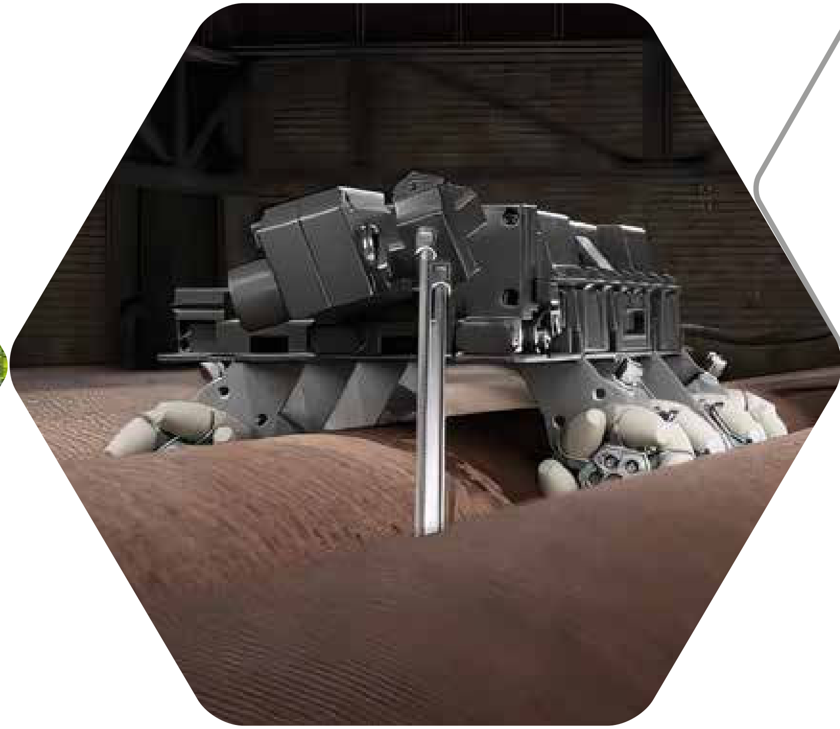
White Paper: A Techno-Economic Overview of Fouling in Steam Crackers and Available Solutions



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Glossary

BOE	Barrel of Oil Equivalent
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
DSS	Dilution Steam System
GHG	Greenhouse Gases
GNP	Gross National Product
Gt	Gigaton (1 mln metric tons)
GWP	Global Warming Potential
HSE	Health, Safety & Environment
INDC	Intended Nationally Determined Contributions
LOS	Line-Of-Sight
PE	Polyethylene
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
T-EPC	Technology, Engineering, Procurement, Contracting (services)
TLE	Transfer Line Exchanger
TSCA	Toxic Substances Control Act (US Legislation)
tpa	(metric) tons per annum
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU Directive)
VOC	Volatile Organic Chemicals/Compounds

1. Executive Summary

Fouling of petrochemical manufacturing facilities is well documented as having negative effects on plant throughput, energy requirements, environmental footprint, and product quality. Studies indicate that process fouling within heat transfer equipment costs some industrialised countries as much as 0.25% of their Gross National Product (GNP). *According to the Lund University study, in 2020 direct GHG emissions from the petrochemical sector amounted to 1.8 Gt CO_2 eq which is equivalent to 4% of global GHG emissions.

Fouled convection section can increase greenhouse gas (GHG) emissions and create safety hazards. There is a strong case for highly efficient fouling removal techniques, both from financial stakeholders looking for maximum carbon reduction and external bodies including government regulators and consumers pushing for energy efficiency and safety.

**Source: https://lucris.lub.lu.se/ws/portalfiles/portal/117494791/Petrochemicals_climate_change_review_web.pdf*

The following white paper examines the causes and effects of fouling in petrochemical manufacturing plants. Ethylene production via steam cracking relies on complex plant equipment and high-energy chemistry and has fouling vulnerabilities in the reactor tubes and other parts of the plant. It is a useful model for studying the effects of fouling and the benefits of efficient fouling removal.

Key findings and conclusions include:

- Ethylene is a major building block of the chemical industry and many new plants are being constructed to meet demand. The key technology for ethylene production is via steam cracking of naphtha or ethane.
- The energy intensity of an ethylene cracker is such that a 50 °C deviation in design stack temperatures, as witnessed in a fouled furnace convection bank can result in an efficiency loss of 1.5-2.0 %.
- For a plant section with five furnaces in operation, it is estimated that in the three-year period after a robotic clean, a cumulative saving of $5.44 million is possible; as the average cost per furnace is moderate, payback of the initial investment would be within several months,

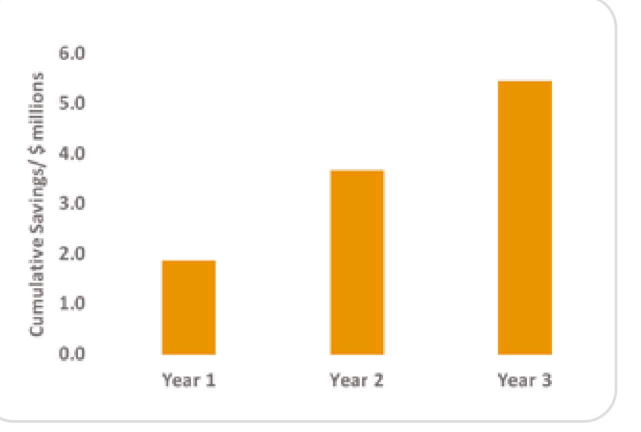
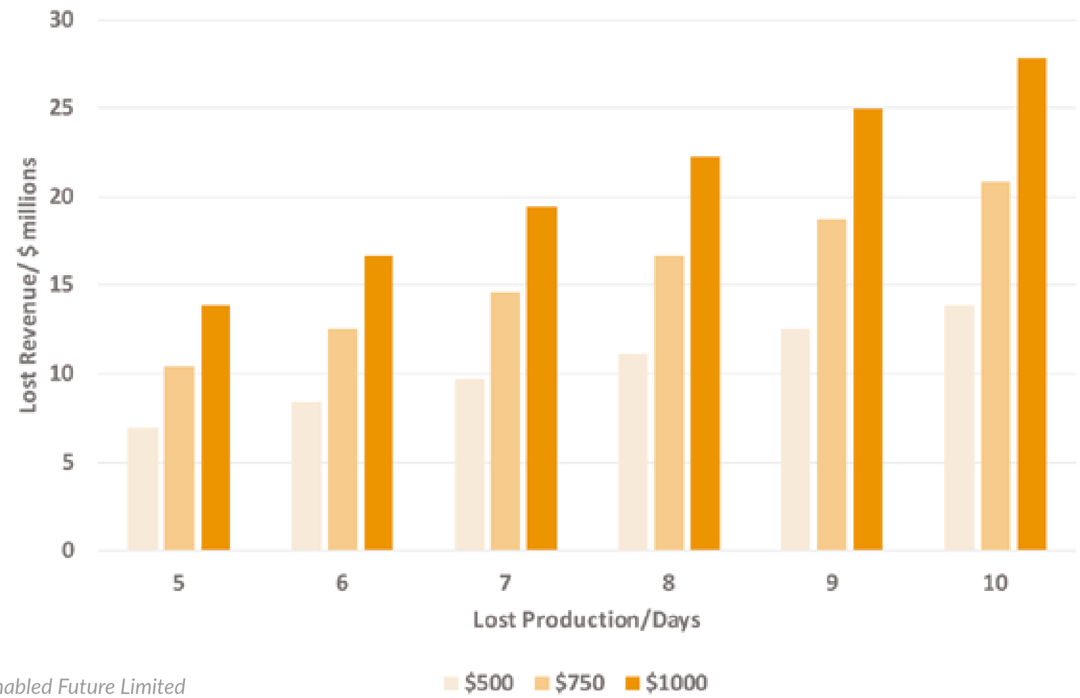


