (product ratio) in any mixture of components. The ratio is dependant only on temperature and phase.

The maximum thermodynamically possible product ratio at temperature T is R1 for liquid phase and R2 for Vapor phase. This is the maximum achievable ratio at reactor outlet and would be possible only with ideal catalyst and infinite residence time which is not practically possible. In reality the product ratios will always be lower than this value. Similar equilibrium curves exist for 2, 2- DMB and 2, 3-DMB which defines maximum achievable product ratios for a specific temperature and phase.

Factors affecting isomerate RON (product ratios) in Penex reactor are as follows:

1. Reactor temperatures
2. Feed Composition
3. Hydrogen/Hydrocarbon ratio.
4. Liquid Hourly Space Velocity (LHSV)
5. System Pressure

Penex reactors operate in series in lead and lag configuration. The lead reactor temperatures are maintained higher than the lag reactor. The temperature inversion across the reactors is to take leverage of kinetics to maximize conversion in the lead reactor and take leverage of thermodynamics to maximize product ratios in the lag reactor. The key product ratios iC5/C5Paraffins, 2, 2-DMB/C6Paraffins, and 2, 3-DMB/C6Paraffins are measured in lead and lag reactor effluent. The reactor outlet temperature (ROT) significantly affects the product ratios due to combined effect of reactor kinetics and thermodynamic limitations. Main components in the Penex reactor feed that affect product ratios are the C6 cyclics and C7+ compounds. The sum of weight percentage of C6 cyclic (CycloHexane, MethylCyclopentane and Benzene) and C7+ compounds is termed as “X” factor. Hydrogen/Hydrocarbon ratio is adjusted to maintain excess of 0.05 moles of hydrogen (at reactor outlet) per mole of hydrocarbon charge to allow the reactions to proceed to completion. This ratio has negligible effect on product ratios. The reactor thruput defines the LHSV and affects the product ratios due to varying residence time. System pressure is maintained constant and is not variable with respect to product ratios.

Concept of operating curves for Penex reactors

The actual product ratios achieved at reactor outlet for any given set of operating parameters is dependent on reactor feed X-factor and residence time. Operating curves are defined for each of iC5, 2, 2- DMB and 2, 3-DMB. They indicate the product ratio (iC5/C5Paraffins, 2, 2-DMB/C6Paraffins, and 2, 3-DMB/C6Paraffins) for a given reactor feed X factor and LHSV with respect to Reactor Outlet Temperature (ROT).

Figure 3 shows Equilibrium curves for iC5 and 2, 2-DMB along with their schematic operating curves for lead and lag reactors. The green curves (right side for lead reactor and left side of lag reactor) represent operating curves for iC5. It shows iC5/C5P ratio achieved with respect to Reactor Outlet Temperature (ROT) for a given X factor and Thruput. It can be seen that the product ratio increases with ROT and then decreases. The left side of the curve peak is rate limiting region and the right side of the curve is equilibrium limiting region. Similar behavior can be seen for brown curves (right side for lead reactor and left side of lag reactor) representing operating curves for 2, 2-DMB. The right red line represents ROT corresponding to peak product ratio of 2, 2 DMB for lead reactor where as right blue line represents ROT corresponding to peak product ratio of 2, 2 DMB for lag reactor. Similarly the left red line represents ROT corresponding to peak product ratio of iC5 for lead reactor whereas left blue line represents ROT corresponding to peak product ratio of iC5 for lag reactor. It can be seen that optimum ROT for 2, 2 DMB maximization is higher than that of iC5. Equilibrium curve for 2, 3 DMB is always constant irrespective of ROT and is therefore corresponding product ratio (2, 3-DMB/C6P) is always constant around 10.5 wt%. The choice of whether to maximize iC5 or 2, 2-DMB depends up on liquid isomerate yield vs isomerate octane. To maximize liquid yield both lead and lag ROTs are optimized for iC5 maximization because of the fact that peak ROT for iC5 is always lower than that of 2, 2-DMB which contributes to lower hydrocracking and thereby increased liquid yield. To maximize isomerate octane, lead and lag ROTs are optimized to maximize iC5 or 2, 2 DMB depending up on weight distribution of C5 paraffins and C6 paraffins and its precursors in reactor feed in such a way that product octane is maximized. The operating curves will shift to the right and down for higher thruput and higher feed X-factor with a reduced slope of the rate limited part of the curve. This shift would result in the unit operating at less than the optimal point. Hence, it would lead to lower product than maximum achievable. Furthermore, the operating curves will shift to the left and up for lower thruput and lower X-factor. This shift would result in the same reactor outlet temperature being higher than that required for maximum isomerization leading to increased hydrocracking and liquid yield loss.

Based on above understanding, temperature optimization for Penex reactors was done as follows: Once key parameters, reactor feed X-factor and thruput are fixed, data and graphs for reactor outlet temperature vs Product ratios (iC5/C5 Paraffins, 2,2-Di Methyl Butane/C6 Paraffins & 2,3-Di Methyl Butane/C6 Paraffins) are generated with varying ROTs in the steps of 2°C. Similar graphs are generated for different set of X factor and thruput values. Now correlations between these independent key parameters and operating curves are generated. Same procedure is repeated for both lead and lag reactors.

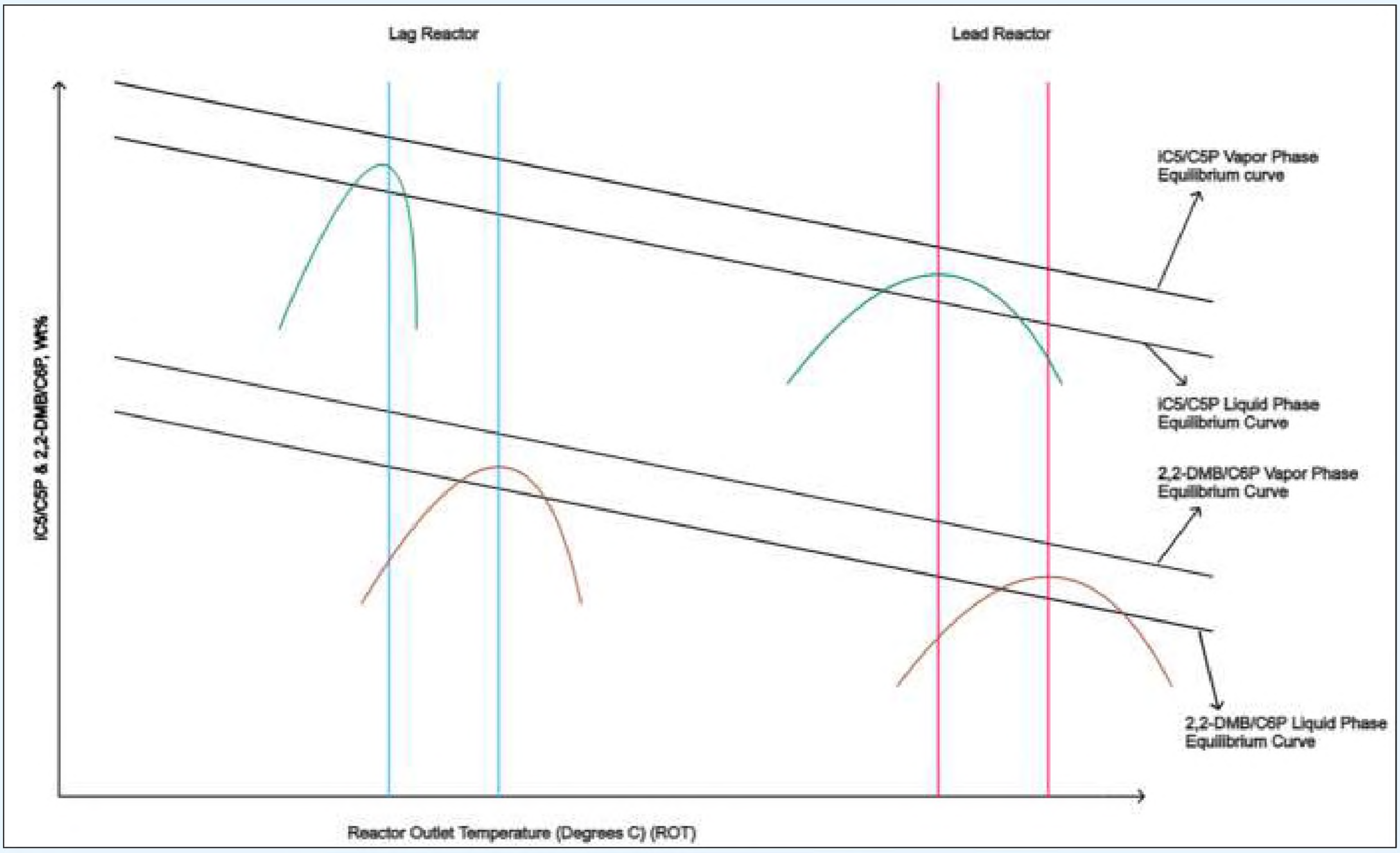


Figure 3: Schematic of operating curves for Penex reactor

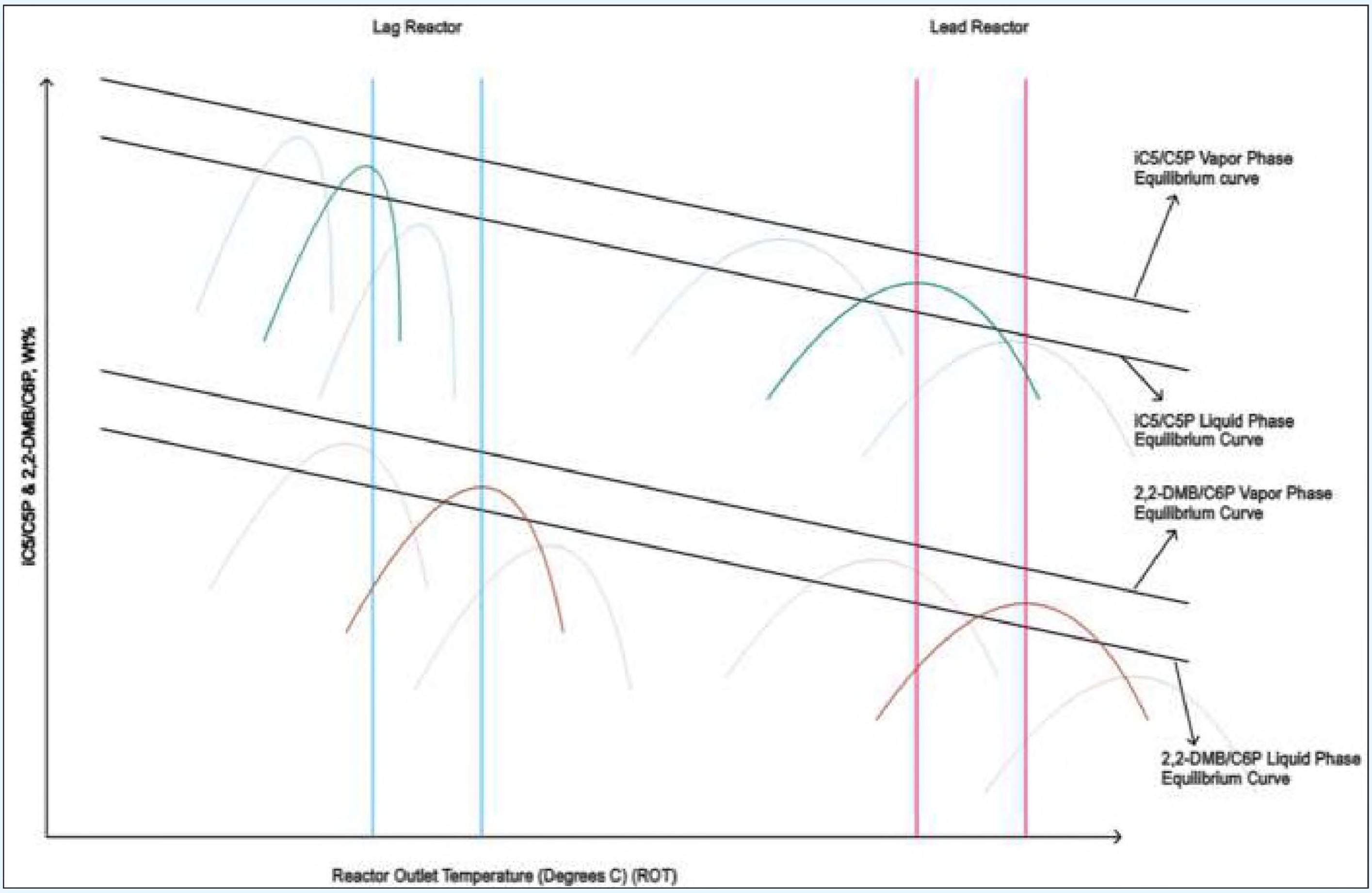


Figure 4: Schematic of operating curves shifting with respect to change in X-factor and Thruput

Plant study data for different cases

Lag ROT (C)	X-factor	Thruput (Tons/Hr)	iC5/C5P product ratio	2,2 DMB/C6P product ratio	Lead ROT	X-factor	Thruput (90 Tons/Hr)	iC5/C5P product rati	2,2 DMB/C6P product ratio
123	28	90	0.701	0.23042	163	28	90	0.685	0.183
125	28	90	0.725	0.249	165	28	90	0.711	0.2
127	28	90	0.74	0.265	167	28	90	0.719	0.22
129	28	90	0.752	0.28	169	28	90	0.73	0.229
131	28	90	0.76	0.289	171	28	90	0.732	0.238
133	28	90	0.762	0.295	173	28	90	0.728	0.24
135	28	90	0.755	0.297	175	28	90	0.725	0.244
137	28	90	0.748	0.29	177	28	90	0.72	0.243
139	28	90	0.745	0.285	179	28	90	0.718	0.238
141	28	90	0.7351	0.28	181	28	90	0.707	0.231
143	28	90	0.72	0.265	183	28	90	0.697	0.218
145	28	90	0.7075	0.248	185	28	90	0.672	0.198

Table 1: Base case data (T90, X28)

Lag ROT (C)	X-factor	Thruput (Tons/Hr)	iC5/C5P product ratio	2,2 DMB/C6P product ratio	Lead ROT	X-factor	Thruput (90 Tons/Hr)	iC5/C5P product rati	2,2 DMB/C6P product ratio
123	33	90	0.651	0.2	163	33	90	0.61	0.09
125	33	90	0.663	0.21242	165	33	90	0.627	0.103
127	33	90	0.687	0.231	167	33	90	0.651	0.12
129	33	90	0.702	0.247	169	33	90	0.666	0.137
131	33	90	0.714	0.262	171	33	90	0.678	0.151
133	33	90	0.722	0.271	173	33	90	0.686	0.156
135	33	90	0.724	0.277	175	33	90	0.688	0.158
137	33	90	0.717	0.279	177	33	90	0.681	0.162
139	33	90	0.71	0.272	179	33	90	0.674	0.16
141	33	90	0.707	0.25	181	33	90	0.671	0.156
143	33	90	0.6971	0.23	183	33	90	0.6611	0.144
145	33	90	0.682	0.21	185	33	90	0.646	0.136

Table 2: Data for increased X-factor (T90, X33)

Lag ROT (C)	X-factor	Thruput (Tons/Hr)	iC5/C5P product ratio	2,2 DMB/C6P product ratio	Lead ROT	X-factor	Thruput (90 Tons/Hr)	iC5/C5P product ratio	2,2 DMB/C6P product ratio
123	28	85	0.651	0.2	163	28	85	0.61	0.09
125	28	85	0.663	0.21242	165	28	85	0.627	0.103
127	28	85	0.687	0.231	167	28	85	0.651	0.12
129	28	85	0.702	0.247	169	28	85	0.666	0.137
131	28	85	0.714	0.262	171	28	85	0.678	0.151
133	28	85	0.722	0.271	173	28	85	0.686	0.156
135	28	85	0.724	0.277	175	28	85	0.688	0.158
137	28	85	0.717	0.279	177	28	85	0.681	0.162
139	28	85	0.71	0.272	179	28	85	0.674	0.16
141	28	85	0.707	0.25	181	28	85	0.671	0.156
143	28	85	0.6971	0.23	183	28	85	0.6611	0.144
145	28	85	0.682	0.21	185	28	85	0.646	0.136

Table 3: Data for decreased thruput (T85, X28)

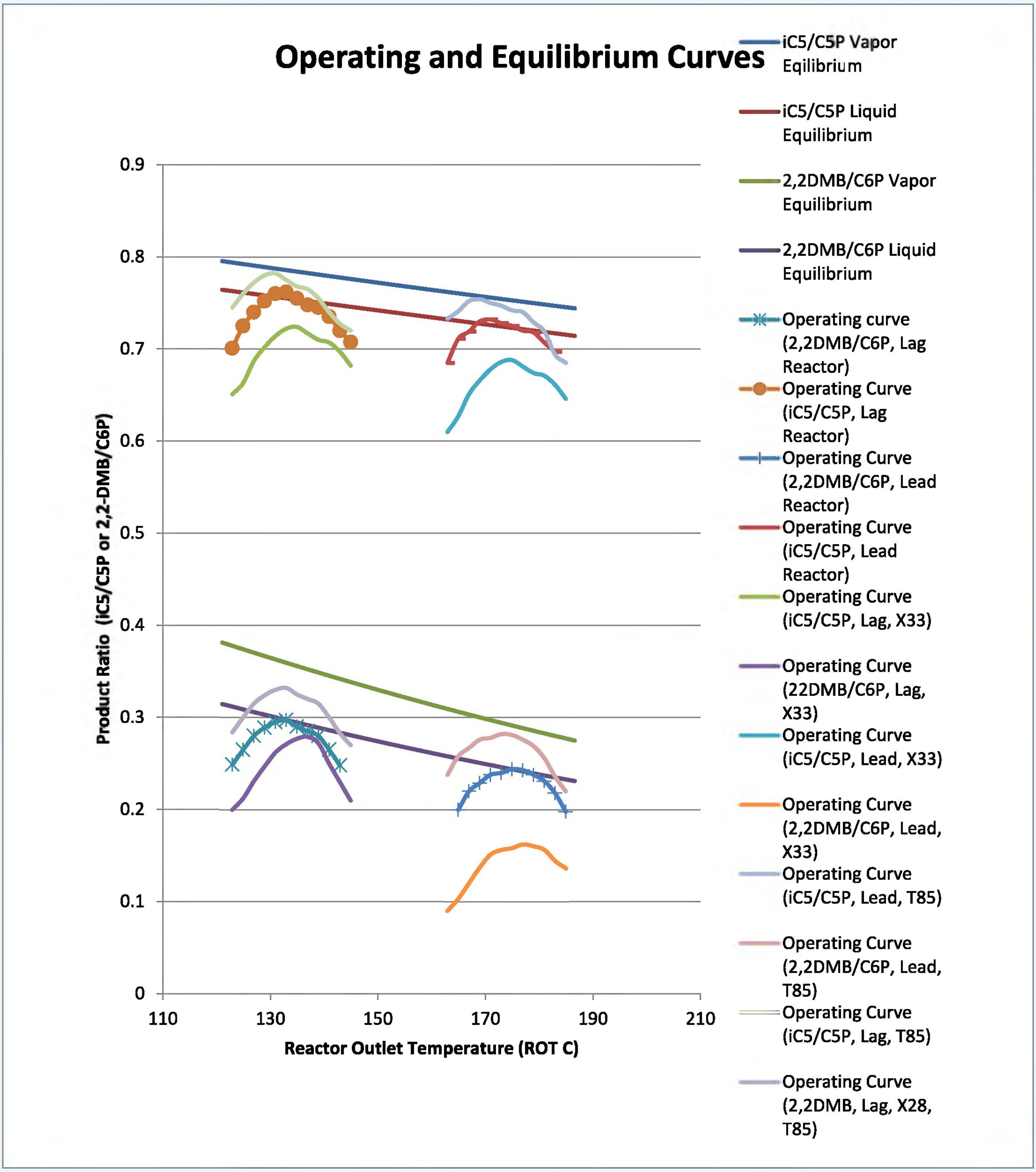


Figure 5: Operating curves generated based on plant data

Plant study results and Conclusion

A base case feed of certain variable parameters (X factor and thruput) were selected and sampling and analysis were done by varying Reactor Outlet Temperature for both lead and lag reactor effluents. This procedure is repeated for varying X factors and thruput. Graphs were plotted to generate operating curves for all the cases. Data for all the cases are tabulated as above and operating curves are presented in figure 5. Operating curves with X33 mentioned in the description refer to the curves when X factor alone is changed to 33 from the base case conditions. Similarly, operating curves with T85 mentioned in the description refer to the curves when Thruput alone is changed to 85 Tons/Hr from the base case conditions. It can be seen that operating curves shift to the right and down with increase in feed X factor from 28 to 33. Maintaining same ROT for increased X factor would result in ROT being lower than required to achieve maximum product ratio and therefore requires increment in ROT. Qualitatively the effect on operating curves would be the same as this case if thruput alone were to be increased instead of increasing X factor alone. Similarly it can be seen that the curves shift to left and up with decrease in thruput from 90 to 85 TPH. Maintaining same ROT for decreased thruput would result in ROT being higher than required to achieve maximum product ratio and therefore requires reduction in ROT. Qualitatively the effect on operating curves would be the same as this case if X-factor alone were to be decreased instead decreasing thruput alone. Temperature optimization can be done accordingly to maximize product ratios with any set of parameters by extrapolation. The deviation of shape of the experimental graphs in figure 5 from that of theoretical/schematic graphs shown in figure 4 could be due to sampling/analysis errors and actual deactivation pattern of the catalyst. Applicability and accuracy of these curves depend on the deactivation of catalyst and maintaining of feed composition close to that of analysis period. These curves hold good for a specific period of time starting from the point of analysis until significant deactivation of the catalyst. Fresh operating curves need to be generated in order to account for the deactivation.

Acknowledgements

1. UOP GOM on Penex Technology
2. IOCL Panipat Penex Unit
3. IOCL Penex plant historian
4. Operating personnel of IOCL Panipat Penex Unit

2.3 Online Tank Bottom Inspection using Robotic Rover

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Mr. Girish Kumar is presently working as an Inspection manager at Digboi Refinery, IOCL. He has 14 years experience in the field of inspection. He was also involved in pre-commissioning and commissioning activity of Panipat Naphtha Cracker Complex during commissioning stage.

Mr. Ananddev Mangish is working as an Inspection Engineer at Digboi Refinery, IOCL. He holds a bachelor degree in Metallurgy Engineering and materials science. He is involved in Maintenance and Inspection activities of Hydrocarbon Storage Tanks at the Refinery.

1. Abstract:

Storage Tanks of varying capacity are used to store petroleum finished product, intermediate products, chemicals, and water in a refinery. Healthiness of tanks play an important role in defining production capacity and reliability of a refinery, hence, timely inspection (internal and external) is very crucial for preventive maintenance of the tanks. Based on the OISD Std. 129 frequency, tanks need to be taken out of service for internal inspection which affects production and storage capacity. Tank shell and roof plate thickness and inspection can be done from outside while tank is in service. But, to inspect bottom plate and carry out its thickness survey the tank needs to be taken out of service.

This requires sludge cleaning from confined space which in turn is time consuming and involves health hazard. To fulfil the internal inspection purpose and to eliminate out of service time for tanks, online tank bottom inspection (ultrasonic inspection) is carried out 1st time at Digboi Refinery using remotely controlled rover. The basic technique involves a remotely controlled Robotic Rover specifically designed to ultrasonically inspect the liquid-filled in-service storage tank bottom plates. It uses an array of immersion UT probes to detect any corrosion metal loss of the bottom plate. Inbuilt Data Acquisition system provides high accuracy and reliable data on tank bottom current condition while the tank remains in service.

2. Introduction:

In today's technology driven world, it is very important for us to adopt high technology enabled machineries for better and efficient productivity. Considering the importance of tank internal inspection, especially tank bottom plate, online inspection (ultrasonic inspection) using robotic rovers provides us with the opportunity to minimize various losses occurring due to conventional internal inspection technique and offer us the scope of flexibility in scheduling of tank internal inspection.

Conventional technique for internal inspection involves various limitations. The tank has to be taken out of service for maintenance and inspection purpose which disrupts normal storage activities and may affect production capacity. High amount of revenue is required for engaging manpower and machineries for inspection. Manpower involved in cleaning of tank is endangered to safety risks of confined space and chemical contents of the tanks. The disposed content of tank may have potential to pollute the environment. To tackle and minimise the above mentioned limitations, remotely controlled robots are used for the purpose of inspection of tank bottom. As effective cleaning is essential for ultrasonic examination, cleaning system is also available with the rovers enabling them to scrap off the sludge present in their path on tank bottom plate. Thus this technique avoids any interruptions to normal storage of tanks, helps in reducing cost of inspection, reduces environmental and safety risks and it supports the innovative technology aspects of inspection

3. Technique involved

The basic technique involves a remotely controlled Robotic Rover specifically designed to ultrasonically inspect the liquid-filled in-service storage tank bottom plates to reduce the tank inspection time & cost. It uses an array of immersion UT probes to detect any corrosion metal loss of the bottom plate. Inbuilt Data Acquisition system provides high accuracy and reliable data on tank bottom current condition while the tank remains in service. This technique is a well-recognised and trusted method throughout the industry and meets the API 653 & OISD 129 requirements.

4. Procedure for online tank bottom inspection

Fire water tanks (FWT-04 and FWT-05) were selected for the purpose of robotic online inspection. The procedure for robotic inspection comprises of mainly two steps-

Step 1: Launching of the rover- The rover (Refer Photo 1) and its accessories (cables, pulley, support system etc) is taken at the roof of the tank. The supports (like a tripod stand) are erected on top of a manhole from where rover has to be launched inside the tank (Refer Photo 2).

Photo 1: Robotic rover

Photo 2: Support Erection for launch of rover

With the help of chain and pulley system, the rover along with its cables is launched inside the tank through the manhole (Refer Photo 3).

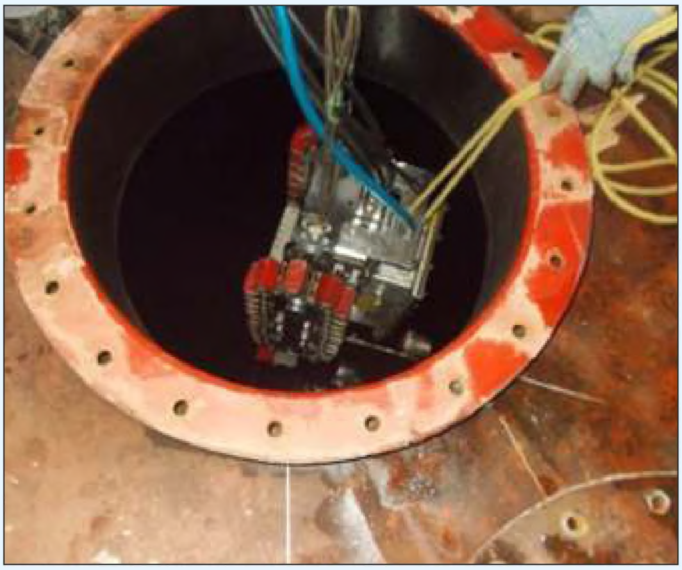

Photo 3: Launching of Rover through roof manhole

Step 2

Movement of rover- After launching, an initial position of the rover (just below the manhole used for launching purpose) is fixed. The movement of the rover inside tank is controlled using a hydraulic system and commands for movement is given by a computer based software. SONAR based technology is used to aid in rover movement and protect it from any obstruction. The tank bottom plate was divided in multiple runs at various angles from the initial position of rover. Each run is consisted of forward movement (in straight line) of rover and then backward movement on the same path till it reaches the initial position. In case of FWT 05, total of 56 UT Scanning runs were systematically taken on the tank bottom area as shown in Photo 4. Thickness scanning measurements were taken in runs of approximately 5 to 12 m long. UT scan raw data were recorded for all runs with 8 UT probes. UT probes are installed at the central chest of the Rover.Probe1 is installed at far right of Rover and Probe8 is installed at far left of the rover. Probe1, 2….8 are placed from right to left of the Rover. All 56 UT runs constitute 54.53% of the total area of the tank. After completion of ultrasonic examination, the rover is taken out of the tank.

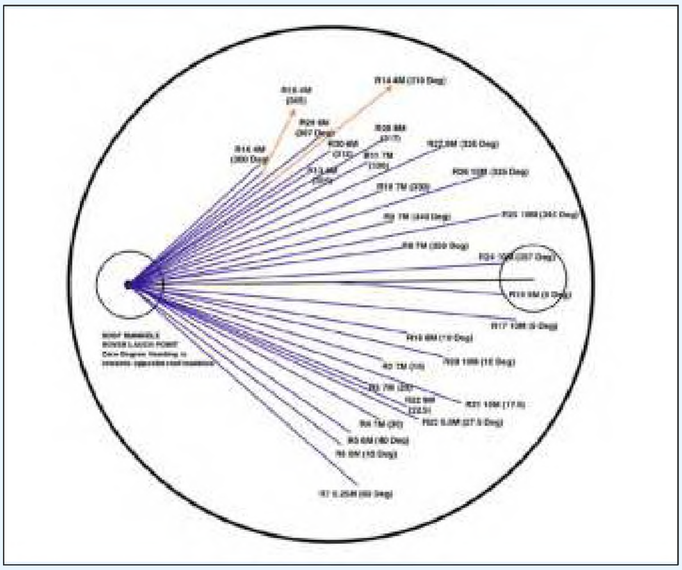

Photo 4: UT Run diagram of FWT 05

5. Authentication of the online inspection

In order to authenticate the effectiveness of the ultrasonic examination by rover, FWT 05 was taken out of service (Fire water) and manual thickness surrey of bottom plate was carried out. A total of seven runs which are Run 2, Run 4, Run 6, Run 7, Run 10, Run 16 and Run 25, were selected for the manual UT thickness measurement. For each run, thickness was taken at every 500 mm interval.

Photo 5: Manual Thickness survey of FWT 05 bottom plate

The following Table 1 summarizes the average thickness reading for various runs with Deviation (Manual thickness – Rover thickness) observed between manual UT readings and rover readings.

Sr. No	Run	Rover Readings	Manual UT Readings	Deviation
		Average Thickness (mm)	Average Thickness (mm)	mm
1	R2	9.9	10.8	+0.9
2	R4	10.2	10.8	+0.6
3	R6	10.5	10.9	+0.4
4	R7	10	10.8	+0.8
5	R10	10.2	10.8	+0.6
6	R16	10	10.9	+0.9
7	R25	10	10.7	+0.7

Table 1

6. Conclusion

Online ultrasonic inspection of FWTs was done with the help of a robotic rover. To authenticate thickness reading, a manual thickness survey was done in fire water tank 05 bottom plates. The locations for manual thickness survey were selected on the basis of angle of rover movement (Refer Photo 4). They may not exactly coincide with the same spots used during rover thickness survey. Comparison of the thickness readings are tabulated in Table-1. Positive deviation in the range of +0.4 mm to +0.9 mm was observed in average thickness readings taken manually, which is less than 10% value of the nominal thickness of bottom plate (i.e 10 mm). It can be concluded that thickness measured by rover is found to be in line with the thickness measured manually.

In a nutshell, thickness scanning of bottom plate of liquid filled in-service storage tanks can be done using remotely controlled robotic scanners which can help in saving tank inspection cost and time. It provides reliable data and can be used for the purpose of health monitoring of storage tanks.

2.4 Improving Energy Efficiency of CDU/VDU with Optimization in Preheat

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Ms. Harshita Gupta holds a Bachelor's degree in Chemical Engineering and presently working as Manager in Engineers India Limited. She has over 10 years of work experience in thermal design, engineering and optimization studies of heat exchangers, air coolers, ejectors and preheat networks. Rich site experience for troubleshooting and prominent speaker in webinars conducted by EIL on heat exchangers.

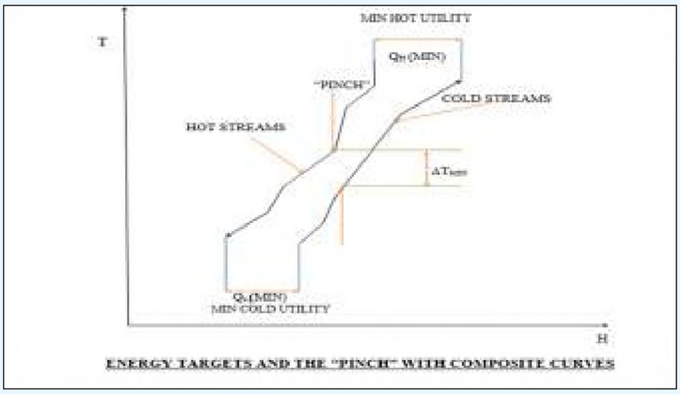
Introduction

As the world transitions to sustainable growth, it is essential for all industries to look for energy efficient innovations to reduce the carbon emissions. The global movement towards Net Zero is mainly shifting the focus towards new and niche development of green technologies. However, there is a need to re-imagine and improvise the conventional processes and products also to enhance their energy efficiencies and augment our approach towards sustainable future.

In a typical petroleum refining, petrochemical or chemical processing plant, approximately 75% energy consumption is attributed to hydrocarbon fuel used in fired heaters and steam boilers for process and power requirements. This offers a challenging and lucrative opportunity for designers to optimize the conventional system for any potential savings. Preheating crude oil to the desired temperature before distillation in CDU/VDU is one of the single largest energy consumption process in a refinery. This crude preheating is achieved in a preheat train network using various product and pump around streams followed by a fired heater. A well-engineered preheat train based on pinch technology and effective heat integration is crucial to reduce the fuel/steam demands and OPEX of CDU/VDU unit.

Methodology

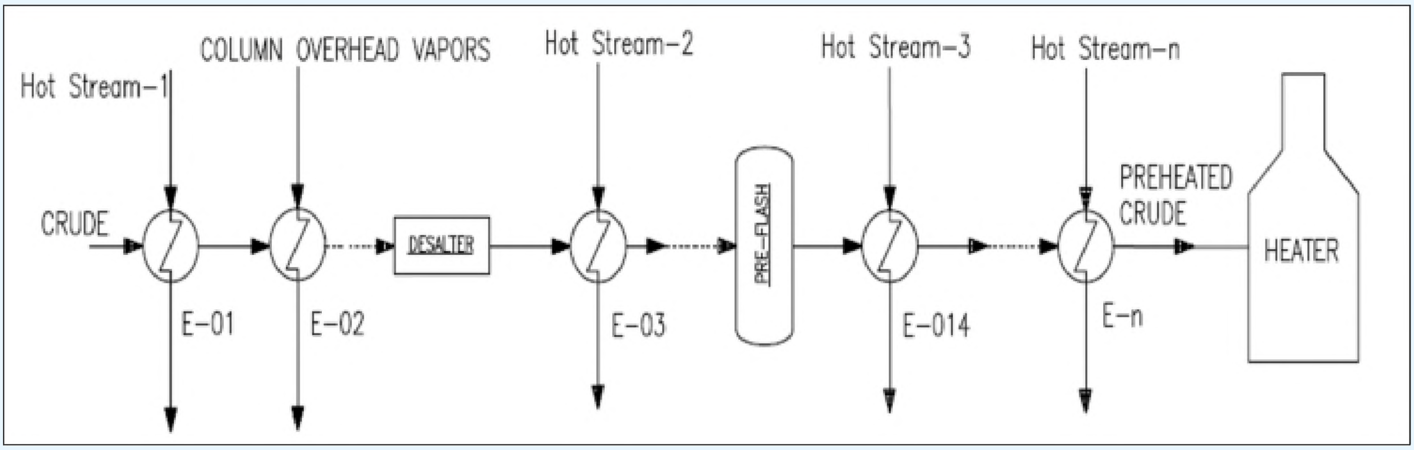
Heat Exchanger network optimization uses the principles of pinch technology in order to achieve maximum heat recovery from hot streams, minimize utility requirements and optimize exchanger areas. This also depends on availability and routing of various hot and cold streams for network synthesis as well as improvement in thermal design methodology. In this paper, various design approaches have been outlined for optimization of HEN which can lead to substantial energy saving.



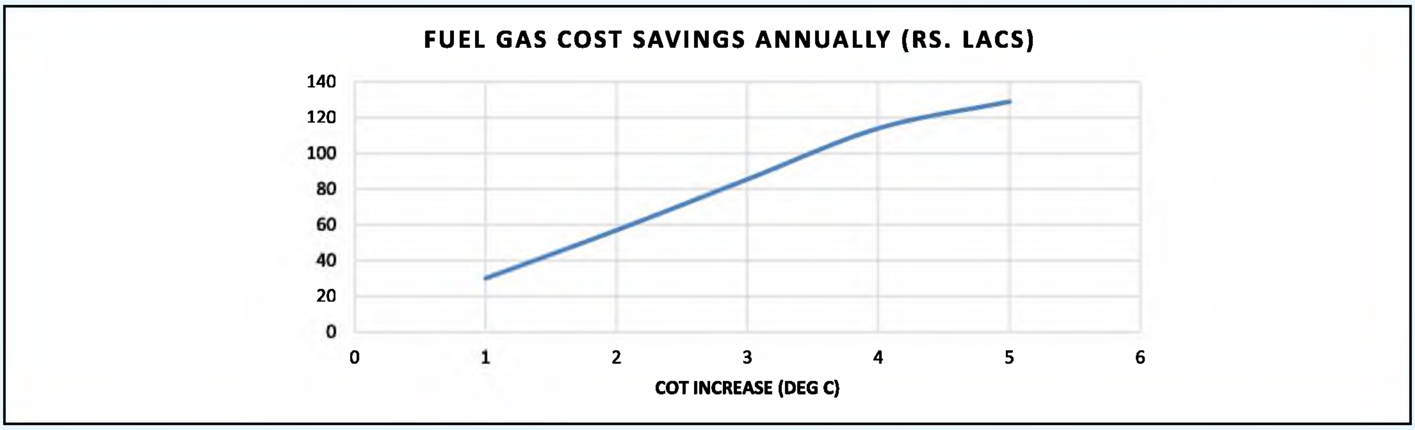
Utilizing Overhead Vapors for Crude Preheating-

Crude overhead vapors generated from CDU distillation column are traditionally cooled with air coolers and trim coolers before sending it as reflux to the column because of its low heat gradient. While designing preheat network, carefully utilizing the low enthalpy of these overhead vapors can offer distinct advantages in energy saving.

This crude overhead and raw crude exchanger shall be placed at the starting of the preheat network to enable maximum heat transfer due to low approach temperatures. The maximum temperature available from overhead vapors is usually on lower side. Hence, to maintain the desalter inlet temperature of crude in the range 125-135 Deg C, exchanger offers highest thermal effectiveness at the start of preheat train.



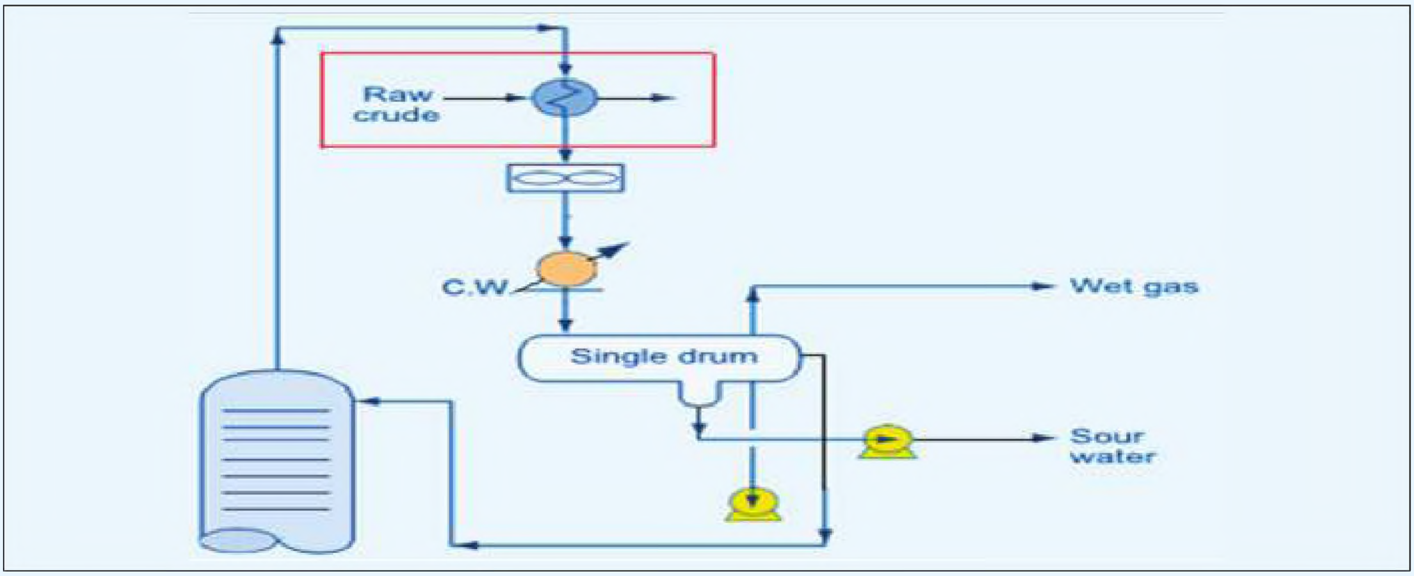
For a refining capacity as low as 1.5 MMTPA and a well synthesized network, a 4-5 deg C increase in crude outlet temperature can be achieved with the addition of overhead vapors as heat source. This will lead to annual fuel gas savings of about ~400 TPA in downstream fired heaters which is an appreciable amount considering the cost of carbon emissions and net zero targets.



