General: This Technology Handbook is intended for general information purposes only and is not intended as an offer, representation or warranty of any kind, or as a statement of any terms or conditions of sale. The information herein is believed to be correct, but is not warranted for correctness or completeness, or for applicability to any particular customer or situation.

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Economic hypothesis and definitions: Unless otherwise specified, OPEX calculations include variable operating costs (utilities, feedstock... ) and fixed costs (labour... ). Natural gas cost is assumed to be $4/mmBTU HHV. In addition, unless otherwise specified, CAPEX is calculated either: a) including all EPC costs (process units, offsite and utilities) but excluding owner’s costs for a plant built on the USGC; or, b) using 1.8xEP costs (process units, offsite and utilities). Price base is 2015. OPEX and CAPEX are indicative and can vary according to the basis of design, such as: product(s) yield and quality, site conditions, feedstock quality, utilities, project scope and plant capacity. Units are metric. Gallons (gal) are US Gallons (3.785 liters). Barrel (bbl) refers to oil barrel (42 gal). Heating value shall be understood as Lower Heating Value (LHV). Exchange rate used is: 1 Euro = 1.1 US Dollar.

Editor: Air Liquide Global E&C Solutions US Inc.
Contact information for suggestions, improvements... email at EditorTH@airliquide.com

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This handbook is also available in the following formats

**PAPERBACK**

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![Amazon](image1)

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**DIGITAL VERSION**

![PDF](image3)

Ask any email address on pages 10/11 or any Air Liquide Global E&C Solutions representative.

**Apps from Air Liquide:**

**GAS ENCYCLOPEDIA**

Allows users to quickly access a host of information on the physical and chemical properties of 64 gas molecules (oxygen, nitrogen, hydrogen, etc.) in their solid, liquid and gaseous states.

Available on Google Play and Appstore (for iPad only)

**EASY GAS CONVERTER**

Gives users the ability to instantly calculate volume conversions from gaseous to liquid state for 14 gas molecules such as nitrogen, oxygen and hydrogen.

Available on Google Play and Appstore
Dear Customer,

We are pleased to share with you our most recent Technology Handbook. This comprehensive overview of some 60 different advanced technologies was made possible thanks to the valuable input of the sought-after experts within our company.

We always strive to leverage our network and engage our experts, scientific and technical leads, solutions development teams and our own Air Liquide plant operators worldwide, so as to increase the value of our technologies and expand our knowledge in order to serve you better. As well, through our product line organization, we are able to be closer to the markets and customers we serve and this allows us to develop and continuously improve on our technological leadership.

Air Liquide Global E&C Solutions’ goal is to provide competitive solutions that are safe and reliable so that our customers can optimize their operations as well as their use of natural resources.

We encourage you to contact us through our regional offices or send an email to one of our technology groups. Our experts and project leaders will be at your disposal to answer your questions and offer additional information to help you move forward with your projects.

Thank you,

Domenico D’Elia
Vice President and Chairman
Air Liquide Global E&C Solutions

Air Liquide Global E&C Solutions’ Technology and Sales activity is organized into six product lines: Standard Plants, Cryogenics, Hydrogen, Downstream & Petrochemicals, Hydrocarbons and Oleochemicals; while operating in four regions: Americas, Asia, Europe and Middle-East & Africa. Such a worldwide set-up allows us to efficiently manage and develop our technology portfolio, be close to the markets we serve, in line with the needs of our customers.
Who We Are

Air Liquide Group

The World leader in gases, technologies and services for Industry and Health

Air Liquide is present in 80 countries with approximately 68,000 employees and serves more than 3 million customers and patients*. Oxygen, nitrogen and hydrogen are essential small molecules for life, matter and energy. They embody Air Liquide’s scientific territory and have been at the core of the company’s activities since its creation in 1902.

Air Liquide’s ambition is to lead its industry, deliver long-term performance and contribute to sustainability. The company’s customer-centric transformation strategy aims at profitable growth over the long term. It relies on operational excellence, selective investments, open innovation and a network organization implemented by the Group worldwide. Through the commitment and inventiveness of its people, Air Liquide leverages energy and environment transition, changes in healthcare and digitization, and delivers greater value to all its stakeholders.

* following the acquisition of Airgas on 23 May 2016

Air Liquide Global E&C Solutions

A technology partner of choice

Air Liquide Global E&C Solutions, the engineering and construction activity of the Air Liquide Group, builds the Group’s production units (mainly air gas separation and hydrogen production units) and also supplies external customers with its portfolio of technologies. Its industrial gas, energy conversion and gas purification solutions enable customers to optimize the use of natural resources.

Air Liquide Global E&C Solutions covers the entire project life-cycle: license engineering services / proprietary equipment, high-end engineering & design capabilities, as well as project management & execution services. Its exclusive and innovative technologies are making a contribution to the transition of the energy sector.

With more than 1,600 patents and 3,500 employees, Air Liquide Global E&C Solutions is at work connecting people and ideas everywhere to create advanced technologies to solve customer issues and position Air Liquide Group for growth over the long term.
Key Figures

15 engineering centers

3,500 employees

3 manufacturing centers

1,600 patents

60 proprietary technologies

6,000 plants built
At Air Liquide Global E&C Solutions, we have one goal with respect to Health, Safety, Environment and Security: **To achieve zero accidents and zero environmental incidents.**

In pursuit of this goal, we strive to:

- Provide a secure work environment
- Prevent all injuries, damage to the environment and damage to property
- Identify and reduce risks and exposure to hazards in a sustainable way
- Improve our Health, Safety, Environment and Security performance continuously
- Enforce Air Liquide Life Saving Rules

**Embodying a safety-first culture**

- Our safety commitment applies not only to our employees, but also to our contractors, customers, adjacent facilities and local communities.
- We ensure that safety is the responsibility of everyone and is a part of the Air Liquide Global E&C Solutions culture. In this way, we are all safety leaders, and all share a commitment to the golden rule of safety first.
- We will not hesitate to stop an activity of whatever nature (design, engineering, construction execution, or manufacturing) if it is not safe or if there is any suspicion that it may end in an accident or incident, now or in the future.
Enabling Cleaner Solutions

Our solutions designed to protect life and the environment represent more than 40% of the company’s sales. As a responsible partner and technology provider, Air Liquide Global E&C Solutions is constantly seeking to reduce the environmental impact of the production facilities it builds for the Air Liquide Group but also offers its third-party customers the most environmentally-friendly technologies and applications available.

Cleaner Natural Gas
Natural gas represents 15% of the world’s energy consumption and is the fastest growing energy source.

Our technologies enable efficient pollutants removal:
• Amine wash
• Membranes
• Cryocap™
• Omnisulf

Cleaner Power
Air Liquide Global E&C Solutions pioneered the development of oxycombustion as a way to capture CO₂ in coal powered plants.

Key technologies are: Large Air Separation Units and Cryocap™ Oxy.

Cleaner Chemicals
Everyday goods such as cosmetics and detergents are produced more and more using green chemicals. Air Liquide Global E&C Solutions’ suite of 13 oleochemicals technologies is a key contributor to the development of such products with a share of more than 60% of the market.

Cleaner fuels
Air Liquide Global E&C Solutions has multiple technologies to remove pollutants from conventional fuels, as well as technologies for the production of biofuels and alternative clean fuels:
• Hydrogen production for sulfur removal
• Biodiesel
• Sulfur free fuels: LNG, Methanol or Gasoline (G2G™)

Cleaner Water
Industrial gases offer alternative solutions to conventional water and waste treatment processes:
• VSA for pure oxygen introduction into biological basins with in-house gas injectors, or oxygen for ozone production
• CO₂ for pH adjustment (such as Cryocap™)
• Removal of chemical contaminants (Phenosolvan, GLS and CLL, part of the FBDB technology package)

61% of our technologies contribute to the protection of the environment
How to reach us

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Yango™ – Standard Air Separation Unit

**Application**
Steel making (basic oxygen furnaces, blast furnaces, electric arc furnaces), chemicals (ethylene oxide, ammonia, etc.)

**Feedstock**
Air + Energy (electrical or steam)

**Product**
Oxygen from 99.6% to 99.8% purity and up to 50 bar

**Co-Product**
Nitrogen, liquid oxygen, liquid nitrogen, liquid argon, compressed dry air

**Capacity**
330 to 770 tpd

**Description**
Yango™ air separation unit is based on air compression, adsorption purification, cryogenic distillation of main components and internal compression of high pressure products.

Yango is a standardized, highly packaged ASU solution to support short-time-to-start-up projects.

Several process schemes are available to optimize both CAPEX and OPEX depending on customer product requirements, energy cost and customer process integration potential.

Air Liquide Global E&C Solutions offers optimized solutions in terms of construction strategy, operating philosophy and reliability.

**Economics**
Specific energy: 400 to 600 kWh/t
Capital intensity:

---

**Contact**
standard-plants@airliquide.com

---

**References**
>20
Sigma – Standard Air Separation Unit

**Application**
Steel making (oxygen boosting, electric arc furnace), chemicals (ethylene oxide, etc.), glass, non-ferrous metals, waste water treatment, pulp and paper

**Feedstock**
Air + Energy (electrical)

**Product**
Oxygen up to 99.6% purity

**Co-product**
Nitrogen, liquid oxygen, nitrogen and argon, compressed dry air

**Capacity**
150 to 350 tpd

**Description**
Sigma units are based on air separation with the following steps: air compression, adsorption, purification, cryogenic distillation of main components, internal compression.

Several process schemes are available to optimize both CAPEX and OPEX depending on customer product requirements.

The Sigma units are designed to reduce construction and time to production with a highly packaged architecture.

Some liquid co-production could be available to refill backup liquid storages.

**Economics**
Specific energy: 280 to 460 kWh/t

Capital intensity:

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**References**
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Latest projects: Baku Steel, Klondyke, Klabin, COP

**Contact**
standard-plants@airliquide.com
Vacuum Swing Adsorption (VSA) – On-Demand Oxygen Generation

**Application**
Steel making, glass, pulp and paper, waste water treatment, mining

**Feedstock**
Air + Energy (electrical)

**Product**
Oxygen from 90% to 93% purity

**Co-product**
none

**Capacity**
40 to 150 tpd

**Economics**
Specific energy: 265 kWh/t
Capital intensity:

**Description**
VSA uses the process of air separation by adsorption. The basic principle of air separation by adsorption relies on the use of specific zeolite adsorbents for the selective adsorption of nitrogen over oxygen and argon.

Main features are:
- Compact design layout
- Fully packaged and pre-tested skids
- Minimized schedule, erection and start-up times
- Automatic and unattended operation

Capitalization of more than 20 years of operating and maintenance experience.

**References**
>100

**Contact**
standard-plants@airliquide.com
Nitrogen Generation System

Application
LNG terminal, crude oil refinery, electronics

Feedstock
Air + Energy (electrical)

Product
Nitrogen (gaseous, liquid) with 100 ppm to 1 ppb O2

Co-product
none

Capacity
500 Nm3/h to 70,000 Nm3/h of nitrogen

Economics
Specific energy: 175 to 280 KWh/t

Capital intensity:

Description
This nitrogen generation system is based on air separation with the following steps: air compression, adsorption, purification, cryogenic distillation of main components.

Several process schemes are available to optimize both CAPEX and OPEX depending on customer product requirements.

Some liquid co-production could be available to refill backup liquid storages.

Systems often include backup vaporizers and storages designed as per customer’s requirements (availability and reliability).

These systems are safe, reliable and easy-to-operate and maintain.