Fig.1 Cumulative Savings from Robotic Cleaning of a Fouled Convection Bank
Basis: Furnace Convection Bank Fired Duty: 109 MW; Five Cracking Furnaces; Stack Design T: 149°C; Actual Stack T: 199°C; Efficiency Loss: 1.86%; Fuel Cost $23/MWh

- In certain instances, fouling can cause a reduction in ethylene plant productivity. A 5–10-day equivalent loss of throughput during an unplanned shutdown can result in $14-28 million in lost revenue at an ethylene price of $1000 per ton. If the fouling exists in the integrated polymer production sites, the problem compounds, giving even bigger margin losses on the finished consumer products.

- Many existing mechanical, chemical and hydroblasting fouling removal methods fall short of the full cleaning potential possible. The task of efficient fouling removal is painstaking, repetitive and requires high accuracy. As in other sectors with similar requirements the Industry 4.0 (Smart Manufacturing) robotic approach performs well.



Source: Enabled Future Limited

Fig.2 Lost Revenue for Ethylene Production via Steam Cracking. Reduced Plant Throughput - Financial Analysis Basis: 1 million tpa; 90% Target Operating Rate (324 days/year onstream); Ethylene Price $500, $750, $1,000 per ton

- Tube Tech Industrial is currently the only company globally to offer a robotic approach with a patented deep cleaning lance system. The company develops custom robotic solutions for fouling remediation and removal where other techniques struggle or have failed. Its robots are equipped with proprietary delivery systems and record in real-time before, during and after fouling removal.

- Tube Tech's robots are specifically designed to remove 90-95+% deposits from tube and fin surface area back to OEM design performance from areas with restricted access, producing minimal waste and achieving close contact cleaning with precision and uniformity due to the programmed, robotic approach.

- Tube Tech's future goal is to provide technology as an integral part of the manufacturing flowsheet – installed on the asset plant-wide from the beginning as a permanent feature, to enable cleanable online assets; keeping the plant running at its most optimal and profitable condition in line with the standard shutdown process. This kind of approach constitutes the gold standard which industry can adopt to meet the desired goals of maximum carbon productivity, profitability and safe, environmentally sound performance.

2. Introduction

Fouling has a profound effect on the running of a manufacturing plant, dragging down its efficiency, throughput, profits and environmental footprint. It leaves the operation susceptible to emergency and even catastrophic shutdowns, dramatic reduction in production and incremental increase in incidents. Unfortunately, market demands often make these inevitable, placing a considerable burden on competitiveness and the economics of a nation.

Fouling of heat transfer equipment is inevitable in the production of chemicals, fuels and power. Fouling negatively impacts plant economics, and environmental performance and causes safety hazards. Various attempts have been made to quantify the costs of fouling [1-5]. While there is not yet a comprehensive industry study in the public domain, top-line statistics make for a compelling case to reduce or avoid fouling altogether:

- Individual small to medium refineries report losses of $3-4 million per annum due to fouling
- Costs associated with refinery preheat train fouling in four major industrialized countries have been estimated to be in the order of $4.5 billion or 0.25% of Gross National Product (GNP)
- Crude fouling in refinery preheat train (PHT) networks costs 0.25% barrel of oil equivalent (BOE) of all refined crude, or 66 million barrels per year (at $50 per barrel equates to $3.3 billion in lost revenue)
- 1-5% of the energy consumed by the industrial sector is used to overcome fouling
- 2.5% of CO_2 emissions (0.8 Gigatons) are due to fouled heat transfer equipment and account for between 3-10% of individual refineries carbon footprint.
- The fouling and the inability to clean preheat train exchangers, especially on the external shell side, can lead to a decline of as much as 12C (22F) in furnace inlet temperature. The subsequent need to burn extra fuel therefore results in higher costs and an increase in CO_2 emissions of more than 20%.
- Deposit build-up on furnace coils and downstream equipment leads to dangerous increases in pressure and temperatures that cause corrosion, cracks and leaks leading to serious safety hazards and often catastrophic shutdowns. Fatal incidents within chemical plants and refineries have been known due to inadequately addressed cleaning standards that have led to such fouling and corrosion.

Fossil fuels are under more scrutiny than ever before given the evidence that greenhouse gas (GHG) emissions are causing an increase in global air temperatures, subsequent climate change and adverse weather events. Legislation and voluntary measures are continually being developed to tackle GHG emissions. More than 190 countries have signed up to the Paris Agreement with a view to limiting global warming to 1.5°C above pre-industrialised levels. Each country has pledged to set out a plan of GHG reductions (Intended Nationally Determined Contributions - INDC) to be enacted within the next decade.

Punitive measures in the form of carbon taxation, fines and loss of investment all await industries that do not react to remedy the situation. Activist investors are demanding better economic, environmental and safety performance from businesses engaged in the production and use of fossil fuels. Recently several high-profile investors have pulled out of these assets altogether. Companies active in the fossil fuels supply chain must carry out process intensification and improvements to meet the expectations of their stakeholders and avoid penalties. Addressing fouling in the most cost-effective and efficient manner possible has never been more of a priority.