(Basis: In-house Data)

Thermal Design of Column Overhead Condensers

The atmospheric crude column overhead system is exposed to corrosion issues, depending on the crude oil type, slop oil processing and de-salter operation. Some overhead systems experience severe corrosion and fouling that may increase the atmospheric column operating pressure and reduce the distillate yield. This leads to change of exchanger bundles at intervals less than the normal turnaround. Some crude columns may have to be shut down to remove the salts deposited on the internals. Furthermore, low crude temperatures entering the crude column overhead vapor exchanger reduces the tube wall temperatures below the water dew point, facilitating strong acid formation.



Typically, horizontal exchangers are used with condensing on either the tube or shell side of the exchangers. Shell-side condensing is most common in such applications. With such orientations, it is more difficult to effectively use water wash or chemically treat the areas around the baffles. Salts and corrosion products deposit in these regions, facilitate under-deposit corrosion.

The fouling factors for crude & column overhead vapor are typically in 0.0004 & 0.0002 hr.m2.deg C/kcal respectively as per TEMA guidelines. Hence, a horizontal configuration has the the advantage of higher heat transfer coefficients because higher crude velocities can be achieved with two-pass flow on tube side. But the calculated pressure drops are extremely high because tube side is in viscous and laminar regime.

The above challenges can be mitigated by changing crude/overhead exchangers to vertical configuration which is self-draining and minimizes possibility of corrosion, fouling and salt deposition.

Design Parameter	Horizontal Shell	Vertical Shell
Tube Side Heat Transfer Coefficient	Higher	Lower by 10-15 %
Mean Temperature Difference	Lower	Higher
Heat Transfer Surface Area	Lower	Higher by 5-6 %
Tube Side Pressure Drop	Higher	Lower
Corrosion and Fouling Tendency	Higher	Lower

(Basis: In-house Data)

Redistributing Circulating Refluxes in Reboilers

Circulating refluxes are the major energy sources in a preheat network. The circulating refluxes are required to be cooled before re-entering the distillation column to maintain the temperature for effective distillation and product quality. These high energy sources are typically used in the preheat networks, often leading to underutilization of enthalpies. Generally, the high heat potential of these circulating refluxes are utilized in reboilers leaving low heat potential for the preheat train.

Option-1:

The high enthalpies of CR Reflux streams can be used effectively as heat source in services like Stabilizer Naphtha Reboiler and Heavy Naphtha Stripper Reboiler etc. Subsequently, the heat potential of CR streams can be recovered in preheat train exchangers. Thus, high level heat is utilized at hot end and low level heat at cold end giving even MTD distribution.

Option-2: Alternatively, the high enthalpies of CR Reflux streams can be directly routed in preheat train network and HP steam is then needed as heating medium for reboiling requirements. This would result in overall increase in crude outlet temperature in the range of 8-10 deg C from preheat network leading to less fuel consumption in fired furnace.

Although higher COT in option-2 may look more lucrative during pinch analysis, however, a comparative study for both the above configurations and in-depth analysis is required in order to select the most optimized option in terms of energy values and process requirement.

An analysis for a 1.5 MMTPA refinery is presented below.

Parameter	Option -1	Option -2	Inference
Fuel Gas in Fired Heater	Base	Base – 800 TPA	Option-2 Better for Fuel Saving
HP Steam Consumption in Reboilers	Base	Base + 20000 TPA	Option-1 Better for Steam Saving
Annual OPEX	Base	Base + 2.2 cr./year	Overall Option-1 more optimum for Energy Consumption

(Basis: In-house Data)

Conclusion

Maximum energy recovery for any process leads to minimization of the required external heating and cooling loads. By applying pinch analysis techniques, we can get many alternative design options for the same process requirement. There is no “one size fits all" approach when it comes to thermal design and heat integration in preheat networks. As seen from above case studies, thorough analysis of all design aspects and energy consumption values is required to arrive at an optimized network. Preheat network design shall be done with all possible iterations by utilizing overhead streams, pump-arounds and product streams for maximum heat recovery and thermal design can be improved based on operational feedbacks. Such simple and incremental improvements in conventional design methodologies can offer significant OPEX savings and reduce carbon emissions.

Part-3
Innovation and Research

> **We cannot solve our problems with the same thinking we used when we created them.**
>
> **- Albert Einstein**

3.1 Hydrogen Economy in Integration with Compressed Biogas Value Chain

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Ms. Lavanya Meesala is working as Senior Manager-FCC in HP Green R&D Centre, Hindustan Petroleum Corporation Limited, Bengaluru, India. She has experience in Hydrogen production technologies, Biofuels, Carbon Nanotubes, Circular economy technology development, Process Design and technical services in refining and gas treating technologies.

Dr. Swapnil Ghungrud is working as Research Associate-FCC in HP Green R&D Centre, Hindustan Petroleum Corporation Limited, Bengaluru, India. He has a knowledge of Hydrogen production technologies, Heterogeneous catalysis, CO2 capture and its utilization, Carbon nanotubes.

Introduction

Transition from the current energy scenario to a net zero carbon world, demands the necessity of alternative sources of energy and technologies. Combining hydrogen economy with compressed biogas value can be considered as one of the sustainable pathway to provide cleaner and pollution free globe to the future generations. For reduction of carbon dioxide (CO2) footprint, hydrogen is considered as one of the potential fuels as it emits only water vapour on combustion, without any CO2 emissions unlike fossil fuel options. Hydrogen (H2) is also a clean energy source not only for transportation sector, but also for hard to abate sectors like steel, fertilizer and refining industry etc.

Depending on the technology adopted for production of hydrogen, different colours have been assigned to hydrogen, though it doesn't own any colour as a molecule. Green Hydrogen is the hydrogen produced from water electrolysis which is powered by renewable electricity. Natural gas reforming with steam (SMR) is another technology which has significant CO2 footprint. Hydrogen produced via SMR combined with carbon capture and sequestration (CCUS) is known to be Blue Hydrogen. Natural gas can also be pyrolyzed for decomposing into hydrogen and solid carbon. Hydrogen produced in this approach is termed as Turquoise Hydrogen. This technology has zero process associated CO2 emissions and nil water footprint as compared to blue hydrogen technology. Hydrogen can also be produced with assistance of nuclear energy and is termed Pink Hydrogen, but this route of production results in harmful radioactive waste. Lastly, hydrogen that is produced by biomass gasification method is labelled as Red Hydrogen (Table 1). BP energy outlook 2023 predicts by 2050, in net zero scenario H2 production may reach of 450 + MMTPA which consists majorly Blue, Green and to a little extent biogenic hydrogen (Figure 1). Utilization of hydrogen and hydrogen derived fuels in transport sector is expected to grow upto >100 MTPA by 2050 in net zero scenario (Figure 2).

Taken into account its huge energy potential and availability several high energy demanding countries like China, India can significantly benefit from utilizing biomass as an energy resource. India has more than 350 Million tons per annum of surplus agricultural residue available which can be utilized as feed stock for producing biogas, majorly consists of methane. In India, animal waste press mud, municipal solid waste and agricultural residues are the primary compressed biogas (CBG) feed sources.

Roughly, the CBG potential of cattle dung and chicken litter is 25 MMT, forest residue is 2 MMT, Agriculture residue is 20 MMT, press mud, spent wash and bagasse combined is 10 MMT, municipal solid waste has 5 MMT, energy crops in barren, waste & single crop land is 30 MMT. This biogas is an excellent sustainable green feedstock for production of hydrogen using turquoise H2 approach.

Government of India announced Hydrogen Mission in 2021 and Programme SATAT for biogas generation as major steps towards India achieving Net Zero goals and energy independence. Under the SATAT scheme, 38 plants have been commissioned in India so far, with over 9000 metric tonnes of CBG sold.

Though the H2 economy is an important vector to achieve Net Zero target of the nation, downstream infrastructure required for 100% H2 transport (like H2 pipelines) still needs to be evolved. A mixture of 15-20 Vol% hydrogen in compressed natural gas known as HCNG can serve as interim option for hydrogen economy. Hydrogen enriched compressed national gas (HCNG) can be transported in an existing natural gas pipeline network and used as a transportation fuel in CNG engine infrastructure without any physical modification.

On the technical front, natural gas (CNG) possesses a lower flame speed and hence causes an ignition lag and slower combustion in the internal combustion engines of vehicles. On the other hand, hydrogen with its high energy density and better flammability range can overcome these cons and hence prove to be more efficient. Inclusion of hydrogen in CNG results in low carbon monoxide and residual hydrocarbon tail gas emissions after combustion. IS 17314: 2019 is an IS standard released for a standard for HCNG to be used as automotive fuel (Table 2).

Conventionally, HCNG can be produced by physical blending of hydrogen and natural gas or by compact steam reforming. CO2 footprint of conventional grey hydrogen produced by steam reforming of methane (SMR) is ~10 Kg CO2/ Kg H2 produced. Stoichiometric water footprint of SMR is 4.5 Kg H2O/ Kg H2 (Figure 3).

HPCL developed HP- HCNG technology for converting biogas from anaerobic digestion (CBG) to hydrogen and high value carbon nanotubes (CNT) without producing CO2 and with nil water footprint. A low-cost proprietary catalyst is developed using circular economy approach for production of HCNG and green CNT using direct decomposition of compressed biogas as feed. This technology demonstrated at pilot scale. Generated CNTs are multi-walled in nature. CNT generated in this process does not need any further purification as they are of >90% purity.

Methane Pyrolysis Chemistry

Methane pyrolysis is endothermic in nature, which means it needs energy to decompose methane to H2 and solid carbon. This required energy can be obtained from the renewable electricity, bio-methane or low carbon hydrogen to minimize CO2 emissions from the process.

The reaction is shown below,

Required reaction temperature for methane pyrolysis can significantly brought down by application of catalyst. A major challenge of hydrogen production through methane pyrolysis is the downstream utilisation of the produced solid carbon. A metal based catalyst used in methane pyrolysis process nucleates the carbon formed in this technology as carbon nanotubes. The in-built elasticity, electromechanical, chemical, and optical properties of carbon nanotubes make them to validate its potential application in diverse fields such as biomedical application, hydrogen storage, water treatment, catalysis, battery applications, polymer composites, paints, etc.

$$CH_4 \rightarrow C + 2H_2$$

HPCL Approach for CBG Decomposition to HCNG and Carbon nanotubes

HPCL developed a proprietary catalyst (HP- HCNG catalyst) for production of HCNG using circular economy approach.

Where, major component of catalyst was made out of refinery waste stream.
HPGRDC is equipped with compressed bio gas plant which utilizes different kinds of waste as feed stock to convert to compressed bio gas. This biogas was used as feedstock to produce HCNG.
HP- HCNG catalyst was used as a catalyst for the decomposition of CBG to H2 and Carbon nanotubes (Figure 4).

Lab Scale Studies

Non catalytic methane pyrolysis takes place above 1100 °C for complete conversion. This temperature was brought down to < 550 °C for partial decomposition of biogas to meet HCNG specifications by utilization of combination of HP-HCNG catalyst, innovative reactor design and process parameters.

Catalyst evaluation in lab scale was conducted at 50 g scale. After encouraging results at lab scale, a pilot plant of 25 kg/ day of feed capacity was designed and commissioned at HPCL R&D Centre.

Pilot Plant Studies

The catalyst formulation which was developed in lab was scaled-up from grams to several Kgs level. This prepared catalyst was evaluated in HCNG pilot plant using in-house produced CBG as a feedstock for CBG decomposition into HCNG and carbon nanotubes (Figure 5).

HPCL has developed patented reactor configuration for methane pyrolysis process.
From the obtained results from pilot plant operation, it was revealed that prepared catalyst was stable for >45 h time-on-stream and H2 concentration in product gas meeting the HCNG specification of 18 Vol%. CO2 present in bio gas reacts into CO. This can be further purified using pressure swing adsorption system. These results also provides a platform for production of green synthesis gas (mixture of CO and H2) for further chemicals production. The spent catalyst recovered from the pilot plant results in the formation of >90% multi-walled CNTs confirmed from the Thermo Gravimetric Analysis (TGA) and Scanning Electron Microscopy (SEM) (Figure 6, 7).

Conclusions

HPCL has developed patented HP-HCNG technology for production of HCNG. Techno economic analysis suggests that even CNTs selling price of less than $20/Kg can prove this process competitive against other H2 production technologies without taking CO2 credits into account. In India, as part of CBG drive, CBG plants can be fitted with modular HP- HCNG units for generating carbon negative HCNG and value-added green carbon nanotubes.

References

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2. BP Energy Outlook edition 2022.
3. Kriti Yadav et al (2022). Fundamentals and developments of compressed biogas in city gas distribution network in India: A review Petroleum research, 3 (7), 409-418.

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Table-1: Colours of hydrogen derived from their production methods.

Colour of H_2	Production Route	GHG Emissions
Grey Hydrogen	Steam methane reforming of fossil fuel to hydrogen	8 – 12 kg CO_2 / kg of H_2
Brown / Black Hydrogen	Coal Gasification	18 – 20 kg CO_2 / kg of H_2
Blue Hydrogen	Grey hydrogen with carbon capture and storage	CO_2 captured and stored
Turquoise Hydrogen	Decomposition of CH_4 into solid carbon and H_2	No direct CO_2 emission
Green Hydrogen	Water electrolysis and green power	No CO_2 emission
Red Hydrogen	Biomass gasification	Low net CO_2 emission
Pink Hydrogen	Nuclear Energy	Radioactive waste

Table-2: Requirements for Hydrogen enriched Compressed Natural Gas (HCNG) for Automotive Purposes.

Sr. No.	Characteristic	Requirement (3)
i	Hydrogen (percent volume)	18.0±1.0
ii	Methane, Min	72.0
iii	Other hydrocarbons (percent volume)	
	a) Ethane, Max	6.0
	b) C_3 and higher HC, Max	3.0
	c) C_6 and higher HC, Max	0.5
	d) Total unsaturated HC, Max	0.5
iv	Impurities	
	a) Water content, mg/m3, Max	5.0
	b) Total sulphur, mg/m3, Max	20
	c) Oxygen, volume percent, Max	0.5
	d) Carbon dioxide and nitrogen, volume percent, Max	3.5
	e) Carbon monoxide, Max	0.1

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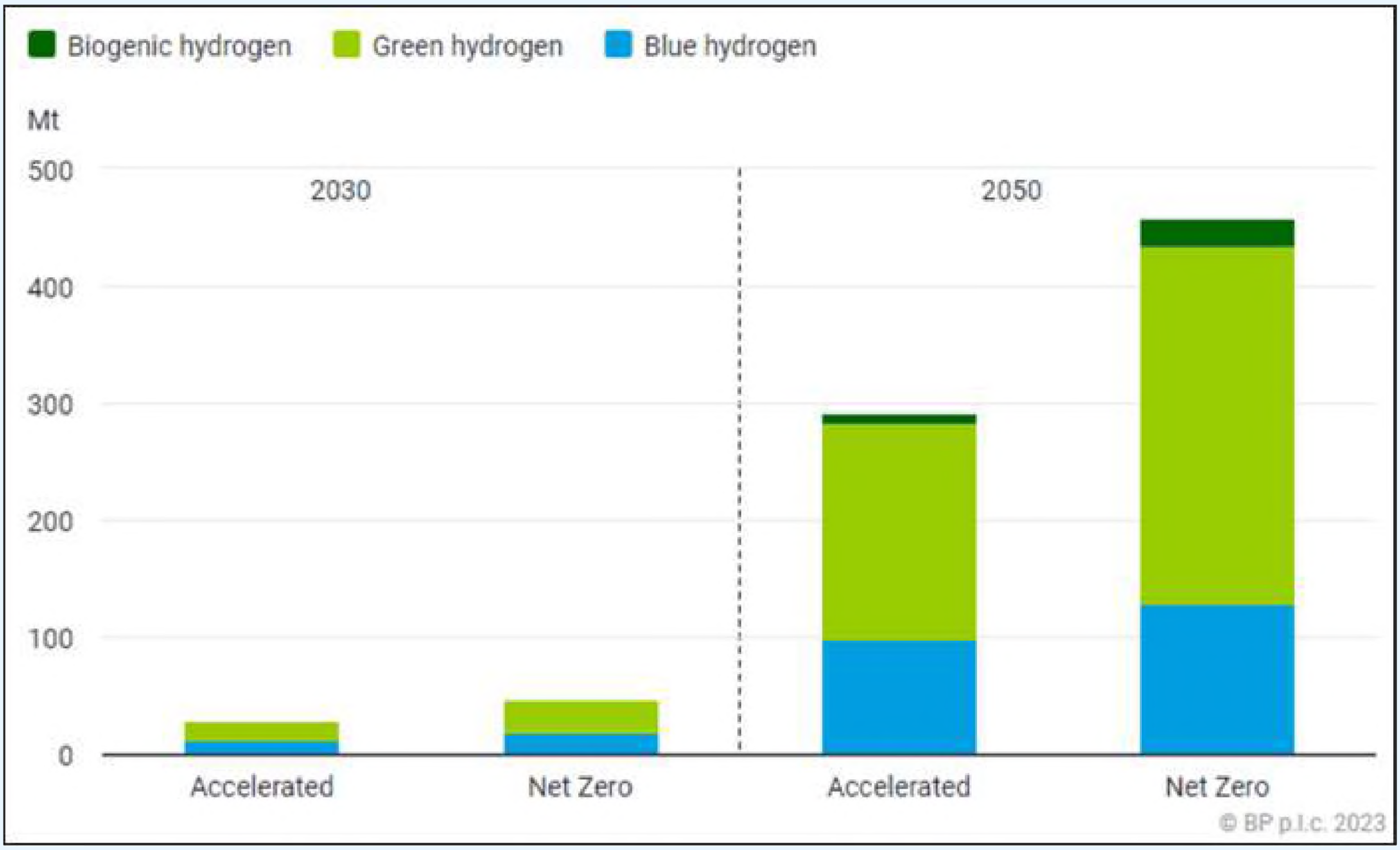

Figure-1: Global Low Carbon Hydrogen Supply (Source: BP Energy Outlook 2023).

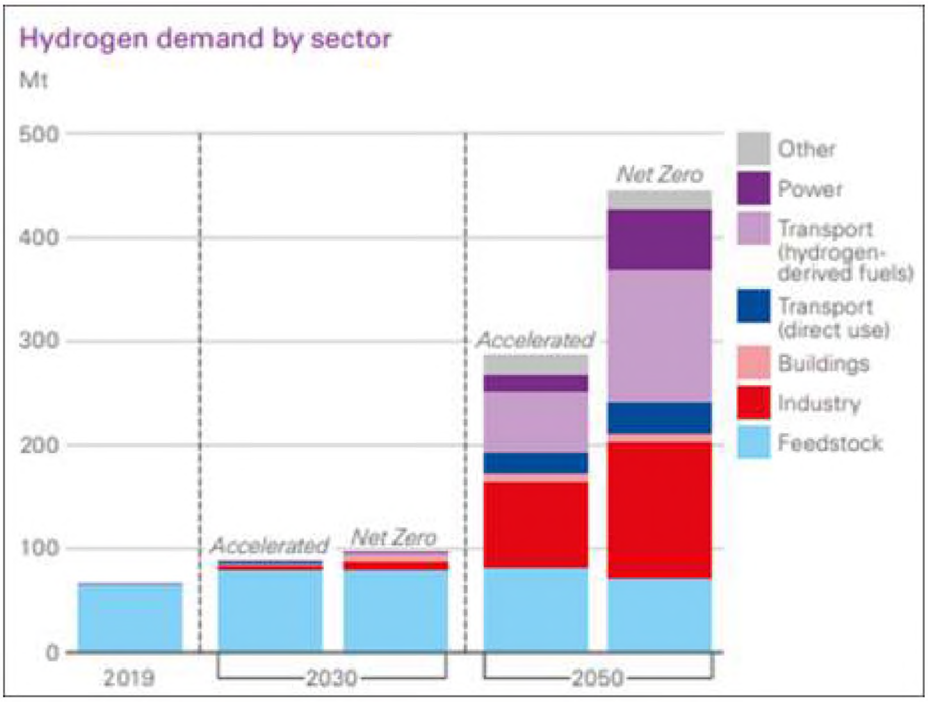

Figure-2: Global Hydrogen Demand (by sector) (Source: BP Energy Outlook 2022).

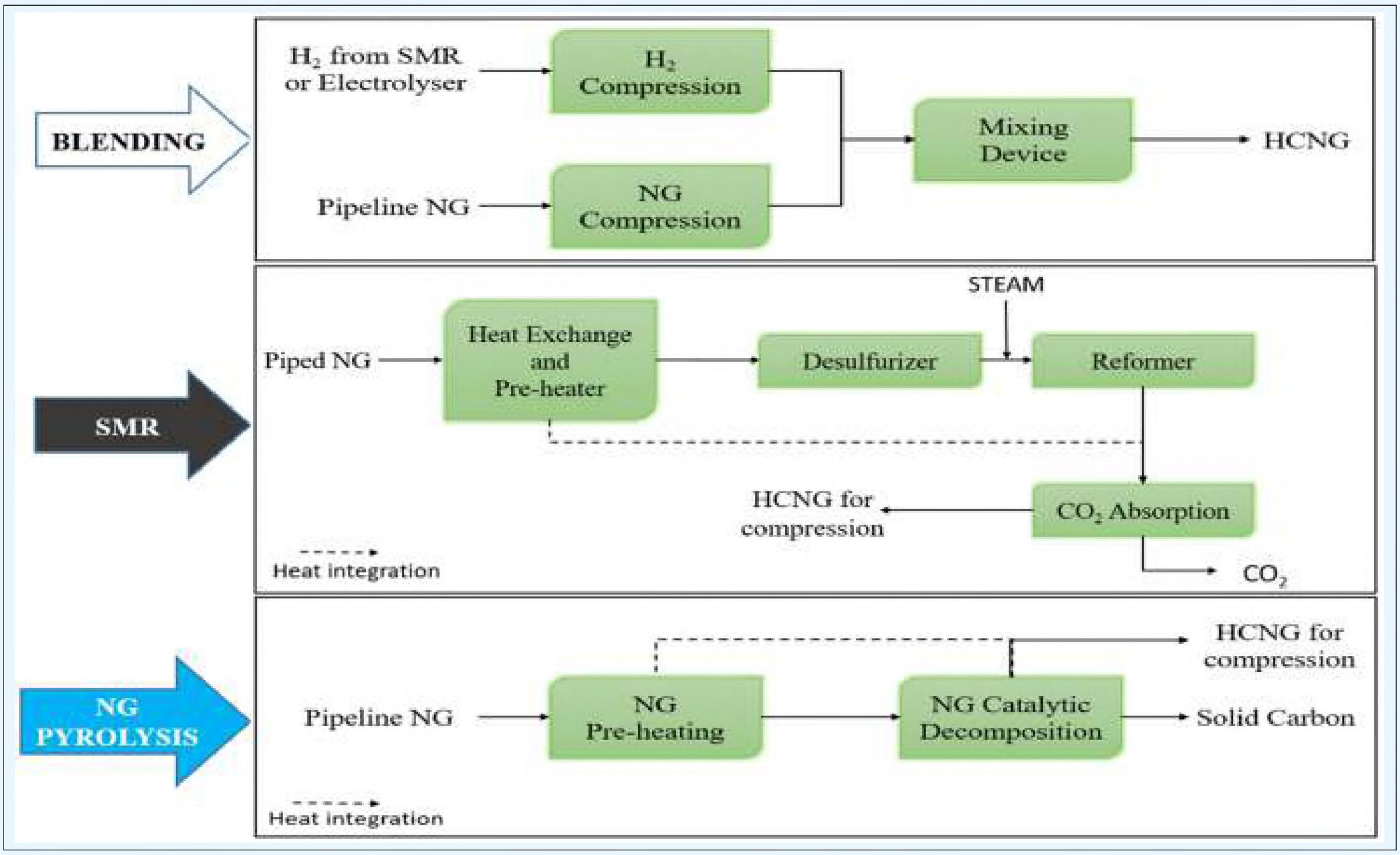

Figure-3: H-CNG Production Methods.

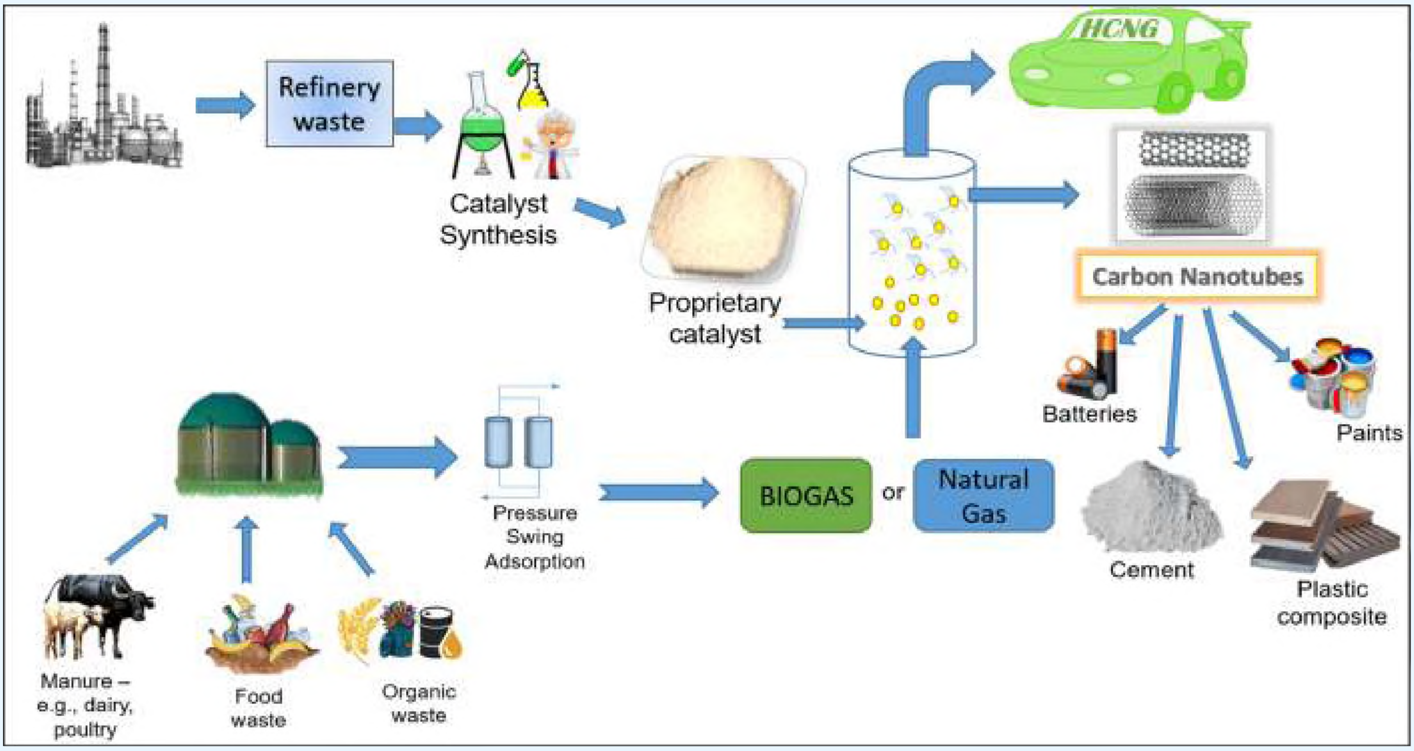

Figure-4: HPCL Approach for CBG Decomposition to H2 and Carbon nanotubes.

Figure-5: HP-HCNG Pilot Plant at HPGRDC Bengaluru.

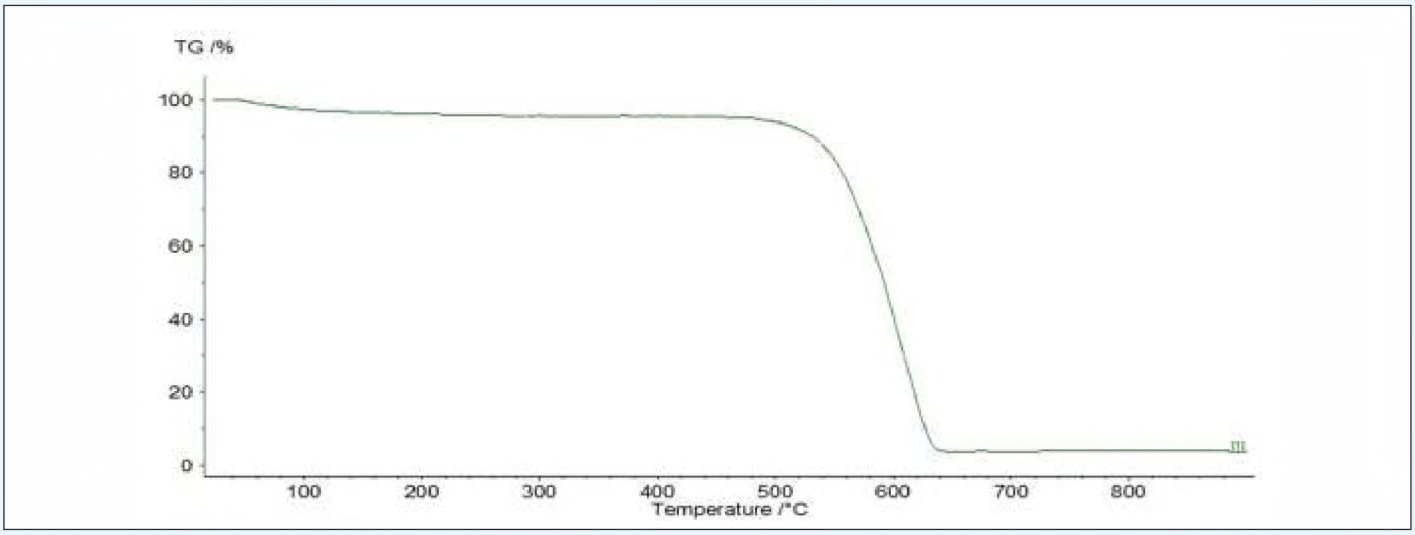

Figure-6: Thermo gravimetric analysis of spent catalyst from HP HCNG Technology

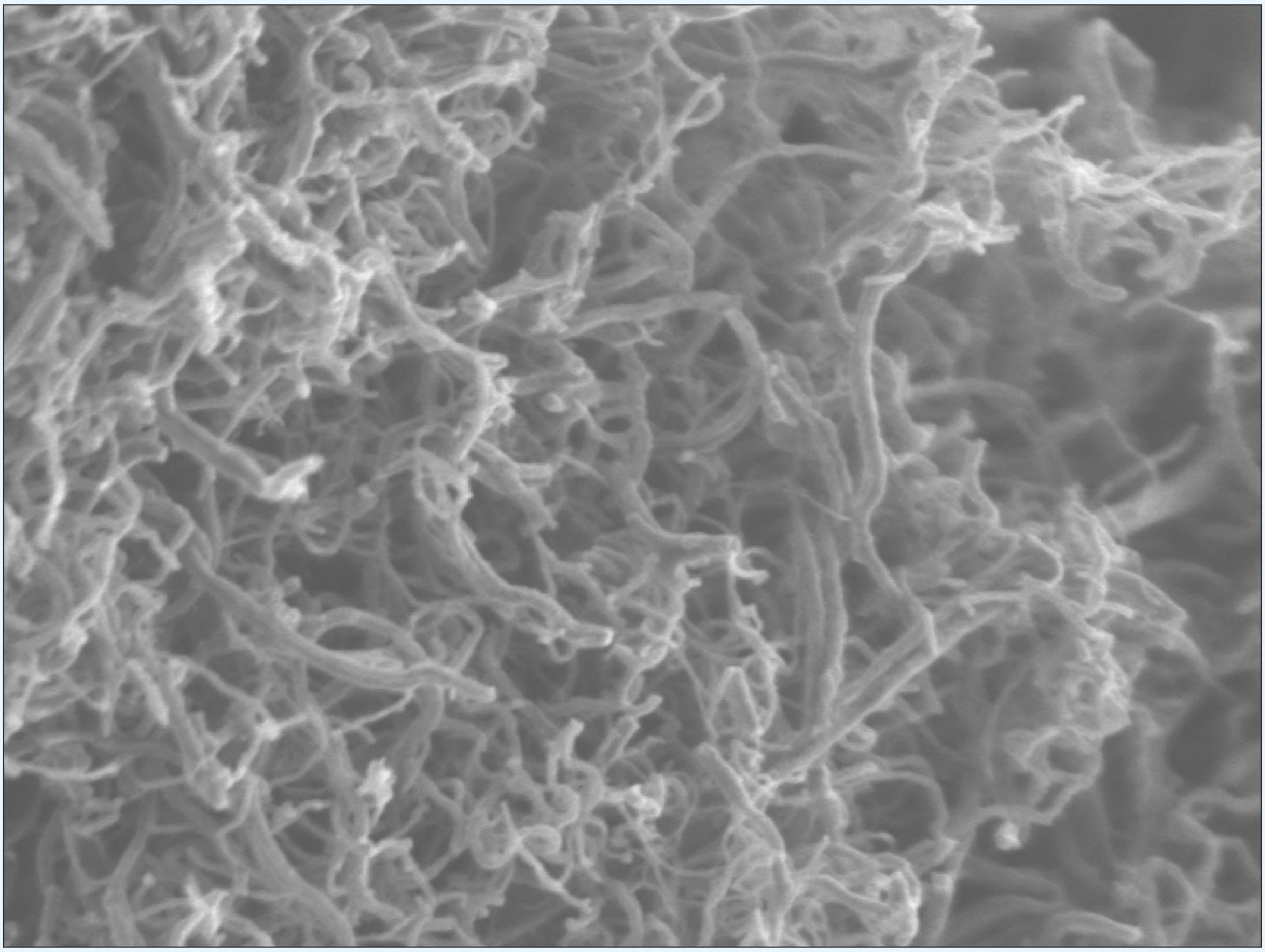

Figure-7: Scanning electron microscopy of spent catalyst showing CNT generated in HP HCNG technology

3.2 Catalytic Co-Processing of delayed coker naphtha with VGO streams

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Abstract

Upgrading delayed coker naphtha in fluid catalytic cracking (FCC) unit has been investigated, with the aim of producing light olefins and a high-octane gasoline. Coker naphtha is a suboptimal low value blending component in the gasoline pool owing to its high sulphur content, di-olefin content, and low octane rating. It is generally offset with the highly olefinic FCC naphtha and aromatic rich reformate. The acid catalysts used in FCC can improve the naphtha olefinicity as well as crack and hydrogenate the diolefin species thereby enhancing the overall octane rating. The high sulphur content of coker naphtha can also be mitigated in the FCC to a limited extent. With the advent of BS-VI emission norms in India, gasoline sulphur specification has been limited to <10 ppm. The heavier sulphur compounds in coker naphtha can be cracked into lighter and manageable species and in the case of very high sulphur naphtha, gasoline sulphur reducing additives as well as gasoline treatment units can be leveraged. High severity FCC units can also profit from higher quantity of naphtha range feedstock to improve light olefin yields. However, the limit on how much coker naphtha can be processed depends on the catalyst's and coker naphtha's properties as well as the available treatment units.

1. Introduction

In recent times, oil refiners have invested sizable capital in equipment in order to fulfill the increasingly stringent environmental standards. The general

trend in the extraction of petroleum has continuously been towards heavier and increasingly contaminated oil Consequently, heavy oil is becoming the primary feedstock of refineries all over the world and heavy oil upgrading units play a key role to the best utilization of oil resources and increasing profitability. [1][2]

In this context, catalytic cracking and hydrocracking units perform relevant roles in the upgradation of intermediate oils whereas cokers and visbreakers intensify heavier oils and residue. [3][4] Amongst the aforementioned upgraded streams, thermally cracked naphthas require special consideration as they consist of complex mixtures of low-quality components in the C5− C12 range. Coker naphtha in particular is characterized with high sulphur concentration and low octane rating. [5]. Upgrading such low-quality stream entails selective hydrogenation. However, with the increasing quantum of heavy oil and residue, many refineries end up with a surplus of thermally cracked naphtha which negatively affects the profitability [6].

FCC (fluid catalytic cracking) is a key process in the profitability of a refinery. This process was originally conceived in order to maximize the production of gasoline, and it subsequently proved to be efficient in meeting the increasing demand for light olefins. [9] FCC units maximize production of gasoline and light olefins from a variety of heavy gas oils originating from: (i) the atmospheric distillation column (atmospheric residue, AR); (ii) vacuum distillation tower (vacuum gasoil, VGO); and (iii) coker units (coker gasoil). It is well-established that the FCC unit can handle secondary refinery streams (UCO, naphtha) or alternative streams (biomass, plastics) either pure or blended with the conventional FCC feedstock (vacuum gasoil, VGO) [7][8].

In this context, this work undertakes the co-processing of heavy delayed coker naphtha (DCN) with VGO in FCC. Furthermore, pure VGO and DCN have also been tested to properly evaluate the effect of the blending with the naphtha on the conversion level and on the products distribution. The cracking experiments were carried out using an industrial equilibrated catalyst (E-CAT). The effect of blending DCN on the value of RON was studied. An attempt to investigate the in-situ cracking of sulphur compounds is also presented.

2. Experimental - Materials and Methods

2.1 Feedstock

The heavy delayed coker naphtha (DCN), which is a thermally cracked naphtha obtained in a coker unit, has been directly provided by Bharat Petroleum Corporation Ltd from their facilities located in Kochi (Kerala). Given the tendency of this stream to form gums when contacted with oxygen, special care was taken to store it. The base feed is a hydrotreated vacuum gas oil (VGO) sourced from the same facility, which is the usual feed of any FCC unit. Hydrotreated VGO was chosen in this study to exclude the deleterious effects of contaminants present in the VGO itself. The physiochemical properties relevant to our study are listed out in Table 1.

The fractions are characterized by simulated distillation as per ASTM D7169 standards. Density and sulphur content have been computed following the procedures described in the ASTM D4052 and ASTM D4294 standards respectively. The chemical composition and RON have been obtained by chromatographic methods following ASTM D5443 and shown in Figure 1.

Table 1. Feedstock Characteristics

	VGO	DCN
Density at 15°C (g cm-1)	0.8929	0.7792
Simulated distillation		
IBP	-	65
10%	359	104
30%	420	136
50%	453	150
70%	478	169
90%	540	187
FBP	-	200
Sulphur (ppmwt)	76	6342
RON	-	60

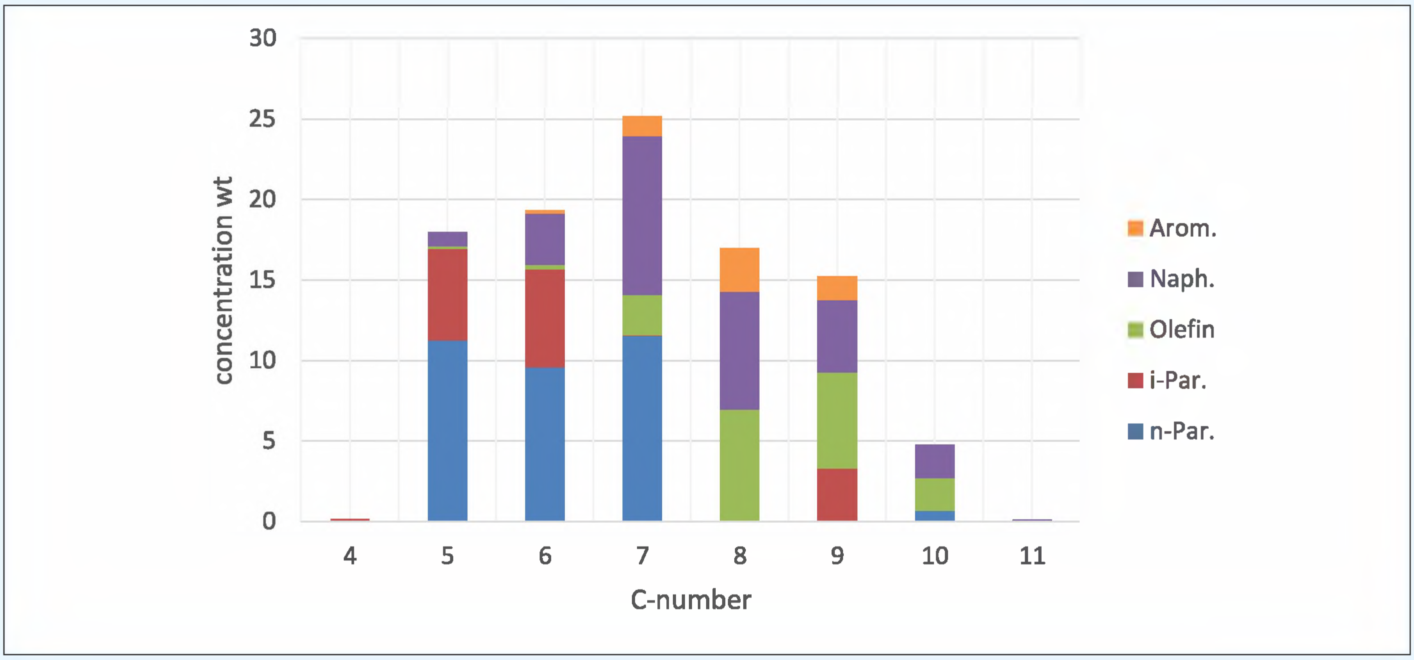


Figure 1. Distribution of DCN components with their chemical structure and carbon number

2.2 Catalyst

An equilibrated catalyst (E-CAT) from an industrial FCC supplied by Bharat Petroleum Refinery (Kochi) was used for the cracking experiments. The catalysts have been characterized by means of several techniques and their main properties have been collected in Table 2.