References
>100

Latest projects: Gorgon LNG, South Hook LNG, Peru LNG, Moscow Refinery, Toshiba

Contact
standard-plants@airliquide.com
HYOS™ R – Hydrogen Generation System

**Application**
Glass manufacturing, steel making, food, chemicals, electronics, hydrogen energy

**Feedstock**
Natural gas

**Product**
Gaseous hydrogen of 99.999% purity

**Co-product**
none

**Capacity**
270 Nm3/h

**Economics**
Yield: 0.47 (Nm3 Natural gas/Nm3 Hydrogen)

**Description**
HYOS™ R plants are skidded, modular hydrogen generators, that produce high purity gaseous hydrogen from natural gas (methane) and water.

HYOS™ R uses the Steam Methane Reforming (SMR) process to generate the reformate (mixture of H₂, CO₂, water) and the Pressure Swing Adsorption (PSA) process to purify the reformate into pure hydrogen.

Turndown ratio can reach 50%.

The benefits of HYOS™ R are a small footprint and low installation cost by skidded design, no steam import required due to an integrated steam generator.

HYOS™ R is designed as a stand-alone plant which can be operated unattended.

**References**
9

Latest project: Ternium (2011), Sisecam (2012)

**Contact**
standard-plants@airliquide.com
Large Air Separation Unit

**Application**
Steel making (basic oxygen furnaces, blast furnaces, electric arc furnaces), gas monetization (gas-to-methanol, -propylene, -liquids), coal gasification, chemicals (ethylene and propylene oxide, etc.), clean power (IGCC, oxycombustion)

**Feedstock**
Air + Energy (electrical or steam)

**Product**
Oxygen up to 99.8% purity and 100 bara

**Co-product**
Nitrogen, rare gases (Kr, Xe, He, Ne), liquid oxygen, nitrogen and argon, compressed dry air

**Capacity**
Up to 6,000 tpd

**Economics**
Specific energy: 160 to 500 kWh/t

Capital intensity:

Several processes are available to optimize economics depending on product requirements, energy cost and process integration.

**Description**
Large air separation units are based on adsorption purification, cryogenic distillation of main components and internal compression of high pressure products.

From the small standard of a few hundred tonnes per day to Mega ASU complex (multi train) of more than 15,000 tonnes per day, Air Liquide Global E&C Solutions offers optimized solutions in terms of construction strategy, operating philosophy and reliability.

**References**
>4000

Latest project: Sasol: 5,800 tpd (at sea level) in construction in South Africa

**Contact**
cryogenics@airliquide.com
**CO Cold Box – Syngas Separation and Purification**

**Application**
Carbon monoxide (CO) production from synthesis gas and/or a ratio-adjusted synthesis gas stream for use in chemical industry

**Feedstock**
Synthesis gas from natural gas/naphtha or coal/residue gasification

**Product**
CO up to 99.99% purity

**Co-product**
Hydrogen, oxogas, methane, LNG

**Capacity**
Up to 2,400 tpd

**Economics**
Specific energy: 18 to 600 kWh/tonne

Capital intensity:

<table>
<thead>
<tr>
<th>Min USD</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
</table>

Economics are highly dependent on the type and quality of feedstock (coal gasification or natural gas), as well as of the required CO pressure (MDI/TDI, PC, AcAc, MEG, etc.).

**Description**
CO cold box process is based on cryogenic separation technology using the difference in boiling points of the main components from the synthesis gas.

Feed gas is pretreated to remove impurities which will freeze at cryogenic temperatures encountered in the process. Every cryogenic process is tailor-made to fit the customer’s specifications and other requirements on co-products.

Available CO Cold Box processes:
- "M": Methane Wash
- "P": Partial Condensation
- "C": Carbon Monoxide Wash

**References**
>40
Latest project in 2015 (Malaysia)

**Contact**
cryogenics@airliquide.com
Liquid Nitrogen Wash

Application
Production of synthesis gas for ammonia plants

Feedstock
Raw hydrogen (from shift/Rectisol™)

Product
Ammonia synthesis gas with a stoechiometric N₂/H₂ ratio of 1:3

Co-product
Methane, LNG

Capacity
Up to 2,200 tpd

Economics
Utilities:
• LIN: 0 to 0.02 tonne/tonne of syngas
• Power (if LNG co-production):
  900 kWh/tonne (of LNG)

Capital intensity:

<table>
<thead>
<tr>
<th>with LNG</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
</table>

Description
Raw hydrogen and high pressure nitrogen are fed to the liquid nitrogen wash unit. Both streams are cooled down against product gas.

Raw hydrogen is fed to the bottom of the nitrogen wash column and condensed nitrogen liquid is fed to the top. Trace impurities, like methane, argon and carbon monoxide, are removed and recycled as fuel gas.

To establish the desired H₂/N₂ ratio, high pressure nitrogen is added to the process stream.

References
17

Latest project in 2015 (China)

Contact
cryogenics@airliquide.com
Hydrogen and Argon Recovery

**Application**
Recover hydrogen, nitrogen, argon and methane from ammonia plant purge gas using the cryogenic process

**Feedstock**
Ammonia plant purge gas

**Product**
Liquid argon, H₂ (> 97% recovery)

**Co-product**
N₂, fuel gas, LNG, liquefied nitrogen

**Capacity**
Up to 50 tpd of argon

**Description**
Water is removed from ammonia plant purge gas before it enters the cold box. The feed is cooled and partially condensed in a two stage exchanger. The hydrogen goes mainly in the vapor phase while the condensed phase is sent to separation pots and distillation columns. Nitrogen, argon and methane are further separated.

A nitrogen cycle compressor and a nitrogen turbine ensure the necessary cold production and duty for the distillation.

**Economics**
Specific energy: 85kW/tonne

Capital intensity:

<table>
<thead>
<tr>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
</tr>
</thead>
</table>

Hydrogen and argon recovery plants are economically favored when there is a need for recovery argon in remote areas where the price of argon is high.

**References**
13

Latest project: Shiraz (Iran)

**Contact**
cryogenics@airliquide.com
**Cryocap™ H2 – Cryogenic CO2 Separation**

**Application**
CO₂ capture from H₂ production plants

**Feedstock**
Offgas from H₂ plant

**Product**
CO₂

**Co-product**
H₂

**Capacity**
From 500 to 2,000 tpd

**Economics**
OPEX+CAPEX: 45 USD/tonne of CO₂
Increase H₂ production by 13% to 20%

Cryocap™ H₂ offers the lowest costs for CO₂ production from H₂ plant (20% less capex than amines)

**Description**
The offgas is compressed, dried and sent to a cryogenic unit, where the CO₂ is separated from the other components by a combination of partial condensation and distillation. A pure and pressurized CO₂ flow is produced from the cold box.

The non condensed gases are recycled through a membrane system to recover H₂ and CO₂. Residual gas is sent to the burners of the reformer.

The CO₂ product is compressed up to supercritical pressure or liquefied and stored in liquid storage.

Food-grade quality can be achieved by an additional purification on a catalytic bed where all remaining hydrocarbons and alcohols are destroyed.

Cryocap™ H₂ can be installed for greenfield as well as brownfield H₂ plants.

**References**
France, Port Jérôme, 2015, 100 kt/year food-grade CO2

**Contact**
cryogenics@airliquide.com
Cryocap™ Oxy – Cryogenic CO2 Separation for Oxycombustion

**Application**
CO₂ capture from power plants

**Feedstock**
Oxycombustion flue gas

**Product**
CO₂

**Co-product**
none

**Capacity**
From 1,000 to 15,000 tpd

**Economics**
Cryocap™ Oxy allows very high CO₂ recovery and near zero-emission to the atmosphere (SOx, particulate matters, NOx, Hg).

**Description**
The flue gas issued from the boiler plant is first treated in a pre-treatment unit, which aims to cool the gas and remove the SOx, HF, HCl, most of the NOx, and the dust. Then the gas is compressed and dried before entering the cryogenic purification unit.

In the cold box, CO₂ is recovered by combination of partial condensation and distillations, which allow the removal of the heavy compounds such as NOx and the light elements such as O₂, Ar, N₂, NO and CO.

The CO₂ product is compressed, condensed and pumped up to supercritical pressure.

**References**
- Australia, Callide, 2012, 75 tpd
- Spain, Ciuden, 2012, 200 tpd (warm) and 10 tpd (cold box)
- United States, FutureGen2.0, 2013, 3,200 tpd

**Contact**
cryogenics@airliquide.com
**Helium Extraction and Liquefaction**

**Application**
Pure liquid helium production and loading into ISO containers

**Feedstock**
Natural gas or impure helium gas extracted as non-condensable side-product from LNG units or impure helium gas extracted from nitrogen rejection units

**Product**
Liquid helium

**Co-product**
none

**Capacity**
Up to 20 tpd (one train)

**Economics**
The highly efficient process combined with the vapor recovery system allows for a very high helium recovery (> 99%).

Capital intensity:

**Description**
The impure helium feed gas is purified in a first section, where N2, CH4, H2, CO, Ar, O2, water and CO2 are separated from helium. It is composed of a cryogenic partial condensation unit, a hydrogen removal system and a Pressure Swing Adsorber (PSA) unit.

Then, the pure gaseous helium is cooled and liquefied via a helium cycle and the use of cryogenic expanders with a highly optimized cryogenic exchanger arrangement. Expanders are based on a proprietary technology using static gas bearing, ensuring high reliability and efficiency.

Liquid helium is continuously produced and stored in tanks. The unit is equipped with loading bays to fill ISO containers. All helium vapors from the containers are collected and recycled within the unit.

**References**
Qatar, Ras Laffan, 2013, 20 tpd
Qatar, Ras Laffan, 2005, 9 tpd

**Contact**
cryogenics@airliquide.com
Hydrogen
Small-Scale Steam Methane Reformer

**Application**
Highly modularized and standardized production of hydrogen

**Feedstock**
Natural gas, refinery offgas

**Product**
Hydrogen

**Co-product**
Steam

**Capacity**
10,000 to 40,000 Nm3/h Hydrogen

**Description**
The small-scale SMR product is a hydrogen plant concept including four different plant sizes with pre-defined equipment, piping arrangement and modules.

A steam ejector can be included to allow a wide range of feed pressures.

For export steam production of high quality, the plant can include a process condensate vaporizer.

OPEX can be optimized for high and low export steam flow rates.

Those units are highly modularized and standardized units with compact layout and short project execution time (<15 months FOB).

**Economics**
Feed+fuel-steam: 12.5 to 13.2 MJ/Nm3

Capital intensity:

![Graph showing capital intensity](image)

**References**
>10

Latest reference: Huafon H2 Plant in China

**Contact**
hydrogen@airliquide.com
Steam Methane Reforming (SMR) – Hydrogen Production

**Application**
Production of hydrogen by steam methane reforming of hydrocarbon feed in catalyst filled tubes heated in a top-fired furnace

**Feedstock**
Natural gas, refinery offgas, LPG, naphtha

**Product**
Hydrogen

**Co-product**
Steam

**Capacity**
40,000 to 200,000 Nm3/h H₂

**Economics**
Feed+fuel-steam: 12.3 to 13.2 MJ/Nm³ H₂

Steam production: 0.4 to 1.2 kg/Nm³ H₂

Capital intensity:

**Description**
Desulfurized feed gas is mixed with steam and pre-heated.

Feed and steam are reformed to H₂, CO and CO₂ in the proprietary top-fired steam reformer at pressures in the range of 15-45 barg.

Methane conversion requirements of downstream steps are adjusted via the main process parameters, reforming temperature and steam-to-carbon ratio.

CO is shifted with steam to hydrogen and CO₂. Hydrogen is separated in a pressure swing adsorption and the remaining gas is used as fuel in the reformer.

**References**
130 (all types of SMRs)

Latest references: Yanbu K.S.A, Canada, Netherlands and USA

**Contact**
hydrogen@airliquide.com
**SMR-X™ – Zero Steam Hydrogen Production**

**Application**
Production of hydrogen without co-producing steam in a radiative heat exchange steam methane reformer (SMR)

**Feedstock**
Natural gas, naphtha

**Product**
Hydrogen

**Co-product**
None

**Capacity**
Up to 100,000 Nm3/h hydrogen

**Economics**
Feed+fuel: 13.8 MJ/Nm3 H2

**Description**
Compared to conventional steam reformers, the reformed gas at the outlet of the catalyst-filled reformer tubes is cooled by heat exchange with process gas inside the tubes.