3. Cleaning Process

There are a range of fouling removal methods for heat transfer equipment and chemical reactors. Some specialist measures for ethylene plants include protective coatings and anti-foulants. In recent years, amine-neutralized sulfonate anti-foulant treatments have been used in some ethylene plants to reduce furnace coil fouling. These compounds, however, have failed to prevent coking and fouling of Transfer Line Exchangers (TLEs) immediately downstream of the furnace. The failure with respect to the TLEs may be due to premature degradation of the treatments in the ethylene furnace which sees temperatures in the range 1,000° - 1,700°F (538 - 927°C).

Cleaning maintenance contractors range from small local companies with straightforward mechanical and hydroblasting methods to larger more sophisticated companies with several de-fouling methods in their portfolio. Many manufacturing plant operators tend to operate on a fixed budget, even if there is less than complete removal of fouling rather than opting for an expensive but more thorough approach. In the long term, this does not make economic sense. Even a fraction of a per cent deviation in planned output results in $ millions in lowered revenue. This is even before the costs of additional energy, reduced equipment lifetime, higher CAPEX and potential for safety issues or incidents are considered. Ideally, operators would choose a plant cleaning method which ensured that no additional plant slowdown, shutdown, or loss of yield, attributable to fouling occurred. Such an approach requires a top-down management strategy, however, rather than a siloed approach which penalises the maintenance department for having a higher cost structure.

The difficulty here is that the term “clean” is subjective. How clean is clean? With no descriptor or mandate such as an API (American Petroleum Institute) document to guide plant operators it inevitably falls back to a slightly misguided philosophy of “it’s been done this way for so long why change” philosophy.

One such “out of sight out of mind” asset is the horizontal convection banks that sit above the vertical radiant tube section.

Methods typically used to remove fouling from deep within each finned convection bank that can consist of up to 12 rows of finned tubes, include relatively crude approaches such as mechanical and abrasive blasting techniques. These are slow, messy, hazardous, cause wear and risk damage to equipment and tend to remove no more than 20% of the foulant at best when applied in isolation due to their inability to remove fouling from all finned, heat transfer tubes.

Thermal techniques are useful where high-pressure methods cannot be employed due to the risk of refractory and tube damage. However, they are slow batch processes which need to be executed offline.

Manual spray injection of chemicals can remove higher proportions of foulant than mechanical techniques but as they take the least path of resistance, efficacy cannot be measured until after the unit is back in service which is not ideal. In addition, chemical cleaning generally relies on shear forces of 1.5m and 2 metres per second in order to optimise fouling removal effects. They also rely on organic chemicals and solvents which then pose challenges with emissions of Volatile Organic Compounds (VOC), ensuring worker exposure is kept to legislated limits and the need to comply with tightening toxic substances legislation i.e. the US Toxic Substances Control Act (TSCA) and the European Directive on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).

The use of cryogenic substances such as solid carbon dioxide known as dry ice and liquid nitrogen, offer the benefits of being safe with ventilation and having a zero-secondary waste profile. Equipment damage and corrosion are near zero especially with liquid nitrogen, deep cleaning outside of LOS is possible. The downsides are the expense of the cryogen which requires gas separation processes and refrigeration techniques with high utility requirements and the fact that **neither can clean past the first two rows of a convection bank**.

The use of manual high-pressure water blasting lances is a commonly employed technique offered both by smaller and larger contractors. Its downside is that carried out manually it is a line-of-sight (LOS) only technique where incidents of refractory damage have been inadvertently caused by operator carelessness or fatigue. Deposits mixed with water cascade down between tube rows creating a **mud-like paste that cements itself after run-up**; the pressure of the water and contact with the equipment can be less than uniform and as with manual cryogenic and chemical methods it is only able to deliver its pressure to the second tube row at best. Tube and insulation damage have been known, as well as under-scale corrosion due to aggregate formation as the water reacts with the foulant. Hydro blasting generates high volumes of waste water which may be classified as hazardous, increasing the expense of disposal.

Fig.3 Tube Tech Robotic Cleaning Technology

Fig.4 Convection Bank Cleaning using Robotic Technology

The use of pre-programmed robotics offers a safer step-change improvement over more mature manual lancing systems. The use of customised robots allows 90-95+% surface area cleanliness of convection banks between every tube row, regardless of fouling levels with cleaning standards verified using real-time digital video capture.

IGS Tube Tech is the only service globally offering such robotic cleaning systems. Its robots use proprietary lance and nozzle technologies which achieve very close tube surface contact in situ.