Table 2. Catalyst Properties

	E-CAT
Specific Surface area (m^2g^{-1})	230
Micropore area (m^2g^{-1})	132
Pore Volume ($cm^3\ g^{-1}$)	0.156
Micropore Volume ($cm^3\ g^{-1}$)	0.051
Unit cell size (Å)	24.67
Average Particle Size (µm)	78
Total acidity ($mmol_{NH3}\ g\text{-}^{1}$)	0.018

The surface area measurements through nitrogen adsorption/ studies for the catalyst sample were done using a BELSorp Max (Microtrac BEL, Japan) unit. Nitrogen adsorption/desorption isotherms were measured at -196 °C after degassing about 70 mg of sample below 10-3 torr at 300 °C for 3 hrs. The BET specific surface area (SBET) was estimated by following ASTM method D3663-99 using desorption data in a relative pressure range from 0.008 to 0.08. Likewise, zeolite and matrix surface areas were estimated based on the guidelines described in ASTM 4365-95 method using T- plot method. This approach was also employed for estimation of micro pore volume. Particle size distribution (PSD) of the catalyst was carried out using Mastersizer 3000 Laser Particle size analyzer (Malvern Panalytical, UK) using water as the dispersion medium. Typically, 0.2 -0.5 g of the sample was dispersed in 500 mL of water and analyzed for particle size distribution. Finally, unit cell parameters of the zeolite have been determined by X-ray diffractograms obtained in a Philips X'Pert PRO powder diffractometer equipped with a PIXcel detector based on the solid-state technology and with a secondary monochromator with CuKα radiation in accordance with ASTM D3942 Standard. Both total acidity and acidic strength have been determined by means of ammonia temperature programmed desorption in a Netzch TG-DSC.

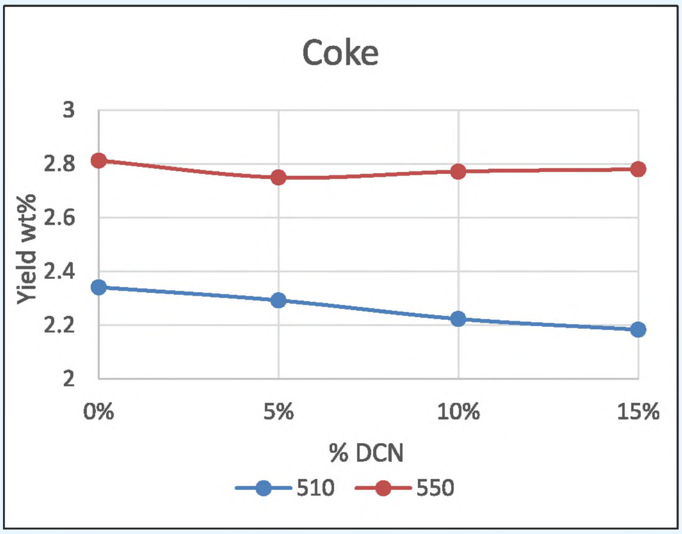
2.3 Cracking

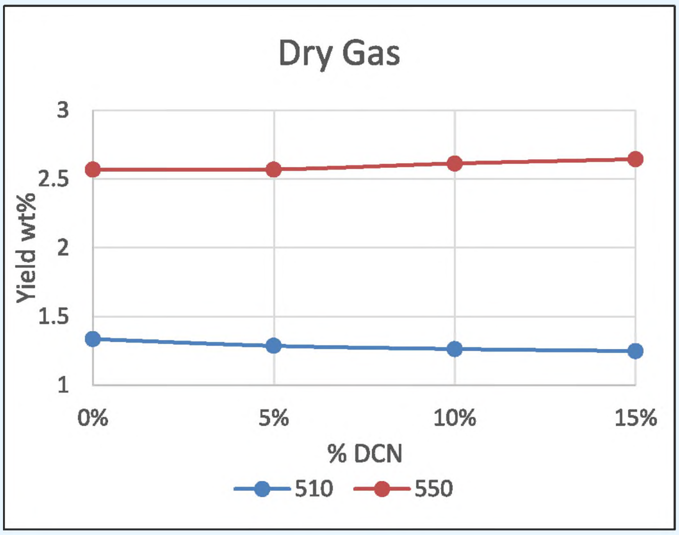
The cracking performance of the VGO, DCN and its blends were investigated using the Advanced Cracking Evaluation (ACE R+MM) unit developed by KTI Technology Company, USA.

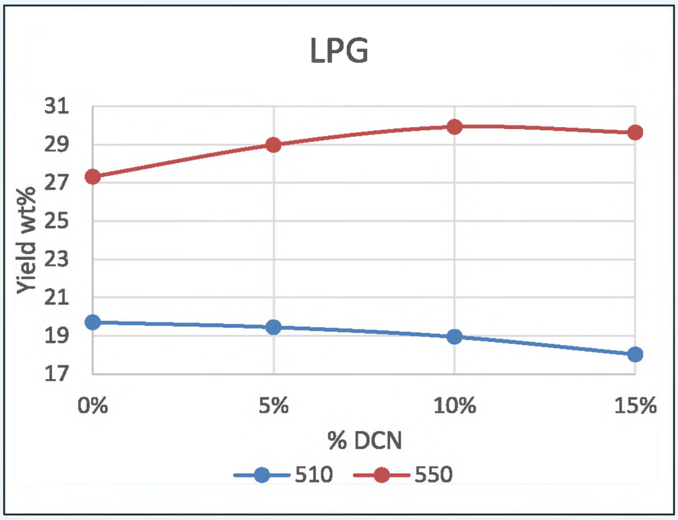
The device is equipped with a single fixed fluidized bed reactor in which reaction, stripping and regeneration processes take place. In this experiment, the weighed catalyst is pneumatically injected into the reactor through the injection system followed by the feedstock through a syringe pump system. The catalyst and feedstock react under a preset reaction temperature and cat to oil weight ratio (CTO). The reacted catalyst is stripped using nitrogen while the liquid products are collected in a condenser. Gaseous products are collected and weighed in a gravimetric gas collector. The liquid and gas product composition analysis are conducted in accordance with ASTM-D7169 and ASTM D7833 respectively. The catalyst after reaction is stripped and regenerated. The coke yield is estimated using flue gas analysis.[10]

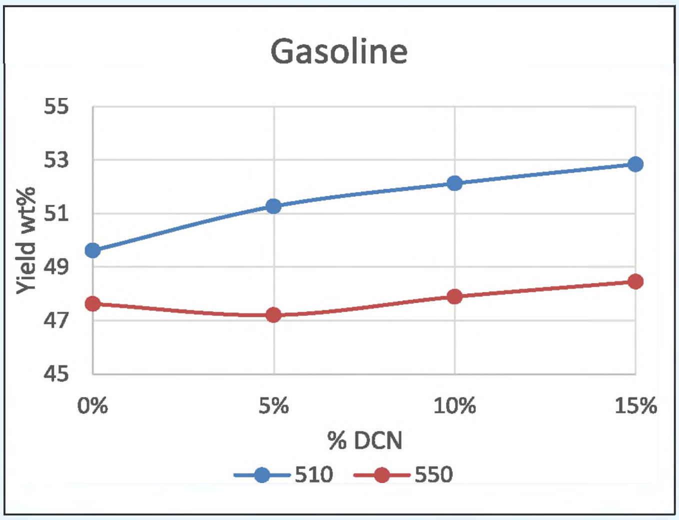
3.0 Results and Discussion

Cracking Experiments were performed using the aforementioned catalyst by feeding VGO and VGO-DCN mixtures with the proportion of DCN varying as 5%, 10% and 15% by weight. The reaction conditions were the following, temperature 510°C and 550°C; cat to oil ratio: 6w/w; and injection time: 8 seconds. The motivation behind these two temperatures is that naphtha cracking reactions are said to gain prominence beyond 530°C. Also, the typical operating conditions for low severity FCC are between 500°C to 520°C whereas for high severity FCC is above 530°C. [11] The cracked products are analyzed using the aforementioned methods. The product hydrogen, methane, ethane and ethylene is characterized as dry gas (DG), the C3 and C4 hydrocarbons are considered LPG. The liquid cracked products are characterized based on their distillation characteristics as follows: IBP to 195°C is considered cracked gasoline (CCN), 195°C to 340°C is light cycle oil (LCO), 340°C to 360°C is heavy cycle oil (HCO) and 425°C+ is clarified oil (CLO). The yields of the product fractions obtained at both temperatures in the cracking of the VGO/DCN blends and of the pure VGO have been tabulated in Table 3.









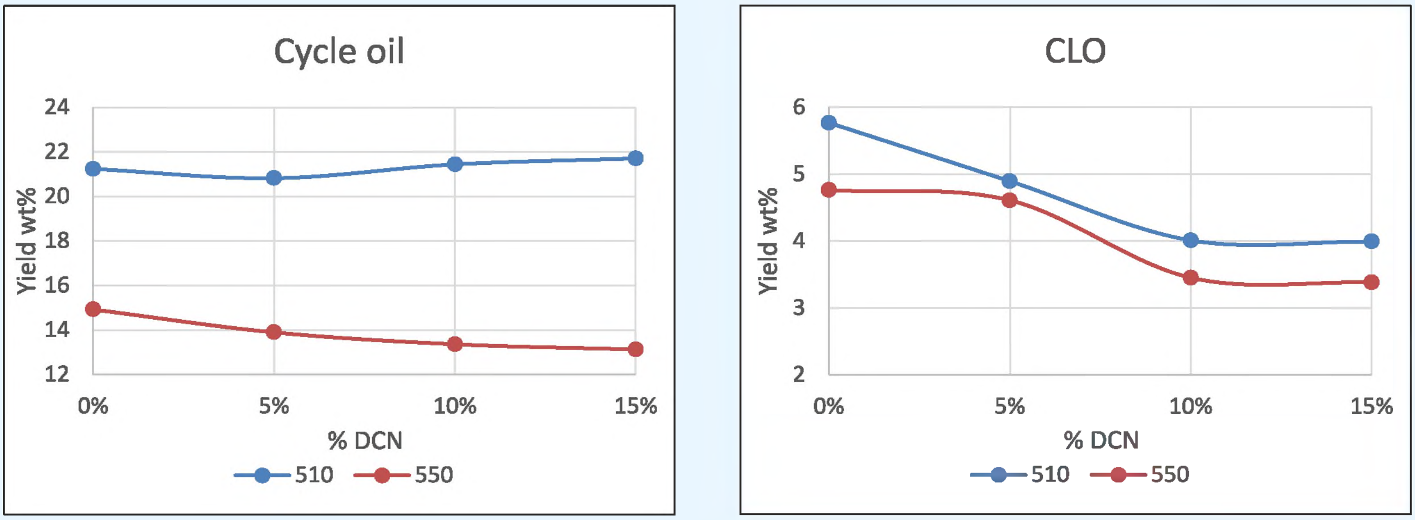


Figure 2. Product selectivity with DCN co-processing at low (510°C) and high severity (550°C)

At both lower severity and higher severity, it is observed that coke make is lower than that obtained with the VGO. Coke is catalytically formed by dehydrogenation and condensation reactions and additive coke is also formed from the multiring aromatics already present in the feedstock [12]. Consequently, the blending of the VGO with DCN free of these heavy molecules will lead to a reduction of the amount of coke deposited. The lesser formation of coke must be considered in the heat balance of the unit and will require either a higher preheating temperature of the feedstock or modifications in the regenerator operation.

Overall, dry gases, i.e., methane, ethane, and ethylene, are mainly formed at high temperatures, given the endothermic nature of the cracking reactions that produce them [13]. This increase is more pronounced at higher severity for the blends with increasing proportion of DCN given its higher tendency towards secondary cracking reactions. The yield of LPG also follows similar trends however since the cracking mechanism of LPG production is more catalytic in nature as opposed to thermal [14]. At higher DCN processing ratios, the LPG yield marginally reduces. At lower severity endothermic gasoline cracking is not feasible and the primary contributor to the overall gas yield is VGO. Hence both dry gas and LPG yields reduce with the increasing proportion of DCN processed.

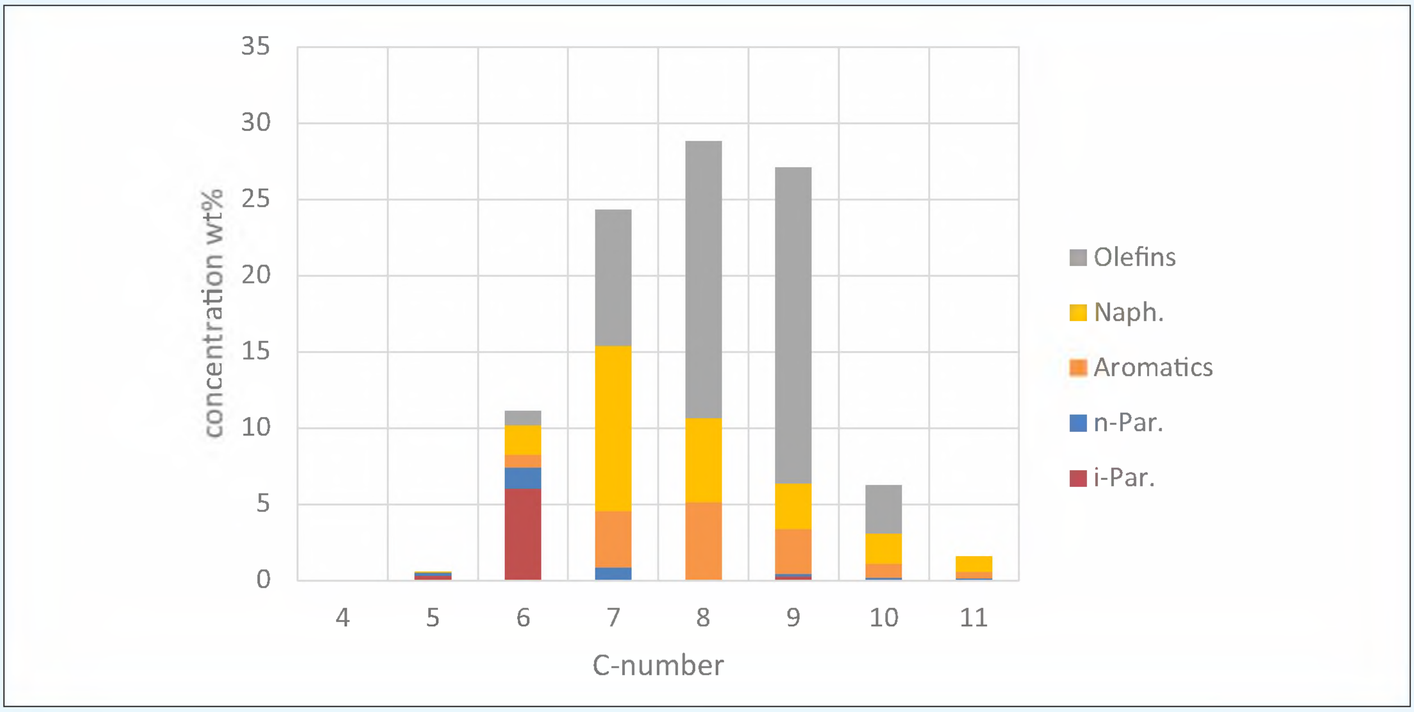


Figure 3(a). Distribution of CCN components without DCN processing

Figure 3(a) and Figure 3(b) depict the effect of DCN processing on the distribution and nature of hydrocarbons in the cracked gasoline product. On comparison with Figure 1, conclusions can be drawn on the cracking chemistry in the C5-C12 hydrocarbon range. Typically cracked gasoline is formed due to catalytic cracking of heavier molecules. This leads to gasoline being highly olefinic as seen in Figure 3(a).

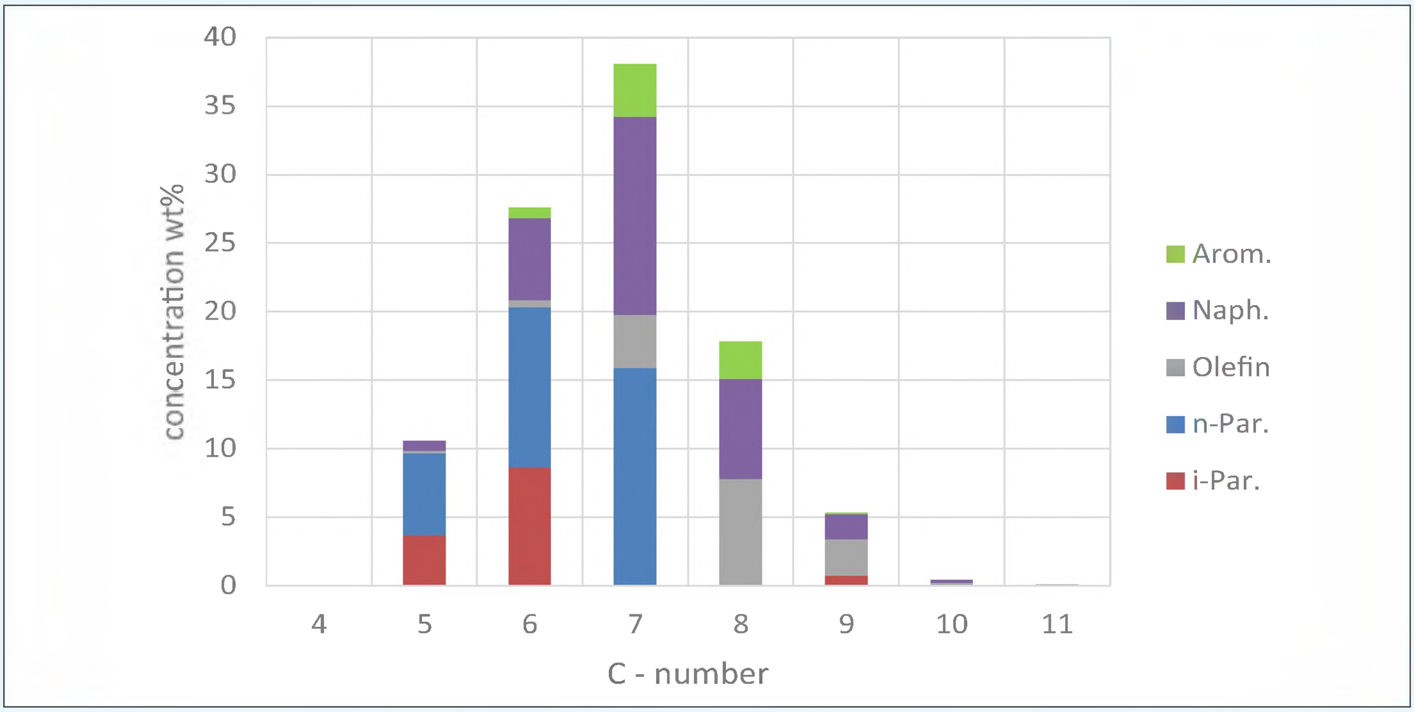


Figure 3(b). Distribution of CCN components with 15% DCN processing

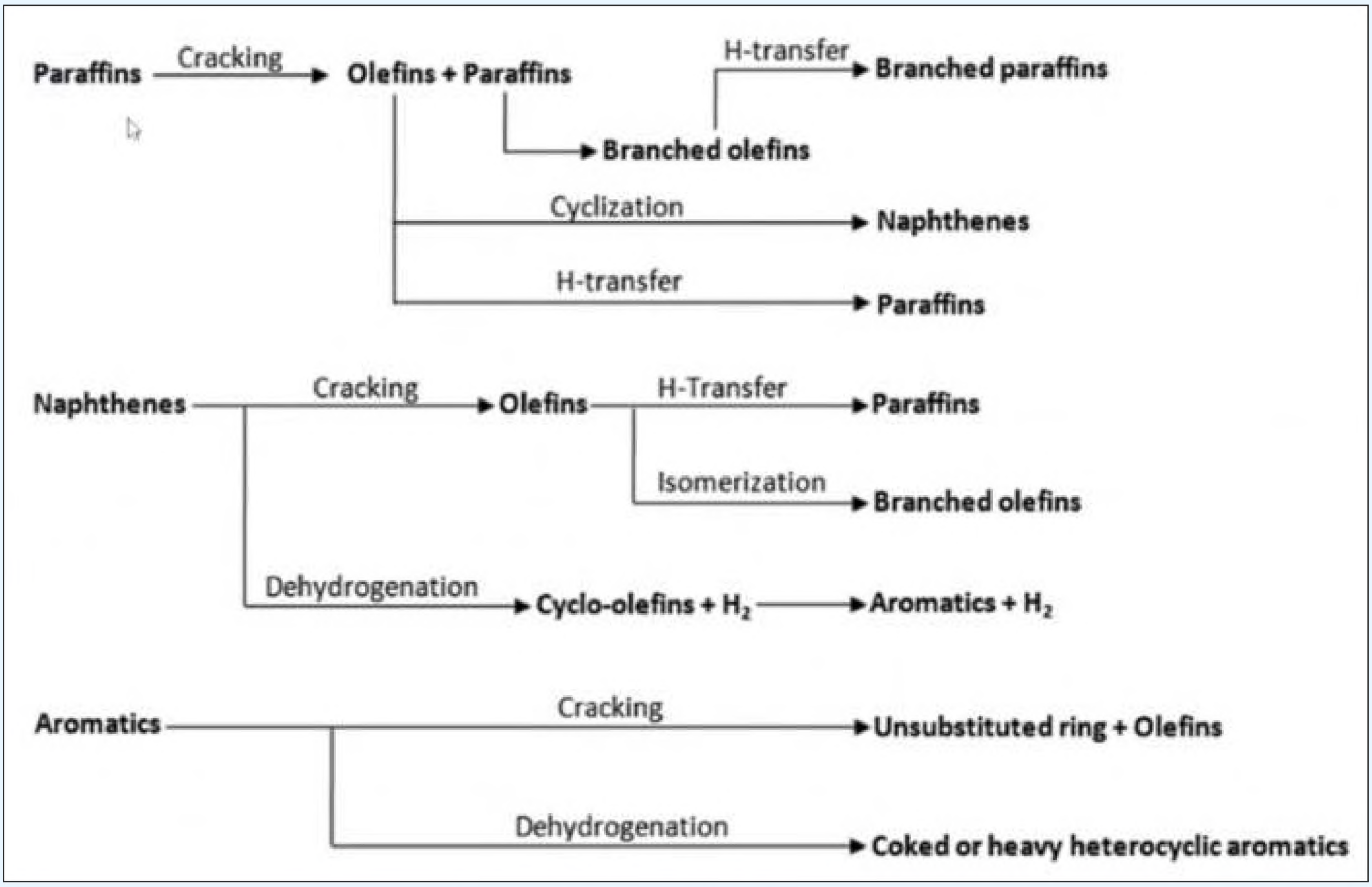


Figure 4. Overview of Reactions in FCC

Some of the gasoline range olefins undergo cyclization + dehydrogenation and contribute to the gasoline's aromaticity. Both these reactions contribute to the gasoline's RON. At high severity a portion of the gasoline also cracks into lighter olefins i.e., propylene/ethylene. When DCN is co-processed, a fraction similarly cracks into lighter olefins ideally at high severity. DCN also consists of saturated naphthene rings and heavy paraffins. In Figure 3(b) it is observed that the C-8, C-9 naphthene rings dehydrogenate to aromatics and C-9, C-10 paraffins crack into gasoline range olefins. Also, C-5 paraffins crack into lighter olefins. In this way, the olefinicity of the DCN increases although the overall cracked gasoline product is naphthene rich which lowers the RON slightly.

For the case with pure VGO as the feedstock, gasoline (CCN) and LCO yield reduces with increasing severity due to reasons explained above. However, at lower severity there is limited upgradation of DCN. This is apparent when the trend of RON is studied. RON is the most meaningful parameter when characterizing gasoline fraction, as marketed automotive fuels must have a RON of 95 or 98 to comply with the current legislation. Gasoline yielded at higher severity has higher olefinicity which is apparent by the improvement in RON (Table 3). The addition of DCN lowers the RON value due to the reasons mentioned above, but the olefinicity of the processed DCN fractions increases which ensures the RON reduction is not significant.

Table 3. Cracked Gasoline Quality w.r.t RON and Sulfur Content

	VGO	VGO DCN	VGO DCN	VGO DCN
DCN %	0%	5%	10%	15%
	510			
Sulfur (ppmwt)	18.74	25.37	65.43	94.32
RON	93.3	92.2	90.6	85
	550			
Sulfur (ppmwt)	11.56	20.8	59.49	81.34
RON	95.7	93.1	91.7	88.4

With the implementation of Bharat Stage VI regulations, automotive gasoline sulphur content is mandated to be <10 ppm. DCN is a high sulphur stream which requires treatment prior to gasoline pool blending. Processing DCN in FCC reduces sulphur content marginally via cracking of heavier sulphur species to H2S. This can be further improved by use of gasoline sulphur reducing additives or installing a gasoline treatment unit.

Another point worth consideration is that gasoline treatment units saturate a portion of the stream thereby further reducing the octane rating. The only other alternative for DCN sulphur reduction is via diesel hydrotreaters / hydrodesulphurization, but at the cost of diesel throughput.

Delayed cokers being used for needle coke production usually operate on low sulphur feedstocks. In such cases DCN will have low sulphur content and would make an excellent feedstock for FCC units.

Conclusions

Coker naphtha is a suboptimal blending stream for the automotive gasoline pool. A limited volume of coker naphtha can be processed in fluidized catalytic crackers to upgrade it to high octane naphtha and light olefins (ethylene/propylene). Processing coker naphtha in FCC at high severity increases the LPG yield and lowers the coke, LCO and CLO production. The constraint on the coker naphtha processing volume depends on the depreciation of the cracked naphtha's octane number and the sulphur content. Based on the aforementioned results, a plant trial was carried out in BPCL's Kochi refinery FCC. Results of the plant trial agree with the trend observed at laboratory scale; however, the results are withheld due to confidentiality. The refiner has to weigh the pros/cons to make an informed decision to maximize the refinery margin in a sustainable fashion.

Acknowledgement:

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3.3 Enhancing Hydrogen and Propylene yields by integration of HGU & OPDH processes

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Dr. Madhusudan Sau is a Chemical Engineer with 3 decades of rich professional experience in R&D related to multifaceted aspects of downstream petroleum refining. He was instrumental in the development and commercialization of numerous cutting edge in-house refining Processes & Catalysts Technologies for fuel quality improvement, value addition and upgradation of bottom-of-the barrel. He is currently heading the Refining Technology, Catalyst and Petrochemicals research domains of Indian Oil Corporation Limited as Executive Director.

Abstract

On-purpose light olefin production technologies like propane dehydrogenation have gained momentum in the recent past due to the increased demand of light olefins, which are building blocks for petrochemicals production. In order to overcome the problem of lower alkane conversion due to thermodynamic limitations of this process, mild oxidant such as, carbon dioxide is used as co-feed in alkane dehydrogenation process, wherein the carbon dioxide reacts with the hydrogen product and thereby shifts the equilibrium reaction forward. The major refinery sources for CO2 are flue gases from furnaces and FCC regenerator which comprise of 10-30 wt% CO2. For oxidative alkane dehydrogenation process enriched stream of CO2 is required and hence, the flue gas stream needs to be sent for separation which increases the capital expenditure. On the other hand, Hydrogen is considered as carrier of energy & fuel of the future, as it produces zero carbon when burnt. One of the conventional and major sources of hydrogen production is steam reforming of natural gas or naphtha, wherein CO2 is formed as by-product. For meeting the net zero emission target of the country, the CO2 emitted in such processes needs to be reduced or re-used in other processes. Further, with the increasing demand for hydrogen as fuel, H2 production needs to be increased.

The present paper provides an economically attractive solution for the enhancing the production of hydrogen and light olefins by synergetic integration of Hydrogen Generation Unit (HGU) and Oxidative propane dehydrogenation (OPDH) process. More than 9% enhancement in hydrogen yield at HGU and >95 wt% propylene yield from OPDH process could be achieved. The overall hydrogen production potential of OPDH process is sustained, as the water formed in OPDH process is converted to H2 in shift reactor of HGU. Additional cost for CO2 purification/ separation system at upstream and additional PSA for H2 recovery at downstream of OPDH process can be circumvented by the synergetic integration of HGU and OPDH processes.

Introduction

Oxidative propane dehydrogenation (OPDH)

Global demand for light olefins such as ethylene, propylene and butylenes is rapidly increasing due to wide applications of their derivates in the field of consumer durables, packaging, automotives, construction, medical, etc. Conventional sources of propylene are Steam Cracking of light hydrocarbons and Fluid Catalytic Cracking (FCC). With the discovery of shale gas reserves, ethylene production has increased significantly by steam cracking of lighter feedstock while propylene or butylene is obtained as by-product. This has resulted in a gap between the supply and demand for propylene or butylene. In such scenario, alternative routes for on-purpose propylene/ butylene production such as propane/ butane dehydrogenation have become prominent. Propylene production from on-purpose technologies is expected to reach 40 MMT by 2026 (Figure 1). CAGR (2021-31) of propylene in India is 5.3% and globally it is 5%.

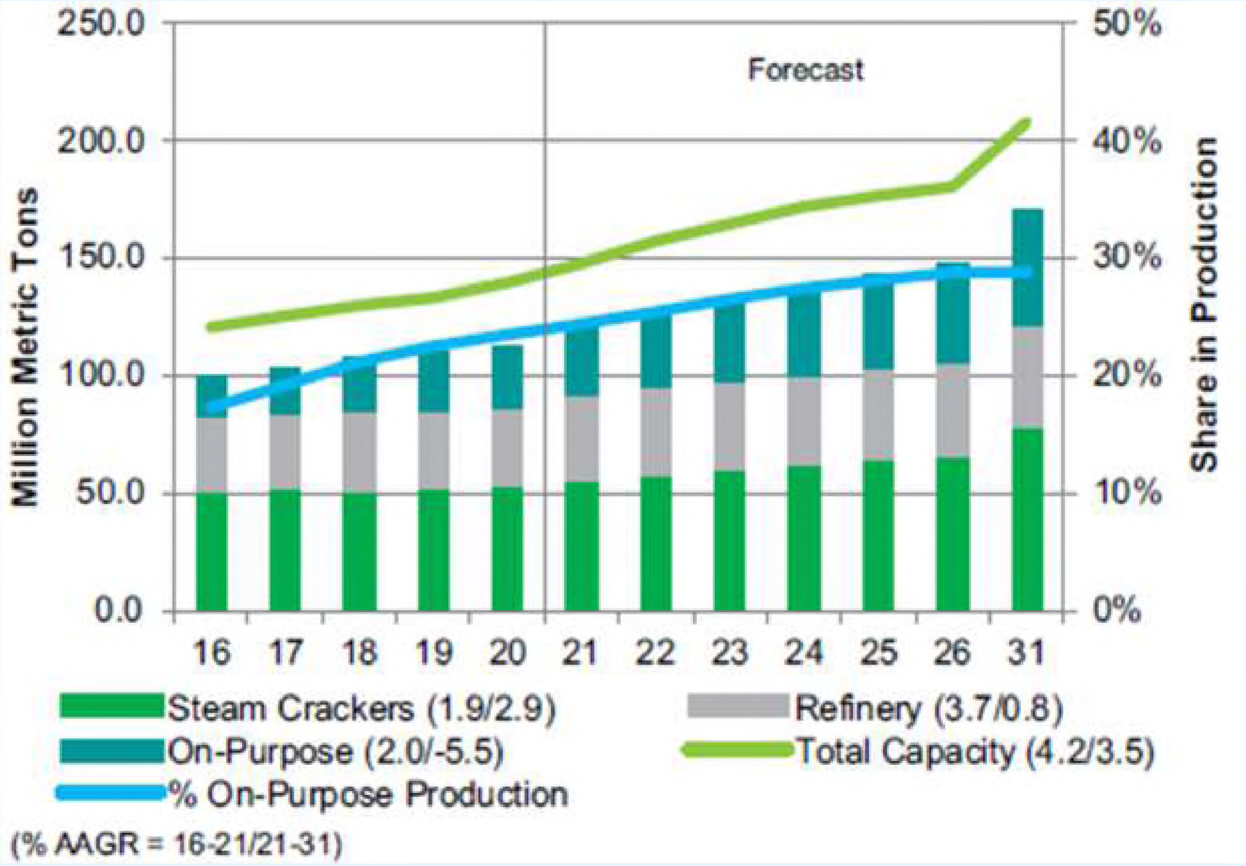

Figure 1. World propylene production by technology (Source: IHS Markit)

Alkane Dehydrogenation is a chemical reaction where one or more hydrogen atoms are removed from a saturated molecule to produce an unsaturated compound. Dehydrogenation of propane is an endothermic reaction and is limited by its thermodynamic equilibrium, due to which higher temperatures (usually above 600°C) are required to achieve economically feasible conversions. Such high temperatures cause thermal cracking of hydrocarbons lowering selectivity of desired unsaturated hydrocarbon propylene and accelerate catalyst deactivation.

Research studies conducted in the recent past reveal that using mild oxidants, such as CO2, as co-feed can improve the propylene yield, as the carbon dioxide reacts with the hydrogen product and thereby shifts the equilibrium reaction forward. In the presence of carbon dioxide, the propane dehydrogenation proceeds in oxidative pathway whose rate of the reaction is faster than the direct dehydrogenation reaction thereby producing higher yield of propylene [1, 2].

$$C3H8 + CO2 = C3H6 + CO + H2O$$
$$(\Delta H^\circ = 165\ \mathrm{kJ.mol\text{-}1})$$

The major sources for carbon dioxide in refineries are flue gases from furnaces and FCC regenerator which comprise of carbon dioxide in the range of 10-30 wt%. For its use in OPDH process, this flue gas stream needs to be treated for enrichment of CO2 or removal of O2, which is an additional capital expenditure. Therefore, a cheaper source with higher concentration of CO2 is required for making the OPDH process commercially viable.

Hydrogen Production

Hydrogen has several applications in the field of petroleum refining, ammonia production, Methanol production, etc. Hydrogen as fuel is an attractive alternative source of energy since it is clean, non-toxic and renewable. The global hydrogen generation market size is expected to reach USD 226 billion by 2030, registering a CAGR of 6.4% (2022-30). The global hydrogen generation market is likely to be driven by the growing demand for cleaner fuels, coupled with increasing governmental regulations for low sulphur petroleum products, and hence, its production needs to be increased [3].

One of the conventional and major sources of hydrogen production is steam reforming of natural gas or naphtha, wherein methane reacts with steam at temperature of 700-1000 and pressure of 3-25 bar in the presence of a catalyst to produce hydrogen, carbon monoxide, and small amounts of carbon dioxide. Subsequently, by "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen, followed by purification of H2 in Pressure-swing adsorption (PSA). The PSA off-gas stream comprising of carbon dioxide, hydrogen, methane, carbon monoxide and steam is used as fuel for reactor heating. Primary reactions occurring in such Hydrogen Generation unit (HGU) are given below.

$$CH4 + H2O \rightarrow CO + 3H2$$
$$CO + H2O \rightarrow CO2 + H2$$

Typical yield of Hydrogen from HGU is 30-40 wt% and needs to be improved to meet the increasing demand. The amount of CO2 in the PSA off-gas is 80-95 wt%. A typical SMR emits 8-12 MT of CO2 per MT of hydrogen produced [4]. The CO2 emissions from conventional HGU need to be reduced by utilizing the CO2 stream in other processes.

The present paper provides commercially feasible option for the production of hydrogen and light olefins with higher yields by synergetic integration of Hydrogen Generation unit with Oxidative propane dehydrogenation process.

Integration Scheme

The integrated process for HGU and OPDH processes is schematically represented as figure 2. The HGU Reformer reactor is fed with methane and steam where it undergoes reforming reaction at elevated temperatures of about 750-850 deg C and produces effluent gas comprising of hydrogen, carbon monoxide, carbon dioxide and un-reacted methane and steam. In the HGU Shift reactor, the carbon monoxide from Reformer effluent gas gets converted into hydrogen and carbon dioxide in presence of steam. The product gases from the HGU shift reactor consisting of hydrogen, carbon dioxide, carbon monoxide, methane with traces of steam and nitrogen are sent to Pressure Swing Adsorption (PSA) section of HGU where pure hydrogen is separated. The off gases from PSA having a typical composition of carbon dioxide 80-95 wt%, carbon monoxide 0.1-5wt%, methane 0.1-10wt%, hydrogen 0.1-5wt% and traces of steam and nitrogen is routed to furnace of Reformer reactor as fuel.

In the proposed integrated scheme, a fraction of the PSA off-gas predominantly comprising of CO2 is sent to OPDH reactor along with fresh propane feed. As the PSA off-gas comprises of >80 wt% CO2, the off-gas stream can be directly sent to the OPDH reactor without any requirement of additional system for CO2 enrichment. The propane feed reacts with CO2 on a suitable catalyst system to produce propylene and hydrogen and other side products such as ethane, ethylene, methane, etc. The effluent from the ODH reactor is sent to the Gas Separation section, wherein propylene is separated and sent to petrochemical unit. The stream from Gas separation section comprising of CO, H2 and CH4 is recycled to Shift reactor of HGU where the CO is further converted to H2 and CO2 in the presence of steam, and thereby increasing the overall H2 yield at HGU PSA.

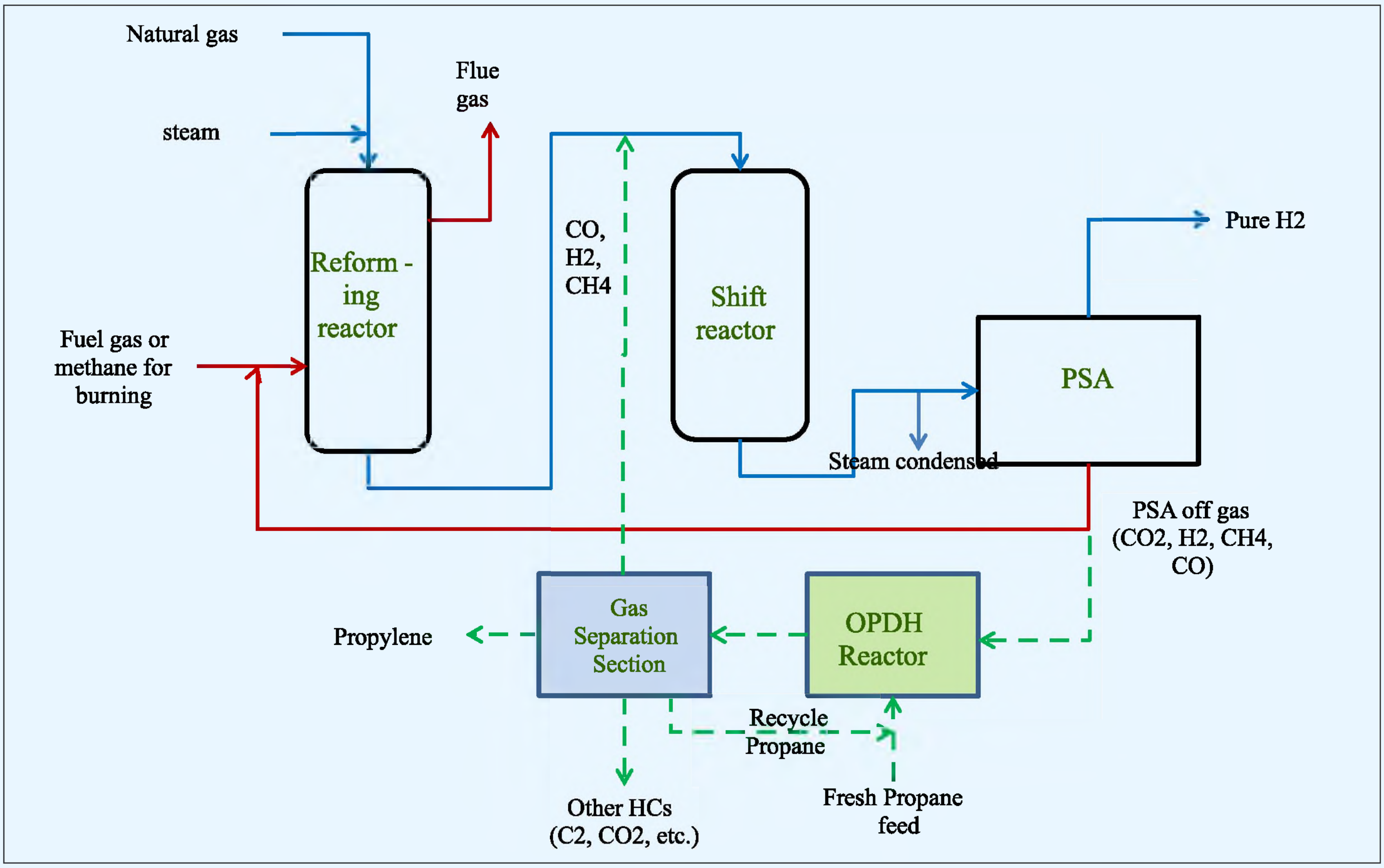

Figure 2. Schematic of integrated process for HGU and OPDH

The detailed flow diagram of OPDH process along with the downstream Gas separation section is shown in Figure 3. The Gas separation section comprises of De-propanizer, De-ethanizer, De-methanizer and C3-splitter. Existing PSU/PRU facility of Naphtha Cracker unit/ FCCU in refinery can be used for this purpose. Fresh propane is mixed with recycle propane and HGU PSA off-gas, then pre-heated using OPDH reactor effluent and sent to OPDH reactor-regenerator system, wherein the propane reacts with CO2 from HGU PSA off-gas to form propylene, CO, H2, water and other hydrocarbons such as ethane, ethylene, methane, etc. The carbon dioxide acts as a mild oxidizing agent and favors the dehydrogenation reaction. Hydrogen and methane in HGU off-gas help in regulating the oxidation state of metals on the catalyst favoring higher alkene selectivity. The OPDH reactor effluent is sent to De-propanizer section which separates C3 hydrocarbons and lighter gases from C4+ hydrocarbons. The top product from De-propanizer section is routed to De-ethanizer section wherein C3 stream consisting of propane and propylene is separated from lighter gases. The C3 stream is sent to C3-splitter for obtaining polymer grade Propylene as top product. The bottom product, propane, is recycled back to the OPDH reactor system for further conversion to propylene.