The geometry and material of the internal heat exchange coils is optimized for reliability and high efficiency, so the new generation SMR does not produce export steam like conventional medium to large-sized ones.

The plant’s steam system is simplified and fewer reformer tubes are required, because approximately 20% of the process heat is supplied by internal heat exchange.

Ecology: CO₂ emissions are 5% lower than those of a conventional SMR.

**References**
Callisto Plant, Belgium

**Contact**
hydrogen@airliquide.com
Pressure Swing Adsorption (PSA) – Hydrogen Purification

**Application**
Recovery and purification of pure hydrogen from different H₂-rich streams

**Feedstock**
Raw hydrogen from SMR, POX, cryogenic purification, methanol plant purge gases, ethylene off-gas, styrene offgas, gasification, ammonia plant, CCR, and other offgases or any combination of the above.

**Product**
Hydrogen up to 99.9999% purity

**Co-product**
none

**Capacity**
5,000 to 200,000 Nm³/h

**Economics**
H₂ recovery rate: 60 to 90%

Capital intensity:

![Capital Intensity Diagram]

**Description**
Pure H₂ product is delivered at a pressure close to feed pressure (pressure drop across PSA could be as low as 0.5 bar) and impurities are removed at a lower pressure (typical PSA offgas pressures range from 1.1 to 10 bara).

The PSA tail-gas, containing impurities, can be sent back to the fuel system (SMR burners or refinery fuel network) with or without the need of a tail-gas compressor. Operation is fully automatic.

PSA units use the most advanced adsorbents on the market and patented high efficiency cycles to provide maximum recovery and productivity. Typical on-stream factors are >99.9%.

Turndown can be as low as 25%.

PSA units are compact, fully skid-mounted and pre-tested units designed for outdoor and unmanned operation.

**References**
> 70 (in operation or under construction)

**Contact**
hydrogen@airliquide.com
Autothermal Reforming (ATR) – Syngas Generation

**Application**
Production of syngas by partial oxidation of hydrocarbon feed followed by a catalytic reforming conversion in a single refractory lined reactor

**Feedstock**
Natural gas, refinery offgas, pre-reformed gas, Fischer-Tropsch tail-gas, LPG, Naphtha

**Product**
Syngas (H₂+CO)

**Co-product**
none

**Capacity**
Up to 1,000,000 Nm³/h (dry)

**Economics**
Yield: 2.5 - 4.0 Nm³ syngas / Nm³ natural gas (including fuel for fired heater)

Oxygen consumption: 0.15 - 0.25 kg O₂ / Nm³ syngas

Capital intensity:

![Capital Intensity Chart](chart.png)

**Description**
Desulfurized feed gas is preheated and optionally pre-reformed prior to entering the ATR reactor. The gas is fed via the proprietary burner into a refractory lined reactor operating at 30 to 100 barg, where it reacts with oxygen and steam to form syngas. The syngas is further reformed via a Ni-based catalyst bed located in the same reactor. The syngas is cooled in a waste heat boiler producing high pressure steam. The syngas can then be used as feedstock for different synthesis processes such as methanol or Fischer-Tropsch synthesis. Syngas components can be also separated to pure products (H₂, CO, CO₂).

Depending on the needed syngas properties of the downstream process this technology can be applied as stand-alone ATR or as a combination of SMR and ATR known as Combined Reforming.

**References**
>30

Recent references:
NatGasoline, USA, 550,000 Nm³/h, start up exp. 2017
YCI, USA, 550,000 Nm³/h, start up exp. 2017

**Contact**
syngas@airliquide.com
Lurgi MPG™ – Multi-Purpose Gasifier

**Application**
Utilization of all kind of liquid residues from refinery or chemical processes for the production of syngas by non-catalytic partial oxidation of hydrocarbon feed.

**Feedstock**
Typical feedstocks are high viscous, low reactivity, heavy residue from oil refining like: asphalt, bitumen, tar, visbreaker residue, hydrocracker residue, FCC residue, vacuum residue, coal tar, oil sand tar, etc.

**Product**
Syngas (H₂ + CO)

**Co-product**
none

**Capacity**
Up to 200,000 Nm³/h dry syngas per gasifier

**Economics**
Individual costs vary significantly depending on feedstock, size, location, integration in refinery, etc.

Oxygen consumption: 1 Nm³ O₂/kg feed

Capital intensity: [Graph]

**Description**
The feedstock together with oxygen and steam is fed via the proprietary MPG-burner into the refractory lined reactor operating at 30 to 100 barg, where it reacts in a non-catalytic partial oxidation at typically 1,200 to 1500 °C to form syngas. The syngas leaving the bottom of the reactor is cooled by quench or in a waste heat boiler, depending on feedstock characteristics and downstream usage.

The proprietary MPG-burner design allows a wide variety of feedstock properties to be handled safely and reliably, covering high viscosity and even particles up to millimeter size. The pressurized water cooling of the burner insures safe operation under all conditions.

The technology may also be adapted to the usage of slurries with solid content or bio-based syncrude.

**References**
Pre-1997: 26 gasification plants with 76 reactors build as exclusive sub-licensor for Shell Gasification Process;
1997: acquisition of commercially proven technology SVZ and enhancements by Lurgi regarding operating pressure and lifetime of burner;
since 2000: 3 gasifications (heavy residue) with MPG-technology

Latest reference: 130,000 Nm³/h H₂ from hydro-cracked residue/vacuum residue from oil sand upgrading in Canada; start up expected 2016

**Contact**
syngas@airliquide.com
**Application**
Coal gasification process for the production of syngas

**Feedstock**
Low-rank (high ash, high water) coals

**Product**
Syngas (H₂ + CO) particularly suited for the production of SNG (synthetic natural gas) or DRI (direct reduction of iron ore)

**Co-Product**
Crude tar acids (phenols), sulfur, tar, oil, naphtha, ammonia

**Capacity**
40,000 to 120,000 Nm³/h dry syngas per gasifier, typically more than 5 reactors per plant, largest plant 40 reactors at one site

**Economics**
Individual costs depend strongly on location, coal quality, etc.

Yield: 2000 Nm³ dry syngas / ton dry coal

Capital intensity (cost base: 7 Mk+ in China)

---

**Description**
Coal is converted into syngas by reacting with oxygen and steam. The raw syngas will be further processed (CO-shift, Rectisol™) to meet the downstream requirements of the processes. Internal streams (e.g. gas-liquor etc.) will be further treated using proprietary technologies (Phenosolvan™, CLL) to reduce the environmental impact of the gasification process.

The key differentiator of this technology is its suitability for low-rank coals which cannot be processed economically by entrained flow gasification.

Notes:
Lurgi FBDB™ is a trademark of Sasol Lurgi Technology Company (Pty) Ltd
CLL process is also known as Chemie Linz Lurgi process.

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**References**
> 100 gasifiers

Largest plant: Sasol, RSA, 3.3 mmNm³/h (2 x 40 gasifiers, start up 1977 / 1982)
Most recent plant: JSPL Coal gasification island for DRI in India (225,000 Nm³/h, 6+1 Mk IV gasifiers), start up 2014

**Contact**
syngas@airliquide.com

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**Lurgi FBDB™ – Fixed Bed Dry Bottom Coal Gasification**
Rectisol™ – Syngas Purification

**Application**
Removal of acid gases (CO₂, H₂S, COS, mercaptans, NH₃, HCN) and nearly all trace components from syngas typically produced by gasification of coal, petcoke, residue or heavy oil

**Feedstock**
Raw syngas deriving from gasification of all carbon containing feedstocks

**Product**
Clean/high purity syngas (H₂+CO)

**Co-product**
CO₂, H₂S rich gas for SRU

**Capacity**
100,000 to 1,000,000 Nm³/h per train

**Economics**
Individual costs vary significantly depending on feedstock, size, purity request, etc.

Capital intensity:

![Capital Intensity Chart](chart)

**Description**
Acid gases contained in raw gases are removed by absorption with a physical solvent (cold methanol). The rich solvent leaving the contactor is regenerated by flashing and stripping. Different process configurations are available to deliver a tailored solution optimised for CAPEX and OPEX for a given syngas specification.

Rectisol™ is the leading process when it comes to the purification of gasification-based syngas for catalytic applications, such as: SNG, methanol, ammonia and Fischer-Tropsch.

Using inexpensive solvent in combination with optimized heat integration, the Rectisol process has extremely low operating costs and high availability.

**Rectisol™ - The “5 in 1” Solution:**
1. Trace contaminant removal
2. Deep Desulfurization (total S < 80 ppb)
3. Bulk CO₂ removal (up to 100%)
4. CO₂ purification (total S < 5 ppmv)
5. Acid Gas Enrichment (S > 25 vol%)

**Syngas suitable for catalytic synthesis processes**

**CO₂ suitable for compression, synthesis or venting**

**Acid gas suitable for sulfur recovery processes**

**Sulfur Recovery**

**References**

>110 (> 35 since 2005)

Largest reference: SNCG CTL project (4.2 mmNm³/h, 4 trains), start up expected 2016.

**Contact**
syngas@airliquide.com
Steam Methane Reforming (SMR) – Syngas Production

**Application**
Production of carbon monoxide, CO+H₂, and syngas by steam methane reforming of hydrocarbon feed in catalyst filled tubes heated in a top-fired furnace.

**Feedstock(s)**
Natural gas

**Product(s)**
Carbon monoxide, oxogas, syngas (H₂+CO)

**Co-product**
Steam, hydrogen

**Capacity**
Up to 40,000 Nm³/h carbon monoxide
Up to 350,000 Nm³/h syngas, dry

**Description**
Feed gas is desulfurized, mixed with steam and pre-heated.

Feed and steam are reformed to H₂, CO and CO₂ in the proprietary top-fired steam reformer at pressures in the range of 15 - 45 barg.

Methane conversion requirements of downstream conversion steps are adjusted via the main process parameters, reforming temperature and steam to carbon ratio.

Carbon dioxide can be recycled and/or imported to save natural gas feed.

**References**
130 (all types of SMRs)

Recent contracts:
2x H₂+CO plant in Germany (Air Liquide and BASF) start-up in 2014 and 2015
3x Syngas plants for methanol in the US
CO plant in the Netherlands

**Contact**
syngas@airliquide.com
Gas POX – Natural Gas Partial Oxidation

**Application**
Production of CO, oxogas and syngas by partial oxidation of hydrocarbon feed in a refractory lined reactor

**Feedstock**
Natural gas, refinery offgas

**Product**
CO, syngas (H₂+CO)

**Co-product**
none

**Capacity**
Up to 150,000 Nm³/h syngas, dry

**Description**
Feed gas is desulfurized, mixed with steam and preheated in a fired heater.

Feed, steam and oxygen are fed from the proprietary burner to a refractory lined reactor operating at 40 to 100 barg, where H₂, CO and CO₂ are produced via partial oxidation.

Reformed gas is cooled down producing high pressure steam. CO₂ is removed from the syngas in an amine wash unit.

The required product ratio (H₂+CO) can be adjusted by a membrane, PSA or CO coldbox.

**Economics**
Feed+fuel: 1.1 Nm³ NG/Nm³ CO

Capital intensity:

![Graph showing capital intensity](image)

**References**
4

Latest: Freiberg (2004), Confidential customer (Germany, 2013)

**Contact**
syngas@airliquide.com
Petrochemicals
Low Pressure (LP) Methanol

Application
Medium-scale production (< 1 million tpa) of methanol from synthesis gas derived from all kinds of carbonaceous material (mainly natural gas and coal)

Feedstock
Natural gas or synthesis gas (H₂+CO)

Product
Methanol in the required specification (AA, IMPCA, etc.)