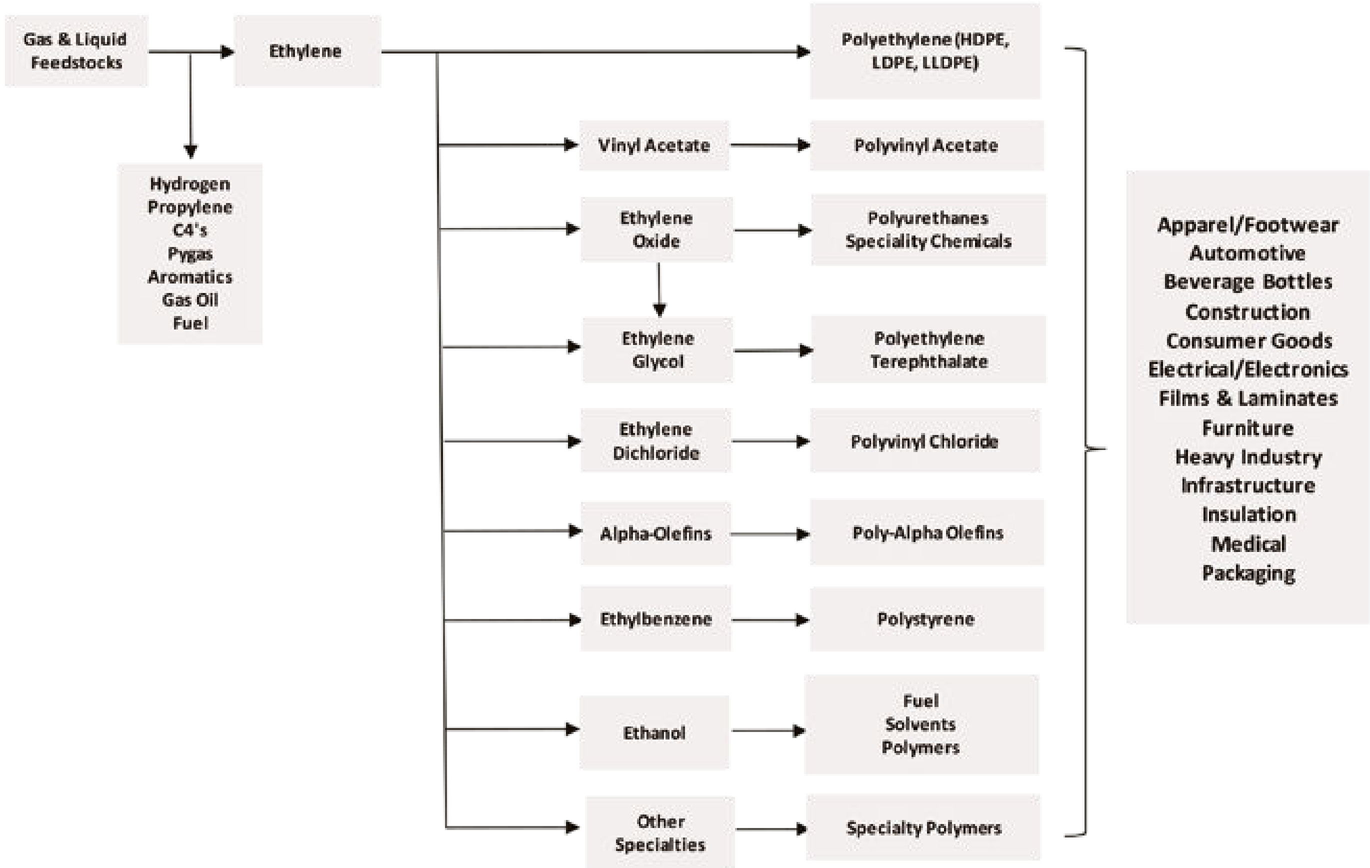
The versatile robots are used with air and high-pressure water. While very high pressures are involved e.g. up to 1,000 bar (15,000 psi), the total volume of water is much lower than standard hydro blasting.

There is minimal risk of refractory damage as the rotary jet on the lance is specifically angled towards the finned tubes. The robot has sensors which are programmed to stop prior the refractory wall. The absorption rate of water during Tube Tech robotic cleaning service has been examined in a collaborative report based on trials around the world.

4. Ethylene Case Study

4.1. Ethylene Value Chain

Ethylene is a major building block of the chemical industry, it is an intermediate product that is highly reactive and serves as a key feedstock for several high-revenue chemicals. These chemicals have complex value chains comprising unique technologies with many process steps. Key ethylene derivatives include polyethylene (PE), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) as well as a broad range of specialty chemicals. Virtually every industry contributing to GDP growth relies on products derived from an ethylene-based chemical. The global ethylene capacity was 223.86 mtpa in 2022 and is expected to grow at an AAGR of more than 6% during 2022-2027 [8]. To meet this demand millions of tons of new ethylene capacity are being built.



Source: Enabled Future Limited

Fig.5 Ethylene Chemical Value Chain

4.2. Ethylene Manufacturing via Steam Cracking

An ethylene plant is a multi-billion-dollar complex; the steam cracker is the central processing unit, but it is embedded in a flow sheet containing more than 300 individual units operating from 1,100 to -100°C. The major functions of the different plant sections are to clean up and prepare feedstocks for conversion; remove toxic elements including sulphur; separate out component gases which are not required for the cracking reaction, but which have value elsewhere; heating and pressurising feedstock to reaction conditions; performing the cracking chemistry and separating the product mixture obtained into single components, compressed, and delivered as pure high-pressure streams. The plant's output amounts to millions of dollars of product every day and it is of paramount importance to avoid erosion of margins due to process inefficiencies.

The ethylene production process entails the use of pyrolysis or "cracking" furnaces to produce ethylene from various gaseous and liquid petroleum feedstocks. Typical gaseous feedstocks include ethane, propane, butane and mixtures thereof. These chemicals are referred to as "saturated hydrocarbons" – they are carbons, saturated with hydrogen. The cracking reaction removes some of the hydrogen and produces "unsaturated hydrocarbons" (olefins).

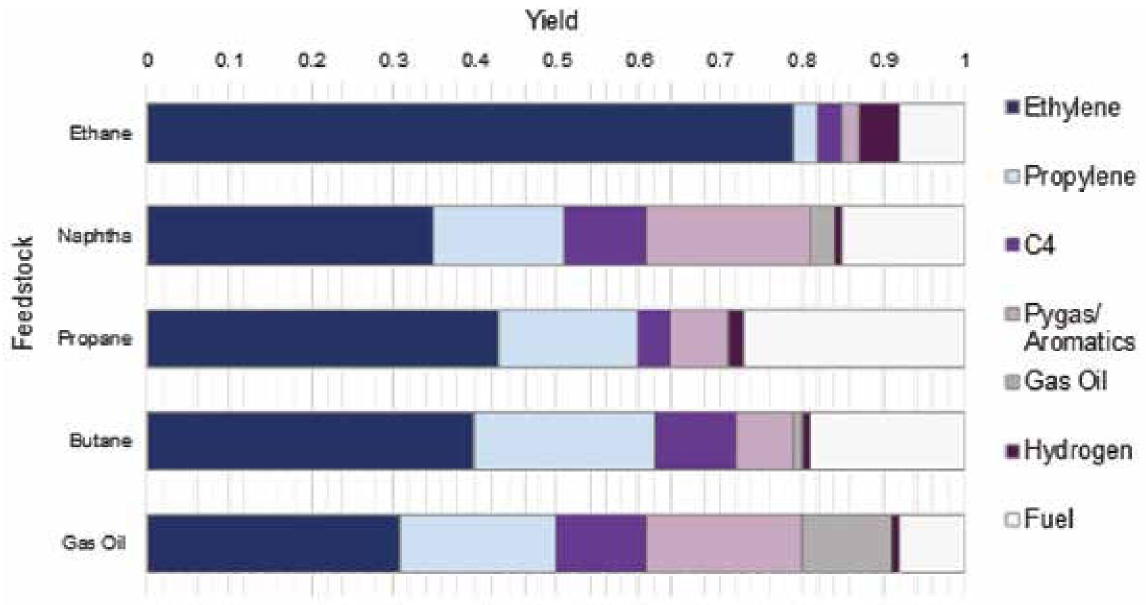


Fig 6. Typical Feedstock Yields for Steam Cracking Process [9]

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Typical liquid feedstocks include naphtha, kerosene, gas oil and crude oil. Product slates vary by feedstock. Ethylene from ethane is the simplest process with the highest yields of ethylene and the fewest by-products. European and Asian feedstocks are typically mixed feeds of heavier streams (naphtha, gas oil and kerosene.). Such processes using liquid feedstocks have a lower yield but a wide-range of valuable by-products.