The top product of De-ethanizer section is further separated in De-methanizer section to two streams (i) a stream consisting of majorly carbon dioxide and small amounts of ethane, ethylene, and (ii) a stream consisting of hydrogen, methane and carbon monoxide. The bottom stream (i) can be recycled to OPDH reactor or sent to C2 splitter section for ethylene recovery. The top stream (ii) from the De-Methanizer section consisting of hydrogen, methane and carbon monoxide is sent to the Shift Reactor of HGU. The CO from this stream is further converted to H2 and CO2 in presence of steam and thus, enhancing the overall H2 production at HGU.

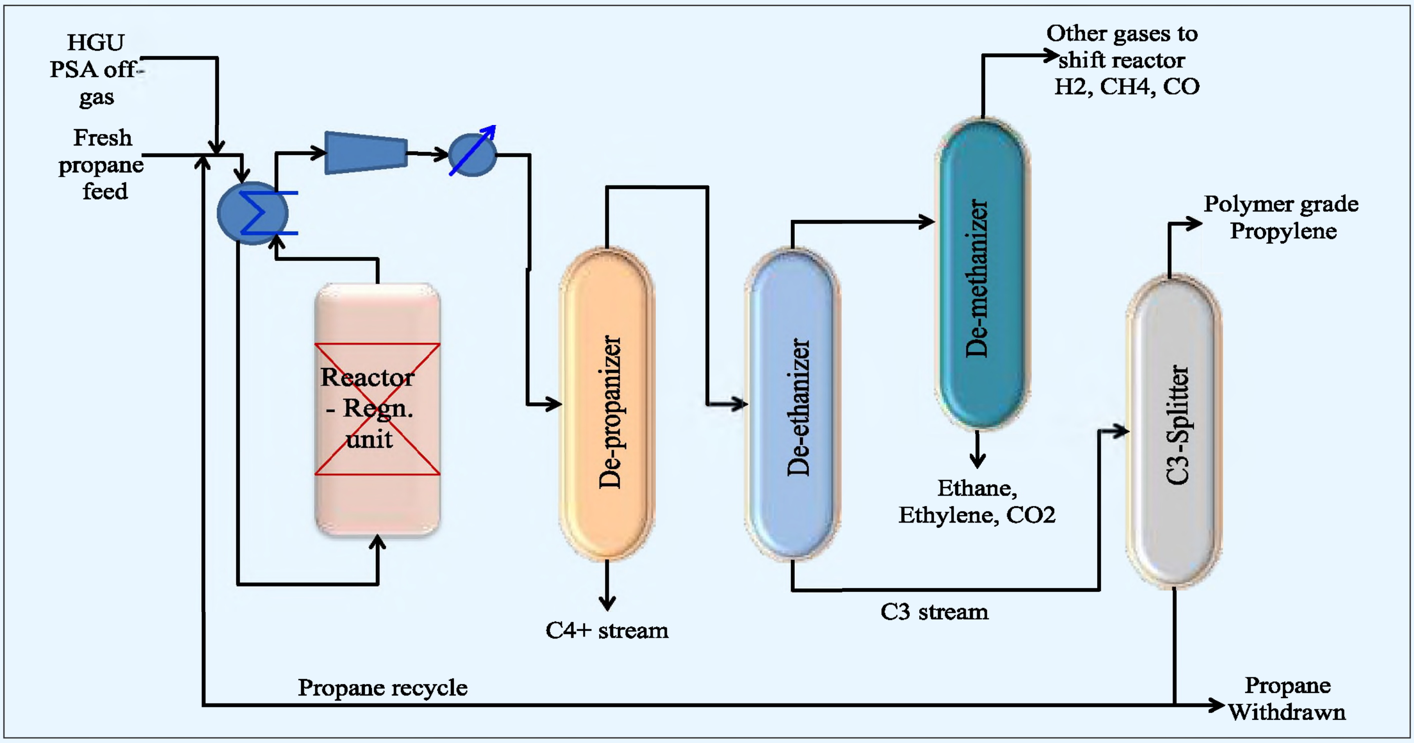

Figure 3. Process flow diagram of OPDH along with product separation section

Case study & simulation

Hydrogen Generation Unit with processing capacity of 26.7MT/h of Natural gas feed (comprising of methane, CO2 and H2) was considered for the study.

The HGU when operated as a standalone unit produces H2 yield of 39.2 wt% (on methane basis) and generates off-gas of 54 MT/h. The composition of PSA off-gas is indicated in table 1.

Component	wt%
H2	1.64
Methane	6.56
CO	3.13
CO2	88.00
Steam	0.67

Table 1. Composition of off-gas from HGU PSA

Lab-scale experiments for Oxidative propane Dehydrogenation process were conducted using a suitable catalyst and synthetic off-gas feed with composition given in table 1. Propane conversion (per pass) of 23.4 wt% with propylene selectivity of 98 wt% was achieved. Fresh propane feed of 3.13 MT/h was considered for the study.

Using the above data, simulation studies were performed in Microsoft Excel for estimation of yields after the integration of HGU and OPDH processes. At steady state, the 29.2 MT/h of HGU PSA off-gas is required as co-feed for OPDH process. With complete propane recycle, 98 wt% propylene yield is obtained. Using the downstream separation system illustrated in figure 3, 9.3 MT/h of off-gas is obtained as the top product of De-methanizer column.

This off-gas is sent to Shift reactor of HGU unit to produce H2 in presence of steam. The H2 formed is separated at PSA and the H2 yield obtained from the integrated process is 42.9 wt% (on methane feed basis). Thus, the overall enhancement in H2 yield at HGU is 9.5%. The overall hydrogen production potential of OPDH process is sustained, as the water formed in OPDH process is converted to H2 in shift reactor of HGU.

Summary of the simulation results is indicated as table 2. HGU when operated as standalone unit produces 7.57 MT/h of Hydrogen and 53.99 MT/h of off-gas which is used as fuel for reactor heating. OPDH unit when operated standalone produces 3.099 MT/h of propylene with 28.1 MT/h of off-gases which is used as fuel gas. With synergetic integration of HGU and OPDH processes, hydrogen production at HGU increased to 8.29 MT/h (9.5% enhancement) and the overall off-gas production reduced to 57.6 MT/h (30% reduction).

Stream	HGU (kg/h)	OPDH (kg/h)	Integrated process (kg/h)
Input			
Feed to reformer	26689	-	26689
Propane feed	-	3135	3135
CO2 Off-gas to OPDH	-	28209	-
steam	59954	-	64191
Output			
H2 produced	7568	-	8287
PSA Off-gas	53988	-	38630
Propylene	-	3099	3099
OPDH off-gas	-	28150	18989

Table 2. Simulation results of the integrated HGU and OPDH process

Conclusions

The present paper provides a commercially viable option to meet the increasing demand of light olefins, such as, propylene, and the requirement of cleaner fuels such as, Hydrogen with by synergetic integration of Hydrogen Generation Unit and Oxidative Propane Dehydrogenation processes. In the integrated process, propane feed is dehydrogenated to propylene in presence of CO2 from the stream of PSA unit of HGU. With the enriched stream of CO2 as co-feed, propylene yield of more than 95 wt% is obtained. After propylene recovery, the OPDH off gas stream containing H2, CH4 and CO is recycled back to Shift Reactor of HGU, where the CO is further converted into H2 and CO2 in presence of steam. Based on the simulation studies performed, the hydrogen yield at HGU is enhanced by 9.5%. Overall reduction in off-gas production is 30%. Such synergetic integration has additional benefits such as, lower capital expenditure by elimination of additional CO2 purification/ separation system at upstream of OPDH process, elimination of additional PSA for H2 recovery and CO mitigation/conversion system at downstream of OPDH process.

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3.4 DEBOTTLENECKING OF MOTOR SPIRIT BLOCK AT NRL

Author: Abhijeet Konwar, Numaligarh Refinery

Mr. Abhijeet Konwar is currently working as DGM(Energy & Environment) at Numaligarh Refinery Limited. He is a chemical engineer with over 24 years of experience in the fields of Refinery Operations, Technical Services and Energy & Environment. He had played a key role in commissioning of major process units of NRL. As a process engineer, he was involved in study of making design changes to process units and their trouble-shooting. He was the lead member in revamp of MS Block at NRL implementing the same from key concept to final execution & commissioning.

Abstract

Motor Spirit of MS Block was debottlenecked in the year 2019 using a very innovative approach. The MS Block consists of Catalytic Reforming Unit and Isomerization Unit with naphtha feed pre-treatment facility through a common Naphtha Hydrotreater Unit. First commissioned in 2006, the original capacities of the units were – NHTU (225 TMTA), CRU (166.7 TMTA) and ISOM (55.1 TMTA). The units were subsequently revamped to 122% of original capacity of NHTU (331 TMTA) , 150% capacity of CRU (253 TMTA) and 200% capacity of ISOM (110.2 TMTA).

CRU capacity increase to 150% of its original design was possible by installing a new Sulfur Guard bed to process additional naphtha feed (Hydrocracker heavy naphtha) from Hydrocracker Unit. This innovative design avoided costlier debottlenecking of NHTU unit since any sulfur removal from Hydrocracker Heavy Naphtha was taken care of by the sulfur guard bed instead of additional capacity increment of NHTU unit.

Introduction

MS Block of NRL is designed to produce BS-VI grade Motor Spirit . It consists of a semi-regenerative Catalytic Reforming Unit (CRU) and Isomerization Unit (ISOM) with De-Isohexanizer column. Feed naphtha feed pre-treatment facility is through a common Naphtha Hydrotreater Unit. The process licensor of the unit is M/s Axens, France. The main products of the MS Block are Reformate (from CRU) and Isomerate (from ISOM) which are the major MS components. Other valuable products include Hydrogen Rich Gas, LPG and Fuel Gas. The unit was first commissioned in the year 2006 and revamped in the year 2019 to process additional identified feed (Hydrocracker Heavy Naphtha & CDU Heavy Naphtha)

	Original Capacity -TMTA	Revamp Capacity -TMTA
NHTU	271	331
CRU	166.7	253
ISOM	55.2	110

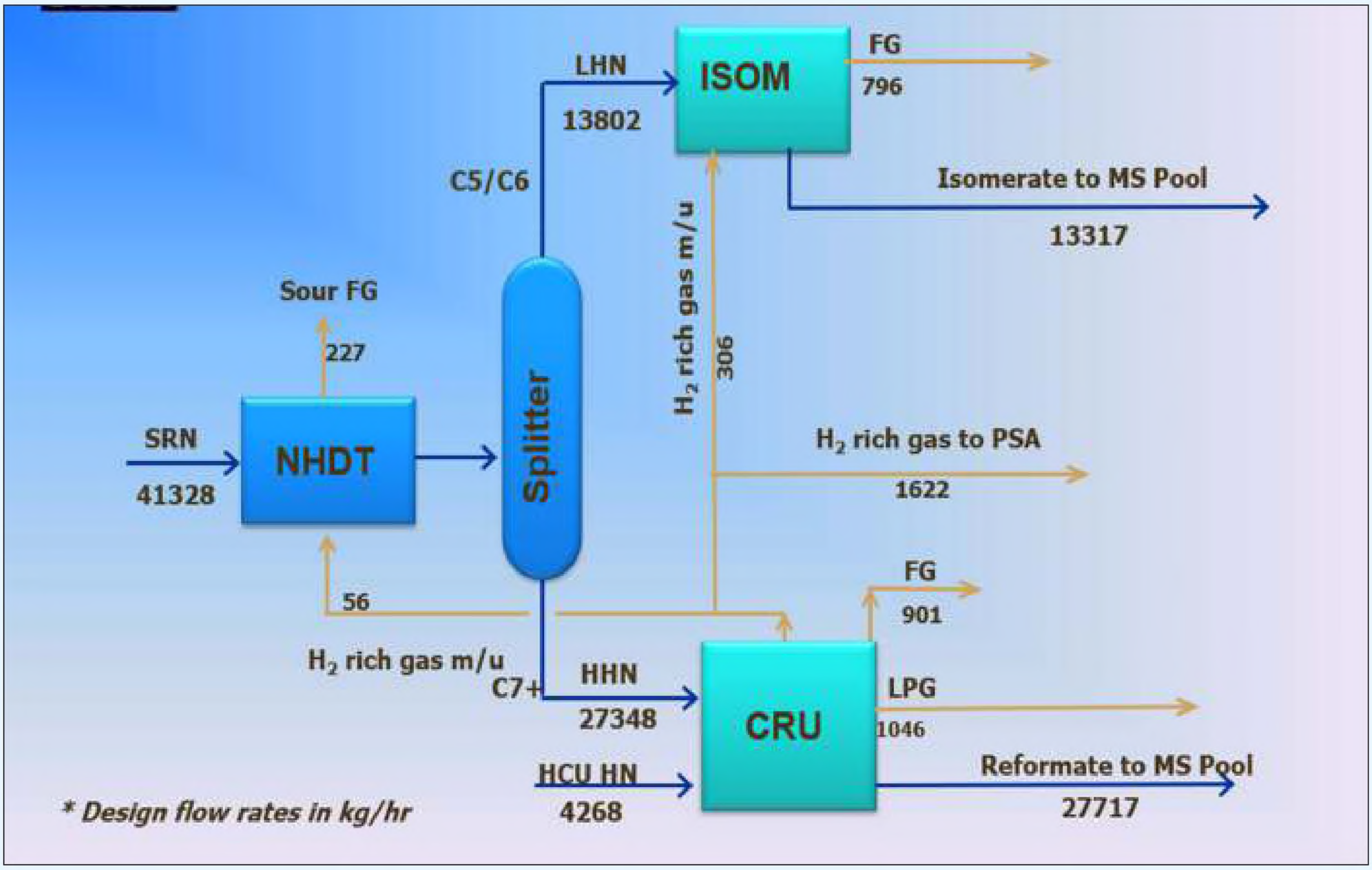

Fig. 1 MS Block Flowsheet after revamp

Requirement for revamp and philosophy adopted :

MS production at NRL is of utmost priority due to high margins of MS sales and resulting profitability to the company. Hence it was always endeavoured to run the units of MS block at highest possible throughput i.e. more than the nameplate/design capacity.

However, it was difficult to sustain the high throughputs on a continuous basis due to equipment limitations and natural degradation of catalyst activity from start to end of the run cycle. Although MS can be produced by importing costly blend components like pye-gas and MTBE, producing higher quantity of internal blend components i.e. Reformate and Isomerate is a more economically viable option.

Therefore, possibility of debottlenecking of MS Block units were studied and implemented subsequently.

Availability of Naphtha Feed for the additional capacity increase

Original design feed to MS Block is Straight Run Naphtha (SRN) from CDU. To increase capacity further, it was proposed to utilize Hydrocracker Heavy Naphtha (HCU HN) as additional feed to MS Plant (which was used in diesel blend) and also Heavy Naphtha from CDU. Based on feed Naphtha availability, it was found that increase in capacity of CRU to 150% and ISOM to 200% was possible in case units are revamped.

However, increase of CRU thruput required a corresponding debottlenecking of NHTU capacity to 148% of original design capacity. **To reduce CAPEX of revamp, it was decided to adopt a unique approach of routing the additional feed naphtha (i.e. HCU Heavy Naphtha) through a new sulfur guard bed to CRU thereby bypassing the NHTU. This design would avoid costly revamp of the NHTU.**

	Design (100%) TMTA	Post revamp scenario TMTA
Reformate ex- CRU	137.1	222
Isomerate ex- ISOM	50.2	107
Total MS Components from unit	187.3	329
H2-rich gas to PSA (avg.H2 purity = 85 mol%/ 40 wt%)	8.8	16

Post revamp production of products from MS Block

Identification of bottlenecks for increasing capacity of MS Block

Limitations in equipment were expected at 150% capacity of CRU. Major bottlenecks for increasing capacities identified through in-house study in CRU were Packinox exchanger, Recycle Gas Compressor (RGC) and Process Heaters. The Original Equipment Manufacturers (OEM) of these equipments were contacted to provide a solution for removing the capacity limitations. Key findings of technical solution by OEM for revamp of the above equipments were :

Packinox Heat Exchanger

OEM (Alfa Laval) had indicated that although the Packinox is adequate hydraulically at 150% load, thermal efficiency would correspondingly decrease which will have negative effect on the furnace preheat temperature. Hence, they had suggested to replace the plate bundle in existing shell. Its heat duty would be revised from 13 MMKCal/hr (design) to 19.5 MMKcal/hr.

Recycle Gas Compressor (RGC): OEM (BHEL) had indicated revamp of existing rotor & diaphragms to increase flow by approx. 25% and higher head of the compressor to meet revamp requirement. Change in turbine internals had also been proposed due to higher power requirement at increased CRU capacity.

Process Heaters

OEM (L&T HE) had suggested new 2nd inter heater (15FF003) and process coils in convection zone of 1st inter heater (15FF002) where the major heat duty limitations are expected. Through these modifications, around 30%-40% duty increment in these heaters from current design is estimated which is in line with 150% revamp requirement.

Apart from above major equipment, bottlenecks were also calculated in hydraulic capacity of some process lines & pumps, duty limitations of air-fin coolers , exchangers etc.With the feed naphtha availability as well as options for debottlenecking process equipment, licensor M/s Axens was approached for a comprehensive solution for revamp of the MS Block. M/s Axens had confirmed that it is possible to increase CRU capacity to 150% as well as maintain the desired Reformate RON of 98 while meeting the minimum catalyst cycle length of 02 years.

Execution methodology of Revamp project

Licensor M/s Axens was awarded the basic engineering /licensing job for the revamp project and they had submitted complete Basic Engineering Design Package (BEDP) within 20 weeks from zero date i.e. Kick off meeting as per the agreed schedule (in February 2018) after completing PFD/P&ID review phase.

M/s EIL was appointed as the Detail Design Consultant (DDC) for the MS revamp project and carried out review/checking of BEDP and Process data sheet, Scheduling, Cost Engineering, Residual Process Design, Process Design of Offsite /Utilities, Detailed Engineering, HAZOP Analysis, Preparation of MR and MTO, Tender, Assistance for Transportation of Over Dimensional Consignments including route survey, Assistance in Quality Assurance etc.

The philosophy adopted behind the revamp was to have it executed within the minimum timeframe possible so as to reduce downtime costs due to loss of MS production. Therefore, entire revamp schedule was planned for 30 days coinciding with the refinery's annual turnaround during December 2019.

Benefits achieved through the revamp

Some of the benefits to NRL achieved as a result of implementation of the MS Revamp are :

CRU feed-in through new sulfur guard: CRU capacity increased by an additional 50% by routing additional identified naphtha feed i.e. HCU Heavy

Naphtha through a new Sulfur Guard adsorbent vessel. Around 4 m3/hr of HCU HN (meeting sulfur specifications) could be processed in CRU for converting to MS Blend component. This was an innovative approach first utilized in NRL to process naphtha as feed without hydrotreatment in NHTU .With online sulfur analyzer installed, it is now possible to continuously monitor the inlet sulfur as well as outlet sulfur of sulfur guard bed.

Steam savings by superheating excess HP steam generation from steam drum

Around 4 to 5 T /hr of saturated HP steam was being generated from CRU heaters waste heat boiler before revamp. The saturated HP steam was in surplus as the generation was more than the fixed consumption in the column HP reboilers. Whereas around 10 – 11 T/hr of saturated HP steam was generated in the WHB, consumption in HP reboiler of NHTU Stripper & Reformate Stabilizer was fixed at around 5 T/hr. Therefore, the excess steam had to be vented to atmosphere which was a direct loss. M/s EIL was requested to carry out the detailed study for feasibility of superheating the surplus HP steam with the heater convection flue gas thereby generating superheated HP steam and routing the same to the refinery HP header which would stop venting and reduce import of HP steam. Two additional blank rows in tube-sheet of evaporator zone were identified to insert new tube bundle and re-design the entire steam generation section to produce around 5 T/hr of HP Steam which was routed to RGC turbine. With this modification, RGC turbine inlet steam temp. also improved after revamp by around 50 degC. Energy savings works out to be around 2800 SRFT per annum.

Unique design of CRU 2nd interheater (15-FF-004)

One of the main challenges of MS Revamp was to modify or replace existing CRU 2nd interheater 15-FF-003 to more than double the existing heat duty from 0.845 to 2.16 MMKCal/hr. Limiting heat duty of this heater was one of the main bottlenecks before revamp to increase CRU load and reformate RON. For the revised duty requirement, plot availability was a major issue to set up a new heater (while discarding the original heater). Whereas the original heater was an all-radiant process design, EIL offered the solution of installing a new heater with an additional process convection section on the existing foundation of the original heater without any structural reinforcement or modification. This was possible because of the unique approach of using ceramic fibre blanketing inside the heater instead of the usual refractory castable due to which the net overall increase in weight of the heater was around 5 Tons only. As a result, pre-shutdown piling works could also be avoided. The added convection section also helped in reducing the final common convection section stack outlet temp. from 274 degC (> 100%load) to around 240 degC.

Introduction of additional heat exchanger trains in NHTU Feed Effluent Exchanger train

During PFD review stage, it was decided to introduce additional 02 heat exchangers in NHTU Feed Effluent train. This modification increased preheat of NHTU feed by 22 degC from 228 degC to 240 degC thus saving on fuel costs and avoiding costly revamp of NHTU heater.

Increase of Isomerisation Unit (ISOM) load to 200% while retaining DIH (de-isohexanizer) column:

The capacity of Isom unit could be revamped to 200% while maintaining a minimum DIH column recycle flow . Additionally, with loading of new generation catalyst ATIS-2L in the lag reactor which offers 1.2 point RON benefit at same severity, the Isomerate RON could be increased to average of 85 (viz guarantee of 82 min.) This involved only minor modification in Isom Unit like resizing of unit feed and product rundown lines and rundown cooler/ exchangers.

Top pressure reduction in 15-CC-001 (Reformate Stabilizer)

Operating top pressure of reformate stabilizer column was reduced to 10 kg/cm2g from original design of 21 kg/cm2g. as per new PFD. With this modification, stabilized LPG was recovered directly from column . This also led to considerable reduction of operating costs and energy savings by reduction of column bottom temperature (and corresponding reboiler duty) from 229 degC to 220 degC.

Economic Benefit due to additional MS Production post revamp

Benefit calculation was done for additional MS production due to revamp of the unit . On design basis (NHTU at 122%, CRU at 150% and ISOM at 200%), additional MS production post revamp is 79.9 TMT for which additional benefit is INR 192 Cr. per year.

Conclusion

The revamp of MS Block at NRL is an exemplary example of NRL's strive to identify and implement opportune projects to improve its bottom line. Although fraught with some hurdles during the execution in terms of logistics/transportation due to the remote location of the refinery, the project was implemented successfully with the cooperation of all departments. From Project end, innovative solutions like tendering with delivery incentives, on the spot clearance and approval of drawings were adopted. There was relentless follow up of the process side by Tech. and Operations along with licensor's representative at site. As already explained, the project enabled increased production of MS and enhanced profit margins since available naphtha could be upgraded to valuable MS product.

* * *

3.5 Debottlenecking of Process Units to improve productivity by Physical water treatment than conventional way of chemical water treatment

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Mr. Sunil S. Gadad is Technical Director of VEKAN Solutions, Pune, India. He is having hands on 25 years in the engineering field as well as he proudly served his knowledge for Indian Army & Indian Navy. His Company Utilises, refers said research by Subject Author for their product VULCAN-Physical water treatment, De-scaling Water Scale & Pipe Metal Rust protection

Abstract /Back Ground

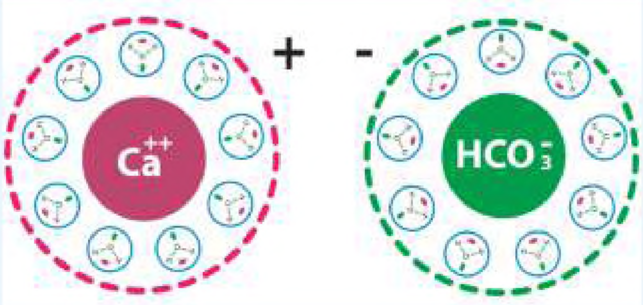
Handling Large quantity of Water for applications at cooling towers at Refineries has been a challenge, while facing the scale & rust related issues faced at pipes lines, evaporation process accelerating creates higher TDS concentrations of circuit water resulting in Clogging and rusting, there by blanketing the metal surface , impacting effective heat transfer at heat exchangers, condensers etc., Traditionally large amount of Acids and Chemicals are used to descale, causing oxidation issue at pipe metals and there by metal erosion and metal life reduction. However gradual increase in concentration, leading to regular water blow down, pipe maintenance, replacements of pipes, causing down times and increase in clean up frequencies, resulting higher operations cost.

About Vekan Solutions

VEKAN SOLUTIONS, since 2019, Pune based company has been working on Raw Water scale and rust related concerns. Handling uniquely, i.e. by Physical water treatment technology. Said technology exist since last four decades, 100 plus countries, 7000 + global + local successful clientele installations running, consistently. Prime leverage, ease of installation extra minimal operating cost, no moving parts no spares. While having unique selling proposition, being a proactive and reactive tool, uncompromised straight 2 Km effect of pipe descaling. Capabilities to add value on all types of pipe material, ranging from ½" OD to 40" OD and invariably any flow of water. Thereby delivering descaling conserving heat, rust protection conserving water clean-up frequency prolongation metal life increase .

Alternative, Physical water treatment than conventional way of chemical water treatment.

How Does It Function:



INTRODUCTION

Since the 1990s, water treatment using physical principles has been used in real-world applications and steadily improved by our team. It has proven its efficacy during this time while also being questioned and denied. Is there a reason for that? Several reasons were brought up As far as I can tell, the only possibility of resolving the fraud accusation and identifying the black sheep that led to it would be to examine the physical foundations that explain the way these processes work. These questions are addressed in the following.

Furthermore, there is supporting research coming from reputable institutions, such as the Ludwig-Maximilian University Munich Physiological Institute, that supports my experience with the device. Following the installation of this physical water

treatment device, laser tubes that previously required replacement due to furring could be avoided (pdf: Physiological Institute).

Many chats with hoteliers, instructors, and private users confirm this action, although it is also often lamented that it does not work. Since many private users have no idea who made the device (it was usually said that the device was cheap and purchased in a superstore), we can only infer that some devices do not meet the physical requirements to be effective. The treatment principle itself, however, can't be considered useless or ineffective.

There is also a tendency to give this impression in serious publications, without any scientific proof or any evidence oriented toward the action in any manner that makes them credible. It is necessary to explain why water pipes fur up before the physical water treatment can be explained in a plausible manner. Thus, in physical water treatment, lime is the target.

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LIME IN WATER

Question: How can it be dissolved in the water then? Answer: When water that contains carbon dioxide passes chalky grounds, lime is released and is present in the water as calcium hydrogen carbonate $Ca(HCO3)2$. This is possible as carbon dioxide $CO2$ together with water $H2O$ forms carbon acid $H2CO3$. As everybody knows from the everyday household life, acidic cleaning agents are needed to remove lime deposits. It seems like splitting hairs to underline the difference between dissolved and undissolved lime, but this is exactly where the lack of argumentation in favour of the action of these devices lies.

Thereupon the following question is raised: why does lime separate anyway? The dissolved amount of calcium hydrogen carbonate in the drinking water never reaches the saturation limit that if exceeded leads to the separation of the dissolved substance as a crystal.

If we look at the points in the pipes where lime deposits, the answer is already given. Primary spots for lime deposits are pipe bends, branches and the ending points (faucets) and especially the warm water areas. In the last mentioned case we have to differentiate: warm water containers are generally speaking free from deposits; heating bars, heater spirals or heat exchangers, surfaces that transmit the heat to the water, are always affected.

Why these spots? The answer is pretty easy: there has to be an energy gradient that leads to the opening of the water cages around the dissolved ions so that they can react with each other. At the same time the so called lime -carbonic acid- balance has to be disturbed, this means that it has to come to a local lack of $CO2$. Then the elements look for a crystallization point (nucleus) where to start the crystallization. These spots are always located on the walls of the pipes, these represent the solid base on which the crystals can grow. More and more elements deposit, the lime deposits grow and incrustations, also known as scale, develop. They consist of calcium carbonate mixed with magnesium compounds, gypsum, silicates and iron

Compounds (therefore the yellow brownish color). These sedimentations favor corrosion and worsen the heat transmission of heating bars and heat exchangers.

How is it possible that there are local energy differences in the water? In the case of heating bars it is easy, heat is transmitted to the water. In pipe bends the water is accelerated, the energy for this process comes from the inner energy of the water, pressure and temperature changes are the consequences. The same goes for branches and ending points. Here, turbulences are caused, also with the inner energy of the water and with the same consequences.

If we take a look at pipes that have been used over years, we can see that incrustations always start in pipe bends or branches and from there grow into the straight areas. When a pipe clogs up, the affected areas are normally these areas, while the predominant part of the pipe system is still completely in working order and able to let the water flow through.

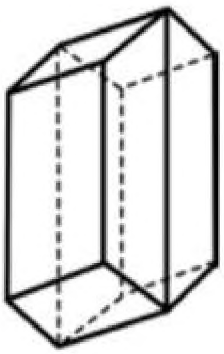
What happens chemically during the crystallization? The following formula (1) explains it:

$$\mathbf{Ca\ (HCO3)2 \leftrightarrow CaCO3 + H2O + CO2\ (1)}$$

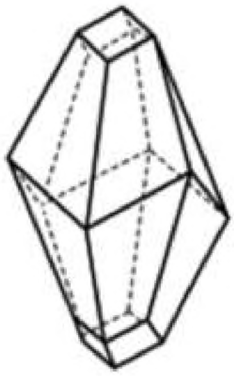
In the first place it is remarkable that the described reactions towards a lime formation can also take place the other way around, i.e. the lime can also dissolve again (see above). Which of the two reactions takes place depends on the lime- carbonic acid- balance. If there is a surplus of CO2, lime is dissolved, if not, lime is secreted. These processes are also dependent on pressure and temperature changes, therefore on physical parameters.

At this point, it is appropriate to say something about the lime crystal. It is known that almost all substances defined as solid are crystalline. Crystals are divided in 7 crystal systems and 32 crystal classes, which differ from each other through their lattice structure.

Lime can crystallize in two different structures which are chemically completely identical. The lattice structures are different but related. Afterwards, the lattice type Aragonite (picture 1) or Calcite (picture 2) is formed. When the chemical structure is the same, it depends on thermodynamic circumstances (pressure, temperature) which modification is produced. As the pictures show, in both unit cells, one axis is longer than the others. This means that a crystal grows faster in this direction than in the others. The grow velocity is anisotropic, i.e. dependent on the direction.



Picture 1: Unit cell of an aragonite (Rhombic system)



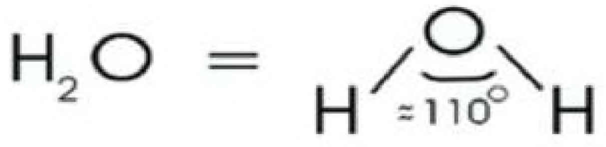
Picture 2: Unit cell of a calcite (Trigonal system)

So what do devices do when they show the promised effects?

1. They do not convert lime into what should they? The devices cause that Calcium hydrogen carbonate Ca(HCO3)2 turns out as Calcium carbonate CaCO3, which is electrically and chemically neutral in water. And this is a solid with the special concomitant that the crystal does not crystallize on an already existing solid but is formed in the flowing water. Such a crystal forms according to laws of nature with typical parameters valid for every substance and it takes on a form according to the law of nature.
2. The result is that these crystals do not have special characteristics but special forms that do not attach to each other anymore and therefore prevent calcification. At this point the described mechanism is effective.

WATER

To understand the following processes, now some information about water is given. It is way more than what the formula H2O says. The two hydrogen atoms and the oxygen atom form an equilateral triangle and incircle a ~110° angle, as shown in picture 3.



Picture 3: Angle structure of a water molecule

This is the reason for a lot of characteristics that distinguish water from other, similar molecules. Two gases that react with each other form a liquid and not a gas, as it is e.g. with carbon dioxide CO2 (solid substance and gas!), a molecule a lot heavier. Because of this angle position water molecules form chains and clusters that cause the fluid state.

This is possibly the reason why water may have a "memory" in which it adopts structures in the chains and clusters that do not change even when the water moves. These chains and clusters are held together by Van de Waals powers or dispersion powers or hydrogen bridges. The bond is based on the attraction of electric dipoles present in molecules with polarized bonds or angled structure. At the University of Stuttgart, scientific researches are conducted concerning this problem and first results show that the behaviour of water is influenced by electric and magnetic fields. Such phenomena have been known for a long time but have never been investigated scientifically.

This molecule form leads to a further special characteristic. Water shows a dipole character. Through the bond, both elements strive for an inert gas configuration in their outer electrons shells. In the case of hydrogen there are two electrons, in the case of oxygen eight. Oxygen is missing two and each hydrogen one electron. In the molecule the total of two bonding electrons is available for all three atoms, so that an inert gas configuration can be reached by all molecules.

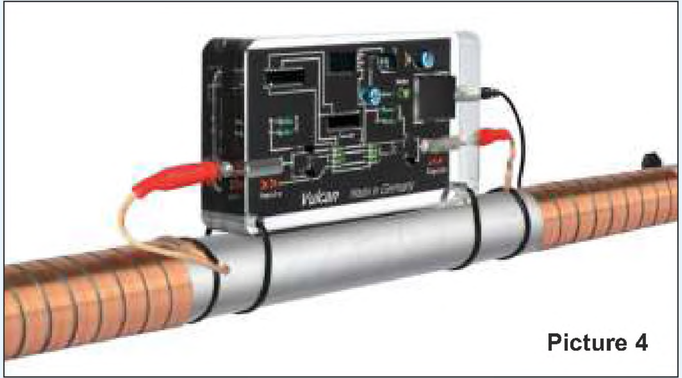
In all homopolar bonds of diverse atoms, the bond is polarized, i.e. the bonding electrons pair is moved towards the direction of the bonding partner with the higher electron affinity, in this case the oxygen atom. If the water molecule is put in an electric field, it lines up so that the oxygen shows towards the positive electric side and the hydrogen molecules towards the negative electric side. So the water molecule is charged a little bit more negatively on the side of the oxygen and a little bit more positively on the side of the hydrogen.

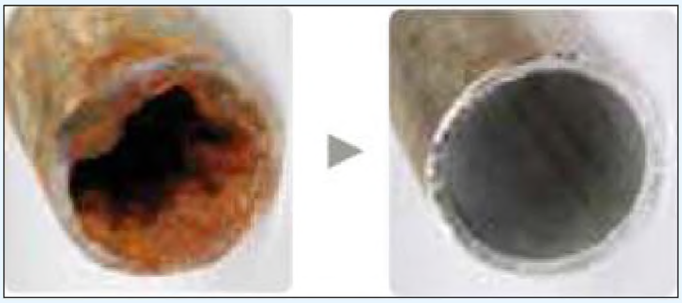
This fact, together with the molecule form, plays an important role for the dissolving ability of water and for the physical water treatment. At this point further anomalies are only briefly mentioned: when water passes to a solid state (ice) its density decreases. If the ice is put under pressure, it liquefies again. Normally, liquids under pressure pass to a solid, crystalline state. These few indication already show that there is probably a lot more about water than today's modern research has discovered so far.

PHYSICS AND CHEMISTRY

What happens physically and chemically when a physical water treatment device is used? As there are a lot of different application principles, from magnets introduced in the water pipes to the injection of seed crystals in the water, around which lime particles attach, in the following only one principle often offered and often controversially discussed is going to be examined.

The processes are described on the basis of a device with an appearance often found and which effects are questioned. Picture 4 represents this device. The test explained here is based on the functioning and mode of action of this device. It is a black box from which two cables exit and are wound around the pipe. These cables transmit oscillations to the water that are supposed to "convert" the dissolved lime and render it harmlessThis formulation has been chosen intentionally because it essentially corresponds to the description of the function of offered devices and therefore already puts in doubt the repute and seriousness.


Picture 4



What kind of oscillations are transmitted?

Some descriptions do not even talk about calcium being converted; the producers seem to come from the times of the al alchemist. Some say that the pipe material does not matter and that the device can even remove already existing lime incrustations.

How can oscillations achieve all this?

Seriously, who thinks to understand just a little bit of physics and chemistry already finds enough apparently scientific arguments to question the functioning.

What does a device do that really prevents lime deposits in pipes? At this point the first question has to be what it has to do to fulfil this demand?

The answer is easy: It has to create the conditions under which the calcium hydrogen carbonate $Ca(HCO3)2$ is washed away with the water as a crystal and does not attach to the pipe walls as calcium carbonate crystal $CaCO3$.

In the following, the physical and electrical possibilities that an effective physical water treatment system has to offer are examined. This simply means that it has to cause the effect that the dissolved lime does not attach in crystalline form to the walls or contact points with the pipes, to devices and fittings in contact with water. This is only possible if the dissolved lime crystallizes in the water before the contact with these areas.

Therefore two conditions in the water have to be fulfilled:

1. Crystallization nuclei have to be present or created.
2. The lime- carbonic acid- balance has to be changed so that dissolved lime becomes solid.

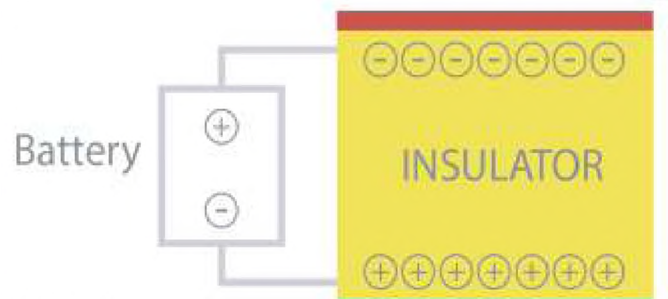
Experience has shown that the introduction of magnetic or electric fields in the water can have such effects, even if with different success. In the following, only the effects of electric fields are examined, but from these the conditions under which magnetic fields can also be effective can be derived.

If we take a look at picture 4, we can see the two windings through which impulses are transmitted. A lot of producers call these windings "coils" because they look like coils, but electrically speaking they are not. So an "inductive" coupling is not possible and if it was inductance, the device would fail in the case of iron pipes, but it does not.

The winding represents a part of a capacity, it is one capacitor surface, the other one is the water This winding is a technological compromise; a metal foil placed around the pipe on the same length would have a slightly higher capacity, but would also have to be custom made for every pipe diameter. Normal loudspeaker cables instead are sold in meters and adapt to the different pipe diameters without any problems.

How can, with this arrangement, an electric field be caused in the water even through every pipe material?

This is the point where most doubts begin. With this arrangement, it comes to a physical effect widely spread in the electric everyday life but not well known: the influence. In picture 5 the principle of the process is shown on the basis of a capacitor.



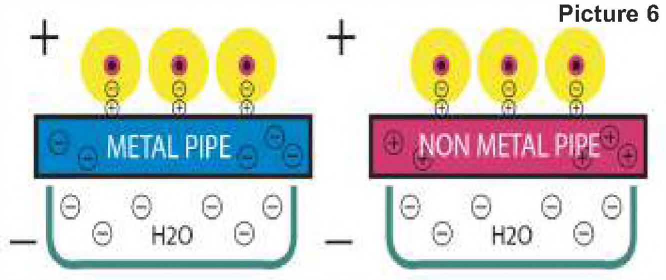
Picture 5

When voltage is transmitted to the two capacitor plates, a charge displacement in the dielectric (insulator) is caused, which is the opposite of the charge of the plates. When the plates are discharged, the polarisation of the insulator also disappears as in the insulator electrons cannot move but only bound electrons are displaced.