Co-product
none

Capacity
Up to 3,500 tpd

Economics
With combined reforming:
Yield:
Natural gas consumption:
29 MMBTU (LHV)/tonne
(this includes the energy for the oxygen production: 0.4-0.5 tonne oxygen/tonne)

Capital intensity:

<table>
<thead>
<tr>
<th>Capital intensity</th>
<th>USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>1,000</td>
<td>1,500</td>
</tr>
<tr>
<td>1,500</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Description
In the LP methanol unit (either with integrated gas generation based on natural gas or downstream of a coal gasification unit) syngas is converted over a copper catalyst in water-cooled reactor to produce raw methanol.

Unconverted synthesis gas is recycled back to the synthesis loop to enhance yield and carbon efficiency.

Raw methanol leaving the synthesis loop is further distilled to meet the required specification.

References
45 in operation

Key reference: Hainan Methanol (China), 2,000 tpd

Contact
petrochemicals@airliquide.com

Note: scheme represents only the methanol synthesis unit
**Lurgi MegaMethanol™**

**Application**
Large scale production (> 1 million tpa) of methanol from synthesis gas derived from all kinds of carbonaceous material (mainly natural gas and coal)

**Feedstock**
Natural gas or synthesis gas (H₂+CO)

**Product**
Methanol in the required specification (AA, IMPCA, etc.)

**Co-product**
none

**Capacity**
2,500 to 7,000 tpd
10,000 tpd (GigaMethanol)

**Economics**
With combined reforming:
Yield:
29 MMBTU (LHV)/tonne
(this includes the energy for the oxygen production: 0.4-0.5 tonne oxygen/tonne)

Capital intensity:

<table>
<thead>
<tr>
<th>Units</th>
<th>0</th>
<th>500</th>
<th>1,000</th>
<th>1,500</th>
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<tbody>
<tr>
<td>Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Description**
In the Lurgi MegaMethanol™ unit (either with integrated gas generation based on natural gas or down-stream of a coal gasification unit) syngas is converted over a copper catalyst in a two-stage reactor system (water-cooled followed by gas-cooled) to produce raw methanol. Unconverted synthesis gas is recycled back to the synthesis loop to enhance yield and carbon efficiency.

Raw methanol leaving the synthesis loop is further distilled to meet the required specification.

Due to high energy integration of the unit and the low recycle ratio in the synthesis loop, Lurgi MegaMethanol™ yields the lowest production cost.

Our most recent design (GigaMethanol) can produce up to 10,000 tpd in one single train.

*Note: scheme represents only the methanol synthesis unit*

**References**
7 in operation (4 gas based, 3 coal based), 4 in construction (2 gas based, 2 coal based).

Largest reference: 11,000 tonnes per day in two trains (coal based, under construction).

**Contact**
petrochemicals@airliquide.com
Application
The on-purpose production of propylene from methanol is a way to produce propylene independently from crude oil and/or natural gas liquids. Hence it supports the utilization of land-locked coal or natural gas reserves as feedstock for petrochemical processes.

Feedstock
Methanol

Product
Polymer-grade propylene

Co-product
Gasoline and LPG

Capacity
500 to 1,500 tpd

Economics
Yield: 3.5 tonnes methanol/tonne propylene
Capital intensity:

Description
In a first step, methanol is converted into dimethyl-ether (DME) which is, together with recycled hydrocarbon streams, the feedstock for the fixed-bed MTP reactor filled with proprietary zeolite catalyst. The effluent from the MTP reactor is cooled and enters a separation sequence similar to the one applied in steam-crackers. During this sequence, the effluent is separated into different hydrocarbon streams which are partially recycled to the reactor in order to maximise the propylene yield. The last step of the separation sequence is the production of polymer-grade propylene.

Compared to crude-based processes (naphta cracking, metathesis, PDH) the MTP process has the lowest cash cost.

References
3 references in operation (all coal based), first natural gas based plant in engineering stage.

Contact
petrochemicals@airliquide.com
**Application**
Recovery of 1,3 butadiene from a crude C4 stream from olefins plants by extractive distillation

**Feedstock**
Crude C4

**Product**
1,3 butadiene

**Co-product**
none

**Capacity**
6 to 35 t/h

**Economics**
Utility consumption (per tonne butadiene)
- Steam: 1.7 t/t
- Electricity: 150 kWh/t
- Water, cooling: 150 m3/t

Capital intensity:

<table>
<thead>
<tr>
<th>Capacity (t/h)</th>
<th>Capital Intensity (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>35</td>
<td>500</td>
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</table>

**Description**
In the pre-distillation tower methyl acetylene, propadiene and other light components are removed from the raw C4 cut feedstock which then enters the bottom section of the main washer column while NMP solvent enters at the top. C4 raffinate consisting of butanes and butenes is drawn off as overhead product. The loaded solvent is sent to the rectifier. The divided wall arrangement in the upper part allows it to strip less soluble butenes in the first compartment which are fed back to the main washer and to separate C4 acetylenes in the second compartment. The solvent from the rectifier is sent to the degassing tower where hydrocarbons are removed. The solvent is the recycled to the rectifier via compression.

The side stream of the degassing tower containing diluted C4 acetylenes is fed into a scrubber to recover NMP solvent. After further dilution with raffinate or other suitable materials, the C4 acetylene stream is discharged to battery limits for further processing. The crude butadiene withdrawn as overhead product from the rectifier is sent to the butadiene column for final purification. The butadiene product is withdrawn as liquid side product.

Ecology: NMP biodegrades readily and has low toxicity to aquatic life. Compared to other technologies, this process is much more eco-friendly.

**References**
36 units in operation

**Contact**
petrochemicals@airliquide.com
Lurgi / Nippon Kayaku Acrylic Acid

**Application**
The combined Lurgi/Nippon Kayaku technology produces ester-grade acrylic acid (EAA). Main uses are adhesives, paints and coatings (acrylic esters).

**Feedstock**
Propylene

**Product**
Ester-grade acrylic acid

**Co-product**
none

**Capacity**
Up to 20 t/h (single train)

**Economics**
Utility costs: 7.7 USD/tonne
Capital intensity:

**Description**
Reaction: Acrylic acid is produced by catalyzed oxidation of propylene in a two-stage tubular fixed-bed reactor system. The reactors are cooled by circulating molten heat transfer salt. The heat of reaction is used to produce steam.

Quench: The AA is recovered from the reactor product gas in a quench tower. The AA solution is routed to an extractor. Uncondensed gases are sent to an offgas treater to recover the remaining AA. A side draw from the offgas is sent to incineration. Overhead gas is recycled to the first reactor.

Solvent extraction: Liquid-liquid extraction is used to separate water and AA. The solvent is recovered and recycled. In a first step, water and acetic acid are removed to achieve a crude AA to be further purified in the next process steps. The extractor bottom is sent to the raffinate stripper to recover remaining solvents.

Crude AA recovery: In this section, solvent and acetic acid are removed from crude AA using two columns.

Raffinate stripping: The raffinate stripper recovers solvents from the wastewater streams.

The Lurgi/Nippon Kayaku technology combines high performance catalysts with highest acrylic acid yields and outstanding catalyst longevity with an optimized process. With low raw material and energy consumption, low environmental impact and high onstream time, this technology exhibits competitive production costs.

Acrylic acid purification: Crude AA is purified in the Ester grade AA column. To maximize AA recovery dimer could be converted to AA in a dedimerizer.

**References**
One plant with a capacity of 140,000 tpa of EAA is operated in China; startup took place in 2012.

**Contact**
petrochemicals@airliquide.com
**Methyl Acrylate (Hexion Licensed)**

**Application**
Production of methylacrylate (MA) by the esterification reaction of acrylic acid with methanol. The methylacrylate is used mainly for adhesives, paints and coatings.

**Feedstock**
Acrylic acid, methanol

**Product**
Methylacrylate

**Co-product**
none

**Capacity**
Up to 4 t/h

**Economics**
Process configuration is optimized resulting in low raw material consumption, optimized energy integration and low utility requirements. Environmental impact minimized. On stream times exceeding 8,000 hours per year could be achieved.

**Description**
The reaction is catalyzed in a fixed bed reactor by means of a strong acid solid catalyst (ion-exchange resin).

The reactor effluents are routed to the fractionation section to separate unreacted acrylic acid from crude methylacrylate, process water and methanol.

Further purification of the crude methylacrylate takes place in the alcohol extractor and the light ends column where process water and methanol as well as other light ends are removed. The final product column separates high boiling components to be routed to the AA regeneration section and the purified MA product can be send to storage.

In the AA regeneration section acrylic acid is recovered to be recycled to the reactor. The high boiling components are routed to the decomposer where they could partly be converted back to methanol, methylacrylate and acrylic acid to be recycled. Remaining unconverted components are discharged to battery limit for further treatment.

The bottom product of the alcohol extractor is routed to the methanol regeneration section to recover methanol to be recycled to the reactor. The water is partly reused in the process as well as routed to battery limit for further treatment.

Methylacrylate is prone to polymerization. In order to minimize polymerization effects, an inhibitor injection system is foreseen at critical locations in the plant.

**References**
One plant with 12,000 tpa operated by Hexion in Czech Republic

**Contact**
petrochemicals@airliquide.com

![Flow diagram of Methyl Acrylate process](image-url)
Ethyl Acrylate (Hexion Licensed)

**Application**
Production of ethylacrylate (EA) by the esterification reaction of acrylic acid with ethanol. The ethylacrylate is used mainly for adhesives, paints and coatings.

**Feedstock**
Acrylic acid, ethanol

**Product**
Ethylacrylate

**Co-product**
none

**Capacity**
Up to 4 t/h

**Economics**
Process configuration is optimized resulting in low raw material consumption, optimized energy integration and low utility requirements. Environmental impact minimized. On stream times exceeding 8,000 hours per year could be achieved.

**Description**
The reaction is catalyzed in a fixed bed reactor by means of a strong acid solid catalyst (ion-exchange resin).

The reactor effluents are routed to the fractionation section to separate unreacted acrylic acid from crude ethylacrylate, process water and ethanol. Further purification of the crude ethylacrylate takes place in the alcohol extractor and in the light ends column where process water and ethanol as well as other light ends are removed. The final product column separates high boiling components to be routed to the AA regeneration section and the purified EA product can be sent to storage.

In the AA regeneration section the acrylic acid is recovered and recycled to the reactor. The high boiling components are routed to the decomposer where they are partly converted back to ethanol, ethylacrylate and acrylic acid to be recycled. Remaining unconverted components are discharged to battery limit for further treatment.

The bottom product of the alcohol extractor is routed to the EIOH regeneration section to recover ethanol to be recycled to the reactor. The water is partly reused in the process as well as routed to battery limit for further treatment.

Ethylacrylate is prone to polymerization. In order to minimize polymerization effects, an inhibitor injection system is foreseen at critical locations in the plant.

**References**
One plant with 11,000 tpa operated by Hexion in Czech Republic

**Contact**
[petrochemicals@airliquide.com](mailto:petrochemicals@airliquide.com)
**Butyl Acrylate (Hexion Licensed)**

**Application**
Production of butylacrylate (BA) by the esterification reaction of acrylic acid (AA) with butanol. The butylacrylate is used mainly for adhesives, paints and coatings.

**Feedstock**
Acrylic acid, butanol

**Product**
Butylacrylate

**Co-product**
none

**Capacity**
Up to 20 t/h

**Economics**
Process configuration is optimized resulting in low raw material consumption, optimized energy integration and low utility requirements. Environmental impact minimized. On stream times exceeding 8,000 hours per year can be achieved.