Chemical bonds are strong, and it takes considerable energy input to crack open these bonds. The resulting "free-radical" species are highly reactive and undergo rapid reactions to regain stability. Free radical chemistry occurs in three stages: initiation, propagation and termination. The key primary reactions for ethane cracking are shown below. Further secondary reactions (not shown) occur which result in products with longer carbon chains and coke.

Initiation

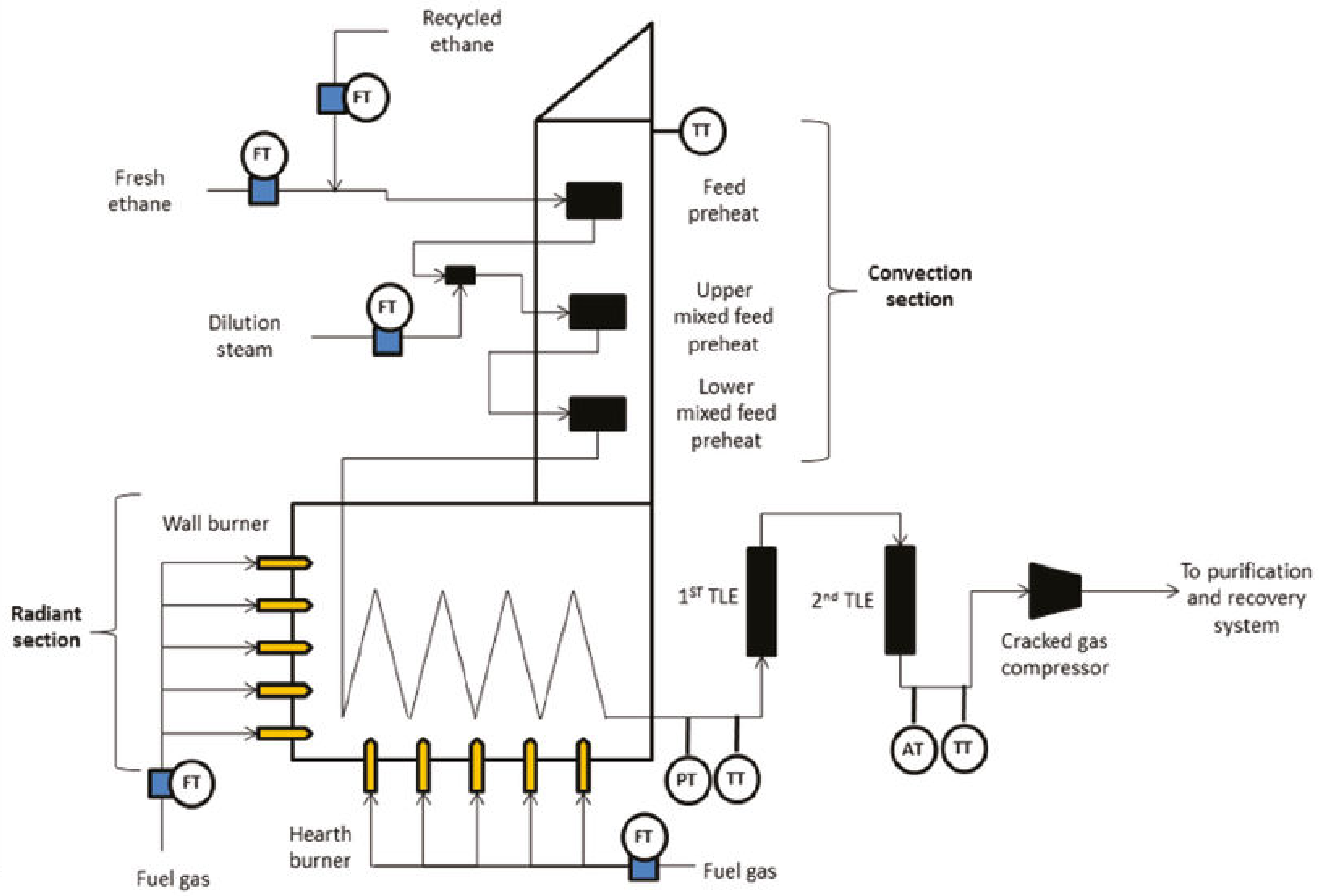
C_2H_6 Ethane			→	$2CH_3\bullet$ Methyl Radicals		

Propagation

$CH_3\bullet$ Methyl Radical	+	C_2H_6 Ethane	→	CH_4 Methane	+	$CH_3CH_2\bullet$ Ethyl Radical
$CH_3CH_2\bullet$ Ethyl Radical			→	C_2H_4 Ethylene	+	$H\bullet$ Hydrogen Radical
$H\bullet$ Hydrogen Radical	+	C_2H_6 Ethane	→	CH_4 Methane	+	$CH_3CH_2\bullet$ Ethyl Radical

Termination

$2CH_3CH_2\bullet$ Ethyl Radicals			→	C_4H_{10} Butane		
$H\bullet$ Hydrogen Ion	+	$CH_3CH_2\bullet$ Ethyl Radical	→	C_2H_6 Ethane		
$H\bullet$ Hydrogen Radical	+	$CH_3\bullet$ Methyl Radical	→	CH_4 Methane		
$H\bullet + H\bullet$ Hydrogen Radicals			→	H_2 Hydrogen		



Source: Simulation of ethane steam cracking with severity evaluation - Scientific Figure on ResearchGate. (see Ref 10). Provided under license CC-BY-3.0

Fig.7. Simple Flow Diagram of a Typical Steam Cracker Facility [10]

Steam cracker plants have three broad sections: the radiant section where heat transfer relies more on radiation, the convection section and the Transfer Line Exchanger (TLE). Steam serves the dual purposes of lowering hydrocarbon partial pressure which increases yields of primary products (ethylene and propylene) as well as reducing coke formation.