But if on the other hand e.g. two metal sheets laid on top of each other (electric conductor) are put into the electric field between the capacitor plates, the charge separation is the following: the surface of one metal sheet gets a negative charge (opposite of the positive capacitor plate) and the other one gets an equivalent negative charge..

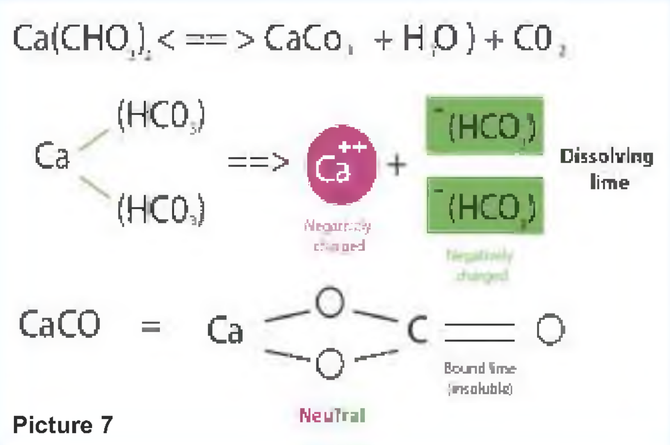
This phenomenon is called influence. If the two plates in the electrical field are separated, one of the plates shows a negative charge (surplus of electrons) and the other one a positive charge (shortage of electrons). A capacitor is impermeable for direct voltage but not for alternating voltage. This fact is used when it comes to introduce electric alternating fields in the pipes. Picture 6 is an instant photograph of this process. You can see that the pipe material does not have any influence on the capacitor effect in the

Picture 6



Picture 6: Transfer of an electric field into the water by influence If the winding wire is charged by a pole of a power source, the same electric charge of the opposite sign is bound in the water pipe through influence (by flow from the earth). If it is a temporal periodic charge transfer, or, respectively, a charge and discharge, a so-called displacement current is produced – like in a capacitor (apparently) influenced by alternating current – Between the insulated winding wire and the pipe wall (this can be calculated with the Maxwell equation). This is the continuation of an alternating (+-+-+-…) or pulsating (0+0+0+0… or 0-0-0-…) conduction current which develops between the pipe (including the water) and the ground.

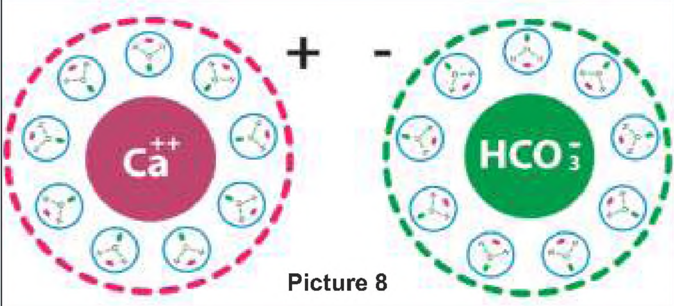
This results on the one hand from an alternating or pulsating electric field orientated in the longitudinal direction of the pipe and on the other hand from a magnetic eddy field centrically wound around the pipe. Measurements have shown that an effective voltage of ≈1 Volt is produced between the winding and the water and that there is a displacement current of ≤ 5μA. At this point, some more attention has to be paid to the lime dissolved in the water. Picture 7 shows the connections. The dissolved lime – calcium hydrogen carbonate – dissociates in one double positively charged calcium ion and two negatively



Picture 7

charged hydrogen carbonate ions. These ions are surrounded by a water cage. The water molecules settle around the calcium so that the oxygen points towards the calcium and the hydrogen towards the outside. Electrostatic powers hold these clusters together. The carbonate remnants are surrounded in the same way only that the oxygen atoms of the water molecules point to the outside. These clusters altogether show a positive or respectively negative charge.

A schematic representation is given in picture 8, the clusters just have to be imagined as minute spheres. They have a diameter of 1 to 2 nanometres (nm), assuming that about 100 to 200 water molecules are involved. If the mass of these clusters is calculated, it results that the mass of the Ca- clusters as well as the mass of the bicarbonate remnants is of 30×10-22g up to 60×10-22 g. These results are interesting for the water treatment.



Picture 8

Picture 8: State of lime dissolved in water (schematic)
Coming back to the inducted electric alternating field, it is to say that that the periodically alternating field in the inside of the pipe influences the ions or dipolar molecules closed in water cages in the water in a way that they move from the one direction of the pipe to the other to the beat of the alternating field. The electric oscillation has led to an oscillation of matter which spreads axially. Physically, this is a mechanical (acoustic) longitudinal wave or shock wave. Areas with overpressure and negative pressure alternate. In atomic and molecular fields, this locally causes an adhering of the CO2. If the oscillation frequency is suitable, the water cages disintegrate and this also leads to a local decrease of the CO2 concentration. The lime- carbonic acid balance is locally disturbed and at the same time the dissolved lime ions that are freed from the water cage can meet and react with each other: a lime molecule has been produced which now serves as crystallization nucleus.*) Other molecules are taken up by this nucleus and form a lime crystal in the water. This lime crystal is electronically neutral and does not react in tap water any more. Therefore, this lime crystal is not taken up by existing lime deposits on the pipe walls anymore.
To cause these processes, the electric alternating field has to contain frequencies that if possible lead to resonance oscillations of the water cages. Since all tap waters that correspond to the German drinking water decree are different regarding the quantity of dissolved minerals, the pH-value and the conductivity, the formation of the electric alternating field is also influenced. Besides, there is the changing flow velocity. Devices that work with only one frequency can also successfully set off this cycle by chance, but most of the times they do not show any success.

A couple of technical data about the device examined here are known as well as positive experiences about the effect. Therefore, it makes sense to theoretically and (as far as possible) practically assess the effectiveness of the device by means of these information.

The device is provided with two windings. Each winding receives impulses with a clock frequency of 10 Hz, 50 ms pulse duration, 50 ms rest and de-energize. When one has the rest and de-energize, the other one receives the impulses. Each impulse has a frequency response of ca. 3 to 15 kHz, spread on 50 ms. As there was no suitable measuring technique, the frequency response could not be measured. If 10 oscillations are counted per kHz, the pulse duration is approximately reached. At this point it has to be particularly emphasized one more time that this is only an attempt to generally explain the effectiveness. The complexity of the excited oscillations including the overlapping of different waveforms (overtones) cannot be taken into consideration.

The device is supposed to safely treat 5000 liters of water per hour. In the case of a half inch pipe this means the flow of a water column of 11.3 mm/ms, in the case of a one inch pipe it would be 2.8 mm/ ms and in the case of a two inch pipe 0.7 mm/ms. As the length of the effect of an electric alternating field is of ≈ 500 mm (the producer indicates ≈ 1000 mm), this means that this distance is just covered. Every ion water cage has enough time to fall apart.

What about the reaction velocity of the chemical components? The Max-Born-Institute for nonlinear optics and transient spectroscopy in Berlin has examined the velocity of the formation of molecules on the basis of water molecules with a special laser array. The result was a time between 10 and 20 femto seconds (1 fs = 10-15 second). This time is as inconceivably short as the universe is inconceivably big. The distance light travels in 1 fs gives us an approximate idea of how short this time is: ≈ 0.3 µm. In the time light travels 6 mm, 1000 molecules can be formed. Therefore, it is very probable that the molecule formation and the formation of nucleus crystals take place in the section treated.

PROTECTIVE LAYERS & INCRUSTATIONS

At this point the formation of incrustations is only briefly mentioned for the processes in pipe bends. The flowing water accelerates in the pipe bends. The water flowing in the outer radius is faster than the water in the inner radius. According to the simplified Bernoulli's equation (2), the sum of the static and the dynamic pressure is constant:

$$Pdyn + Pstat = \text{const.} \quad (2)$$

In the water that flows faster, the dynamic pressure increases and the static pressure decreases. This means that CO2 escapes from the inner radius towards the outer radius and the lime- carbonic acid-balance is disturbed. Lime is set free, looks for a crystallization point and finds this point on the walls of the inner radius. Little by little, a layer of lime epitaxially grows in which other minerals also As indicated above, from here the incrustations grow into the straight sections of the pipe. This process takes places as long as there is dissolved lime in the water. But most of the lime transported in the water is washed out of the pipe without depositing. After all, with a water consumption of 100 m^3 per year and a water hardness of 28°d, about 45 kg of lime are transported through the pipes. If the lime has been transformed into crystals in the water as described above, the lime is washed out of the pipe with the water in form of a fine sub microscopic crystal, a crystallization on the walls of the pipes is not possible anymore. The lime crystals deposit irregularly, as shown in picture 11.

This condition stays the same also in warm water. Applications have shown that further dissolved minerals deposit on the nuclei build o the lime crystals and sink to the bottom of e.g. water boilers in form of dust without deposit. On this irregular surface turbulences develop, the same happens in pipe branches because of pressure fluctuations, so that in both cases lime deposits develop.

As water, and therefore also the CO2, evaporates in faucets and shower heads, also here lime deposits develop. On heated surfaces the CO2 is also removed from the closer surrounding area, so that theses surfaces are also favorite crystallization points for the lime.

For two reasons, the presence of lime in drinking water is important and therefore a minimal amount that corresponds to a water hardness of 8.4°d is stipulated by the German drinking water decree. Firstly, the drinking water provides a big part of calcium the body needs and secondly, the bicarbonate remnants of the dissolved lime reacts with the metal of the pipe and so forms a metal carbonate protective layer. This is especially important in the case of copper pipes (see below). Picture 9 shows a detail of such a protection layer. You can see how the crystals grow on the metal surface. Such bundles of crystals cover the surface and protect the pipe against corrosion.

Picture 10 shows this even better. It is an electron microscopic picture of an artificially produced phosphate protective layer against corrosion. Phosphates crystallize in a similar crystal system as carbonates. In time, this desirable quality of lime becomes a disadvantage as more and more lime deposits grow in these protective layers since they are ideal crystallization points. Slowly, a pipe clogs up, starting in the pipe bends and branches.

Picture 11: Lime dust deposits


Picture 9: Lime protective layer


Picture 10: phosphate protective layer

growing on the heating bars. This way, 2 kg of lime dust deposits could be removed from a 150 liter water boiler after a year of operation, the heating bars were absolutely scale free. User report that the heat exchangers for the hot-water supply in the case of district heating also stay lime free on the secondary side. Since the installation of the examined device four years ago, no cleaning has been necessary. The lime has been made harmless but has not been removed and is still physiologically present. Another consequence of this is that water drops that dry on surfaces leave lime dust which can be removed with a humid cloth. But if it is left in a humid surrounding for a while, it can locally dissolve under the influence of the CO2 in the air and if it dries again, a crystallization on the surface is possible: This incrustation can only be removed with a decalcifier.

But these devices are also supposed to remove existing deposits and to prevent rust or corrosion. Is this possible? And if it is possible, how does it work?

REMOVAL OF DEPOSITS AND PROTECTION AGAINST CORROSION

First of all, some information about the removal of lime deposits: If we take a closer look at the equation (1) we can see that the chemical reaction can not only take place from the left to right side (lime segregation) but also from the right to the left (lime dissolution). Here again, the lime- carbonic acid balance plays a crucial role. If there is a surplus of carbonic acid, lime is dissolved. With each dissolved lime molecule crystallized in the water one carbonic acid molecule is produced. This carbonic acid gradually attacks and dissolves the lime deposits on the pipe walls and so removes the lime. Depending on the level of the incrustations in the pipe (water hardness, working life), this process can take between half a year and two years. During this time, light lime deposits outside the water develop again. When this process is finished, no more incrustations develop. The lime is removed, but the carbonate protective layer is maintained.

Of course the lime crystal in the water is also exposed to this influence. But the crystal produced in the water has been able develop in an almost weightless state and therefore a crystal structure forms that shows only a few lattice defects such as vacancies, interstitial atoms, substitution atoms and molecules, displacement and stacking faults. Therefore, this crystal offers less targets than the incrustation presenting these errors and therefore also a bigger surface and with that a higher inner energy. This is why this incrustation is attacked more, often with a selective dissolution, what leads to the eruption of coarser lime particles which can accumulate in the aerators.

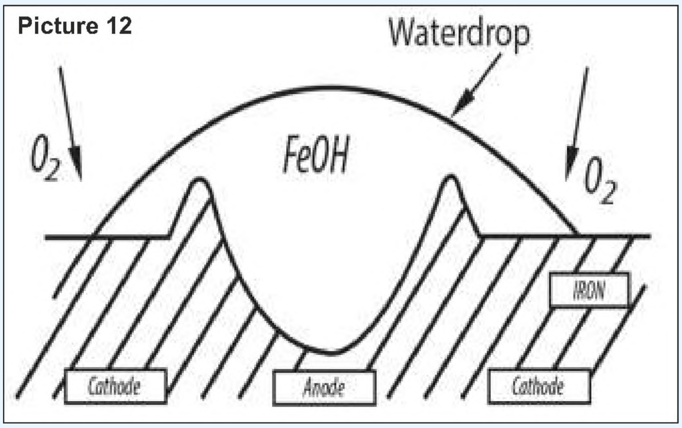
Now the equation (1) represents a balanced stationary state. But in nature fixed equilibria do not exist, only flowing equilibria. At the melting point of water e.g. ice and water exist at the same time, therefore balanced. This means that statistically in one time unit the same amount of water molecules changes from the liquid to the solid state as water molecules melt from the ice.

The equilibrium is flowing. The lime segregation as well as the lime dissolution described in the equation (1) is also subject to this static process, if there is no intervention from the outside. The processes in the section treated will not catch all present molecules. Even if in smaller amounts, there will still be dissolved lime in the pipe which can also segregate but then be dissolved again. But since the physical water treatment intervenes in favor of the dissolution of the lime and the removal of the deposits, new incrustations do not form. Statistically, it is possible that during these processes surfaces that are not yet covered with metal carbonate crystals (see pictures 9 and 10) now form such crystals and so make the corrosion protection layer thicker.

The described mechanism of the formation of a protective layer is not the only effect preventing corrosion. Since there is already a protective layer, normally no corrosion should occur, but as experiences show corrosion does occur, in galvanized iron pipes as well as in copper pipes. What is the reason?

In technology there is a corrosion process called ventilation element. Picture 12 describes this process. Iron is an electric conductor, water is an electrolyte. When a water drop lies on the iron, an electrolytic element has been formed; the only thing missing is the electric voltage. At the edge of the water drop the oxygen contact towards the metal surface is stronger; the center of the drop is less ventilated. Thus a potential difference between these two areas develops; the edge of the water drop becomes a cathode (surplus of electrons) and the centre of the drop an anode (shortage of electrons). Being an electrolyte, the water now enables the closed electrical circuit between anode and cathode. At the anode, positively charged ions of the prevailing metal dissolve, react with the water and deposit as rust, while the electrons take the way through the metal to the cathode. In principle, the process is the same in the case of copper. In principle, the same process takes places in our pipes, the only difference lies in the reasons for the different oxygen contacts to metallic surfaces. Picture 12a schematically represents this constellation. As long as the water is not physically treated, lime favors to deposit, as described above. Between the areas with strong lime deposits and the lime free areas, this causes that the more or less strong oxygen contact in the water effects the surfaces with a different concentration. This way, the same process as in the ventilation element is caused. As it is generally known, most of the times corrosion occurs in pipe bend branches and T-pieces which show thick deposits. If these deposits are removed leaving only the protective layer, the oxygen contact is the same everywhere and an electric potential cannot develop anymore. This process is especially important for copper pipes, as with a high oxygen content and pH values lower than 6.5 copper is especially corrosion endangered and specially tends to pitting corrosion. In these cases a thick protective layer is especially important, also because of the impurity of the copper (supplier of cheap products) that favors the formation of local elements. Thus, more and more copper comes into the water and this is unfavourable for the health. According to the recommendations of the Federal Ministry of health, babies should not drink tap water in these cases. Water suppliers call copper the “lead of the 20th century”.

Picture 12

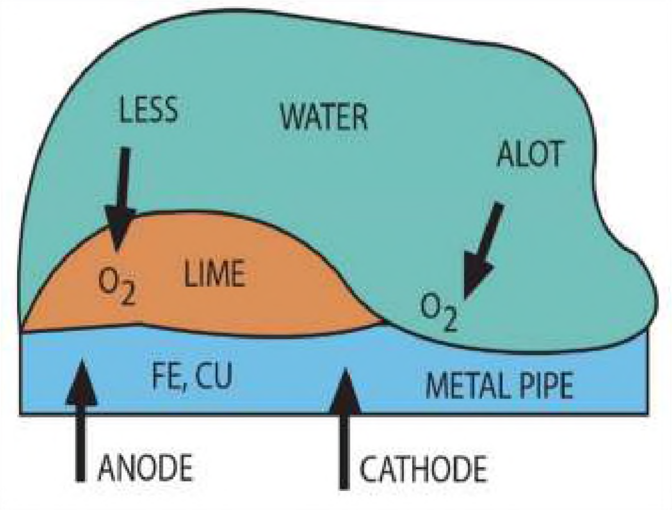


Closing Remarks

The dealt facts show that the effectiveness of the physical water treatment has not only been proven by users but that there are also theoretical and practical physical-chemical proofs. But a precondition is that the device offered more or less fulfils the described parameters. In general, the electronic technological demand is pretty high, so that most of the times cheap devices cannot fulfil the demands. The mode of action of these devices shows that the usual test procedures to determine the effectiveness, especially short tests have to fail and provide false results. A new testing procedure has to be developed which can also provide a quantitative proof of the theoretic connections described here.

I would like to thank Prof. Dr. H. Ungenannt, Mageburg, for the support during the interpretation of the electric processes, Mr. K. Matthies, Dipl.-Ing., Berlin, for the help concerning the measurement technology, Prof. Dr. W. Morgner, Eichenbarleben, for the critical discussions of the present work and the engineering firm for physical water treatment Helmut Siegmund, Königs-Wusterhausen, for the provision of the device.

(1) Information about the device can be sought over the manufacturer — Christiani Wassertechnik GmbH, Köpenicker Str. 154, 10997 Berlin, Germany.



How Does the unit look like
VULCAN DESCALING UNIT

Built in Germany

- Manufactured by Christiani Wassertechnik GmbH (CWT) Berlin
- Over 30 years' experience in physical water treatment
- More than 150,000 satisfied customers world-wide
- 10 Year maintenance-free warranty
- Deployed in more than 40 countries

Vulcan Benefits:

- Maximum working life of machinery
- Less time and effort spent on cleaning
- Easier grease trap handling
- Reduction of maintenance
- Food and beverages keep their natural taste
- Improved performance of kitchen equipment
- More reliable water supply in sanitary facilities
- "… I also have to emphasize the fact that all these years the leaves of the plants had a white color and not the well-known green color. That is, of course, because of too much scale in the water. Installing the Vulcan S25 device, I found out that there is no more white sedimentation on the leaves and soil. Most of all I realized a big improvement in the growth of my plants. I also found out that there is better and quicker lathering, when we wash our hands or even clothes etc.
  Finally, I must say that I really found the solution to my problem, which has been bothering me for all these years…"

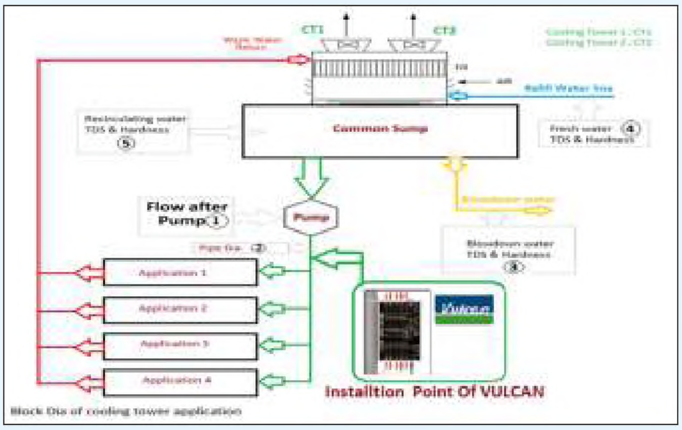
Vulcan Reference from a Tree Nursery in Greece

Vulcan – Against Scale and Rust
Vulcan is the eco-friendly water treatment system which protects your pipes and equipment against scale and rust.

- Eco-friendly solution without chemicals or salt
- Reduction of existing scale in the piping system
- Maximum working life of machinery and equipment
- Important minerals remain in the water
- Long life – fully cast in acrylic
- Maintenance-free
- 10 year international warranty
- Easy installation without cutting the pipe
- From 1/2"up to 20"pipe diameter
- Works on all pipe materials – iron, copper, plastic, stainless steel, PVC, compound pipes, PE-X, etc.
- Eco-friendly solution without chemicals or salt
- Reduction of existing scale in the piping system
- Maximum working life of machinery and equipment
- Important minerals remain in the water

Installation of Vulcan:

More efficient use of energy for heating water



Conclusion

The precious resource on earth Water, thereby can be utilized effectively, efficiently for its industrial application on using this dependable, sustainable, proven Physical water treatment technology for the future needs, Protecting environment, Process improvement, Improving profitability, Carbon footprint control, lowering operational cost, prolongation of maintenance frequencies, down time controls and Water conservation = GO GREEN.

Photo credit

- Pictures 1 and 2: W. Kleber, Einführung in die Kristallographie, Verlag Technik Berlin
- Picture 4, 6, 9 and 11: Information script from Christiani Wassertechnik GmbH
- Picture 10: Information script from the BMW motorcycle factory Berlin
- Picture 12: W. Schatt (editor), Einführung in die Werkstoffwissenschaft, VEB Deutsche Verlag für Grundstoffindustrie, Leipzig

Part-4

Reliability

> I'd put my money on sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.
>
> - Thomas A. Edison

4.1 Reliability Enhancement of Petrochemical Plant by Overcoming Grid Fluctuations Using Wide-Band Scheme.

Authors: Mathew P Thomas, Suji Paul, Jibu Varghese, Amon T C R, BPCL-Kochi Refinery

Mr. Mathew P Thomas is currently holding the role of GM I/C (Power & Utilities). He has got about 32 years of experience in different areas of petroleum refining including project conceptualisation, engineering, construction, commissioning and operation of various process units. Also had taken active lead roles in technical services functions such as Energy & Environment as well.

Mr. Suji Paul is serving as Deputy General Manager I/c (Electrical) at BPCL Kochi Refinery. He has 24 years of experience in refinery electrical systems, which include conceptualization, design, execution and commissioning of Electrical system for Refinery and Petrochemical Process units under Projects Department (16 years), design, engineering and execution of various minor projects / process improvement schemes of Refinery Units under Engineering and Construction Department (6 years) and operation and maintenance of electrical system of a 15.5MMTPA Refinery (2 years).

Mr. Jibu Varghese is serving as Chief Manager in BPCL, Kochi Refinery . He has over 15 years experience covering Electrical maintenance, contract management & execution and electrical design. His area of interest also includes exploring energy improvement measures.

Mr. Amon T C R is serving as Senior Manager (Electrical) in BPCL Kochi Refinery. He has 15 years of experience in Electrical Operations and Maintenance of Refinery and Petrochemical Electrical systems which includes Captive power plant, Process plants, Electrical Control System (ECS), Refinery Fire Alarm Systems, Capital/Revamp Projects and Commissioning & Maintenance of First Niche Petrochemical plants of BPCL.

Abstract:

Power quality fluctuations like voltage sag and frequency variations was creating upsets in petrochemical plants resulting in shutdown of plants and in some cases forced maintenance due to polymerization issues associated with the process. As in-house generation was not sufficient to cater entire demand and an external infinite source of power has to be available to feed reactive power during in-house faults for sustaining operations, refinery was dependent on State/National grid power. On parallel operation with grid, the disturbances on the grid will also be reflected on the process plants.
Disturbance on grid can't be mitigated since this network is spread across whole country and a disturbance anywhere may reflect locally. Hence a solution was looked into for fronting the grid disturbances, overcome same and sustain the operations. After studying many options and combinations, a solution was formulated using 'Wide Band Coil Contactor' with inductance mitigation. With this, voltage disturbances in grid had least effect on the operation of petrochemical plant and hence reliability was enhanced.

Introduction:

BPCL group refinery (Kochi Refinery) commissioned a Petro-FCCU as part of Integrated Refinery Expansion Project. 250 KTPA of propylene from Petro-FCCU was envisaged to utilize in PDPP (Propylene Derivative Petrochemical Project, at Kochi, India) for producing niche petrochemicals like Acrylic acid, Oxo alcohols and Acrylates.

Power to the Petrochemical plant (PDPP) is catered by a parallel combination of five gas turbines and 220kV state grid (KSEB) supply. Thus power for operation to PDPP is a blend of in-house generation and State/National grid. When disturbances happens on any part of grid due to lightning, thunderstorms, high-tension line touched by other objects and equipment damages, this gets reflected on entire connected system (200 plus disturbances were recorded in FY 2021-22 alone). When fluctuation happens and voltage level gets reduced, this makes the feeders (which feeds power to process loads) get off. Thus external reasons were contributing to the voltage disturbances and consequently shutting down of petrochemical plant (16 shutdowns in a time period of 16 months prior to scheme implementation, Table:1).

Of many options, one solution which is less complex, redundant and cost efficient was envisaged. This eventually led to development of a scheme which can surpass all voltage dips in network and sustain the loads in a plant. Breaker modification was carried out on the loads by incorporating 'Wide Band Contactors'. Post implementation of new scheme, the grid disturbances has least effect on the plant loads, surpassing 42 nos of grid disturbances without any upset till 01.01.2023.

Sl No	Date of disturbance	Time of disturbance	Dip of voltage against healthy value (%)			Duration of disturbance (ms)	Reason
			R-ph Voltage	Y-ph Voltage	B-ph Voltage		
1	29.01.2021	11:36	95.2	63.5	61.9	80	Heavy line Dip at KSEB
2	05.02.2021	14:10	59.5	94.4	93.7	140	Due to heavy fault in KSEB along with GT-2 and GT 4 tripping, Stage-4 loadshedding actuated.
3	20.03.2021	09:01	91.3	55.6	93.7	115	PT flash occured on I/C1 from Edayar feeding to Kalamassery 110kV S/S, due to this jumper failure occured in Kalamassery 110kV S/S and resulted in bus fault.
4	01-05-2021	20:02	91.3	94.4	52.4	120	Due to fault in Pallikkara-Aluva 220kV line, KSEB-2 alone got OFF.
5	10.10.2021	13:05:00	100.0	64.3	61.9	85	KSEB - 220KV Brahmapuram lower periyar feeder tripped on earth fault
6	27.10.2021	16:20:00	99.2	86.5	100.0	320	Voltage dip due to Aluva-Kothamangalam 220kV Feeder tripping
7	03.11.2021	17:51:00	92.1	43.7	74.6	200	Kalamassery Brahmapuram feeder 2 tripped
8	06.11.2021	18:47:00	42.1	95.2	93.7	80	Kalamassery 110kV flash occurred
9	27.11.2021	13:18:00	60.3	54.0	55.6	75	Idukki- Lower Periyar feeder tripped
10	03.12.2021	17:22:00	89.7	61.9	61.9	110	IDUKY - LP 220 kV FDR TRIP
11	21.01.2022	20:41:00	96.0	96.0	76.2	380	Grid-1 Islanded from in-house generation and 220kV B/C-1 breaker opened due to Kallamassery-Edayar Feeder 1 & 2 fault tripping
12	21.01.2022	23:58:00	69.0	87.3	94.4	110	Line disturbance at KSEB
13	03.04.2022	17:16:00	84.9	73.8	74.6	410	Line disturbance at KSEB
14	06.04.2022	17:13:00	21.4	100.8	98.4	80	Line disturbance at KSEB
15	18.04.2022	17:43:00	67.5	87.3	95.2	110	Line disturbance at KSEB
16	18.04.2022	17:43:00	35.7	91.3	94.4	90	Brahmapuram Lower periyar feeder 1& 2 tripped.

Table.1 Instances and reasons of Petrochemical plant disturbances due to state grid upsets

Methodology:

Voltage disturbances, which is inevitable, cause the contactor of LT motors to drop off. Thus the contactor was the primary spot of modification for over-riding during any disturbances. Sample wide band contactor was tested at in-house lab for confirming the datasheet values and its response during voltage dips. This was also done to confirm its suitability and any challenges connected with it. Critical load identification was done along with the Operations team. Modified contactor was then replaced at site, which has wide band of operation of voltages, such that even if voltage drops, contactor remains at same state. All the connected auxiliaries like Bowden wire, reset mechanism were changed to make the seating and fitting correct and to make them mechanically aligned.

Since the voltage holding level was enhanced, this impacted inversely by low voltage holding or not stopping of motors. This was further addressed by two set of circuit modifications, one for local stop from field and other for DCS stop.

- Not stopping from field: By utilizing the second element of push button station element, such that the cable will be in earthed position always. When required to stop by actuating push button, earth is removed from cable and cable gives path to stop element to actuate (Fig: 1).
- Not stopping from DCS: Since DCS stop path was connected is continuation with all control circuits, modified scheme would make DCS stopping ineffective. To address this, main circuit of DCS stop was separated and only auxiliary was wired to main one (Fig: 2).

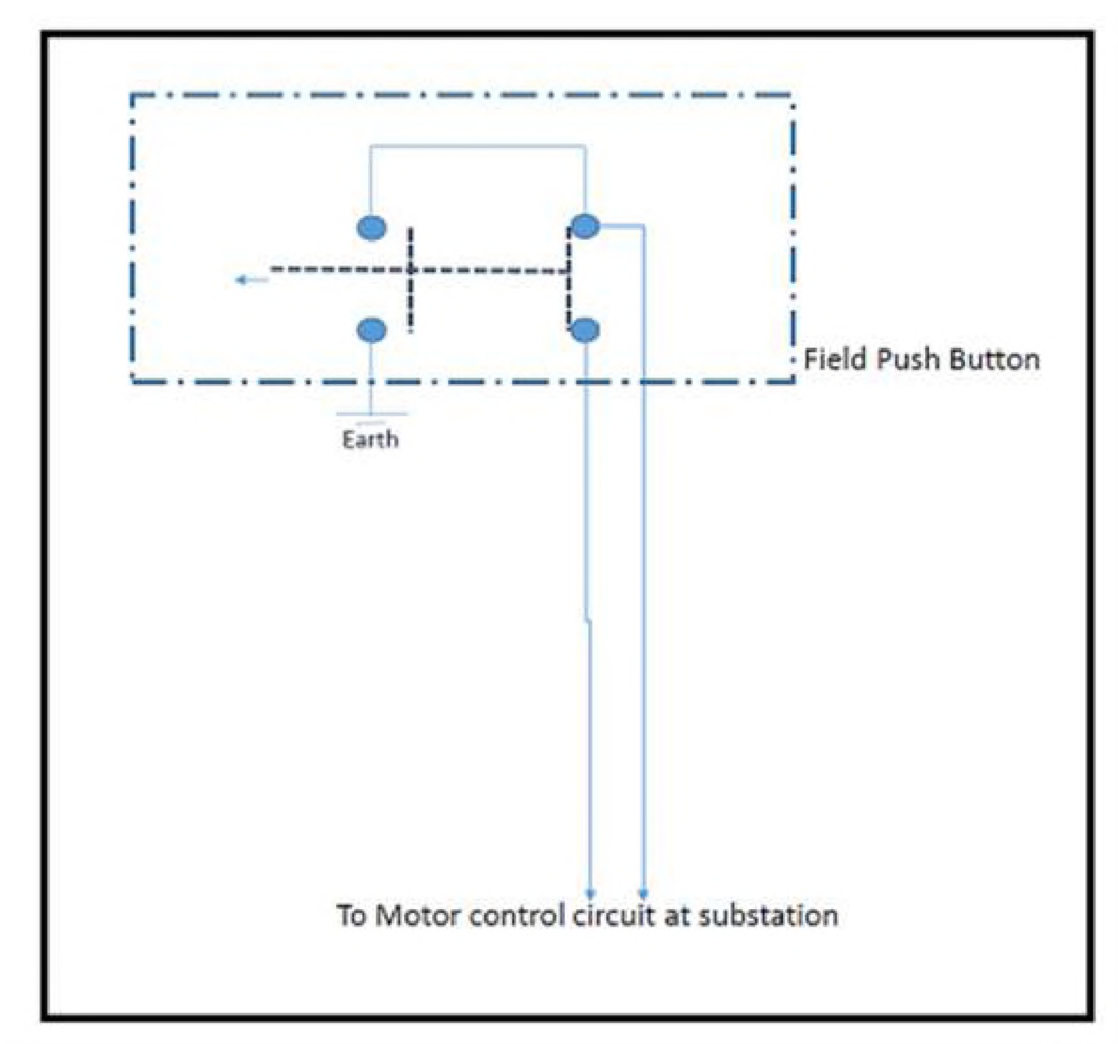


Fig 1: Modified scheme to overcome induction

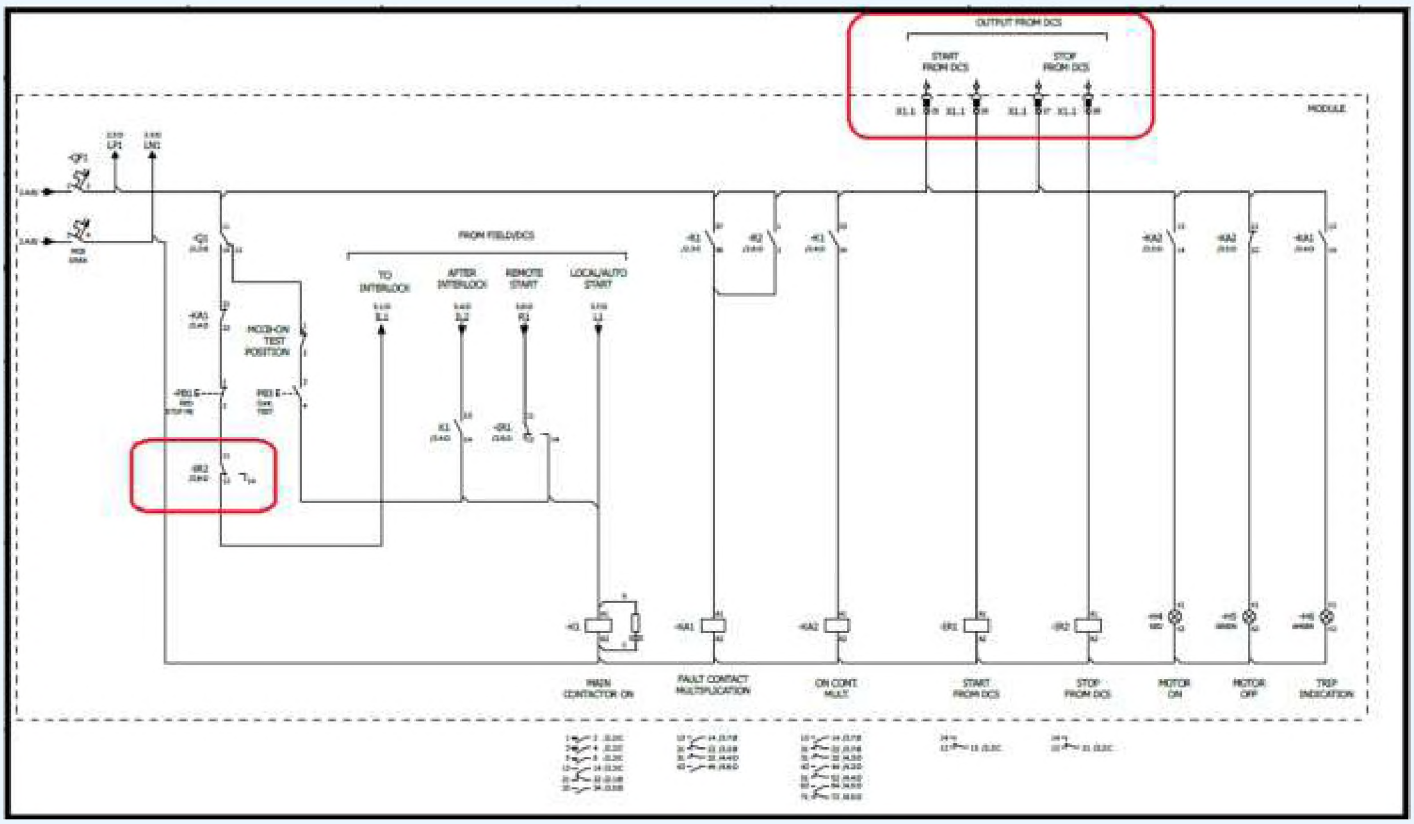


Fig:2 Separation of DCS stop from main circuit

Challenges:

Two main challenges were encountered while executing this modification.

1. Space constraints, modularity concerns and suitability on existing infrastructures where the design was not envisaged for extra modifications.
2. Not stopping of motors due to low voltage holding value of new contactors.

Result:

Grid disturbances has effected plant operations 16 times in a time period of 16 months prior to the scheme implementation (Table 1). After the scheme implementation, there were 42 disturbances till 01.01.2023 of same nature and magnitude in the grid and all these were successfully overcome without any disturbance on the operations and thus enhancing the reliability of process.

Conclusion:

Wide band contactor scheme has changed the operating voltage band of LT motor contactors and enhanced the reliability of petrochemical plant operations by sustaining voltage dips (Fig:3 and Fig:4). Apart from petrochemicals, refineries can adopt the scheme based on criticality and mode of power drawn. However while implementing the scheme, a comprehensive study is required including the power source capacity, reliability and availability of grids and switchgear capacity which is vital for design. This scheme is effective during parallel operation with State/National grids such that reliability is guaranteed with back up from state grid and availability from Captive Power Plant. Load selection shall be carried out to make the scheme cost effective and have high IRR. Proper load selection shall help in maintaining the recovery phase parameters after a voltage disturbance such that collateral effects can be averted on all connected loads.

Fig:3 Impact on Operations w.r.t Voltage Level during Grid Disturbances (Before Scheme Implementation)

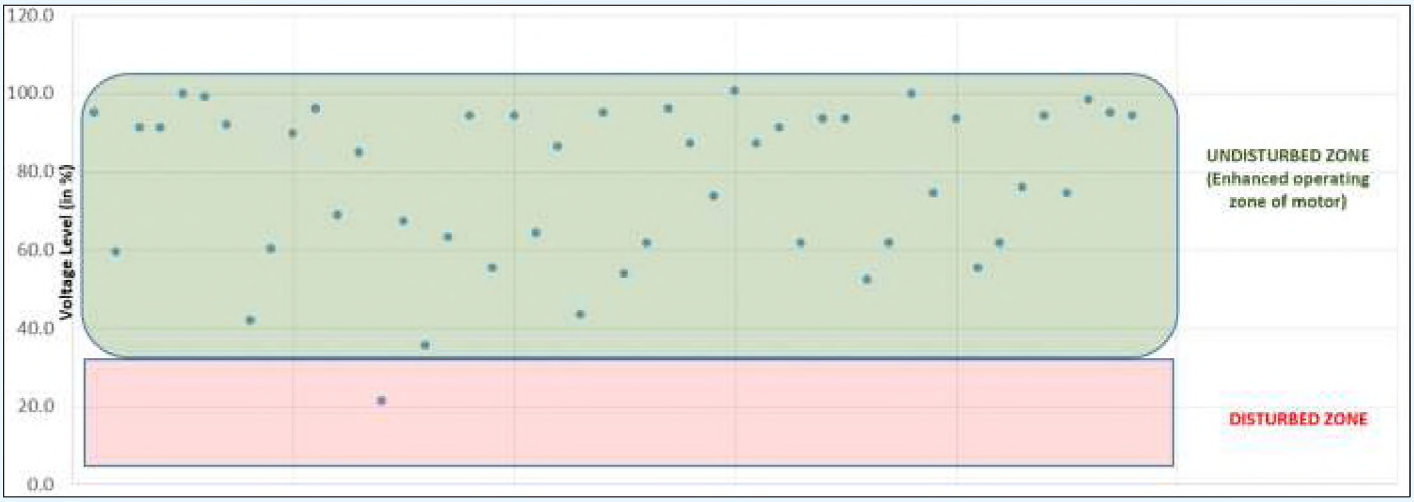


Fig:4 Improvement in the reliability during grid disturbances post scheme implementation

* * *

4.2 Strategies for Profitability of Base Oil Manufacturing Plants

Author: Attilio Donarelli, Lube Study Manager, HSB Solomon Associates LLC

Attilio Donarelli is the Lube Study Manager at HSB Solomon Associates LLC (Solomon), with more than 25 years of experience in the downstream energy sector. His experience covers the technical/operational side of the refining business (major plant turnarounds, process plants' troubleshooting, process simulation, and LP modelling) and the strategic/commercial side (due diligence, investment and financial analysis, capital cost estimates, and change management initiatives). He is a Chartered Chemical Engineer in the UK, a Fellow of the Institution of Chemical Engineers, and holds a Master's in Business Administration from the Open University, UK

Introduction

HSB Solomon Associates LLC (Solomon) is a technical and management consulting firm active in the energy industry. Solomon's flagship products are global benchmarking surveys (or "studies") in all sectors of the energy value chain: upstream, midstream, chemicals, refining, power and utilities, and base oil manufacturing. Solomon's idea is that, through data-driven analysis, participants can identify performance gaps against best-in-class peers and implement both tactical improvements plans and strategic initiatives to maintain competitiveness. The Worldwide Paraffinic Lube Refinery Performance Analysis (Lube Study) is one of Solomon's flagship studies. Collecting lube plants' data for over 35 years, the Lube Study consists of a statistical comparison analysis of base oil manufacturing plants (or lube refinery) in the world along with hundreds of operational efficiency metrics relative to an array of peer groups across different geographies and configurations.