**Description**
The reaction is catalyzed by means of para-toluene sulphuric acid (PTSA). A four stage reactor system ensures the conversion. The process water generated by the reaction is continuously removed from the reactor system. Process water, unconverted butanol and acrylic acid leaving the reactor system are separated in the dehydration columns. The organic phase (mainly butanol and AA) is recycled. The liquid crude BA and the catalyst are routed to the catalyst extraction column where the catalyst is extracted by means of process water and is recycled to the reactors. Residual acrylic acid in the crude BA is neutralized in the neutralization column by means of a caustic soda solution.

In the purification section light ends are removed from the crude BA and recycled back to the reactor system. In a second step high boiling components are separated and the final pure BA product is generated to be sent to storage. The high boiling components are transferred to the decomposer where they could partly be converted back to mainly BA to be recycled to the reactor section. Remaining unconverted components are discharged to battery limit for further treatment.

Butylacrylate is prone to polymerization. In order to minimize polymerization effects, an inhibitor injection system is foreseen at critical locations in the plant.

**References**
One plant with 16,500 tpa operated by Hexion in Czech Republic

**Contact**
petrochemicals@airliquide.com
**2-Ethylhexyl Acrylate (Hexion Licensed)**

**Application**
Production of 2-ethylhexylacrylate (2EHA) by the esterification reaction of acrylic acid with 2-ethylhexanol (2EHOH). The 2EHA produced is used mainly for adhesives, paints and coatings.

**Feedstock**
Acrylic acid, 2-ethylhexanol

**Product**
2-ethylhexylacrylate

**Co-product**
none

**Capacity**
Up to 5 t/h

**Economics**
Process configuration is optimized resulting in low raw material consumption, optimized energy integration and low utility requirements. Environmental impact minimized. On stream times exceeding 8,000 hours per year could be achieved.

**Description**
The reaction is catalyzed by means of para-toluene sulphuric acid (PTSA). A three stage reactor system ensures the conversion. The process water generated by the reaction is removed continuously by an azeotropic distillation step with a carrier agent. The reactor effluent which contains the reacted 2EHA, non reacted 2EHOH and PTSA is routed to the extraction section where the PTSA catalyst is extracted by means of process water and recycled to the Catalyst Regeneration Column. Additional 2EHOH is introduced via this column into the process and the extraction water is separated. The recovered PTSA catalyst and the preheated 2EHOH is routed to the first reactor.

In the Coalescer Section water is removed from the extracted crude 2EHA. The following Purification Section separates unreacted alcohol which is recycled to the Reaction Section. Furthermore, high boiling components are removed and the final pure 2EHA product is generated to be sent to storage. The high boilers are discharged to the Heavy End Decomposer where they are partly converted back to 2EHA and EHOH and recycled to the reactor section. Remaining unconverted components are discharged to battery limit for further treatment.

2EHA is prone to polymerization. In order to minimize polymerization effects, an inhibitor injection system is foreseen at critical locations in the plant.

**References**
One plant with 26,500 tpa operated by Hexion in Czech Republic

**Contact**
petrochemicals@airliquide.com
**Distapex™ – Aromatics Extractive Distillation**

**Application**
Recovery of aromatics from a heart-cut feedstock by extractive distillation

**Feedstock**
Pyrolysis gasoline

**Product**
Benzene

**Co-product**
none

**Capacity**
Up to 40 t/h

**Economics**
Recovery rate: > 99.5%
Utility costs: 8.8 USD/tonne
Utilities (per tonne benzene)
Steam, tonne 0.7
Electricity, kWh 8
Water, cooling, m³ 19
Solvent loss, kg 0.01

Capital intensity:

<table>
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<th>m USD</th>
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**Description**
The aromatics in the feedstock are separated by extractive distillation using N-methylpyrrolidone (NMP) as a solvent. The raffinate product containing the non-aromatics leave the extractive distillation column via the top. The loaded solvent is routed to a stripper column where the final aromatic product is recovered at the column top and routed to battery limit. The lean solvent is recycled to the extractive distillation column.

Ecology: Due to the unique properties of NMP, the process has an excellent ecological footprint.

The DistapexTM process requires a minimum number of equipment items and is especially renowned for reliability and availability as well as low operating costs. Due to the low boiling point of the solvent only medium-pressure steam is required.

**References**
> 27

**Contact**
petrochemicals@airliquide.com
**G2G™ – Gas-to-Gasoline**

**Application**
Lurgi MegaMethanol™ and ExxonMobil MTG technologies licensed in an integrated approach to monetize low cost feedstock, usually natural gas or coal, to high value oil products. Air Liquide can also leverage its global network of ASUs and syngas facilities to provide synergistic solutions for G2G™ projects.

**Feedstock**
Natural gas (NG), coal, heavy hydrocarbons, biomass

**Product**
Sulfur free gasoline/petrol

**Co-product**
LPG (optional)

**Capacity**
1,000 to 32,000 bpd
Standardized design: 16,100 bpd

**Economics**
Yield: 9,100 scf natural gas/barrel
Opex: 8.5 USD/barrel

Profitability is driven by low feedstock prices relative to market value of wholesale oil products.

**Description**
G2G™ technology presents an opportunity to monetize low cost feedstock into transportation fuels either for domestic use or for export markets. Projects are driven by the spread between the price of feedstock and oil products. Low cost gas or stranded gas can enhance profitability even at low-moderate oil price scenarios. The gasoline product from G2G™ is low in benzene and has no sulfur compounds. Product can be used as on-spec gasoline that meets or exceeds any typical (stringent) environmental standards or as a refinery blending stock.

**References**
Lurgi Methanol is well referenced with more than 50 units in service.

ExxonMobil Zealand MTG plant operated from 1985 until 1997 with a high on-stream factor, plus new units underway in China.

**Contact**
g2g@airliquide.com

![Diagram of G2G™ technology](chart.png)
Natural Gas Treatment
### Nitrogen Rejection Unit

**Application**
Removal of nitrogen from natural gas, associated gases and unconventional gas sources

**Feedstock**
Natural gas with high nitrogen content

**Product**
Natural gas, nitrogen

**Co-product**
LNG, liquid nitrogen, crude helium

**Capacity**
Up to 1,000,000 Nm3/h

**Economics**
Economics are highly dependent on feedstock and requirements (high efficiency or low CAPEX).

Contact us for more information.

**Description**
Natural gas feed is partially condensed, then methane and nitrogen are separated into a system of distillation column(s). Depending on the feed composition and pressure, the system can include one to three distillation columns.

The process scheme selection is done according to project-specific parameters such as feed evolution with time and product specifications.

Air Liquide Global E&C Solutions offers a wide range of solutions, such as the ability to treat any N2/CH4 mixtures (5-90%), high efficiency, flexibility and recovery (>99% methane), minimization of greenhouse gases emissions to the atmosphere (methane in N2 vent << 1%), CAPEX optimization, operation flexibility thanks to proprietary design.

**References**
Nitrogen Rejection from syngas: QIANXI COAL CHEMICAL (China), BASF ANTWERP (Belgium), YIMA CSU (China)

Nitrogen Rejection from natural gas: FEED major gas processing plant (Russia), Bayern Gas (Germany)

**Contact**
gas-treatment@airliquide.com
**Combined Natural Gas Liquids Recovery & NRU**

**Application**
NGL recovery associated with the removal of nitrogen from natural gas, associated gases and unconventional gas sources.

**Feedstock**
Natural gas with NGL

**Product**
NGL (C₂⁺), natural gas

**Co-product**
LNG, liquid nitrogen, crude helium

**Capacity**
Up to 1,000,000 Nm³/h

**Economics**
High NGL recovery with sales gas on specifications easily achieved with significant reduction in capital and operating costs when compared to conventional independent units.

Economics are highly dependent on feedstock and requirements (high efficiency or low CAPEX).

Contact us for more information.

**Description**
Air Liquide Global E&C Solutions offers state-of-the art NGL technology with high efficiency C₂ recovery (90% to >98%) and low energy consumption.

Combined with Air Liquide’s know-how in nitrogen rejection and expertise in cryogenics, Air Liquide solutions differentiate through thermal integration and synergies to provide overall optimised NGL/ NRU plants.

**References**
FEED major gas processing plant (Russia), many references of NGL separation (NGL plants, Lurgi MTPTM columns) and nitrogen rejection (syngas and natural gas references)

**Contact**
gas-treatment@airliquide.com
Amine Wash for Acid Gas Removal

**Application**
Removal of acid gases (CO₂, H₂S, COS, light mercaptans RSH) from natural gas, associated gases and unconventional gas sources

**Feedstock**
Natural gas with low acid gases content (typically <15%)

**Product**
Natural gas

**Co-product**
Acid gases

**Capacity**
Up to 1,500,000 Nm³/h

**Economics**
Economics are highly dependent on feedstock and requirements (high efficiency or low CAPEX).

Contact us for more information.

**Description**
Acid gases contained in raw gases are removed by absorption with a chemical or a mixture of chemical and physical solvent. The rich solvent leaving the contactor is regenerated by flashing.

Different process configurations can be combined to various solvent types and concentrations to meet requirements for individual applications. Air Liquide Global E&C Solutions can offer very energy-efficient processes such as the BASF OASE purple, formulated for pipeline or LNG specifications.

This process presents the advantage of very low hydrocarbon co-absorption.

**References**
> 50 (Implemented with BASF OASE purple, MEA, DEA, MDEA solvents)

Largest reference: QATARGAS LNG phases 2, 3 and 4 with each 1,500 MMSCFD – Removal of CO₂, COS and H₂S from natural gas feedstock.

**Contact**
gas-treatment@airliquide.com
Combined Membrane/Amine Wash for Acid Gas Removal

**Application**
Removal of CO₂ and H₂S from medium acid gas fields

**Feedstock**
Natural gas with medium acid gas content (typically 15-35%)

**Product**
Natural gas

**Co-product**
Acid gases

**Capacity**
Up to 1,500,000 Nm³/h

**Economics**
Economics are highly dependent on feedstock and requirements (high efficiency or low CAPEX).

Contact us for more information.

**Description**
Acid gases contained in raw gases are removed in a 2-step separation:

1) **CO₂** bulk removal by CO₂-selective hollow fiber membrane (MEDAL™) reducing the CO₂ content at the amine inlet to such content that the overall plant sizing exhibits optimum economics.

2) **CO₂** and sulfur species are removed by absorption with an aqueous solution of amine. The rich amine solution leaving the contactor is regenerated by flashing or stripping.

**References**
> 10 in operation

**Contact**
gas-treatment@airliquide.com
**Application**
Sweetening and processing of natural gas by removing CO₂, H₂S, COS, mercaptans, water and mercury to pipeline or LNG specifications as well as production of liquid, elemental sulfur while minimizing SO₂ emissions to the atmosphere to meet most stringent environmental regulations.

**Feedstock**
Raw natural gas, associated gas

**Product**
Natural gas, sulphur (99.9% purity)

**Co-product**
None

**Capacity**
Up to 1,500,000 Nm³/h

**Economics**
Economics are highly dependent on feedstock and requirements (high efficiency or low CAPEX).

Contact us for more information

**Description**
The Omnisulf™ technology encompasses the following proprietary key processes:

Acidic components are removed using BASF’s OASE® technology and the cleaned gas is routed to a dehydration and mercaptan removal unit (DMR) that removes moisture and mercaptans with special 13X zeolite technology. If necessary, mercury is removed from the sweet gas with impregnated activated carbon. Mercaptans are recovered from the regeneration gas with the Lurgi Purisol™ technology. All gas streams containing sulfur are routed to a sulfur recovery unit (SRU). Elemental sulfur is produced in the Claus process (equipped with a Lurgi Multi-Purpose Burner) followed by a Lurgi tail gas treatment (LTGT) unit combined with an acid gas enrichment system to boost sulfur recovery and reduce SO₂ emissions. The sulfur product is then treated further by applying an Aquisulf™ degassing process that removes H₂S concentrations below 10 ppm. Offgases are incinerated before being safely released to the atmosphere.