After the furnace the effluent passes through the TLE where it is initially cooled to between 400 and 600 °C. Further cooling then occurs in the quenching tower or the primary fractionator. After sufficient cooling, the stream must be compressed before being fractionated into the various products. Compression is usually performed with interstage cooling and temperature control to keep the cracked gas below 100 °C to prevent the olefin product reacting (i.e. polymerization) and causing equipment fouling. On specification, ethylene and by-products are either integrated into downstream chemical production or sold via pipeline or compressed freight.

Unit operations the compressor, cryogenics and fractionation, cryogenics are also complex units and comprise of numerous capital-intensive equipment, heat exchangers, condensers and pumps. Today, a greenfield ethylene facility requires a total fixed investment of billions of dollars. Within this footprint there are thousands of individual pieces of equipment which can become fouled and the combined effect on the process economics is considerable.

Ethylene plant technology is mature although it is subject to continuous incremental improvements. Key ethylene licensors include: KBR, Linde, Lummus and Technip, who provide technology, engineering, procurement and construction (T-EPC) services. Licensor agreements with producers often govern the maintenance of the steam crackers until a specific production milestone is achieved. A key technology development of late has been to increase the scale of steam crackers up to 1-1.5 million tons, thereby rendering older, smaller ethylene plants less competitive due to economies of scale and bringing a focus on debottlenecking, improved process maintenance and integration into key product slates and grades to remain competitive. Improved fouling removal procedures play a key role.

4.3. Ethylene Plant Fouling

Fouling in petrochemical plants can arise in the reactors and other process units, process lines, compressors, pumps and heat transfer equipment. There are thousands of individual pieces of equipment in an ethylene plant which can become fouled. There are various mechanisms involved. At the temperatures involved, cracking of hydrocarbons can lead to free radicals which react to form coke which partially and completely blocks tubes and process lines. Emulsions are also a major nuisance in steam cracking plants. They form because of mixing between lighter hydrocarbons and polymerised material which meet in the quench tower and separator. Emulsions can pass through process lines and transfer from one unit into another causing all kinds of disruption from pressure drop to off-spec product. Other fouling processes include chemical reactions, biological processes, crystallisation, corrosion, particulate build-up (sedimentation), precipitation and metal salt accumulation. Each of the main fouling issues is outlined below.

- Dilution Steam System (DSS). In the ethylene plant fouling in the DSS creates many difficulties including increased steam consumption, reduced efficiency, increased wastewater costs, reduced pygas yields and unplanned downtime for cleaning. [11]
- Transfer Line Exchangers (TLE). TLEs are usually shell and tube exchangers but other designs including horizontal and vertical tubes or concentric tubes are also possible. Fouling is caused by condensation and coke formation. Corrosion also occurs due to accumulation of boiler feed water (BFW) solids leading to a pH high enough to get through the protective magnetite layer. [12] Anti-fouling treatments such as amine neutralized sulfonates employed in the furnace coils can protect TLEs to a certain degree but are not sufficient, especially for TLEs located just downstream of the furnace. [13] The failure in respect of the TLEs may be due to premature degradation of the treatments in the ethylene furnace which sees temperatures in the range 1,000° - 1,700°F (about 535 - 930°C).
- Gas compressors. Fouling can occur on the balance drum and discharge lines, diffusers, inlet guide vanes and labyrinths seals between the wheels. The effect is gas leaking, increased polymer and emulsions formation, knock-on fouling in the quench system and the fractionation towers. [14]
- Quench water and quench oil systems. Fouling in quench systems is common and is caused by high pour-point material build up. It is especially problematic in gas-based crackers because there may not be a quench oil tower which would otherwise remove coke fines and tars. [15] Additional measures such as fitment of re-distillation units are required. These separate out and route lower pour point hydrocarbon back into the quench tower to moderate the pour point. This adds to the plant CAPEX, OPEX and maintenance requirements.
- Cracking furnace coils. Coking is to be expected when hydrocarbon molecules are being smashed up at high temperatures and pressures where free radical reaction mechanisms are operating. It is further promoted by impurities in naphtha feed streams such as sodium, nickel and iron oxide but also forms due to reactions at the tube surface. Heat flux resistance and pressure drop due to coke build up at some point necessitate a decoking exercise. Excessive coking in the furnace coils leads to more frequent need for decoking cycles, increased particulate waste inventory, reduced operating rates, lower product yield, shortened furnace life and higher maintenance costs. [17]
- Fractionation trains. Polymer build-up in the de-ethanizer and de-propaniser causes bottlenecks depending on plant configuration and are exacerbated by acetylene feed impurities. This can result in a severe capacity loss due to premature flooding, high tower pressure drop, abrupt and severe tower bottom level reductions during furnace feed slate switches, separation efficiency reduction such as high concentration of heavy components in the pygas, and difficulties controlling quench oil viscosity.

There are a multitude of mechanisms by which fouling can stop an ethylene plant from running smoothly. Keeping fouling under control is a time-consuming and expensive endeavour. Planned shutdowns for each unit varies widely from months to years and this may mean that fouling can build up in certain areas and work arounds are employed to avoid accelerating the maintenance schedule, effectively patching a problem rather than solving it which is far from ideal. In the next section, the economic downside potential from fouling in a gas-fed cracker is considered.

4.4. Financial Losses due to Fouling

The effects of fouling on ethylene plants cash cost of production and capital cost is typically considered in five key areas:

1. **Maintenance costs** – increased costs due to planned and unplanned maintenance due to fouling
2. **Energy costs** – fouling increases energy costs due to reduced heat transfer efficiency
3. **Yield** – fouling affects conversion of feedstock in the steam cracker
4. **Annual operating rate** – unplanned downtime leading to falling behind on production plan operating target set by market conditions

Total CAPEX (total fixed investment) – equipment overdesign to account for fouling

Each of these directly impacts the cash cost of production. The most significant issues are those which impact the energy requirements of the plant e.g. utility costs and the total plant output i.e. loss of yield or operating rate.

4.4.1. Financial Costs of Heat Exchanger Inefficiency

The ethylene plant requires a vast amount of energy for its operation. A mega cracker, of over 1 million tpa of capacity has a heat requirement of over 5,000 kWh per ton of ethylene. As a result, the efficiency of heat transfer in the plant is of paramount importance.