Strategies for Profitability of Base Oil Manufacturing Plants

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Leveraging enormous amounts of data, Solomon's advisors, with decades of real-world experience matured in operating companies, draw actionable insights to help clients close gaps to become more profitable with lower cost. The balance mixing of these ingredients (see Figure 1) put Solomon in a unique position to support clients' success like no other consulting firm. The Worldwide Paraffinic Lube Refinery Performance Analysis (Lube Study) is one of Solomon's flagship studies. Collecting lube plants' data for over 35 years, the Lube Study consists of a statistical comparison analysis of base oil manufacturing plants (or lube refinery) in the world along with hundreds of operational efficiency metrics relative to an array of peer groups across different geographies and configurations.

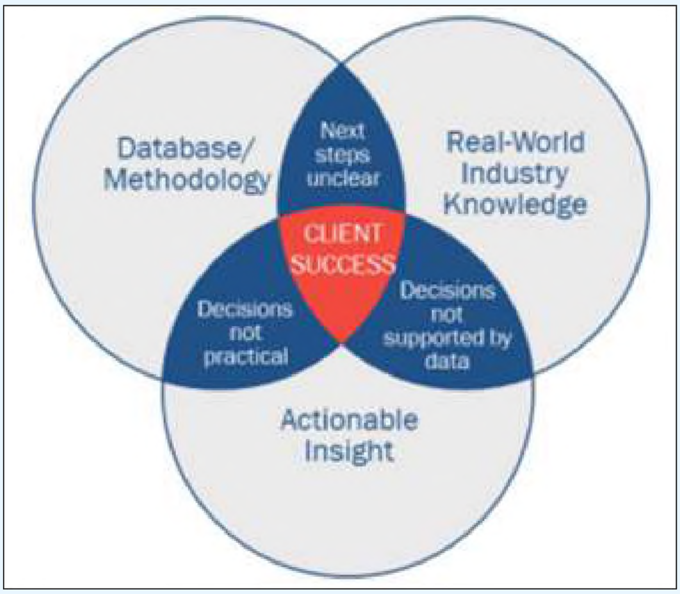

Figure 1. Solomon Enables Client's Success by Adding Three Essential Ingredients

Problem Definition

The base oil manufacturing industry has seen substantial transformations since the first Solomon study in 1987. More stringent automotive fuels efficiency specifications continued to drive changes in base oil manufacturing types, causing the demand decline of Group 1 base oils (produced via solvent technology) and the advent of Group 2 and 3 base oils (that instead use the hydroprocessing technology to improve the chemical and physical properties of base oils). Much of the capacity rationalization has been among Group 1 producers while new capacity has emerged in favor of Group 2 (newer technologies). The mobility barriers to move from one type of production to the other are high in terms of capital cost (between 1 and 2 billion United States dollars (USD)) for a Group 2 plant of 1 million tons of capacity1, which could be considered a standard capacity for newly built plants. Yet, since Group 1 base oils are still necessary for lubricant formulation, some Group 1 base oils manufacturers maintain a competitive edge in terms of profitability. Figure 2 shows the average relative2 net cash margin (NCM) per barrel of Lube, Waxes, and Specialties (LWS) of the two main types of base oil manufacturing plants (solvent and hydroprocessing) participating in Solomon's Lube Study. Hydroprocessing plant's NCM are, on average, 30–40% more profitable than solvent plants, depending on their market conditions.

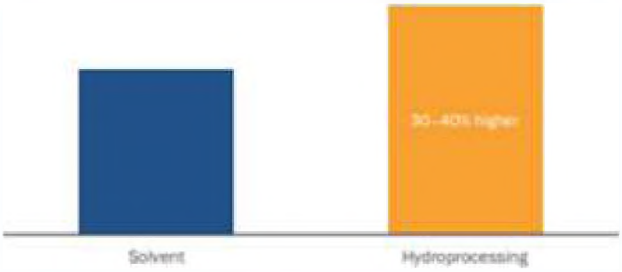

Figure 2. Relative NCM of Solvent and Hydroprocessing Base Oil Manufacturing Plants

However, when looking more in detail at the distribution curves of the NCM of the two types of plants (Figure 3), it is evident that pacesetter solvent plants in the first quarter (blue bars) achieve similar profitability as pacesetter hydro processing plants (orange bars) and at par or higher than laggard hydro processing plants.

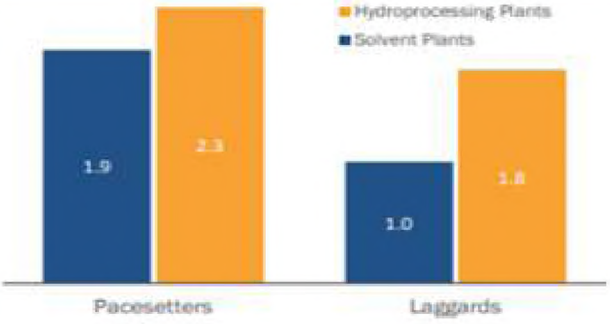

Figure 3. Relative NCM of Solvent and Hydroprocessing Base Oil Manufacturing Plants

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1 Solomon capital cost model estimates

2 Based on 2018 and 2020 Lube Study population

The scope of this paper is to investigate what strategies are adopted by the most profitable base oil manufacturing plants, differentiating between solvent and hydroprocessing technology. The methodology that we use will be quantitative, drawing statistical data from Solomon's multi-year database of real plant data.

Profitability Sources

LWS Products Value

The Lube Study compares the profitability of participant lube plants by calculating their NCM on an annual average basis. Each participant provides a reconciled mass and volume balance for the year of the study, together with the details of the cost sustained during the year. The calculation of the NCM is carried out by assigning a price to each line item in the mass balance and deducting operating costs as actually incurred. In developing the Lube Study pricing basis, Solomon provides a methodology that is consistent and interrelated on a worldwide basis with the objective to reflect the real, "arm's length" marketplace prices in each study year. These price assessments provide an objective basis for evaluating the relative profitability of participating lube refineries. Solomon avoids reproducing any special situations or the internal pricing bases of any lube refiner or group of lube refiners. Prices for products that have limited or no published pricing basis such as some waxes, white oils, cylinder oils, high-viscosity-index base stocks, specialty extracts, and other specialty products are based primarily on input from numerous study participants and selected specialty products marketers/brokers. When analyzing pricing data, it is possible to create a relative scale of product values in Figure 4 that shows the price of each main base oil manufacturing plant in comparison to a common grade. The graph does not intend to be dogmatic, as prices and relative values of base oil fluctuates depending on market conditions, supply and demand conditions, special geographies, or short-term trading positions. However, the scale in Figure 4 is representative of the average price conditions in the most recent Solomon Lube Studies. Future values and prices might vary. Prices of each grade have been expressed as a ratio versus the price of a commonly traded grade in recent years (Group 2 Light Neutral (GR2 LN) in Figure 4). This grade is chosen as a standard for comparison as it is the grade that is widely recognized as the "workhorse grade" for lubricant blenders to formulate finished lubricants, especially in the automotive industry.

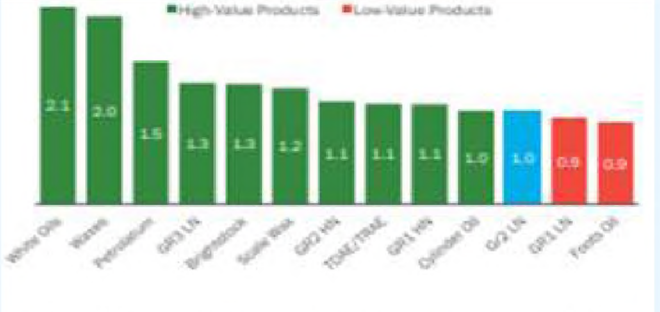

Figure 4. Prices of Main LWS Products Relative to GR2 LN.

The key takeaway is that many LWS grades attract higher prices than the Group 2 light grades. For instance, heavy grades (both Group 1 and Group 2) attract higher prices as blenders assign a premium to the higher viscosity of those grades. Group 1 and Group 2 base oils of similar viscosities are often priced close to each other with regional differences. Similarly, brightstock attracts a strong viscosity premium well over Group 2 light and heavy neutrals. Group 3 grades also attract higher prices, partially due to the supply and demand dynamics and partially due to the higher cost of production of those grades. Finally, it must be remarked that certain specialties products, such as white oils, waxes, and petrolatum might be valued between 2–2.5 times GR2 LN. Some of these products are made predominantly through solvent extraction and dewaxing processes and are less threatened by substitute products made from hydroprocessing routes.

Byproducts Values

For the purpose of this paper, we will define "byproducts" as all those products made by a base oil manufacturing plant that are not LWSs. Typically, these products are added to the fuel's refinery feedstock or fuels blend pools. Due to the nature of the processes, byproducts from solvent and hydroprocessing plants are very different. Solvent plants byproducts are aromatics extracts from the solvent extraction process, asphaltene pitch from solvent deasphalting processes, or slack-waxes from solvent de-waxing processes unless further processed to produce refined waxes as a finished product. Hydroprocessing plants byproducts instead include naphtha and distillates (often of low sulfur and high quality). An obvious strategy to increase profitability is to maximize the yield of the highest value products and to make the highest value byproducts while maintaining the cost basis as low as possible. However, solvent and hydroprocessing plants present significant differences.

Value Generation

Solvent Plants

A solvent plant produces Group 1 base oils. These are generally priced lower or at par with similar Group 2 viscosity grades in the lower viscosity range (the GR1 LN price is around 90% the price of GR2 LN in Figure 4). However, Group 1 base stocks attract a similar price as their Group 2 counterparts in the heavy viscosity range (the GR1 HN price is 1.1 the price of GR2 LN at the same level of GR2 HN in Figure 4) and a substantial premium at very high viscosity (the Brightstock price is around 1.3 times the price of GR2 LN in Figure 4). In addition to base oil products, solvent plants can also make a range of specialties products that hydroprocessing plants cannot make, such as Treated Distillate Aromatic or Residue Extracts (TDAE/TRAE), waxes, white oils, and petrolatum. These products attract the highest value (see the prices of these products in Figure 4 in comparison to GR2 LN). Finally, solvent plants can make byproducts at relatively high value (see Figure 5), such as labelled extracts and asphalt, which attract similar prices as low distillates that are blended in finished diesel. Successful solvent plants have found a way to convert byproducts into finished products, for instance, by converting "labeled" extracts into "unlabeled" TDAE/TRAE or deoiling slack waxes. Figure 5 shows the price of some solvent plants' byproducts at fuel value parity (i.e., when their price is determined by their fuel market equivalent rather than lube). For instance, slack wax is sometimes used as Fluid Catalytic Cracking (FCC) feedstock given the high paraffins content. However, it would be oftentimes more profitable to find a customer and push that product out of the lube plant as a specialty wax product rather than cracking it to its fuel value.

Figure 5. Prices of Main Byproducts Relative to GR2 LN

Figure 6 shows the yields for two groups of plants participating in the Lube Study. The first (TOP4SOL in orange bars) is a group of four base oil manufacturing plants that consistently, year after year and study after study, ranks the highest in terms of NCM. The other (NONTOP4SOL in blue bars) is the average of all the other solvent plants that participate in the Lube Study.

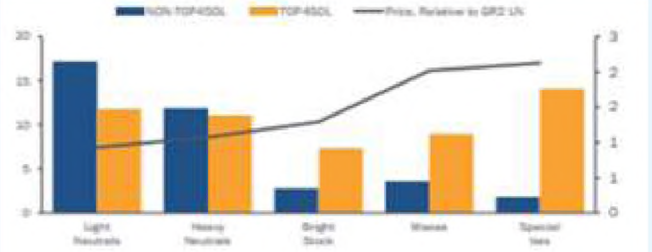

Figure 6. Average Yields from the Solvent Plants Participating in Solomon's Lube Study

The line in the graph shows the price of each product relative to the value of the benchmark grade, as in Figure 4. It is noticeable that the TOP4SOL plants produce larger yields of high-value products—in particular, waxes and specialties in comparison to the other group. The NON-TOP4SOL plants, instead, have similar base oil yields (light and heavy neutrals yield is as high as the TOP4SOL) but not the waxes and specialties.

Another major difference between base oil manufacturing plants that consistently rank among the highest in terms of NCM (TOP4SOL) and the others (NON-TOP4SOL) is the total lube, waxes and specialties yield as shown in Figure 7. TOP4SOL are able to convert, on average, 57% of their feedstock into LWS (hence, rejecting only 43% of the feedstock as byproducts), while all the others convert only 38% of their feedstock. This might happen for several reasons, for instance, because the plant does not have the processing units that allow higher conversion or because byproducts are routed to an integrated fuel refinery for fuel oil blending or for feeding conversion units like Hydrocrackers or FCCs. In this latter case, it would be correct to periodically reevaluate the economics of the alternative routing to fuels or to lube and make sure that the right choice is made. Typically, lube products attract the highest value, but fluctuating economic conditions (like in 2022) might dictate the opposite.

Hydroprocessing Plants

The hydroprocessing route to base oil manufacturing produces the highest base oil qualities, in terms of saturates content, lower sulfur, and volatility. For the purpose of this paper, we have excluded plants that produce LWSs through gas-to-liquids processes. Instead, we included all those plants that produce LWSs through hydrocracking (or severe hydrotreating) of vacuum gasoil followed by catalytic dewaxing, or those "hybrid" configurations that come from the upgrade of an original solvent plant with the addition of severe hydrotreating and/or catalytic dewaxing units. This second type of plant often maintains some residual capability to produce Group 1 LWSs but produce predominantly Group 2 and 3.

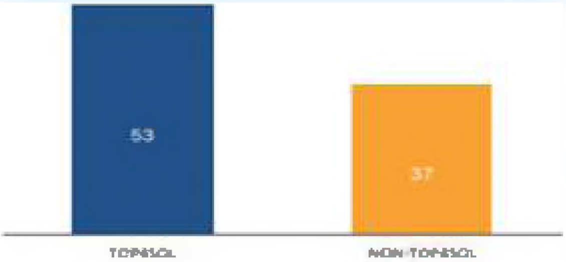

Figure 7. Total LWS Yield – TOP4SOL is a group of solvent base oil manufacturing plants that consistently rank among the highest in terms of NCM among those participating in Solomon's Lube Study. NON-TOP4SOL is all the others.

Since the base oils produced via hydrocracking or severe hydroprocessing are better suited for automotive lube applications than solvent plants, they attract higher prices (on average) than those made from solvent plants. However, a typical hydroprocessing plant is not equipped to rearrange molecules to produce waxes or the entire range of specialties products (although they can make good quality white oils thanks to the high-pressure hydroprocessing capacity).

For this reason, the strategies for profitability for hydroprocessing plants appear to be different than solvent plants.

Figure 8 shows the relative NCM for two groups of hydroprocessing plants consistently participating in the Lube Study. The first (TOP4HYD) is a group of four base oil manufacturing plants that consistently rank the highest in terms of NCM. The other (NON-TOP4HYD) is the average of all the other hydroprocessing plants that participate in Solomon's Lube Study.

Data from the three most recent Lube Studies consistently show that the first group of plants (TOP4HYD) is able to extract 20% more value from their asset than the second group (NON-TOP4HYD).

One major difference between the two group of plants is that the total LWS yield of the TOP4HYD plants is much higher than the other plants, as shown in Figure 9. We have commented that top solvent plants had the same characteristic (see Figure 7). TOP4HYD plant are able to yield 64% of their feedstock as lube, waxes, and specialties, while the others are only 46%.In terms of product slate, it is interesting to notice that there is not much difference between the selectivity of the two groups of plants (see Figure 10). TOP4HYD (those with consistently higher NCM) appear to produce slightly higher yield of light neutrals, but we believe that the difference is small and due to statistical variance rather than a strategic decision.

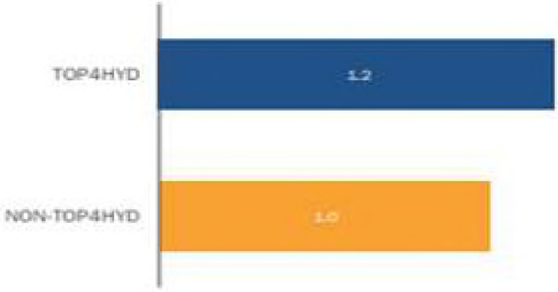

Figure 8. Relative NCM (USD/LWS Bbl) – TOP4HYD is a group of hydroprocessing base oil manufacturing plants that consistently rank the highest in terms of NCM among those participating in Solomon's Lube Study. NON-TOP4HYD is all the others

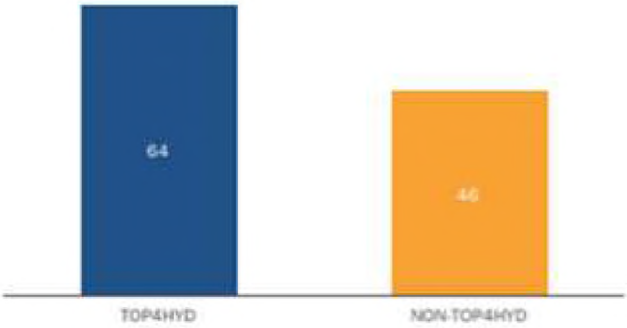

Figure 9. Total LWS Yield of Top NCM Hydroprocessing Plants vs All the Others

The other conclusion that we make from Figure 10 is that, in general, hydroprocessing plants produce a higher proportion of light grades of base oils than heavy grades. This supply of GR2 lightgrades compete with the corresponding viscosity GR1 grades, determining price competition.

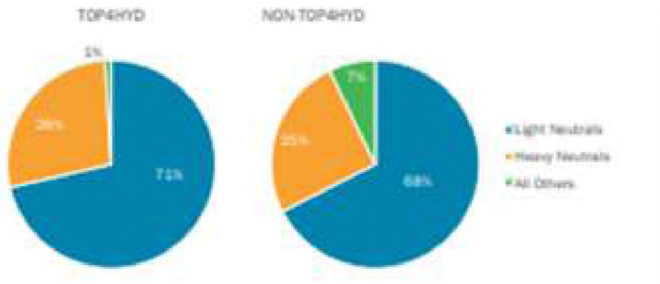

Figure 10. Product Selectivity of Hydroprocessing Base Oil Plants as Percent Volume of the Total LWS Yield for the Two Groups

Operating Costs

The NCM of a base oil manufacturing plant is defined as the net financial result of the manufacturing operations after the operating expenses are deducted. It is intuitive to realize that cost containment strategies are the other lever that lube plants can manipulate to maximize their returns. Economies of scale have, over the years, become larger and are the main differentiator in terms of cost advantages for certain plants. Figure 11 shows the distribution of the capacities in terms of production of LWS plants participating in Solomon's Lube Study. Although the Lube Study does not cover the entire population of existing plants, the picture is quite representative of the average population of the base oil industry. Base oil plants that have a capacity below 10 thousand barrels per day (k bbl/d) of LWS (around 500k tons per year (t/yr)) represent the majority, while mega plants with a capacity above 20k are only 17% of the total.

On average, solvent plants are at a disadvantage in terms of operating cost per barrel of LWS against hydroprocessing plants. This is evident by the comparison of the total height of the bars in Figure 12. Hydroprocessing plants have lower total operating costs per barrel of LWS than solvent plants, regardless of belonging to the TOP4HYD group or the NONTOP4HYD group. One contributing factor is certainly the scale of the plants themselves. The average size (in terms of LWS production capacity) of the solvent plants is approximately half of the average size of hydroprocessing plants participating in the Lube Study. However, Solomon's analysis of the efficiency of the different types of plants shows that hydroprocessing plants are more efficient in terms of energy and fixed costs than solvent plants due to different contributing factors such as plant year of construction (older plants tend to be designed with less consideration for energy conservation, and solvent plants are older than hydroprocessing), technology age (hydroprocessing adopts modern technology), and the process itself (solvent plants have highenergy requirements for solvent separation but also a higher number of process units, hence more staffing requirements and often more maintenance costs). It must be noted that the increased production of specialty products increases operating expenses (OpEx). The high-margin solvent plants recognize this is a cost to obtain the higher margin, which typically more than offsets the increased OpEx. The other consideration from the analysis of Figure 12 is that TOP4HYD plants (i.e., the group of hydroprocessing plants that achieve superior NCM) have lower operating costs than the NON-TOP4HYD plants. On the other hand, TOP4SOL plants have higher operating costs than the NON-TOP4SOL plants. Therefore, it can be concluded that TOP4HYD plants use economy of scale and cost control strategies to achieve their superior profitability. On the other hand, TOP4SOL plants achieve higher profitability in spite of having a higher cost basis.

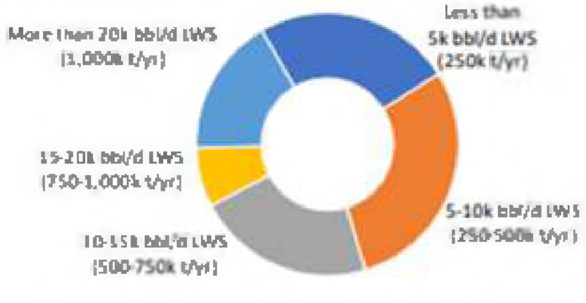

Figure 11. Plant LWS Production Capacity Distribution for Plants Participating in Solomon's Lube Study

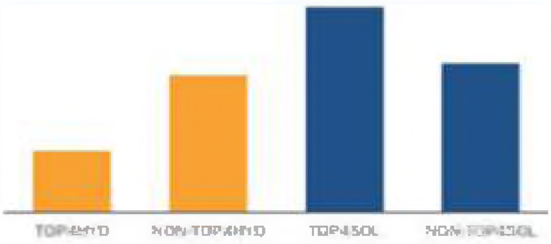

Figure 12. Total Operating Cost per Barrel of LWS Produced for Solvent and Hydroprocessing Plants Participating in Solomon's Lube Study

Conclusion

In this paper we have used Solomon's extensive database of the Lube Study to investigate what strategies the most profitable base oils manufacturing plants adopt to achieve superior profitability. The findings highlight that, in general, hydroprocessing plants achieve superior profitability than solvent plants, but there is a group of solvent plants (TOP4SOL) that achieve the same or superior profitability as hydroprocessing plants. In a declining Group 1 base oil demand, only plants that are able to maintain higher profitability will be able to remain in business. The strategies that TOP4SOL plants adopt to achieve their superior profitability are based on focusing on maximizing the products that attract the highest prices on the market or those that are not substituted by more modern hydroprocessing plants. Indeed, TOP4SOL plants have higher yield of specialties (white oils, TDAE/TRAE, and other types of mineral oils) and waxes (refined, micro, and macro crystalline) than all other plants. TOP4SOL plants do not have the lowest operating costs as they likely see those cost as necessary in order to achieve superior product yields. Therefore, their cost basis per barrel of LWS is higher than all other plants. In essence, successful solvent plants adopt a product differentiation strategy (i.e., identifying what products the market is in demand of and investing efforts and costs to produce products that differentiate them from their competitors). Hydroprocessing plants focus much less on specialties or wax products. The main products they make are Group 2 and 3 base oils, especially light grades due to the cracking reaction mechanisms. Therefore, they root their strategies on large economies of scale which allow them to achieve cost leadership. TOP4HYD (the group of hydroprocessing plants that achieve higher NCM than other plants participating in Solomon's Lube Study) have lower cost per barrel of LWS produced than all other hydroprocessing plants in conjunction with a lower proportion of byproducts through a combination of feedstock selection and catalytic systems. In conclusion, the most profitable lube plants adopt different strategies to achieve their superior returns: product differentiation for solvent plants and cost leadership for hydroprocessing. With a market for Group 1 base oil declining and Group 2 and 3 base oils that might become challenged in the future as a consequence of the changes in the automotive sector, it is fundamental that base oil plants revisit and adopt the right strategy to remain in business.

4.3 Importance of selecting correct ILI technique in managing integrity of a pipeline

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4.1 Abstract:

This paper discusses various aspects of selection of an ILI technique. The process of selection of suitable ILI technique is based on evaluation of expected performance of the in-line inspection system with regard to detection, identification, sizing, locating, and coverage capabilities for the anomalies of interest and pipeline to be inspected; Physical characteristics of the in-line inspection tool, including its size, weight, and environmental limitations; Reporting requirements; Operational reliability of the tool (history, operational success, etc.); Performance on other types of anomalies other than those of interest and Additional operational constraints. If the inspection goals include detection and/ or sizing of multiple anomalies or characteristics, more than one tool or system that can best assess overall condition of the pipeline to be selected. It is important to understand that different tools are designed to address anomaly types and no one tool can address all types of anomalies. Pipeline operators need to be aware of the limitations on any given ILI technology. The paper also discusses some case study on Pipeline failures due to limitation of in-line inspection system. It also highlights some case study on appropriate selection of an in-line inspection system.

Key words: Inline Inspection, ILI, Magnetic flux leakage, MFL, Ultrasonic crack detection, anomaly, defect, threats, integrity

4.2 Introduction

The goal of any pipeline operator is to operate the pipeline in a manner so that there are no adverse effects on public, environment, and customers. The objective is error-free, spill-free, and incident-free operation of the pipeline. An integrity management program provides a means to improve the safety of pipeline systems and to allocate operator resources effectively.

4.3 Integrity threat to pipeline

As per Pipeline Research Council International (PRCI), pipeline integrity threats have been classified into 22 categories:

Table 1: Pipeline integrity threats

Time- dependent threats	**Stable threats**	**Time- independent threats**
1) External Corrosion	4) Defective Pipe Seam	14) Damage Inflicted By First, Second, Or Third Parties (Instantaneous/ Immediate Failure)
2) Internal Corrosion	5) Defective Pipe	15) Previously Damaged Pipe Such As Dents And/Or Gouges (Delayed Failure)
3) SCC	6) Defective Pipe Girth Weld (Circumferential Including Branch And T Joints)	16) Vandalism
	7) Defective Fabrication Weld	17) Incorrect Operational Procedure
	8) Wrinkle Bend Or Buckle	18) Cold Weather
	9) Stripped Threads/Broken Pipe/Coupling Failure	19) Lightning
	10) Gasket Or O-Ring Failure	20) Heavy Rains And Floods
	11) Control/Relief Equipment Malfunction	21) Earth Movement
	12) Seal/Pump Packing Failure	22) Unknown (Root Cause Of Failure Was Not Determined)
	13) Miscellaneous (Failure Of Valve Or Another Component)	

As per ASME B31.8S, first 21 threats out of the total 22 are addressed by pipeline operators in their integrity management program. The category of “unknown” [Threat 22)] is not included in the list of threats to be addressed as prevention and mitigation of an unknown threat is not possible. ASME B31.8S groups the 21 threats as time dependent, stable, or time independent.

As there are physical and regulatory differences between gas and liquid pipelines, so the threat categories may alter to some extent. For example, potential for pressure-cycle-induced fatigue is much greater for liquid pipelines than it is for gas pipelines.

4. 4 In-Line Inspection (ILI) system

Selection of in-line inspection system necessitates consideration of the in-line inspection system capabilities and the pipeline operational and physical characteristics along with expected threats in the pipeline.

The process of selecting an in-line inspection system requires:

- Defining the goals, objectives and required accuracies of the inspection.
- Considering the physical and operational characteristics and constraints of the pipeline; and
- Selecting an appropriate in-line inspection system based on the requirements of inspection and performances capabilities of the in-line inspection system.

Inspection goals and objectives

The goals and objectives of an in-line inspection shall be defined. Goals and objectives shall include, but are not limited to, characteristics of anomalies and features to be detected, identified, and sized and the required accuracies.

Physical and Operational characteristics and constraints

The operator shall provide information on physical characteristics and constraints of the pipeline to ILI service provider, which is typically done through a pipeline questionnaire. They include:

- Physical properties of the pipeline section, such as length, diameter, wall thickness, valves, bends, known physical restrictions, openings, launchers and receivers, etc.
- Characteristics of the fluid such as type and composition, chemical properties (e.g., corrosivity), flow rate, temperature, pressure, and cleanliness of the pipeline.

For two-way flow, such as in storage operations, upstream and downstream flow directions should be clearly defined.

The service provider shall define the constraints under which the in-line inspection tool will operate, such as:

- Restrictions on temperature, pressure, minimum bend or elbow radii.
- Minimum spacing of bends or elbows to each other.
- Maximum and minimum velocities.
- Minimum and maximum wall thickness.
- Any known product characteristics that would limit or preclude a successful inspection.
- Tool weight and overall length.
- Special launching and receiving constraints especially for launching and receiving facilities.
- Requirements for check valve positions
- Minimum bore requirements and drive cups compression.
- Anticipated run length and any concomitant limitations on battery life, data storage capacity and/or mechanical wear.

Selection of In-line inspection system

The process of selecting an in-line inspection system is based on evaluation of:

- Expected performance of the in-line inspection system about detection, identification, sizing, locating, and coverage capabilities for the anomalies of interest and pipeline to be inspected.
- Physical characteristics of the in-line inspection tool, including its size, weight, and environmental limitations.
- Reporting requirements.
- Operational reliability of the tool (history, operational success, etc.).
- Performance on other types of anomalies other than those of interest.
- Additional operational constraints.

If the inspection goals include looking for multiple anomalies or characteristics (e.g., corrosion in dents, cracking with associated corrosion and/or dents, etc.), more than one tool or system that can best assess overall condition of the pipeline to be selected. The operator shall select the appropriate in-line inspection systems, which meet the goals and objectives. The generic classes of ILI tools and a brief overview of their capabilities are shown below in Table 2:

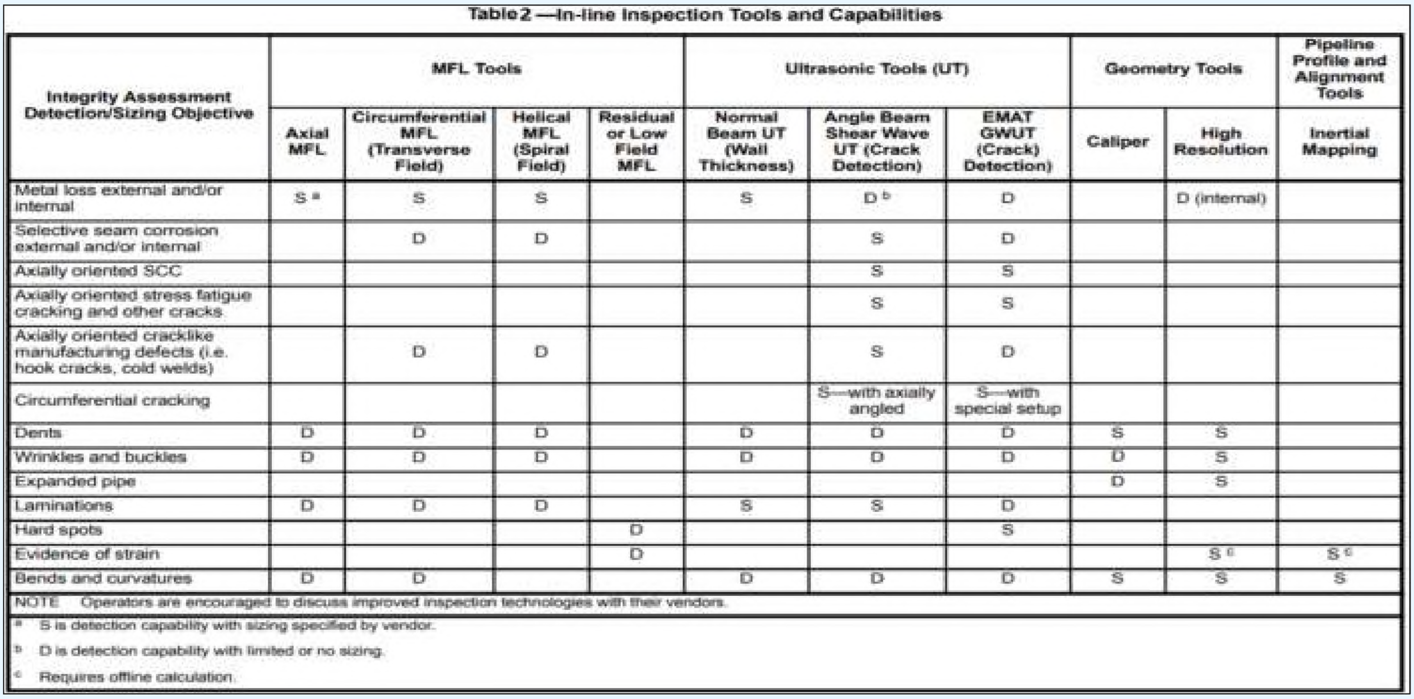


Table 2 —In-line Inspection Tools and Capabilities

Integrity Assessment Detection/Sizing Objective	MFL Tools				Ultrasonic Tools (UT)			Geometry Tools		Pipeline Profile and Alignment Tools
	Axial MFL	Circumferential MFL (Transverse Field)	Helical MFL (Spiral Field)	Residual or Low Field MFL	Normal Beam UT (Wall Thickness)	Angle Beam Shear Wave UT (Crack Detection)	EMAT GWUT (Crack) Detection)	Caliper	High Resolution	Inertial Mapping
Metal loss external and/or internal	S [a]	S	S		S	D [b]	D		D (internal)	
Selective seam corrosion external and/or internal		D	D			S	D			
Axially oriented SCC						S	S			
Axially oriented stress fatigue cracking and other cracks						S	S			
Axially oriented cracklike manufacturing defects (i.e. hook cracks, cold welds)		D	D			S	D			
Circumferential cracking						S—with axially angled	S—with special setup			
Dents	D	D	D		D	D	D	S	S	
Wrinkles and buckles	D	D	D		D	D	D	D	S	
Expanded pipe								D	S	
Laminations	D	D	D		S	S	D			
Hard spots				D			S			
Evidence of strain				D					S [c]	S [c]
Bends and curvatures	D	D			D	D	D	S	S	S

NOTE Operators are encouraged to discuss improved inspection technologies with their vendors.

[a] S is detection capability with sizing specified by vendor.

[b] D is detection capability with limited or no sizing.

[c] Requires offline calculation.

2 Table 1 of API RP 1160: Managing system integrity for hazardous liquid pipelines

Different tools are designed to address anomalies created by different threats; no one tool can address all threats to pipeline integrity. So, the pipeline operator should be aware of the limitations on any given ILI technology.

First, some tools offer global positioning system (GPS) technology to increase accuracy and ease of locating actionable anomalies using Inertial Navigation System (INS) tool that can be attached to the tools to obtain more accurate positioning measurements leading to GPS coordinates.

Second, most technologies will have a threshold anomaly detection size. Detectability will be less than 100 % certain for anomalies below the threshold size, and one should understand these limitations of each type of tool prior to its use.

Third, many tools have the ability to characterize the sizes of anomalies within a certain stated tool tolerance; and as such, the anomaly sizing found upon excavation and measurement are often different to some degree from the sizes predicted by the tools. The operator should determine the amount of tool error associated with a particular tool run by excavating and examining a representative number of anomalies and also considering field measurement error. The statistical distribution of error should be considered in the evaluation of the tool's performance and the evaluation of other anomalies for remedial action.

In some cases, special ILI tools can be set up to locate certain types of anomalies. For examples, if pipe body hard spots are suspected, a low-resolution magnetic flux leakage (MFL) ILI tool can be used in a special setup to locate them.

Lastly, the pipeline operator should be aware that the routine grading of anomalies provided by an ILI operator may not be sufficient to satisfactorily assess certain anomalies. In such cases, the operator may find it advantageous to request a reexamination by the vendor of the raw data acquired by the tool. Analysis of the raw data by the vendor's experts may help in assessing a particular anomaly where the normally reported data were insufficient to resolve the nature of the anomaly particularly when detailed data integration is needed to identify threats.

4.5 Performance Specification

An in-line inspection system may be capable of addressing more than one type of anomaly or characteristic during an inspection run. If so, performance specification shall address each type of anomaly or characteristic. The performance specification shall define capabilities of the in-line inspection system to detect, locate, identify and size anomalies and characteristics in terms of the following parameters:

- Type of anomaly or characteristic covered by the performance specification.
- Detection thresholds and probabilities of detection (POD).
- Probabilities of proper identification (POI).
- Sizing or characterization accuracies.
- Linear (distance) and orientation measurement accuracies.
- Limitations.

The performance specification shall state how the system will measure distance and how reference points will be utilized/required. The performance specification shall state the geometrical limitations of the system in terms of passage capabilities through straight pipe, bends, and fittings. Pipeline Operators Forum (POF) format is utilized for the enlisting the performance specification.

4.6 Case study on Pipeline failures due to limitation of In-line Inspection system

Case- 1: Rupture in pipeline

One pipeline (LSAW) underwent more than one long seam ruptures within a span of 2 years. Upon investigation of the failure incidents, it was observed that the pipeline was vulnerable to weld related defects & fatigue cracks.

The pipeline was previously inspected using Axial MFL ILI tool that was not designed to detect crack or crack like features.

Upon encountering seam ruptures, the pipeline was inspected using conventional Ultrasonic crack detection tool but the tool failed to detect targeted cracks in SAW long seam of the pipe, which subsequently failed after the inspection results were available.

Upon detailed analysis of the technological aspects of the crack detection ILI tool, it was concluded that the orientation of the cracks present was such that the crack detection tool used did not have the capability to identify, this was primarily due to arrangement of UT sensors and secondly due to the limitation in the sensors arrays in capturing the reflected ultrasonic wave from crack /cracklike anomaly (it is also possible that arrangement and number of sensor arrays was incapable to hit the crack/crack like anomaly). As a result, critical anomalies were missed.

Case- 2: Rupture in Crude oil pipeline

The crude oil pipeline underwent corrosion failure. 11 years prior to the failure incident, the pipeline was previously inspected by magnetic flux leakage (MFL) ILI tool, but couldn't detect any metal loss defects at the rupture site.

Only 9 months prior to the failure incident, the pipeline was again inspected using ultrasonic compression wave ILI tool at an ILI frequency of 10 years. Total 336 features were reported in the preliminary report, which were ranked according to severity based on a rupture pressure ratio calculation. Majority of the defects were internal in nature. Most of the features were identified as having "echo loss." When associated with internal and deep external corrosion defects, echo loss indicated that actual wall thickness had not been accurately measured. In this report, metal loss defect at the rupture site had been ranked number 59 in severity and was identified as having echo loss. Due to the defect's ranking at 59, the defect couldn't be attended in time.

Upon investigation of the failure incident, it was found that the corrosion defect was probably 40-45% of the wall thickness at the time of MFL ILI, but was not detected. This may either be due to limitation associated with the old MFL technology or higher sensor loss resulting in inadequate data recording or inaccurate analysis of the raw data. Corrosion continued until the wall had thinned down to 16% of its original thickness and the pipe wall could no longer support the stresses associated with the internal operating pressure and failed. High eco loss encountered during ultrasonic compression wave ILI was due to inadequate cleaning of the pipeline.

Case- 3: Rupture in Crude oil pipeline

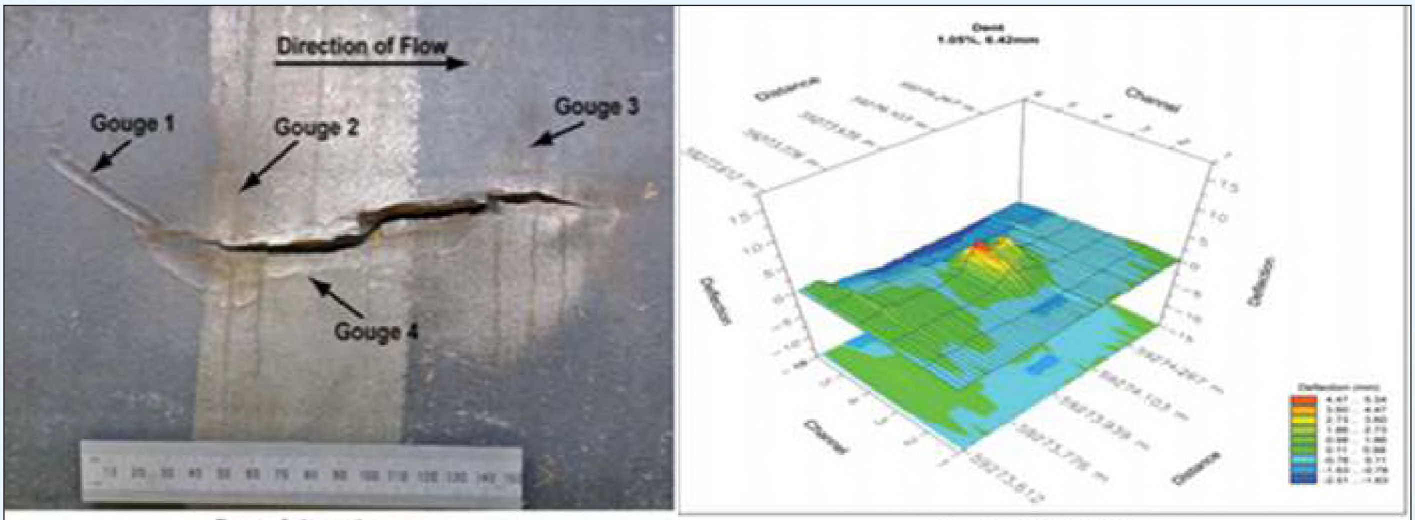
Most recent inspections of the pipeline were:

- 11 year back, a geometrical discontinuity inspection was conducted using a caliper tool.
- 5 years back, a metal loss inspection was conducted using a magnetic flux leakage (MFL) tool.
- 1 year back, a geometrical discontinuity inspection was conducted using a caliper tool.
- 1 year back, a crack inspection was conducted using an ultrasonic crack detection tool.