The Omnisulf™ technology can be tailored for gas reinjection.

**References**
Qatargas LNG phases 2, 3 and 4 are running with the Omnisulf™ process. Two trains are under construction in the Middle-East.

**Contact**
gas-treatment@airliquide.com
Cryocap™ NG for Acid Gas Removal

**Application**
Removal of CO₂ from natural gas, associated gases and unconventional gas sources

**Feedstock**
Natural Gas with high CO₂ content (> 35%)

**Product**
Natural Gas

**Co-product**
Acid Gases

**Capacity**
Up to 1,000,000 Nm³/h

**Economics**
Separation cost: less than 1 USD/MMBTU
Capex savings: > 50% vs. amine wash
Contact us for more information.

**Description**
The CO₂ rich natural gas is first dried and sent to a cold box where it is cooled down and sent to a distillation column.

High CO₂ partial pressure favors the CO₂ partial condensation and thus makes its separation from natural gas even easier. The non-condensable gas is enriched in methane and sent to a membrane for final purification.

The CO₂ purity of the product corresponds to pipeline specifications, generally 1 to 10 mol%. The permeate stream of the membrane enriched in CO₂ is sent back to the cold box. The CO₂ and heavy hydrocarbons condense in the cold box and are collected at high pressure. NGL recovery is possible with almost no additional cost.

Cryocap™ NG is tolerant to a few % H₂S. Cryocap NG also allows for H₂S bulk removal fom NG.

**References**
Cryocap™ H₂ Port Jérôme, Cryocap™ Oxy CIUDEN, Cryocap™ Oxy Callide, FutureGen 2.0 Cryocap™ Oxy FEED

**Contact**
gas-treatment@airliquide.com
Sulfur
**OxyClaus™ Sulfur Recovery Unit**

**Application**
Recovery of sulfur from acid gas streams containing hydrogen sulfide (H₂S) for new units or debottlenecking of existing units

**Feedstock**
Acid gas from sweetening units and sour-water strippers; oxygen

**Product**
Bright yellow sulfur with up to 99.9% purity

**Co-product**
None

**Capacity**
Up to 1,000 tpd

**Economics**
OxyClaus™ provides savings of approximately 30% of the total installed cost of a new sulfur recovery unit and enables increased capacity of existing sulfur recovery units up to 200%.

Contact us for more information.

**Description**
In a conventional Claus plant ambient air is used to oxidise 1/3 of the hydrogen sulfide (H₂S) in the acid gases to sulfur dioxide (SO₂). Up to 80% of the total oxygen demand can be covered with pure oxygen in the OxyClaus™ unit by using a proprietary burner design. Oxygen is injected into the acid gas resulting in an extremely hot flame. By introducing air around the outside of this flame a zone with moderate combustion temperatures are created and therefore conventional refractory materials can be used in the thermal stage.

In downstream catalytic stages of the Claus unit, including reactors, condensers and heaters, no specialized equipment or changes in usual design practice are required.

The unit can be operated with air only or with air + oxygen. This allows for covering peak loads and flexible processing of feed gases with low or high content of H₂S by automatic change-over from air to oxygen operation and vice versa.

**References**
> 40 in operation

**Contact**
sulfur@airliquide.com
Sulfur Recovery Unit

**Application**
Recovery of sulfur from acid gas streams containing hydrogen sulfide (H₂S)

**Feedstock**
Acid gases from sweetening units and sour-water strippers

**Product**
Bright yellow sulfur with up to 99.9% purity

**Co-product**
None

**Capacity**
Up to 1,000 tpd

**Economics**
Sulfur recovery: >95%

Operating costs can be considered negligible if credit is given for steam produced in SRU.

Capital intensity:

![Capital intensity graph]

**Description**
The acid gases are burnt sub-stoichiometrically with air in a refractory lined furnace. Resulting mixture of H₂S and SO₂ reacts to form elemental sulfur which is removed from the process through condensation. In subsequent catalytic stages, typically two or three, the conversion to sulfur is promoted further yielding a sulfur recovery of 94.5% – 97.5% for the Claus unit.

Two tail gas treatment (TGT) options are available to boost the sulfur recovery further.

1) Sulfreen™: A catalytic purification of the Claus tail gas for an overall sulfur recovery of up to 99.5%.

2) LTG™: Claus tail gas is purified in a wet-scrubbing process. Due to the recycling of the H₂S rich stream to the Claus unit, total sulfur recovery can be increased to 99.9%.

In the degassing section, the H₂S content of the sulfur is decreased to a maximum of 10 ppm. For this the catalytically promoted Aquisulf™ technology (registered trademark of Elf Aquitaine) or the Degasulf™ technology can be employed. Offgas from tail gas treatment and degassing is incinerated and released to the atmosphere.

**References**
- > 170 Claus plants (4 to 1,000 tpd)
- > 60 tail gas treatment processes
- > 50 Aquisulf™ in operation

**Contact**
sulfur@airliquide.com

![Diagram of Sulfur Recovery Unit]
Claus – Emission-Free Sulfur Recovery Unit

**Application**
Recovery of sulfur from acid gas streams containing hydrogen sulfide (H₂S) with 100% sulfur recovery

**Feedstock**
Acid gases from acid gas removal unit and sour-water strippers

**Product**
Bright yellow sulfur with up to 99.9% purity

**Co-product**
None

**Capacity**
Up to 1,000 tpd

**Economics**
CAPEX: 25% less than conventional amine-wash tail gas treatment

Sulfur recovery: 100%

Contact us for more information.

**Description**
Raw gas is desulfurized in an AGR and acid gas is sent to the emission-free SRU for sulfur recovery. The conventional Claus process is employed to recover sulfur from the acid gas in elemental form. Gases containing hydrogen sulfide (H₂S) from sour-water strippers can be fed to the Claus unit in addition. The recovered sulfur is degassed and is then available as a sellable product.

Claus tail gas is hydrogenated and cooled before being compressed and routed to the AGR. Here it is desulfurized and recycled, together with the acid gas, back to the Claus unit. Valuable components inside the tail gas, like H₂ and CO end up in the purified gas. With this recycle a sulfur recovery rate of 100% is achieved. The sulfur emissions to the atmosphere in overall complex are significantly reduced.

It is recommended to install an OxyClaus™ in this concept because this reduces the process gas volume and therefore lowers not only investment cost plus operating cost but also the amount of inert gas sent to AGR.

**References**
Three emission-free SRUs have been designed, one has been in operation for 25 years.

**Contact**
sulfur@airliquide.com
Small-scale LNG (Nitrogen Refrigeration Cycle)

**Application**
Liquefaction of natural gas (NG) for small scale plants serving for power applications (peak shaving, remote power) or fuel (marine, truck, rail, etc.)

**Feedstock**
Natural gas

**Product**
LNG

**Co-product**
None

**Capacity**
Up to 600 tpd

**Description**
The process consists of three main modules: pre-treatment, liquefaction and LNG storage and loading (truck trailer, bunkering barge, etc.).

1) Pre-treatment is a combination of an amine system to remove acid gases (typically CO₂) contained in the feed gas and a drying unit to remove moisture (typically Thermal Swing Adsorption).

2) The liquefaction process is based on a nitrogen cycle (closed loop): N₂ is first compressed and boosted. After being cooled down through a Brazed Aluminum Heat Exchanger, it is expanded releasing N₂ at low pressure and low temperature. Cold N₂ (at T < −165°C) is then re-injected into the Main Heat Exchanger to cool down the natural gas and convert it to LNG, which is sent to storage. Warm N₂ is then recycled through the cycle compressor.

3) Storage can be either pre-fabricated (vacuum insulated) for small volumes or flat bottom tanks for larger needs depending on the applications considered. The loading station can be adapted to truck trailer loading or maritime.

**Economics**
Capital intensity:

[Graph showing capital intensity in mm USD]

**References**
15 peakshavers in operation (Canada, United States and Argentina).
Examples: Citizens Gas (United States), Gas Natural Fenosa (Argentina)
90 nitrogen cycle liquefiers (for LIN or LNG)

**Contact**
lng@airliquide.com
**Mid-scale LNG (Mixed Refrigerant Cycle)**

**Application**
Liquefaction of natural gas for mid-scale plants serving for larger power or fuel applications, possibly mid-sized LNG export terminal.

**Feedstock**
Natural gas.

**Product**
LNG, NGLs.

**Co-product**
None.

**Capacity**
600 to 6,000 tpd.

**Economics**
Capital intensity:

![Capital Intensity Chart]

**Description**
The process consists of three main bricks: NG pre-treatment, NG liquefaction, LNG storage and loading (truck trailer, bunkering barge, etc.).

1) NG pre-treatment is a combination of an amine system to remove acid gases (typically CO₂) contained in the feed gas and a drying unit to remove moisture (typically Temperature Swing Adsorption).

2) The liquefaction process is a mixed refrigerant closed loop cycle consisting of a mixture of hydrocarbons and nitrogen. The refrigerant is compressed and separated in liquid and gaseous streams. Lightest fractions of the refrigerant are sent to the cold end of the main heat exchanger, cooled down and sent back to the compressors after being vaporized through the main HX. Heaviest fractions are let down and vaporized at an intermediate level in the main HX. The optimization of the mixed refrigerant cycle consists of taking advantage of the vaporization temperature difference between generated refrigerant streams to optimize the NG liquefaction heat exchange profile. In addition, the heavy hydrocarbons removed from the process can be recovered and sold as NGL.

3) Storage for mid scale LNG plants are usually large flat bottom tanks, though tank farms composed of vacuum insulated tanks can also be a solution in some cases. The loading station can be adapted to truck trailer loading or maritime.

**References**
One 0.7 mtpa in design.

15 peakshavers in operation (Canada, United States and Argentina).
Examples: Citizens Gas (United States), Gas Natural Fenosa (Argentina)

**Contact**
lng@airliquide.com

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**Diagram**

- **Pretreatment**
- **Mixed Refrigerant Compressor**
- **Liquid Separators**
- **Main Heat Exchanger**
- **Natural Gas from pipeline or field**
- **LNG from vacuum insulated tanks**
- **Storage**
- **Heavies (NGL)**
Boil-Off Gas Reliquefaction Unit

**Application**
Recovery of Boil-Off Gas (BOG) for import & export terminals and during ship-to-ship transfer

**Feedstock**
Boil-off gas + energy (electrical or fuel) + gaseous N2 make-up

**Product**
LNG

**Co-product**
None

**Capacity**
50 to 500 tpd

**Economics**
Specific energy: 500 to 800 kWh/tonne
Capital intensity:

**Description**
A BOG reliquefaction unit allows for the recovery of boil-off gas emitted from LNG storage and its reliquefaction.

The system is based on a nitrogen reverse Brayton cycle with one or two expanders scheme, depending on BOG available pressure.

It allows for avoiding BOG flaring and debottlenecking of LNG export terminals.

**References**
For bunkering applications (embarked on board)

**Contact**
lng@airliquide.com
Boil-Off Gas Reliquefaction (LIN)

Application
Recovery of boil-off gas (BOG) for import and export terminals and during ship-to-ship transfer

Feedstock
Boil-off gas + liquid nitrogen

Product
LNG

Co-product
None

Capacity
50 to 500 tpd

Description
LIN to LNG box unit allows for the recovery of large boil-off gas emitted during ship loading or unloading operations.

Liquid nitrogen is delivered and stored continuously in a liquid nitrogen storage, which delivers large liquid nitrogen flow to recover BOG flow emitted during the few hours of ship loading or unloading.

It allows for avoiding BOG flaring and reduces the investment cost compared with BOG reliquefaction solution.