A typical case as shown in Fig. 8, might be a cracking furnace with a fired duty of 109 MW which has a design stack temperature of 149 °C (300.2 °F). After several years the stack temperature increased by 50 °C (122 °F) to 199 °C (390.2 °F) The efficiency loss is 1.83 %, which means that at fuel cost of $20 Euros ($23.4) per MWh the fuel consumption in this furnace is increased by 4 MW or fuel costs of $375,000 per year for just one furnace. If the plant has 5 furnaces in operation this adds up to $1.87 million per year. This loss of efficiency can easily be avoided by adopting a cleaning and maintenance regime which takes the plant back almost to design conditions. It can be avoided by robotic cleaning of the convection section, which has a pay out of less than one year. Over a three-year period after the clean, based on the data model employed here, it is estimated that a saving of $5.44 million can be made.

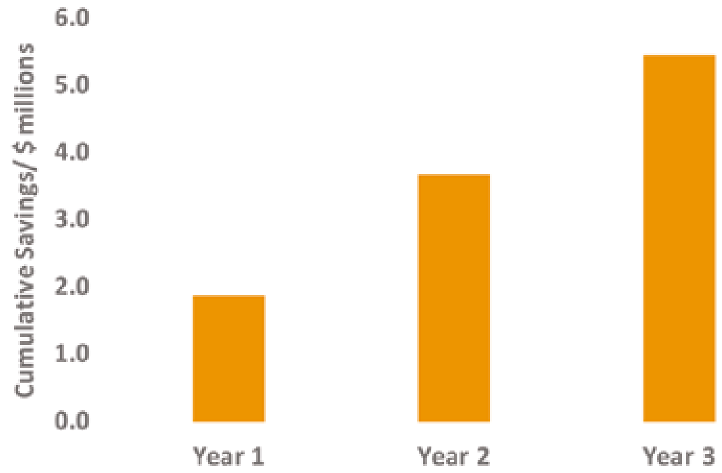


Fig.8 Cumulative Savings from Robotic Cleaning of a Fouled Convection Bank
Basis: Furnace Convection Bank Fired Duty: 109 MW; Five Cracking Furnaces;
Stack Design T: 149°C (300.2 °F); Actual Stack T: 199°C (390.2 °F); Efficiency Loss: 1.86%; Fuel Cost $23/MWh

4.4.2. Ethylene Plant Throughput Costs

If the costs of energy losses in a fouled plant seem dramatic, those associated with downtime and loss of product revenue are by far more significant. Ethylene plants are designed for operation of at least 8,000 hours per year. Fig.9 shows the sensitivity of $ loss in revenue to loss of throughput (shown as days of operation slowdown equivalent) and lowered operating rates. It is based on a 1 million tpa plant with a planned average annual operating rate of 90%, with three different ethylene prices ranging from $500-1,000 per ton. In these scenarios, even 5 days equivalent slowdown due to fouling, results in losses between $7 -14 million.

At historical average US ethylene prices of $750 per ton, a plant would lose $10 million in revenue for 5 days of lost throughput compared with the planned 90% operating rate. For a 10-day loss, at the same ethylene price, the plant would lose $21 million. Prices of ethylene over $1,800 per ton have been witnessed over the last decade in the European region and $1,500 per ton in the USA. [18,19] Even at a conservative value of $1,000 per ton, 10 days of lost throughput start to push the loss of revenue towards the $30 million mark.

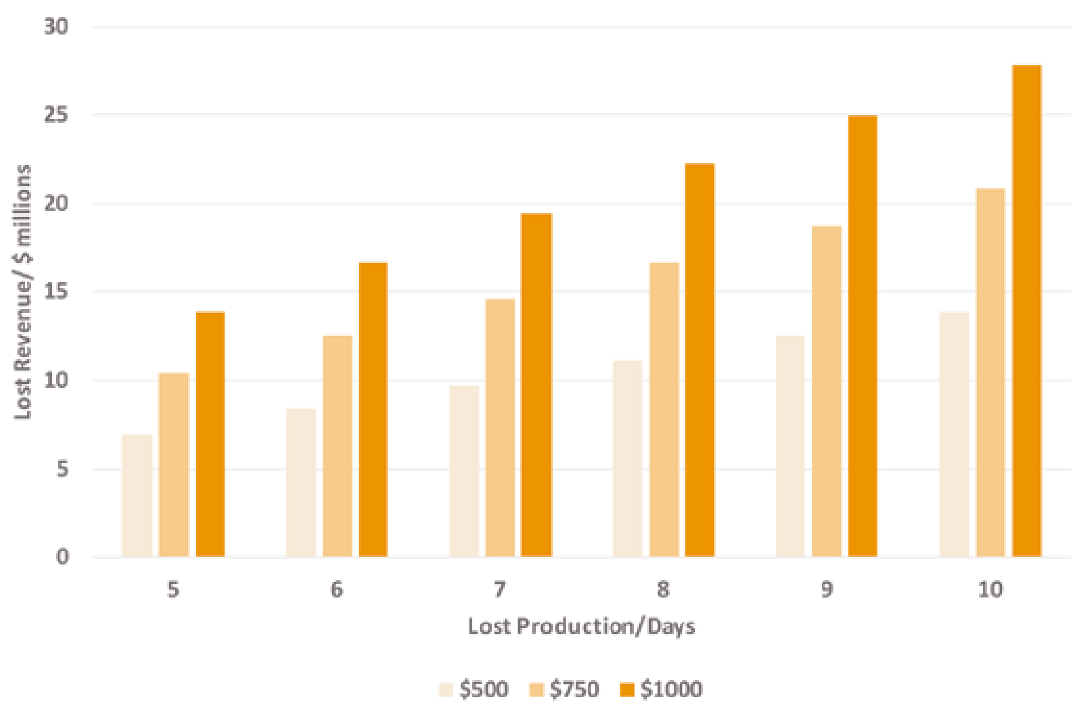


Fig.9 Lost Revenue for Ethylene Production via Steam Cracking. Reduced Plant Throughput - Financial Analysis Basis: 1 million tpa; 90% Target Operating Rate; (324 days/year onstream); Ethylene Price $500, $750, $1,000 per ton

Fouling throughout a petrochemical complex, with downstream PVC, PET and polyolefin units would suffer the compounding effects on the economics and squeeze finished product margins to an even greater degree. The effects in a large oil refinery, where daily revenues are in the order of tens of millions, is an order of magnitude higher than in an ethylene plant.