During 2nd round of inspection, MFL tool detected the dent, but did not identify the gouging, as gouge depth of 0.4 mm was below the detection capability of the tool. The caliper tool used during 3rd round of inspection, detected a double apex dent at the location of leak. However, the dent was not reported since the measured deflection was below the reporting threshold of 2%. During crack inspection as a part of 3rd round of inspection, the tool did detect the dent, but could not, detect secondary features in dents (e.g. gouging) with any reliability. This may either be due to inadequate cleaning or lift- off of the UT sensor or inaccurate data analysis. In addition to reviewing the results of individual inspections, data was also compared between different inspections to identify secondary features. The following comparisons were conducted:

- Data from the MFL ILI was cross-referenced to data from the 1st round of caliper inspection to identify secondary features. Two features met excavation criteria and the locations were excavated.
- Data from the 3rd round of caliper inspection was cross-referenced to data from the MFL ILI to identify secondary features. No features met excavation criteria. At the time of the caliper & crack inspections, it was recognized that double apex dents or dents in close proximity to each other could be linked to stress risers, it did not require ILI companies to report such dents if the depths were less than two per cent of the pipe outside diameter.

Upon incident investigation, it was observed that the failure occurred at a location where dents and gouges had been present prior to the pipe being coated in the field. Judging from the nature and location of the damage, it likely occurred at the time of construction. Following the initial hydrostatic pressure test, the dent would have re-rounded to some degree, resulting in high tensile strains in the root of the gouged area. The pipe material deformation from the gouge resulted in high hardness near the pipe surface which contributed to crack initiation. Because the dent did not fully re-round, it continued to fluctuate with changes in normal line operations and operating pressures. The crack progressed through-wall by pressure cycle induced fatigue.

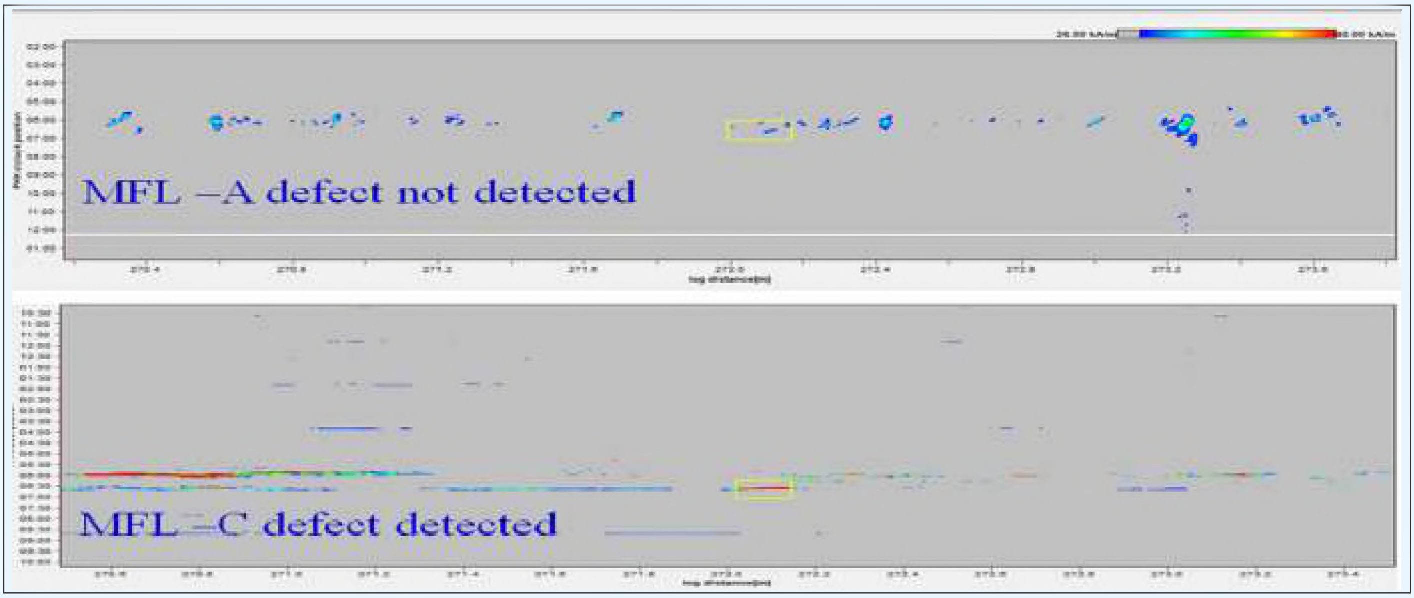


Damaged pipe section

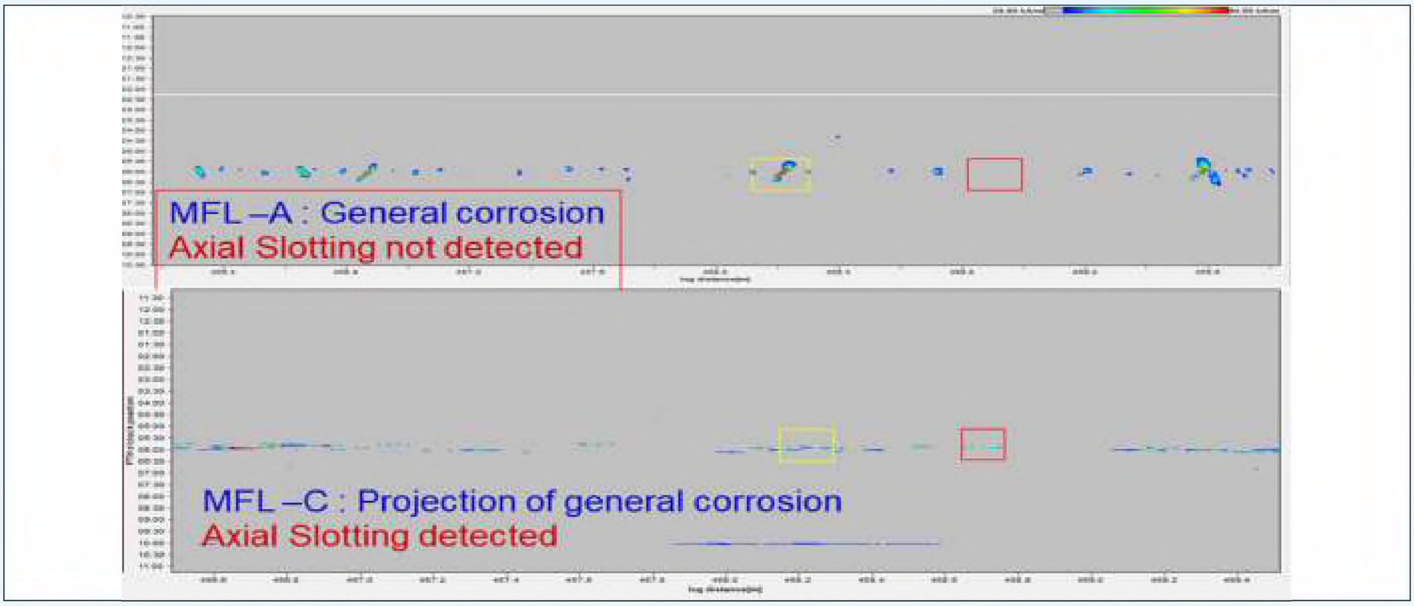
3D screen capture of dent location

4.7 Case study on appropriate selection of In-line Inspection system

Case-1 Detection of Axial defects in offshore crude oil pipelineAn offshore crude oil pipeline was expected to have significant internal corrosion defects in subsea portion as well. An earlier Axial-MFL inspection indicated few general corrosion defects in sub-sea portion which led to an indication that health of sub-sea pipeline is good which was not as expected. Few years later the inspection was done using both Axial-MFL and Circumferential MFL tools. Axial defects which were earlier missed by A-MFL were now detected by C-MFL thus leading more accurate assessment of pipeline health. Also general corrosion detected in A-MFL was seen as a projection only in C-MFL. Circumferential defects were detected by CDP (MFL-A) and were not detected by AFD (MFL-C). Thus both types of MFL tools have their own capabilities and limitations. Combination of both have led to better assessment of pipeline health. A sample C-scan below substantiate the findings i.e. axial grooving defect missed in A-MFL is clearly seen in C-MFL.



A sample C-scan below shows that axial slotting defect missed in A-MFL is clearly seen in C-MFL. Also general corrosion detected by A-MGFL is seen as a projection only in C-MFL.



Case-2 Detection of lamination defects

A high resolution ultrasonic compression wave ILI tool was selected as it was targeted to inspect the pipeline for presence of lamination defects. This was selected as the MFL tool would not have detected most of the laminations, parallel to the pipe wall. Even if the same is detected, its sizing accuracy would not be as good as UT tool. Upon inspection using this UT tool, significant no. of lamination defects was reported and thus intended results were obtained. In addition to this, the UT tool also reported the metal loss defects, thus fulfilling another primary objective of in-line inspection.

4.8 Conclusion:

Selection of proper in-line inspection tool is very much important in getting the injurious defects/ anomalies detected for their further repair in ensuring integrity of the petroleum pipeline. Prior to selection of the ILI technique, goals and objectives of an in-line inspection must be clear. The process of selection of an ILI technique is based on evaluation of expected performance of the in-line inspection system with regard to detection, identification, sizing, locating, and coverage capabilities for the anomalies of interest and pipeline to be inspected; Physical characteristics of the in-line inspection tool, including its size, weight, and environmental limitations; Reporting requirements; Operational reliability of the tool (history, operational success, etc.); Performance on other types of anomalies other than those of interest and Additional operational constraints. If the inspection goals include detection and/ or sizing of multiple anomalies or characteristics, more than one tool or system that can best assess overall condition of the pipeline to be selected. It is important to understand that different tools are designed to address anomalies created by different threats and no one tool can address all threats to pipeline integrity. Pipeline operators need to be aware of the limitations on any given ILI technology.

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Wikipedia

4.4 Reliability based assessment of corroded pipelines

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Abstract

Pipeline integrity management during design and operation is performed by two limit state approaches i.e. deterministic and probabilistic methods. In the first approach safety or usage factors are applied to characteristic loads and resistances whereas the later is based on structural reliability analysis applied to the relevant limit states, e.g. reliability-based limit state methods. For any structural reliability problem the crucial matter for definition is the limit state function(s) which takes the form G(x)=S - L; 'S' is the resistance; 'L' is the load effect; G(x) is the margin of safety and 'x' denotes basic random variables that influence load effect and resistance. Probabilistic models are developed for each of the basic random variables. Most frequently used are normal, log-normal, uniform, Gumbel and Weibull distributions. Monte Carlo simulation is used to evaluate the reliability of the pipeline and compare the reliability with target safety levels that are derived from population density. The estimated reliability of the pipeline is then projected on time scales that help plan timely remedial measures and ensure future safe operation.

Key words: Pipeline integrity, reliability, probabilistic methods, limit state functions, corrosion, Inline inspection (ILI)

Introduction

In the early days of the oil and gas pipeline industry, integrity-related activities such as coating application, cathodic protection, corrosion inhibition, and weld inspection were implemented in response to pipeline failures and incidents. As the pipelines have aged and the size and complexity of pipeline networks have grown, the impact of pipeline failures has increased. More specifically there is increasing public awareness and concern regarding pipeline failures. In response, the industry improved prevention, mitigation, monitoring, and inspection technologies for pipeline hazards. The pipeline integrity now begins from conceptual stage through design and construction. The traditional deterministic methods are being replaced by probabilistic methods.

While the deterministic method originated from the knowledge of allowable stress design and plastic design, the probabilistic method is based on the analytical methods and simulation. Deterministic methods generally employ design checks containing one or more explicit safety factors and a number of implicit measures to achieve the intended level of safety. The implicit measures typically include use of conservative estimates of material strength parameters, and analysis methods that give lower bound estimates of failure loads. The probabilistic (or reliability-based) methods treat the load effects and structural resistances as uncertain quantities, which are explicitly characterized by probability distributions.

The reliability based assessment include identifying relevant limit states and development of corresponding limit state functions followed by development of probabilistic models of basic variables. The design and operational parameters are then defined such that the reliability is within the target limits.

Failure modes and limit states

Corrosion is one of the most damaging mechanisms that affect the long term reliability of buried pipelines. The failure modes resulting from corrosion damage could be small leaks, large leaks or ruptures. For each failure mode, a limit state can be defined. Beyond the limit state, the pipeline no longer satisfies a particular design. A mathematical expression of the below form is used to define limit state function.

$$G(x) = S - L \qquad \textbf{Equation 1}$$

'S' is the resistance; 'L' is the load effect; G(x) is the margin of safety and 'x' denotes basic random variables that influence load effect and resistance. $G(x) \leq 0$ indicate nil or negative safety margin which implies failure. To operate safe, the random variables should be so maintained and monitored that G(x) is always positive.

Different limit state function is used for different modes of failure. For small leaks only three parameters i.e. wall thickness, maximum depth of corrosion and corrosion growth with time are used. The limit state function for burst at a corrosion defect is a variant of the semi-empirical model for failure of a ductile pipe with a longitudinally oriented metal loss defect, which was developed by Battelle (Kiefner, 1969) and later modified by Kiefner and Vieth (1989) and Bubenik et al. (1992). Rupture occurs if unstable growth of the through-wall defect takes place. The limit state function for rupture takes into account the pipe wall thickness and diameter, tensile strength, Folias factor and internal pressure.

Development of probabilistic models of basic variables

The input basic variables for limit state function include pipeline attributes (pipe grade, wall thickness, design pressure, location class); material properties (yield strength, flow stress, tensile strength, toughness, yield to tensile ratio, strain hardening coefficient) and corrosion defect (depth, length, density, corrosion growth rate).

Each basic variable that influences limit state function is treated as a random variable and is characterized by an appropriate probabilistic model. Few of the variables may be assigned a deterministic value, if it is demonstrated that ignoring the uncertainty has an insignificant impact on the probability of failure or that the deterministic value used is conservative. The probabilistic model is mostly assigned on the basis of relevant statistical data. Some of the most frequently used distributions are normal, log-normal, uniform, Gumbel and Weibull for various basic parameters.

Computing reliability

Reliability is calculated considering failure probabilities of a given pipeline segment as shown in

$$2\ R = 1 - Pf \qquad \textbf{Equation-2}$$

Equation R is the reliability, Pf is probability of failure resulting from all limit states. For corroded pipeline, Pf is the cumulative probability of failure resulting from small leak (pfSL) + large leak (pfLL) + ruptures(pfR). For 'n' number of corrosion anomalies reported in a pipeline segment, the failure probability may be written as

$$()_{\prod=}--=_{nifif}pP_{1}11 \qquad \textbf{Equation 3}$$

The failure probabilities are estimated based on Monte Carlo Simulations. Monte Carlo simulation method assumes an indicator function I(x), defined as I(x) = 1 if $G(x) \leq 0$ and I(x) = 0 if G(x) > 0 and is evaluated for each sample point. An unbiased estimator for the failure probability is then given by the sample mean

$$NxIp_{Niif\sum=}=1 \qquad \textbf{Equation 4}$$

Some of the influencing parameters and distribution considered for Monte Carlo simulation are given below:

Table 1 Basic random variables and probabilistic models

S.N.	Parameter	Distribution	Parameters		Source
1.	Yield strength	Deterministic	μ = 1	σ = 0	IOCL spec.
2.	Tensile strength	Deterministic	μ = 1	σ = 0	
3.	Diameter	Deterministic	μ = 1	σ = 0	CSA Z662
4.	Wall thickness	Normal	μ = 1	σ = 0.0025	CSA Z662
5.	Corrosion rate (depth)	Weibull	α (Shape) = 5.8033	β (Scale) = 0.08705	From ILI run comparison
6.	Corrosion rate (length)	Log-Normal	μ = 0.72208	σ = 0.45613	
7.	Defect depth	Normal	μ = 0.94829	σ = 0.20752	From ILI
8.	Defect length	Deterministic	μ = 1	σ = 0	From ILI
9.	Internal pressure	Deterministic	μ = 1	σ = 0	Max. press. (Operational setting)

Since corrosion is a time dependent threat, the probabilities shall take into the time factor. Corrosion growth rates (both in through thickness and longitudinal directions) shall be considered for calculating the probability of failure. With time G(x) 0, the probability of failure increases and the reliability reduces. Suitable mitigation measures shall be taken when the reliability of the pipeline falls below target limits. The reliability targets are defined as a function of pipeline diameter, pressure, and population density. A sample reliability target and corresponding target failure probability for a 28inch diameter pipeline based on population density is shown in Figure-1. The segmentation is done for every 1600m length along the pipeline axis. The targets are defined on a per km-yr basis.

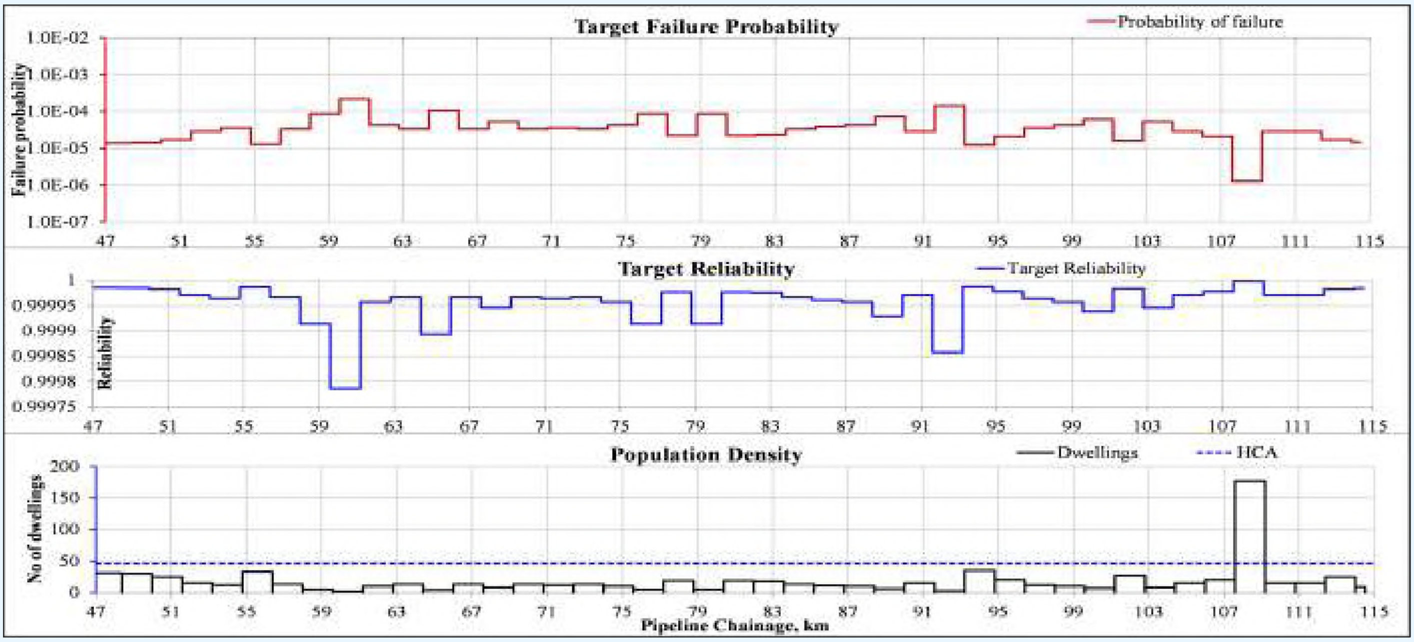

Figure: 1 Target reliability and target failure probability based on population density

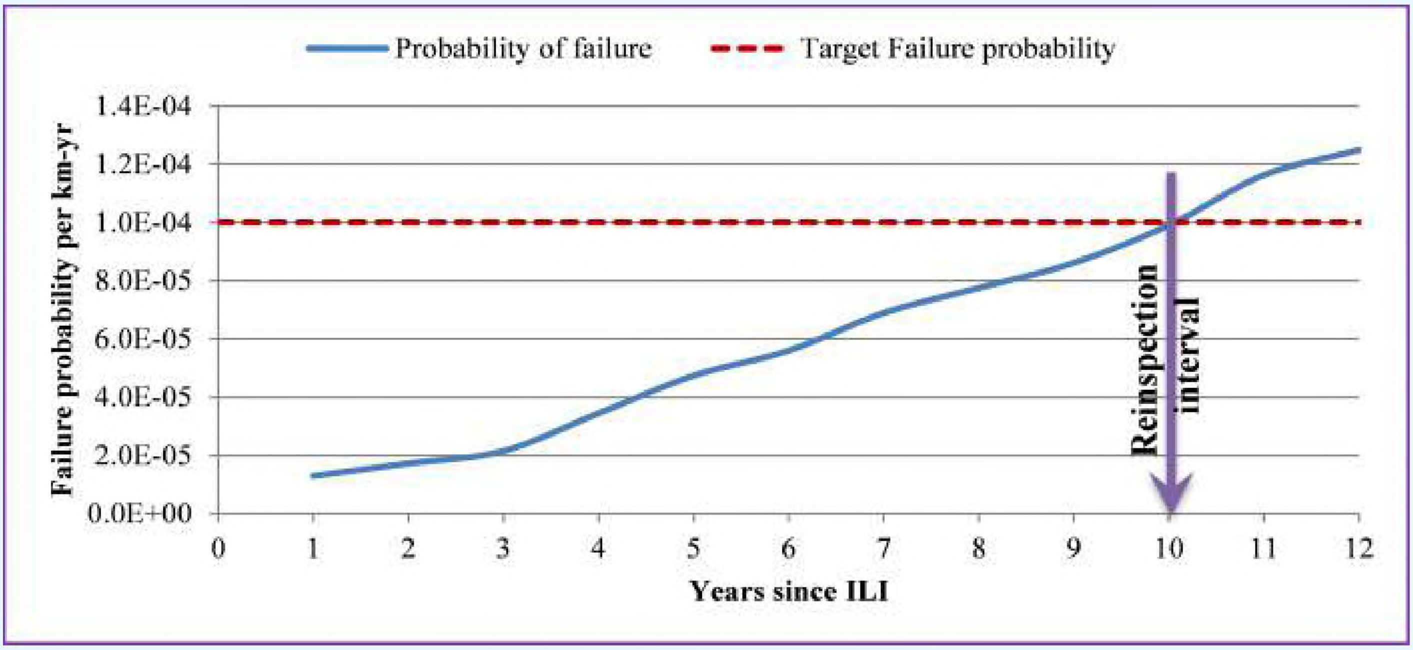

Figure: 2 Estimated Failure probabilities

Projecting failure probabilities on time scale helps the operator to plan the monitoring and mitigation measures such that the reliability is maintained within target limits. Re-inspection intervals may be chosen just before the estimated failure probability falls below target probability. In case the re-inspection is delayed, operating pressure may be reduced suitably to limit failure probabilities within the target failure probability.

Conclusion

Historically, deterministic approach was used to assess integrity of pipeline. This is now being replaced with reliability based design and assessment. In this paper author has made an attempt to explain broad steps used to assess pipeline integrity of corroded pipelines using structural reliability approach. Findings of ILI forms the basis of developing statistical methods for variables related to corrosion damage. Monte Carlo simulation has been used to find probabilities of failure. The estimated reliability is projected on time scale which helps in enhanced maintenance and inspection activities thereby ensuring reliability of pipelines within the target limits.

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4. ASME B31.8S Managing System Integrity of Gas Pipelines

4.5 Enhancing (reducing) The Leak Detection Times In Pipelines: By Deployment Of Real-time Ethernet Protocols In Lieu Of Legacy Protocols, Such As DNP, IEC-60870-5-101 / 104

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Abstract

Cross-country pipelines at times suffer unexpected leaks to the surrounding environment. The challenge faced by pipeline operators is to ensure that the field data is communicated to the Leak Detection System (LDS) as quickly as possible to ensure a leak is caught and located. Acyclic information exchange of data collected at sensors located along the pipeline to the LDS deployed in the control room is must. Data collection rates are typically in the range of about 5 to 15 seconds. Consequently, as "Real-time Transient Modelling" (RTTM) LDS needs time to build up evidence for and confirm the existence of a leak, it can take approximately 10-15 minutes to issue an alarm. By the time, corrective steps taken for "Abnormal Operational Condition" (AOC) occurs after the leak, an enormous quantity of product could have been lost from the pipeline, leading to safety and environmental concerns.

To address the "time to detect" issue an operator can turn to "Negative Pressure Wave (NPW)" technologies to provide a solution. However, the efficacy and location accuracy of such systems depends on the data sample frequency – with sample rates in the order of 10-100msec being preferred. Typically, NPW systems are deployed at the RTU level, so that the required sample data rates can be achieved but with increased CAPEX, installation and maintenance cost.

This paper presents a use case deployment of more advanced Ethernet protocol, the so-called Real-time Ethernet Deterministic Protocols, to reduce the data acquisition time. This is possibly the first time in the pipeline industry that data acquisition rates in the order of 10msec is achieved specifically for improvement of NPW leak detection performance.

1. Introduction

A Reuters commodities report dated 30 Sep'2017 quotes that analysis of the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) data for the 6 years prior to the report indicates occurrences of 466 incidents of a leakage in pipelines carrying crude oil or refined products. An Advanced Leak Detection system has detected 105 of 466 incidents i.e. 22% only, which provided a good reference for the problem statement for the development work undertaken.

In some parts of the world, thieves, who steal the product in very small quantities and over very short times, evade detection by staying within the flowmeter inaccuracies or leak detection filter levels which poses great challenge to advanced leak detection systems.
This paper details the focused development work done and use case deployment along with results in an endeavor to overcome the stated challenges. The identified challenge areas are twofold: (1) whether data update or polling rates can be improved from present 5- 15 sec range to required 10- 100 milliseconds by NPW methods, and (2) if achieved,

what could be the new leak detection efficacy levels.

1.1. Current SCADA Protocols in Use – Legacy Protocols

Typical current SCADA protocols / traditional – legacy SCADA communication protocols in use are Modus-Serial, Modbus over IP, DNP-Serial, 'DNP over IP', IEC 60870-5-101 and IEC 60870-5-104. These protocols are used in cross-country pipelines and electric transmission systems designed for harsh conditions in remote and inaccessible locations and meant to work in unreliable communication regimes to address failovers in SCADA to RTU communication; to enable recovery of data in case of RTU failover; to support clock synchronization such as "Network Time Synchronization Protocol (NTP)"; and to permit remote configuration and download of configuration among other features. Assuming that leak detection data of flow, pressure, etc. are polled in 5 sec intervals, the SCADA servers themselves take 5-10 sec processing time and then update to leak detection server database can occur in the next 5-10 sec. A "Real-Time Transient Model (RTTM)" based "Leak detection system (LDS)" needs many scans of data to build up evidence for, and confirm the existence of, a leak. Therefore, the minimum leak detection time is minutes, rather than seconds.

The developmental endeavor documented here is to reduce the polling time and to get the data directly to the server – avoiding the communication hops mentioned above.

1.2 Leak Detection Improvement

Over the past few years, there has been a move for pipeline companies to deploy multiple independent leak detection technologies on pipelines. Indeed, in some countries to operate a pipeline it is a statutory requirement [3]. Two major technologies in the field of leak detection are RTTM -based systems and NPW systems.

A real-time transient model (RTTM) based LDS updates receipt of each new data, between 5-15 seconds. However, processing and analyzing the data to determine a real leak takes many cycles. The LDS works by computing the difference between changes in pipeline inventory as computed from the model and the flow balance in the pipeline system. This density distribution and flow balance comes from the pressure measurements and the flow measurements. These differences or volume imbalance issues an alarm when the imbalance exceeds a given threshold [1, 2]. An RTTM is complex model with many configuration parameters to describe the pipeline and fluids. Some of these parameters are easily available (pipe inner diameter and length) and others onerous (soil thermal conductivity or pipe wall roughness).

And these required parameters estimated values are subjected to errors in the model along with the inaccuracy associated with the sub-models. Likewise, there are errors in the measured values that are used to both drive the model and compute the volume balance. Effectively the time to detect a leak is very much dependent on the size of the leak in RTTM based system. A small leak takes a very long time to detect hours perhaps unlike of a rupture detection. The imbalance from a tiny leak may not be enough to drive the imbalance over the threshold and hence never detected.

Detecting leaks in shut-in sections of pipeline also present a challenge to RTTMs when the flow balance is identically zero with some pressure measurement, and there is only the line pack to provide the critical information regarding the integrity of the pipeline. However, under shut-in conditions, for the line pack the role of the temperature profile becomes significant which affects the line packing. Herein lies an issue: to model the temperature of the fluid under shut- in conditions when the only driver is the ground temperature then the thermal configuration parameters along with ground temperature must be available with accuracy: this is not often the case. However, emerging technologies in the area may help address this problem, see [11] for example.

Another drawback of RTTM based LDS is the accuracy of the declared leak location. Predominantly for the same reasons there is a leak detection threshold, the declared leak location will only be accurate, at best, to within a few percent with the location accuracy deteriorating with leak size (worse for small leaks), distance between (flow) sensors, and compressibility of the fluid (worse in gas pipeline systems) and a few percent for a pipeline is a few kilometers which implies a lot of ground to inspect.

To overcome these limitations of an RTTM with increased sensitivity, robustness, reliability, and accuracy of a leak detection system, it is common for a pipeline company to deploy a complementary Negative Pressure Wave system.

The concept of a NPW system is simpler – the onset of a leak will generate a pressure wave, which will

travel outwards away from the leak site. If this pressure wave can be detected upstream and downstream of the leak, then the location of the leak can be determined with higher accuracy.

The leak location accuracy in an NPW system is a function of the data scan rate. Faster the data acquisition rate higher the accuracy. Hence the data acquisition rates in order of milliseconds can lead to location accuracies within tens of meters. Since the system is only reliant on detecting pressure waves, an NPW will be effective under shut-in conditions also when the volume losses are small similar to product theft.

NPW systems do have their own drawbacks. A leak signal if missed, or misinterpreted, then there is no second chance. Leak signals can attenuate quickly such that pressure sensors typically are required every 30-40 km to provide leak detection coverage over a longer pipeline. The instrument noise and poor repeatability can also have a detrimental impact on the ability to detect a pressure wave; operational “noise”, such as pulsation from reciprocating pumps can mask leak pressure waves [5].

However, the biggest drawback of an NPW system is in the architecture: to achieve higher data acquisition rates the wave detection algorithm needs deployment of an RTU in very close proximity to the pressure sensor. Once a “leak signature” wave is detected, a message is sent to central server the server collates and analyses these wave messages from all RTUs to determine if the data is commensurate with a leak.

Hence, in a NPW system many RTUs are required to be installed, commissioned and maintained in the field which is expensive. However, the ability to deploy the wave detection algorithms in a centralized server will significantly improve the installation, configuration and maintenance of a NPW system by removing the reliance on remotely deployed RTUs.

The work presented here demonstrate that the developed infrastructure and communication protocols can provide the bandwidth to achieve our goal of a centralized NPW system to support an RTTM.

2. MATERIALS AND METHODS

Hereunder, the details of materials and methods deployed are detailed.

2.1. Reliable Communication Over Optical Fiber Cable (OFC) Based Digital Communication Systems

Hindustan Petroleum Corporation Limited (HPCL) commenced using OFC-based digital communication systems by laying these cables in the pipeline trenches, thus creating private network for pipeline operations. Interestingly, this work started on the day of Christmas Eve of 1985. Since then, it has become the de facto standard of communication systems not only in HPCL’s pipelines but also in all pipelines operating in India.

Digital communication also has evolved from past PDH to present “Synchronous Digital Hierarchy (SDH)” systems and currently moving in the direction of MPLS systems eliminating the unreliability associated with communications based on radio – telecom modems and VSATs.

The bandwidth of this mode of communication has increased from a modest 32MBPS (PDH) to “Synchronous Transport Module - i.e. data rate 10GBPS (STM64)”. giving the opportunity to look beyond legacy forms of SCADA communication such as documented in this developmental and use case study.

2.2. Background of available communication Protocols

As stated in the Introduction, typical traditional – legacy SCADA communication protocols in use such as Modbus-Serial / IP, DNP-Serial / IP, and IEC 60870-5-101 / 104, are used in electric transmission systems and cross- country pipelines which operate with similar SCADA requirements. They continued to work in modern era digital communication systems and GSM modems as well. Even with wide onset of Ethernet based TCP/IP protocols the use of original serial protocols remained relevant – by conversion of original communication data frame structures to TCP/IP compliant data frame structures. However, it did not bring about the needed sea change in the polling rates and eventual leak detection performance. To sum up, these protocols will continue to be in use in pipelines and are best for purpose in LDS systems using the RTTM technology.

2.3. Evolution of new class of Real-time Deterministic Protocols

A new class of Ethernet protocols, better known under their classification name of “real-time deterministic Ethernet protocols”, started evolving around 2000 [6]. These protocols have been mostly deployed in factory environments where multi-axis robots need to work very rapidly, in a limited area on a

LAN (Local Area Network) environment.
Towards this need, “Data Acquisition system (DAQ)” was developed, using real-time (soft real-time) deterministic Ethernet protocols. The DAQ also supports the NTP for network-wide time synchronization and time stamping of pressures measured at remote pipeline sites, which is essential for any LDS to work, particularly a system as sensitive to time differences as NPW.

2.4. Details Of the Communication Protocols and Their Comparative Study

Enlisted in below Table.1, are such real-time communication protocols [6].

Protocol Name	TCP/IP	Nature of Software	Response Time (for 100 axils) /Jitter #
EtherCAT	Modified	Open	0.1ms/ <0.1msec
EtherNet/IP	Standard	Standard	1ms/ <1msec
SERCOS III	Modified	Open	<0.5ms/ /0.1msec
Profinet RT	Standard	Open	5 to 10ms*/ **1msec
Profinet IRT	Modified	Open	<1msec/ <1msec

Table Source:
* As per Profinet Organization
** As per Site Conditions
\# At Data Rate in 100 Mbits/s

Table 1: Comparision Of Real-time Communication Protocol

Profinet-RT was selected as the preferred protocol, as it supports “soft real-time” application and is designed to work in any standard Ethernet-supporting hardware, implying no special hardware needs. Further, the Ethernet over SDH technology in pipeline deployment does not support Time Sensitive Networking (TSN) or precision time protocol support as defined in IEEE1588. This effectively rules out most of the protocols listed in Table 1.

One enhancement needed in the user level implementation was the time stamp, which is essential component for the LDS application. NTP was used towards this purpose, which met the purpose [7].

Profinet-RT can optimize the absolute transmission time by factor of 6-10 and minimize the variance in transmission times by factor of 5-9. Refer Figure.1
The Profinet Ethernet frame structure is shown in Figure 2. A type number of 8892 shown in the below frame identifies an Ethernet frame to be a Profinet RT frame. VLAN tagging and priority support in network devices is mandatory for the protocol to work. Refer to Figure 2 [8].

In the handling process, the Profinet–RT protocol, as stated, always sets the priority bits ‘On’ and also sets the VLAN tag as per IEEE 802.Q. While in other situations also one may use VLAN Tag application, the priority bit enabling gives very efficient handling. How the Ethernet frame handling is different is depicted in Figure 3 [8].

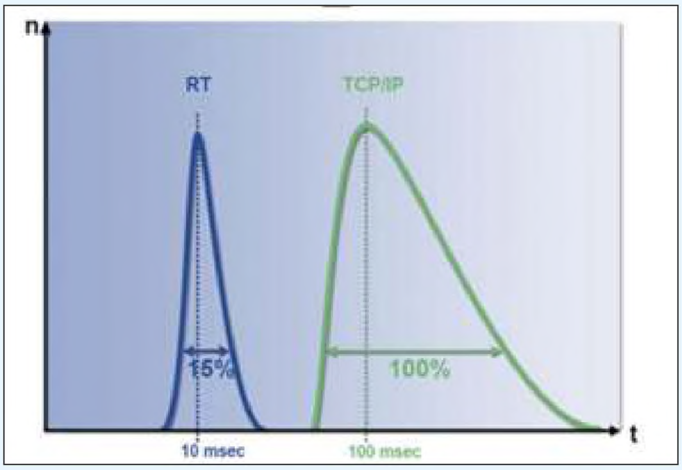


Figure 1: Profinet RT And Normal Ethernet Comparision

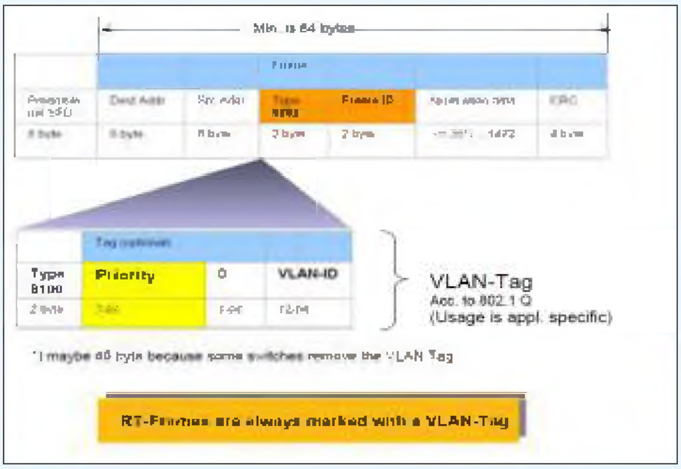


Figure 2: Profinet RT Framing Details

2.5. Data Acquisition System DAQ Micro Architecture

To achieve the project objectives for fast data acquisition purpose, design and development of a purpose-built DAQ was built (see Figure 4). The DAQ was in principle a single board computer (SBC), having Texas Instrument's Sitara model processor based "system-on-chip" Module [8]. Yocto Linux is the operating system used for this SBC.

The SBC fully supports the real-time deterministic protocol as a slave device for Profinet- RT protocol chosen for the project with input sub-system for high sampling rate (analog input of 4-20mA) and support to digital input.

Further, the SBC has independent Ethernet ports for supporting "Secure Shell Logins (SSL)" for interrogating the DAQs, "File Transfer Protocol (FTP)" for Configuration transfer and NTP time synchronization.

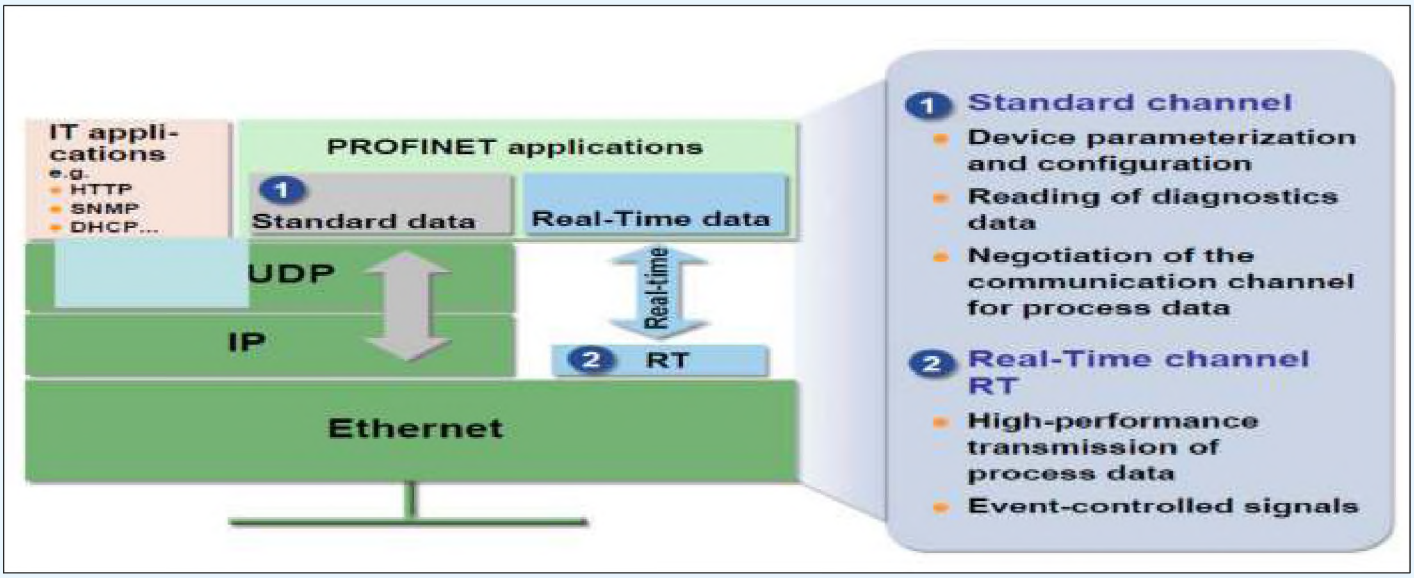


Figure 3: Profinet RT Frame Handling Vis-à-vis Normal TCP/IP Frames

2.6. Data Acquisition System – DAQ Macro Architecture - A Brief Discussion

As can be seen in Figure 4, the DAQ has two types of Ethernet traffic – one is for SSL / FTP / NTP traffic and the other is real-time protocol traffic. The normal Ethernet frame is 0x8000 and the Profinet-RT frame is of type 0x8892. Ethernet over SDH technology (OFC based communication) is used for transporting this data from Slave device to the LDS server, which also acts as Profinet-RT master. The LDS server directly uses the data, eliminating the communication hops of passing through SCADA servers, as in most installations. The Ethernet traffic architecture is as detailed in the Figure 4, on the following page.