Economics
LIN consumption: 1.3 to 1.5 mol/mol

Capital intensity:

Contact
lng@airliquide.com
Sliding Cell Extractor – Seed Crushing and Extraction

**Application**
Production of crude edible oils

**Feedstock**
Oil seeds (soybean, canola/rapeseed, sunflower, palm kernel...)

**Product**
Crude edible oils for use in food or technical applications after refining
Meal for animal feed

**Co-product**
Crude lecithin

**Capacity**
Up to 5,000 tpd

**Economics**
Economics are highly dependent on the type of feedstock and required meal quality.

Capital intensity:

![Graph](image)

**Description**
The oil content of different types of seeds ranges between 20-50 wt.%. After feedstock specific preparation steps (cleaning, drying, etc.) the oil is gained from the seeds by solvent extraction with hexane. For seeds with higher oil content (e.g. rapeseed, sunflower) the extraction is typically combined with a prepressing step to reduce the load on the extraction.

The Lurgi sliding cell extractor is the core of the extraction plant. It provides high flexibility regarding feedstock changes, very reliable operation and optimum extraction conditions with complete counter-current flow of solvent vs. flakes and large contact areas.

The miscella (oil/solvent mixture) from extraction is separated into its components by distillation and water degumming. The solvent is re-used in the extraction after removing the collected moisture. Gums can be purified to lecithin or recycled to the meal.

The desolventized, toasted, dried and cooled (DTDC) meal can be used as protein rich animal feed.

The whole process is kept under slight vacuum so that emissions can be controlled by absorption to fulfill environmental regulations.

**References**
> 300 plants in China, Southeast Asia, Americas, Europe for different feedstocks

**Contact**
oleo@airliquide.com
Natural Oil Refining

Application
Removal of impurities from crude oils and fats

Feedstock
Crude oils and animal fats

Product
Pretreated and/or refined oils and fats (RBD oil)

Co-product
Fatty acid distillate (FAD), Tocopherol

Capacity
100 tpd to 2,800 tpd

Economics
Economics are highly dependent on application of the refined oil (technical applications or edible oil), the required process steps (e.g. degumming, bleaching, winterisation, deodorisation, hydrogenation, fractionation and interesterification) and the type of process (batch, semi-batch or continuous).

Description
Crude oils and fats contain different contaminants like free fatty acids (FFA), phospholipids (gums), soaps, color, odor, etc. Their removal is called “Refining” for food purposes to reach RBD oil quality (refined, bleached, deodorised) and “Pretreatment” to reach quality for further processing, e.g. for biodiesel production or oil splitting.

Technologies are available for all applications: FFA can be removed chemically by neutralisation or thermally by deacidification. Waxes are separated in winterisation. Color and polycyclic aromatic hydrocarbons (PAHs) are removed in bleaching; odors and pesticides during deodorisation (with vitamin E as potential by-product).

Refining also includes process steps for fat modification like hydrogenation (saturation of double bonds), interesterification (to adjust the melting point) or fractionation (separation according to chain length) and side processes like soapstock splitting or gum drying.

References
> 400 plants in Southeast Asia, China, Americas and Europe based on different feedstocks

Latest reference in 2015

Contact
oleo@airliquide.com
**Application**
Production of biodiesel (Fatty Acid Methyl Ester, FAME)

**Feedstock**
Vegetable or animal oils and fats; major feedstock for fuel applications are rapeseed, soya, tallow or palm oil

**Product**
Biodiesel meeting all international quality standards, incl. EN 14214 and ASTM D6751

**Co-Product**
Crude glycerin (purity > 80%)

**Capacity**
Standard capacities 100 - 1100 tpd

**Economics**
Capital intensity:

---

**Description**
Biodiesel is produced from triglycerides by transesterification with methanol under presence of an alkali catalyst (sodium methylate) at ~65°C and atmospheric pressure.

Key features of Lurgi’s biodiesel technology are maximum yield (1 kg feedstock = 1 kg biodiesel), closed wash water loop (no waste water from core process units) and sediment removal for palm and soya oil to remove sterol glucosides far below limits given by international quality standards.

Only NaOH and HCl are used in the process. Resulting sodium chloride ends up in the glycerin, can easily be removed and does not cause fouling or side reactions during further processing (see glycerin distillation).

---

**References**
> 50 plants since 2000 (Europe, Americas, Southeast Asia, India)

**Contact**
oleo@airliquide.com
Fatty Acid Methyl Ester Distillation/Fractionation

Application
Quality improvement of biodiesel and/or production of fatty acid methyl ester (FAME) fractions and metathised FAME for chemical industry

Feedstock
FAME from transesterification (see Lurgi Biodiesel process)

Product
FAME fractions and/or distilled biodiesel

Co-product
None

Capacity
100 tpd to 1,000 tpd

Economics
Opex: 30-50 USD/tonne (feedstock)
(depending on number of fractions and their related purities)

Description
FAME is separated according to molecular chain lengths to apply specific cuts in a fractionation column. A falling film evaporator and vacuum pressure reduce heat stress to FAME resulting in superior product quality suitable for surfactant or personal care applications.

Distilled FAME can also be sold as top-quality water-clear biodiesel with improved cold flow properties and 50-100 ppm residual water. Sterol glucosides and monoglycerides are removed close to detection limits.

Heat recovery by steam generation makes this process very energy efficient.

References
> 10 plants since 2000 (Southeast Asia) with capacities up to 1,000 tpd.

Contact
oleo@airliquide.com
Glycerin Distillation and Bleaching

**Application**
Purification of glycerin to pharma and technical grade

**Feedstock**
Crude glycerin from biodiesel or oil splitting (fatty acid) plants

**Product**
Pharma grade glycerin (purity > 99.7%)

**Co-product**
Technical grade glycerin (purity 85-90%)

**Capacity**
10 tpd to 600 tpd

**Economics**
Opex: 35 USD/tonne

**Description**
Vacuum distillation is used to separate glycerin from organic components and salts at temperatures up to 175°C. The residue from the column bottom is sent to a post distillation still (not shown) to increase glycerin yield. Salt can be separated from the residue by a decanter to reduce the amount of waste and to increase glycerin recovery even further.

Pharma grade glycerin as the main product is polished by bleaching, i.e. adsorption at fixed beds of activated carbon. Light impurities end up in the by-product, technical grade glycerin, which is 3-5% of the feed.

**References**
45 plants since 2000 (Europe, Southeast Asia, Americas, China, India) including World’s largest glycerin distillation (600 tpd with decanter technology, startup 2010)

**Contact**
oleo@airliquide.com
**Fatty Acid Production (Oil Splitting)**

**Application**
Production of crude fatty acids

**Feedstock**
Seed oils, tropical oils, animal fats

**Product**
Crude fatty acids

**Co-product**
Glycerin water (25-35% glycerin content)

**Capacity**
100 tpd to 1,000 tpd

**Economics**
Opex: 10 USD/tonne (feedstock)

**Description**
Triglycerides are hydrolyzed catalyst-free to fatty acids and glycerin by addition of water at elevated temperatures (~250°C) and elevated pressure (~55 bar) with splitting degrees up to 99.5%.

The fatty acids rise to the top of the splitting column and are dried by flashing before further processing by distillation/fractionation or hydrogenation.

Water and glycerin leave the column at the bottom and are also flashed. The flashing vapors are used for heat recovery.

Final concentration of crude glycerin is 80-88% (almost salt-free), which can be sold or further processed to pharma grade glycerin.

**References**
> 25 plants since 2000 (Europe, Southeast Asia, China, India)

**Contact**
oleo@airliquide.com
**Fatty Acid Distillation/Fractionation**

**Application**
Purification and fractionation of crude fatty acids

**Feedstock**
Crude fatty acids from oil splitting

**Product**
Fatty acids fractions/fatty acid distillate

**Co-product**
None

**Capacity**
100 tpd to 1,000 tpd

**Economics**
Opex: 30-50 USD/tonne(feedstock) (depending on number of fractions and their related purities)

**Description**
Fatty acids are separated from non-volatile components by vacuum distillation.

Fractions of different fatty acid chain lengths with high purity can be obtained with our vacuum fractionation plants.

The use of structured packing and vacuum in the fractionation columns reduces the thermal stress and ensures high product qualities. Steam generation in the condensers makes the process highly energy efficient.

Each fatty acid fractionation plant will be tailor-made by our experts to ensure best fit to the needs of our customers.

**References**
> 50 plants (Europe, Southeast Asia, China, India, Saudi Arabia) with capacities up to 600 tpd.

**Contact**
oleo@airliquide.com
**Fatty Acid Hydrogenation**

**Application**
Saturation of fatty acid double bonds (hardening)

**Feedstock**
Fatty acids from oil splitting

**Product**
Partially or fully hydrogenated fatty acids down to an iodine value of 0.3

**Co-product**
None

**Capacity**
Batch: 50 tpd to 100 tpd  
Continuous: 100 tpd to 600 tpd

**Economics**
Opex:  
- Batch: 11 USD/tonne (feedstock)  
- Continuous: 10 USD/tonne (feedstock)  
(dependending on number of fractions and their related purities)

**Description**
Saturation of fatty acid double bonds by addition of H₂ (~ 99.9% by vol.) under elevated temperatures and pressure (up to 200°C @ ~25 bar) in the presence of a Ni catalyst.

Continuous (for full hydrogenation and large plants) and batch process variants (for full or partial hydrogenation) are available.

**References**
10 plants since 2000 in Southeast Asia up to 400 tpd

**Contact**
oleo@airliquide.com
Fatty Alcohol – Wax Ester Route

**Application**
Production of fatty alcohols via fatty acids

**Feedstock**
Depending on the desired product all kinds of vegetable oils and fats can be used. Biggest market is C12/14 from palm kernel and coconut oil.

**Product**
Fatty acids (intermediate product) and fatty alcohols as fractions of different chain lengths

**Co-product**
Glycerin

**Capacity**
90 tpd to 600 tpd

**Economics**
Opex: 120 USD/tonne

**Description**
Fatty acid fractions (see oil splitting and fatty acid fractionation) are esterified catalyst-free with fatty alcohol into wax ester. Subsequent hydrogenation produces fatty alcohol in a fixed bed reactor in the presence of a Cu catalyst (180-210 °C @ 250 bar). Traces of oxygenates are hydrogenated in a polishing section (carbonyl conversion). The resulting fatty alcohol cuts can further be fractionated into final fatty alcohol products.

The wax ester route is normally chosen if there is no integration required with a methyl ester plant because short chain fatty acids have a higher market price than the corresponding fatty alcohols which would be produced via the methyl ester route.

**References**
6 plants since 1990s up to 480 tpd (India, Indonesia, China, and Saudi Arabia) latest plant under construction

**Contact**
oleo@airliquide.com
**Fatty Alcohol – Methyl Ester Route**

**Application**
Production of fatty alcohols from oils and fats via methyl ester (Lurgi Biodiesel)

**Feedstock**
Depending on the desired product all kinds of vegetable oils and fats can be used.

**Product**
Methyl ester (intermediate product) and fatty alcohols as fractions of different chain lengths

**Co-product**
Glycerin

**Capacity**
90 tpd to 600 tpd

**Economics**
Opex: 115 USD/tonne

**Description**
After production of methyl ester (see Lurgi Biodiesel), the resulting esters are hydrogenated in a fixed bed reactor in the presence of a Cu catalyst (180-210 °C @ 250 bar) to produce fatty alcohol. Methanol can be recycled to the transesterification step.

Traces of oxygenates are hydrogenated in a carbonyl conversion section as polishing.

The methyl ester route is preferred, if a methyl ester plant exists at site or methyl ester will be a side product of the facility.

**References**
2 plants (Indonesia), last plant 2015 (540 tpd)

**Contact**
oleo@airliquide.com
LP3 – Low Pressure Fatty Alcohol Production

**Application**
Improved hydrogenation process for Fatty Alcohol - Wax Ester Route

**Feedstock**
Wax ester

**Products**
Fatty alcohol

**Co-product**
None

**Capacity**
90 tpd to 600 tpd

**Economics**
Opex: 100 USD/tonne

Contact us for more information.