The losses described even at the lowest end, for the cheapest ethylene price, far outweigh the costs of a deep clean using the most advanced methods available. Strategically, manufacturing plants would have better financial performance if they viewed such costs as a part of their overall plant economics, rather than simply a part of the maintenance budget, with pressure to reduce such costs year-on-year.

5. Conclusions

Fouling within manufacturing plants places a considerable burden on performance. Loss of production wipes millions of dollars in revenue from the bottom line, creating supply shortages, and safety hazards and exacerbating a plant's negative environmental and CO_2 footprint. With ever-increasing pressure on energy and chemical-producing sectors to become more green, efficient fouling mitigation and removal methods are increasing in importance. The existing paradigm and historical mindset of seeing cleaning as a cost within the maintenance department which needs to be reduced, rather than an investment opportunity which over time will greatly increase the financial performance of the organisation, create a roadblock to the adoption of modern techniques and innovation which needs to be addressed and overcome. Investors are more environmentally conscious than ever before and are switching their funds from businesses involved in the production and use of fossil fuels to those with more sustainable activities. Even now global refining groups have linked bonuses with CO_2 reduction incentives.

Many have now given time frames whereby inefficient and hazardous human entry be replaced with robotics. It is imperative therefore that companies in the oil and gas and petrochemicals sectors immediately demonstrate to the financial markets their commitment to eliminating process inefficiencies caused by fouling of heat transfer equipment and reactor units.

A range of fouling removal techniques are available, but each has its place. However, the use of robotics for precise, fast operation and avoidance of human labour in hazardous environments is consistent with the manufacturing sector's move towards Industry 4.0/Smart Manufacturing approaches. There is much to be gained both in financial performance, reliability and environmental terms as robotics are increasingly providing the most promising method for maximum process efficiency. In future, it will be possible to install bespoke access for a robotic cleaning system as a permanent feature in the plant, built in from its first day of operation, and ensuring constant housekeeping to prevent heavy fouling from ever forming. Companies which lead the way in adopting the Industry 4.0 cleaning technology involving robotics, zero and minimal waste together with monitoring, measuring and recording of performances can expect to rank in the top percentile as they improve their competitive advantage globally and avoid future penalties on energy consumption.

Ackowledgments

Dr Michelle Lynch, Enabled Future Limited, technical writing and techno-economic analysis.

Ms Khevna Naran, 108 Blocks for technical writing and chemical engineering.

Mr Scott Donson, Tube Tech Industrial Ltd. for robotic cleaning technology

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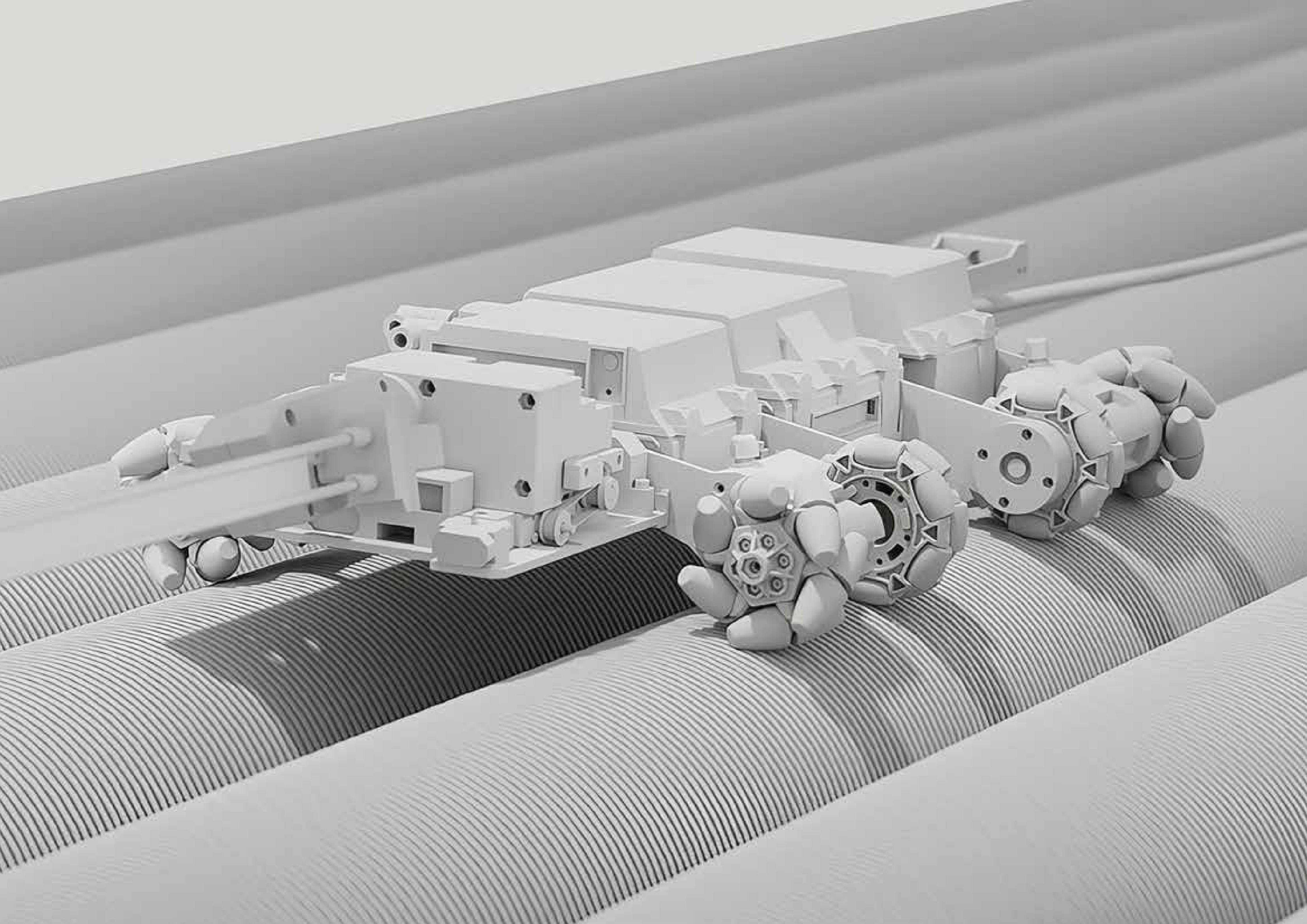

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