2.7. Communication Architecture – A Brief Discussion

HPCL's Vishakha-Vijayawada Pipeline has OFC-based digital communication at STM64 speed interconnecting all pump stations at tier–1 level. The unmanned stations of the pipeline viz. CP stations, SV Stations and telecom repeaters between two pump stations are deemed at Tier-2 level and are at "Synchronous Transport Module- data rate 622MBPS (STM-4)" level.

The communication topology in use is Bus- cum-radial topology. That is, bus at Tier-1 level and radial from a Tier-1 communication node to Tier-2 communication node. The purpose built DAQs were deployed at all the communication nodes of both Tier-1 and Tier-2. The communication Architecture is shown in Figure 5, on the following page.

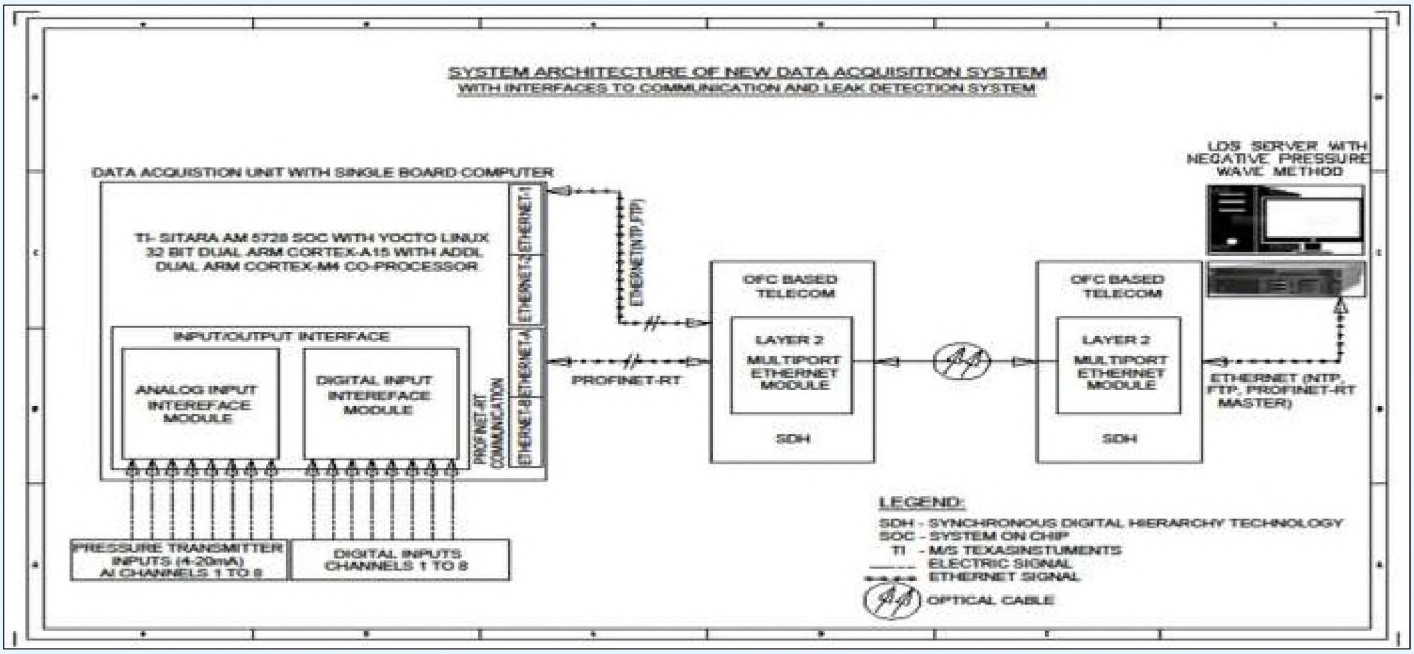
2.8. Negative Pressure Wave

A Negative Pressure Wave (NPW) system relies on the detection of the negative pressure waves associated with the onset of a leak. When a leak develops in a pipeline, the line pressure will drop suddenly at the location of the leak. After the initial drop, the pressure continues to fall but at a slower rate due to the unpacking of the pipeline. The initial pressure drop is often referred to as a rarefaction wave.

The rarefaction wave originates at the leak hole and propagates outwards at the local wave speed, eventually becoming two plane waves, one propagating upstream from the leak site and the other propagating downstream. Low noise, fast response and high-performance pressure transducers with response time of few milliseconds situated along the pipeline can be used to detect these waves.

The location of the leak can be computed knowing the precise time at which the passing wave is observed by each pressure sensor, the distance between the pressure sensors and the sound speed in the fluid.

To ensure that the rarefaction wave is not missed, pressure transmitters chosen and deployed have a time response as low as 2 msec and a maximum of 10 msec. The maximum response value has application when the pipeline is operating in a thermal environment that is sub-zero. DAQ electronic noise cancellation design is used only for prevention and minimization of electronic and magnetic interference.



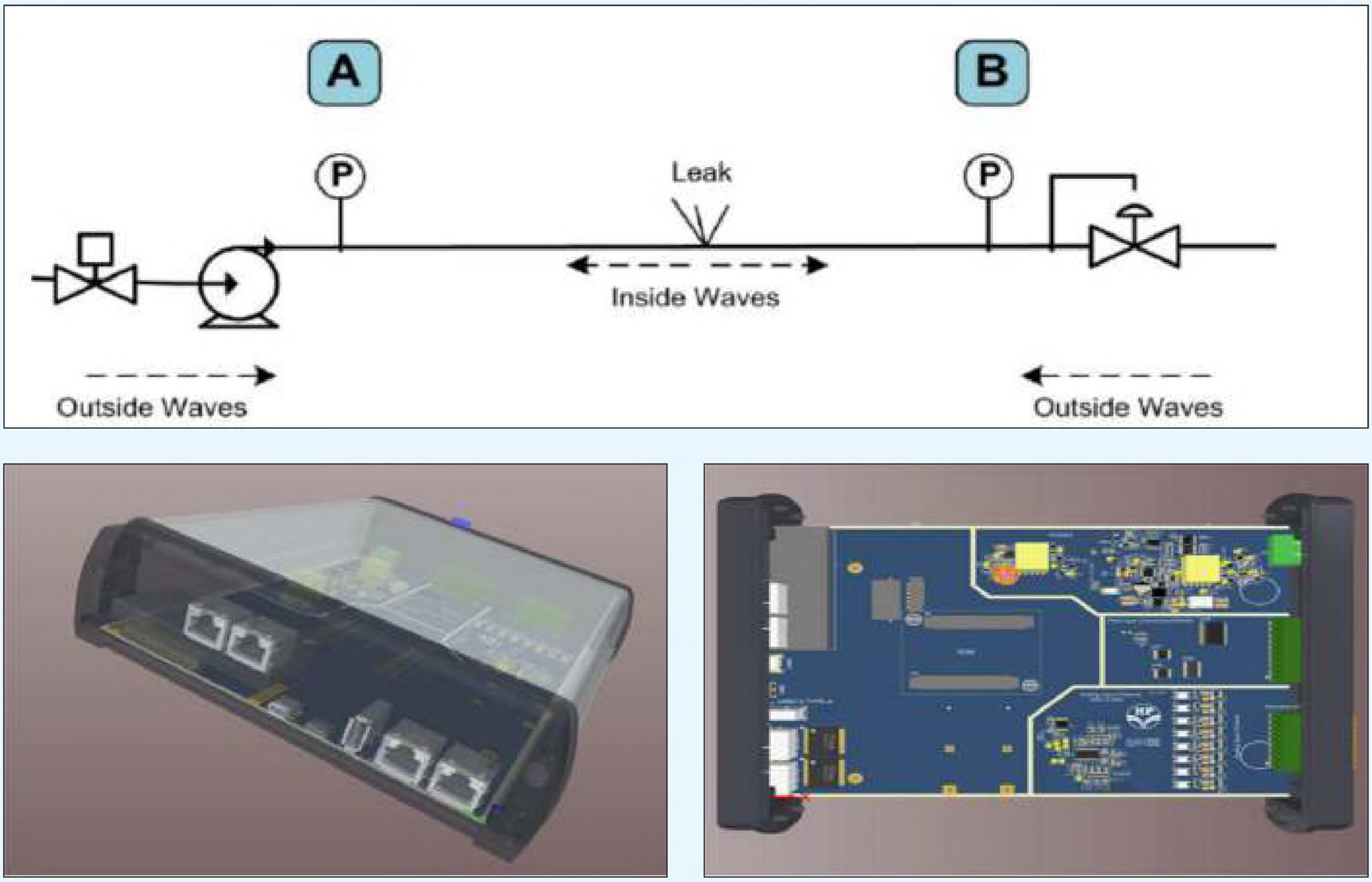


Figure 4: Data Acquisition System - DAQ Architecture (i-hardware Architecture; ii-working Principle of NPW; iii- Developed DAQ Exterior View; iv- Developed DAQ Interior View

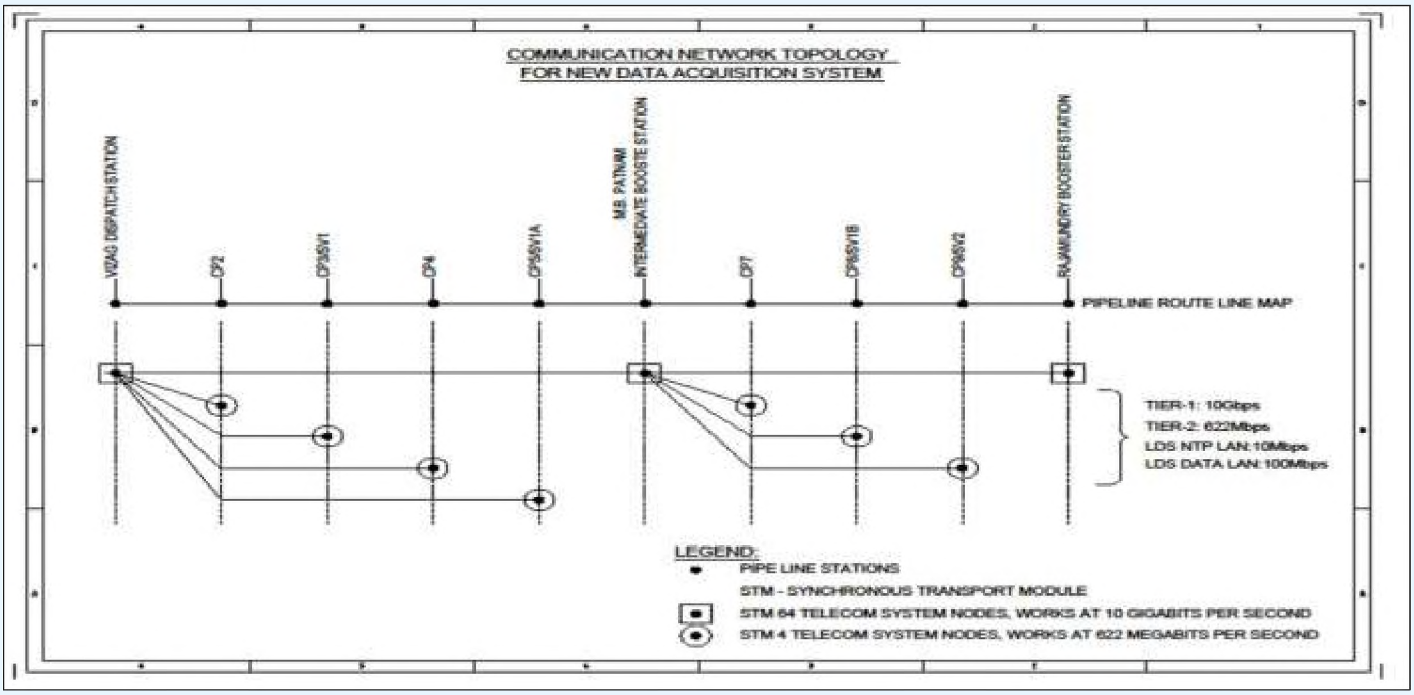


Figure 5: Communication Network Topology

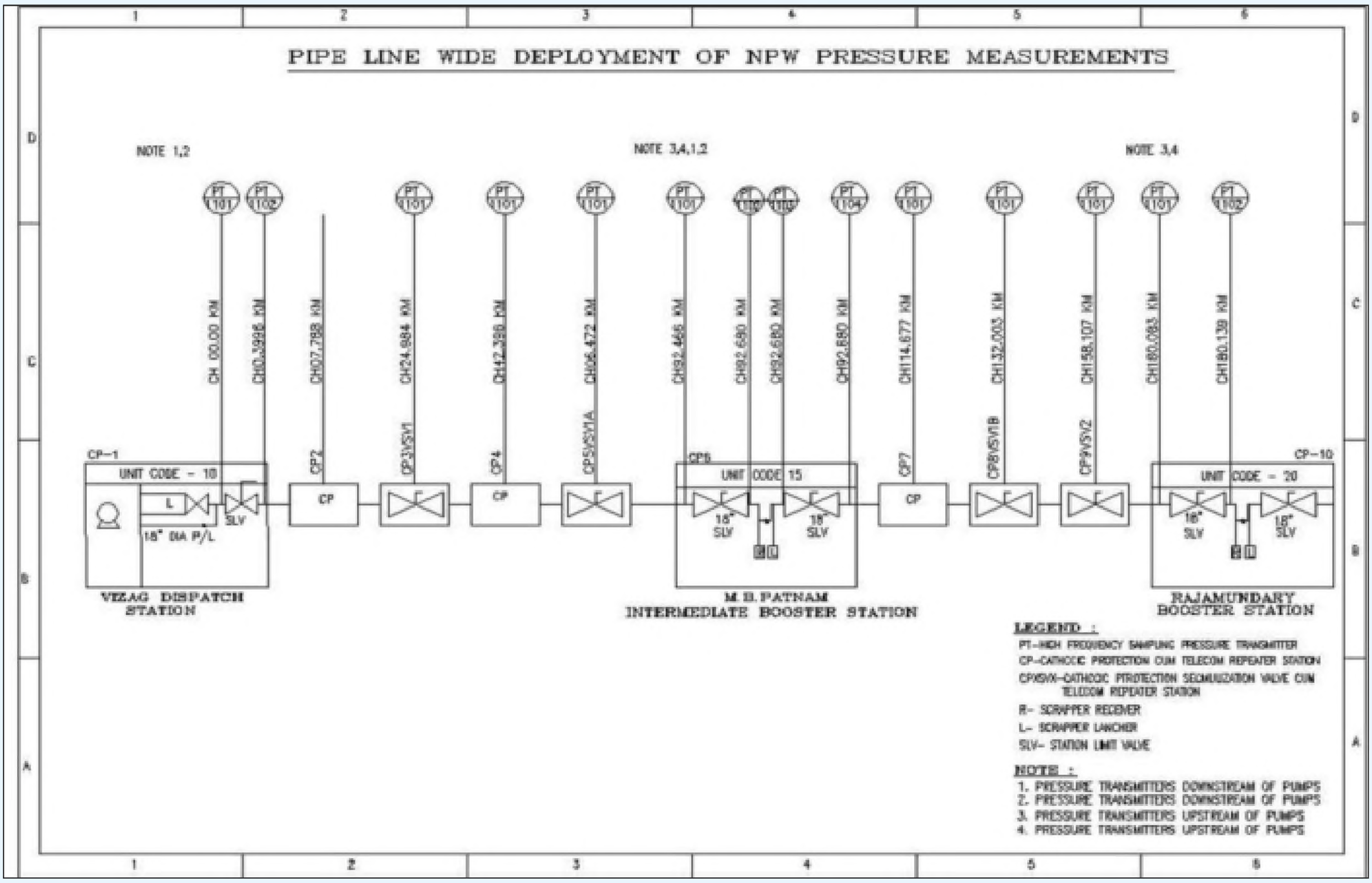


Figure 6: Pipeline Wide NPW Pressure Measurements

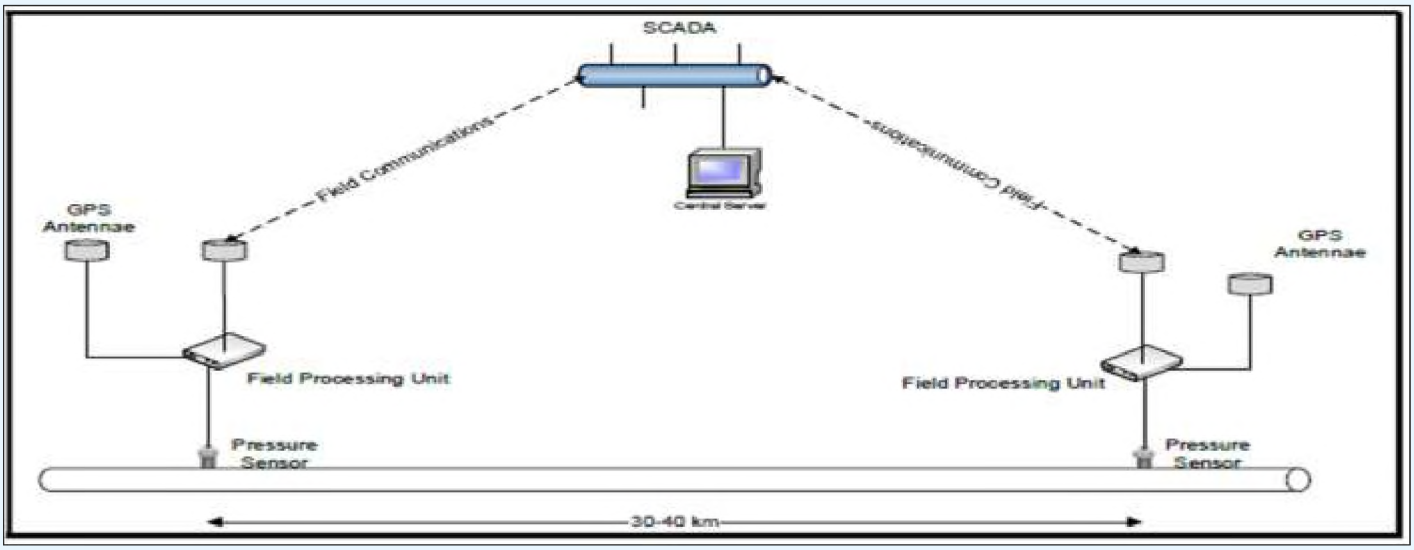


Figure 7: Typical Distributed NPW System

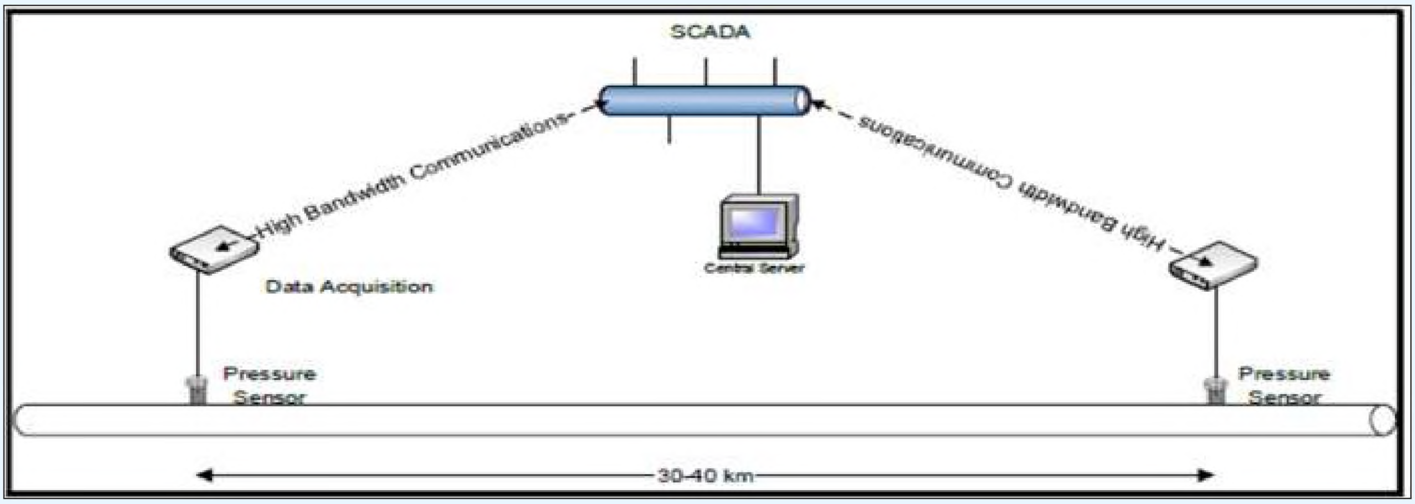


Figure 8: Localized NPW Infrastructure

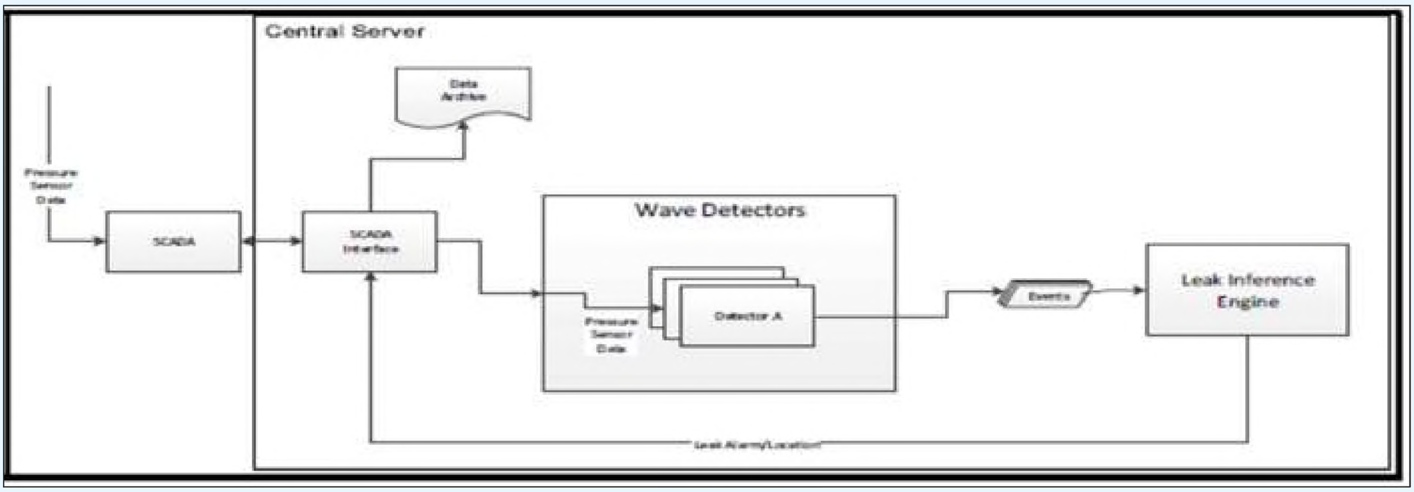


Figure 9: NPW Software Data Flow

Due to inherent data smoothing due to pressure sensor response times, necessary data filtering to reduce noise, uncertainty in the fluid wave speed, and possible system lags leading to discrepancies in the time stamping synchronization of pressure measurements, currently available NPW system cannot achieve location uncertainty of one meter. However, the rate of time stamped data acquisition is certainly a critical factor in providing accurate leak location.

The field processing unit (custom built RTU) will capture, and time stamp, the pressure data every few milliseconds, filter and pre-process the data and then analyze it to determine if there is evidence of a passing rarefaction wave that is commensurate with the onset of a leak. Should a rarefaction wave, or a wave that exhibits similar characteristics to a rarefaction wave, be detected, then a datagram containing the details of the detected wave will be sent to a central server (see figure 7). Algorithms enacted in software running on the central server examine all received detected wave signals and assesses them to determine if there are pairs of time stamped signals opposite ends of the pipeline that could have been produced by the onset of a leak and if so, the location of that leak along the pipeline.

With the evolution of the new class of real-time deterministic communication protocols and data transfer over an optical fiber network the field processing units can be dispensed with, and the data filtering, processing and wave detection algorithms can be deployed directly on the central server (see figure 8).

This has several advantages, easier to install, configure, commission, and maintain a centralized system in addition to develop and deploy the software architecture on a standard Windows platform rather than an embedded system running on a proprietary RTU.

The newly developed DAQ provides the time stamping of the pressure data with source clock hosted on the central NPW server and time synchronization distributed over the Ethernet channel (see Figure.4) which minimizes the loss of time stamp integrity.

The data interface between the centrally located NPW system and SCADA very much resembles a typical RTTM-SCADA data interface but with modifications in the receipt of packaged data and data fetch rates in the order of milliseconds. Once received and unpackaged, the data is farmed out to virtual field processing units for processing and analysis. This provides great opportunity for parallel processing. The event pairing and alarms generation remain unchanged (see figure 9).

2.9. System Deployment and Testing: Details of Pipeline

The system was deployed between Vishakhapatnam Dispatch Station and Rajahmundry Intermediate Pumping station, in Southern State of Andhra Pradesh, India – which are apart by 180 Kms and all the intervening CP/SV/ Telecom Repeater Stations. The details of the pipeline are shown in Figure 6. Leak withdrawal tests were conducted at CP/SV1 and IP1 stations.

2.10. Details Of the Tests Undertaken

The leak simulation is performed with orifice plates of different hole diameter sizes which can be inserted between 2” flanges with hand operated valve control. The amount of product withdrawn is also controlled by keeping the valve open at 25%, 50%, 75% and 100% at any time for having wide range of leak situations–The tests used an orifice plate of ¾” (20mm) and ½” (12.7mm) in all cases. Tests were conducted both in steady-state operation of pipeline as well as transient mode of operation. A pump start / stop was used for the transient state for the purpose of the study.

Most of the steady state tests were done at M.B.Patnam Intermediate Pump Station (unit code 15), as can be noted in Figure 6 above. The transient mode tests were done at CP/SV1.

3. Results And Disussions

The developmental work objectives and eventual test results set out to be achieved are shown below, in brief:

DATA ACQUITION TIME	LEAK DETECTION TIME	LOCATION ACCURACY
PRESENT SYSTEM		
10-15 Sec	10 – 15 Minutes	+ / - 2 to 3 KMS
R&D PROTECT DELIVERABLE		
10 to 20 msec	2 to 3 Minutes	+/- 200 Mtrs
PROJECT OBJECTIVES AS BEING DELIVERED		
1.5 to 1.6 Scans in 10 msec	Within 2 – 4 Minutes	Statistics below

Table 2: Performance Objective And Results Achived

3.1. DISCUSSION

3.1.1. Polling rates

Data updates were taking place at 150 - 160 times a second, translating to 1.5 - 1.6 updates in every 10 msec, which shows vast improvement over the traditional protocols and that the intent of the developmental work performed on the DAQ side was achieved.

3.1.2. Steady state leak simulations

Steady state leak simulation results are tabulated in Table no.3. The time difference between Leak Simulation Start and End is noted in synchronization with the time of the NPW server. In addition, the leak detection time is as per the NPW system announcement. Similarly, the difference between actual leak location and leak-detected location is by the KM Post.

The outliers are highlighted in gray, which are noted to be very few.

Further, the fractional size of the leak compared to the mainline flow rate is also tabulated in Table no.3.
For statistical analysis, certain data sets cannot be used and were omitted when (a) the leak was detected earlier than the actual leak start time – an obvious human error in noting the time and (b) when the confidence level has been advised to be low by NPW technology backend process.

S.NO	Leak Flow Rate in % of Mainline Flowrate in m^3 / hr	Leak Detection Timing from Time of Simulation Start Time hh:mm:ss	Error in Leak Detection Distance in Kms	S.NO	Leak Flow Rate in % of Mainline Flowrate in m^3 / hr	Leak Detection Timing from Time of Simulation Start Time hh:mm:ss	Error in Leak Detection Distance in Kms
1	2.572	0:00:11	-0.06	12	2.727	0:02:19	-44.873
2	2.359	0:00:06	-0.19	13	3.933	0:00:06	0.68
3	2.139	0:00:04	-0.14	14	3.008	0:01:19	0.031
4	1.904	0:00:03	-0.059	15	4.746	0:00:01	0.097
5	1.123	0:52:07	-0.147	16	1.881	0:00:00	0.532
6	2.265	0:00:05	-0.096	17	2.567	0:00:00	0.37
7	4.103	0:00:43	20.945	18	1.852	0:00:00	0.551
8	5.622	0:02:33	-0.034	19	1.613	0:00:04	0.527
9	3.569	0:04:10	11.95	20	1.937	0:00:01	0.598
10	4.694	0:04:19	-0.11	21	3.219	0:02:00	0.5
11	2.749	0:02:04	0.07	22	5.066	0:02:02	0.64

Table 3: Steady State Leak Simulation Results

3.1.1. Transient leak simulations

The transient leak tests list the size of leak created as fraction of valve opening. The leak flow rate could not be measured due to site conditions. The size of the transient is also tabulated by changed of mainline flow rate. Certain leak tests were omitted using the same rules as the steady- state leak tests. Transient leak test results are tabulated in Table no.4.

3.1.2. Kernel Density Plots

The leak detection distance error is clustered around a near-zero mean value with a small variance. Mostly the location accuracy is close to the project goal of +/- 200m of the actual leak. There are obvious outliers, as is often the case with experimentation, and these effect the overall variance, but the advantage of presenting the results as KDE plots is that the outlines do not adversely affect the variance of the central cluster of errors.

Leak Size - Orifice Plate in mm	Valve Size Controlling Leak Flow	2" Valve Open Status in %	Mainline Flow Rate Before and After Transient Creation by Pump Start or Stop Action m3 / hr	NPW System Response / Votes	Leak Detection Timing In hh:mm:ss#	Error in Distance in Kms	Remarks
20	2"	100	343/580	6/3	0:02:53	-0.187	
20	2"	100	620/380	6/3	0:02:47	-0.05	
20	2"	100	420/680	6/3	0:01:59	-0.021	
20	2"	100	580/340	6/3	0:02:45	-0.299	Concurrent events of both transient state & leak start
20	2"	100	430/720	6/3	0:03:55	-0.385	
20	2"	50	580/350	6/3	0:03:00	-0.328	
12.7	2"	100	450/650	3/3	0:00:00	-0.299	Low Confidence Votes
20	2"	25	556/430		0:00:00	#VALUE!	No Detection
20	2"	50	350/450	6/3	0:00:00	-0.437	
20	2"	50	450/292	3/3	0:02:52	-0.173	Low Confidence Votes
20	2"	50	355/590	6/3	0:02:57	-0.176	
20	2"	50	431/280	6/3	0:02:55	-0.248	
20	2"	25	347/562	6/3	0:02:02	-0.299	
20	2"	25	451/315	6/3	0:01:09	-0.299	
20	2"	25	332/520	6/3	0:00:00	-0.306	
20	2"	25	363/555	6/3	0:00:48	-0.167	
20	2"	25	451/300	6/3	0:02:21	-0.21	
20	2"	25	339/554	6/3	0:00:10	-0.141	
20	2"	25	465/294	6/3	0:02:48	-0.234	
12.7	2"	100	344/556	6/3	0:02:01	-0.277	
12.7	2"	100	456/287	6/3	0:01:50	-0.21	
12.7	2"	100	332/534	6/3	0:00:51	2.75	
12.7	2"	100	410/274	6/3	0:03:34	-0.167	
12.7	2"	100	300/492	6/3	0:02:46	30.964	
12.7	2"	100	437/284	6/3	0:01:18	8.074	
12.7	2"	75	315/500	6/3	0:01:48	-0.201	

Table 4: Transient Leak Simulation Test Results

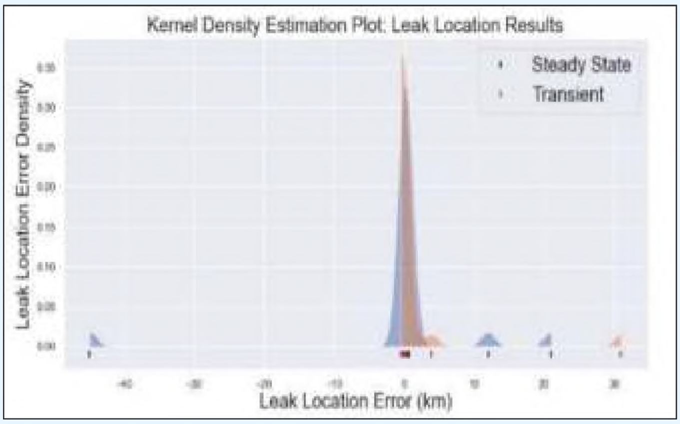


Figure 9: KDE Plot Showing Outliers W.r.t Leak Location Error

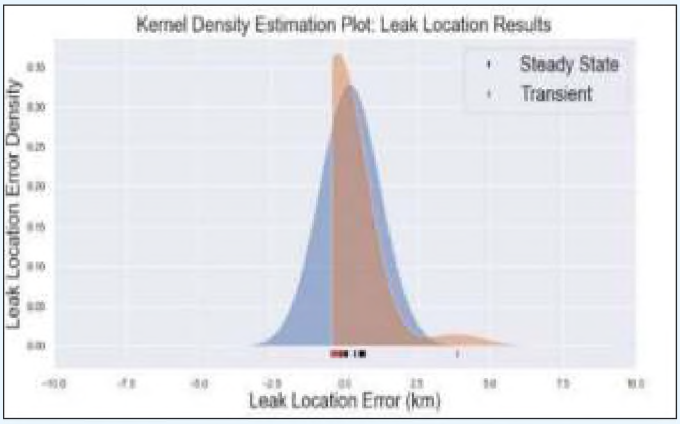


Figure 10: KDE Plot Showing Location Errors

The plots for the time of detection show a far less centralized clustering, as perhaps one would expect. It is clear that, in all but one case, the detection times are all within 5 minutes – which is very pleasing. The time to detect for the steady state leak simulations is more centralized, but with more outliers (reflecting the location accuracy results) and shows that a significant proportion of the leaks were detected within a minute. The time to detect for the transient leak simulations is more spread out – this is due in part to more work being required to find the signal (leak onset pressure wave) over the noise (the transience in the system).

The modified NPW architecture and data interface enabled the receipt and processing of packaged data in the order of milliseconds. The use of virtual field processing units provides great opportunity for parallel processing.

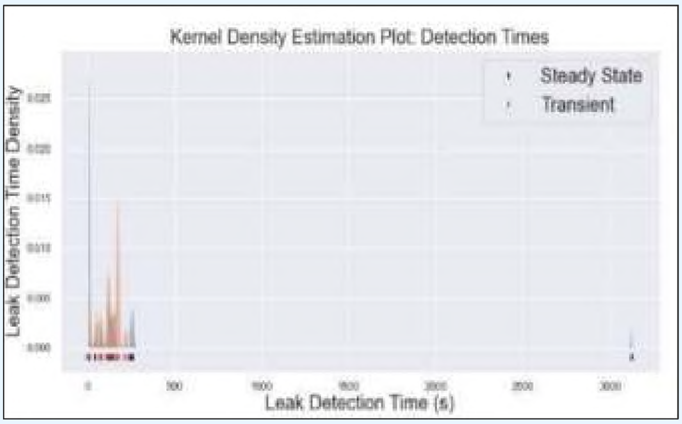


Figure 11: KDE Plot Showing Leak Detection Times

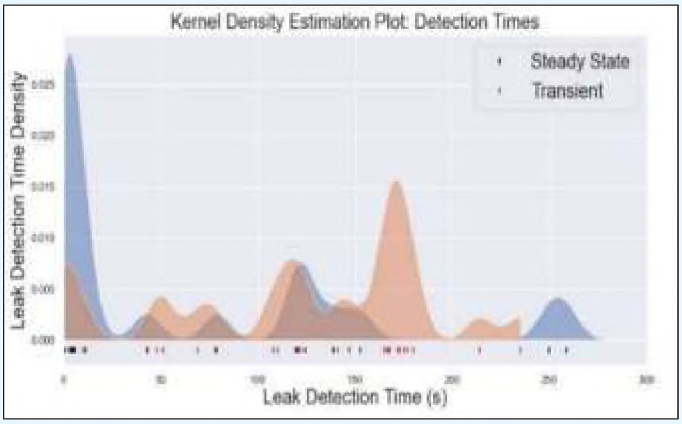


Figure 12: KDE Plot Showing Leak Detection Times In Detail

3.1.3. Cyber security aspects using Real-time Deterministic Ethernet Protocols

Real-time deterministic Ethernet protocols – as they support soft real-time and hard real-time application and very low latencies – invariably are implemented in firmware. This is itself, is a major positive in use of these protocols. Further aspects considered are detailed below.

Deployment in Pipeline wide area networks in Dedicated Private Networks

The dedicated private OFC network owned and operated by the pipeline operator is used for this test which is completely isolated from the Internet with LDS/NPW servers under Operation Technology (OT) domain adding additional security.

IED based implementation

The Profinet-RT slave and Profinet-RT master device (the master is a PCI Express card in NPW server) are both based on ARM processor-based SBCs of embedded design in nature under category of "Intelligent Electronic Devices – IEDs".

The Profinet-RT protocol data frames, once they reach either end, are accessed by ARM computers using chip-to-chip interface protocols (such as Serial Peripheral Interface Protocol).

Any cyber-attack and its datagram packets will not be recognized by ARM SBCs and will be rejected with No Acknowledgement messages.

However, further work is needed to continue to harden the system security.

READ ONLY data

The entire system of Profinet-RT layer is working on read-only data. No write requirement is foreseen in both Profinet-RT slave/master Devices providing strong security of the configuration files.

NTP Protocol

The NTP protocol at Master station also originates from a NTP server, which is a IED device, as long as the system is in Operational State.

Identified Vulnerabilities

However, the designed DAQ can be deemed as Internet of Things – IOT device, as far as remote access for configuration changes, which happens over normal Ethernet communication TCP/IP protocols which can be inferred from Figure. 4.

Though this test system is totally insulated from Internet and is currently working as point-to-point in the master – slave protocol implementation, all the due diligence still needs to be given if the system were to be implemented by use of public communication networks, GSM-based networks such as 4G/5G and satellite-based communication networks, where pipeline companies do not own private dedicated communication network.

Due diligence as per recommendations such as from National Institute of Standards and Technology (of US Department of Commerce)'s Guide to SCADA and Industrial Control Systems Security may be adopted [10].

4. CONCLUSIONS

The approach and technology discussed in this paper provides (1) that it is possible to deploy alternate Ethernet protocols which can enhance the polling rate of leak detection data and (2) a new way of deploying NPW based leak detection systems.

It was confidently concluded that it is possible to deploy real-time deterministic Ethernet Protocols, specifically soft real-time, for data acquisition in cross–country pipelines, providing there is reliable optical fiber cable-based communication system, with Ethernet over SDH or equivalent technology available. With satellite-based internet becoming the order of the day, it should also be possible to do data transmission where optical cable may not be pre-existing.

Such protocols facilitate moving from a distributed NPW system with data processing being undertaken locally at remote RTUs to a system where data processing is undertaken on a central server. Such a change reduces the installation, configuration, commissioning, and maintenance burden whilst maintaining the reliability and efficacy of the NPW leak detection system, and even brings reduction in capital expenditure on standalone NPW deployments.

4.1. Further Work

The SBC-based DAQ deployed with TI Sitara based system-on-chip has ability for AI/ML applications. Hence, it could be possible to use it as an edge computing device to improve the efficacy of the leak detection, especially in transient states of pipeline operations. Further, as DAQ also has IOT capability, another architecture using 4G/5G technology may be done as part of future work.

From the point of view of the NPW architecture, further work needs to be undertaken to determine where bottlenecks might appear in the system and how best these can be dealt with. Edge computing certainly provides potential in this area and may well allow NPW systems in significantly extensive and complex pipeline systems.

Further testing needs to be conducted when multiple products are present in different sections of the pipeline to assess the effect on the efficacy of the NPW system when subjected to multiple different wave speeds. If we assume NPW non-availability when Transmix/Interface is present in Pipeline section – then such non-availability time is for about 2-5% basis actual batching done in Test section in a Calendar month.

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Note

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