**Description**
Hydrogenation of wax ester is improved with LP3 features:

**Liquid Phase:** Proven liquid phase hydrogenation in fixed bed reactors also suitable for long chain fatty alcohols in contrast to vapor phase hydrogenation.

**Low Pressure:** Comparatively low pressure (reduced from 250 bar to 100 bar) reduces energy requirements (OPEX savings approx. 5%) and CAPEX (savings approx. 15-20%).

**Long Performance:** Double reactor system for seamless catalyst changeovers with no disruption to operations and efficient catalyst utilization for more profitable lifecycles (see operation steps in diagram).

The temperature in the catalyst beds is controlled by hydrogen quenches to limit amount of side-products.

**References**
Proven in laboratory scale, under implementation in commercial scale.

**Contact**
oleo@airliquide.com
Bio Propylene Glycol (BASF Licensed)

**Application**
Production of bio propylene glycol (1,2-propanediol, MPG) from glycerin as alternative to petrochemical route

**Feedstock**
Pharma grade glycerin

**Product**
Pharma grade propylene glycol

**Co-product**
None

**Capacity**
50 to 100 tpd

**Economics**
Contact us for more information

**Description**
In this process, licensed from BASF, glycerin is hydrogenated in liquid phase using a copper catalyst. The reaction takes place in two serial fixed bed reactors at a temperature between 175 to 195 °C and pressures between 75 and 200 bar.

The crude product is purified in a two-column distillation unit to yield pharma grade propylene glycol.

**References**
One pilot plant (Germany), one commercial demonstration plant (Belgium, 2012).

**Contact**
oleo@airliquide.com
**Sorbitol**

**Application**
Sorbitol is produced by batchwise hydrogenation of aqueous glucose solution.

**Feedstock**
Glucose from wet milling plants

**Product**
Technical, food or pharma grade sorbitol

**Co-product**
None

**Capacity**
100 to 200 tpd

**Economics**
OPEX: 130-165 USD/tonne w/o feedstock and fixed cost.

Capital intensity:

**Description**
The glucose solution is hydrogenated in a batch reactor using nickel or ruthenium catalysts. Reaction takes place at 110 °C and 40 bar pressure. After reaction, the product slurry is filtered to recover the catalyst. Makeup catalyst compensates catalyst loss and deactivation. The crude sorbitol solution is purified by ion exchange and evaporated to the final concentration. Optionally, sorbitol powder can be obtained by melt crystallisation.

**References**
> 10 plants (Germany, Finland, Thailand, India)

Latest project 2015 (Russia)

**Contact**
oleo@airliquide.com
Engineering Services
Conceptual and Feasibility Studies

Description
Our team of experts can assist owners in early phases of project development. Studies are customized to meet the Customer’s needs. Our typical packages are:

• Screening/Pre-feasibility study comprising first CAPEX/OPEX estimates
• Feasibility study for more detailed economic analysis:
  – class 4 or 5 cost estimate
  – mass and utility balance
  – BFD
  – footprint
• Permitting study: This package is designed to provide the technical information required to apply for an air permit (title V and PSD) early on. It typically comprises:
  – process description
  – BFD
  – mass balance
  – emissions
  – fugitive emissions
  – start-up and shut-down scenarios.

Contact
engineering-services@airliquide.com

or the relevant technology group or local office
**Description**
Profitability enhancement services are the backbone of hydrogen optimization and management solutions.

Our customized, proprietary PIMS simulation software ("LP Modelling") offers industry-leading hydrogen optimization studies.

A typical study comprises the following steps:
- Refinery audit
- Global Refinery Balance
  - Include all hydrogen producers and consumers
  - Close balance
- Unit balance
  - Calibrate make-up and recycle gas rates to have accurate gas/oil ratios
  - Calculate hydrogen partial pressure
  - Calibrate instruments as required

**Contact**
engineering-services@airliquide.com

or the relevant technology group or local office
Project Execution

**Description**
Our team of experts can assist owners in early phases of project implementation.

The most popular packages are:
- Process Design Package (PDP)
- Modularization study and project execution strategy
- Preliminary engineering (FEED)
- Detailed engineering
- Procurement services
- Construction management
- Assistance to commissioning and start-up

**Contact**
engineering-services@airliquide.com

or the relevant technology group or local office
**Oil Refineries Engineering Design**

**Description**
Air Liquide utilizes its 25 years of experience in engineering design and refining technologies to provide refinery services such as:

- Technology evaluation and licensor selection
- Conceptual/feasibility studies
- Basic engineering on the basis of third party PDP documentation
- Front-end engineering design (FEED)
- Detail engineering for revamps of existing units or for new refinery units
- Procurement services
- Construction Management
- Assistance to commissioning and start-up

We have experience in designing the following units:

- Crude Distillation Unit (CDU)
- Vacuum Distillation Unit (VDU)
- Hydrotreatment/ Desulfurization
- Hydrocracking
- Isomerization
- SRU
- Hydrogen plant

We have more than 170 references and experience working with many technology licensors, such as: Axens, UOP, Uhde, Criterion, BASF, ExxonMobil, Chevron...

**Contact**
engineering-services@airliquide.com

or the relevant technology group or local office
Customer Services

Air Liquide Global E&C Solutions’ Services make our customers’ businesses more reliable, competitive and cost-efficient, wherever they are in the world.

Traditionally, Air Liquide Global E&C Solutions offers support and long-term services to the Air Liquide Group. Today, we bring our many years of engineering and operational experience to third party customers through a growing range of services – from spare parts management to long term service agreements. These maximize the efficiency and reliability of our customers’ assets, either engineered by us or by other actors in the market.

Our aim is to be a one-stop service provider, so that customers can enjoy the reassurance of working with one reliable partner, have more visibility over operating costs and fully optimize each process in the short and longer term.

- **Spare Parts Services**: specific lists and supply for your asset management, safety stocks, interchangeability studies, compliance with updated regulations.
- **Site Services**: sending our experts on-site to resolve issues, check performance, install new components, supervise planned or unplanned shut-down events.
- **Product Support Services**: remote technical assistance, monitoring and diagnostics, customer training, EHS consulting.
- **Engineering Services**: conversions, modifications, upgrades: from conceptual and feasibility studies to project execution for the improvement of existing plants, design for third parties and validation, performance improvement programs.
- **Long Term Service Agreements**: extended performance guarantees, special rates on one or more services from the other categories in a single agreement of variable duration to keep plants running at maximum efficiency.

Contact
engineering-services@airliquide.com

or the relevant technology group or local office
Focus on: Engineering for Existing Plants

Description
Air Liquide Global E&C Solutions in all facets of engineering:
- Performance Improvement Programs (PIP)
- Plant upgrades
- Plant relocations
- Environmental performance
- Reliability improvements
- Safety improvements
- Obsolescence management / life extension
- Site audits and reports

Contact
engineering-services@airliquide.com
or the relevant technology group or local office
**Focus on: Customer Training**

**Description**
For more than 100 years, Air Liquide has been a recognized leader in the cryogenic industry and more specifically in the following areas:

- Cryogenic and LNG plant design and operations
- Safety when handling and transporting cryogenics liquids
- Maintenance of cryogenic plants

Our offering includes:

- Compressed Gas Association industry practice
- Basic process training: 1-2 days theoretical classroom process technology overview
- Detailed process training: 1-2 weeks hands-on training on the site
- Maintenance of cryogenic assets
- Safety in operating cryogenic assets
- Safety in transporting and handling cryogenics liquids
- Customized training

Our training offering varies in each region, as it depends on the availability of local experts and technical resources.

**Contact**
engineering-services@airliquide.com

or the relevant technology group or local office
## List of abbreviations and acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2EHA</td>
<td>2-ethylhexylacrylate</td>
</tr>
<tr>
<td>2EHOH</td>
<td>2-ethylhexanol</td>
</tr>
<tr>
<td>AA</td>
<td>Acrylic acid</td>
</tr>
<tr>
<td>AAA</td>
<td>Methanol specification per US federal regulation O-M-232e</td>
</tr>
<tr>
<td>AcAc</td>
<td>Acetic acid</td>
</tr>
<tr>
<td>AGR</td>
<td>Acid gas removal</td>
</tr>
<tr>
<td>APH</td>
<td>Air pre-heater</td>
</tr>
<tr>
<td>Ar</td>
<td>Argon</td>
</tr>
<tr>
<td>ASU</td>
<td>Air Separation Unit</td>
</tr>
<tr>
<td>ATR</td>
<td>Autothermal reformer/reforming</td>
</tr>
<tr>
<td>BA</td>
<td>Butylacrylate</td>
</tr>
<tr>
<td>BFD</td>
<td>Block flow diagram</td>
</tr>
<tr>
<td>BFW</td>
<td>Boiler feedwater</td>
</tr>
<tr>
<td>BOG</td>
<td>boil-off gas</td>
</tr>
<tr>
<td>BTU</td>
<td>British thermal unit</td>
</tr>
<tr>
<td>BuOH</td>
<td>Butanol</td>
</tr>
<tr>
<td>C2+</td>
<td>Hydrocarbons with 2 or more carbons</td>
</tr>
<tr>
<td>C4</td>
<td>Mixture of 4-carbon hydrocarbons (butane, butylenes and butadienes)</td>
</tr>
<tr>
<td>CapEx</td>
<td>Capital expenditures</td>
</tr>
<tr>
<td>CCR</td>
<td>Continuous catalytic reforming</td>
</tr>
<tr>
<td>CDU</td>
<td>Crude distillation unit</td>
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<tr>
<td>CH4</td>
<td>Methane</td>
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<tr>
<td>CLS</td>
<td>Claus</td>
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<tr>
<td>CO</td>
<td>Carbon monoxide</td>
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<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COS</td>
<td>Carbonyl sulfide</td>
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<tr>
<td>CSFT</td>
<td>Cold soak filtration test</td>
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<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>CW</td>
<td>Cooling water</td>
</tr>
<tr>
<td>DEA</td>
<td>Diethanolamine</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl ether</td>
</tr>
<tr>
<td>DMR</td>
<td>Dehydration and mercaptan removal unit</td>
</tr>
<tr>
<td>DRI</td>
<td>Direct reduction of iron ore</td>
</tr>
<tr>
<td>DTDC</td>
<td>Desolventizer, toaster, dryer and cooler</td>
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<tr>
<td>E&amp;C</td>
<td>Engineering and construction</td>
</tr>
<tr>
<td>EA</td>
<td>Ethylacrylate</td>
</tr>
<tr>
<td>EAA</td>
<td>Ester-grade acrylic acid</td>
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<tr>
<td>EOR</td>
<td>Enhanced oil recovery</td>
</tr>
<tr>
<td>EtOH</td>
<td>Ethanol</td>
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<tr>
<td>FAD</td>
<td>Fatty acid distillate</td>
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<tr>
<td>FAME</td>
<td>Fatty acid methyl ester</td>
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<tr>
<td>FBDB</td>
<td>Fixed bed dry bottom gasifier</td>
</tr>
<tr>
<td>FEED</td>
<td>Front-end engineering design</td>
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<tr>
<td>FFA</td>
<td>Free fatty acid</td>
</tr>
<tr>
<td>FOB</td>
<td>Free on board</td>
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<td>F-T</td>
<td>Fischer-Tropsch</td>
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<tr>
<td>G2G</td>
<td>Gas-to-Gasoline</td>
</tr>
<tr>
<td>GAN</td>
<td>Gaseous nitrogen</td>
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<tr>
<td>GAR</td>
<td>Gaseous argon</td>
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<tr>
<td>GNG</td>
<td>Gaseous natural gas</td>
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<td>GOX</td>
<td>Gaseous oxygen</td>
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<td>Hydrogen</td>
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<td>H2S</td>
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<td>Hydrogen cyanide</td>
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<td>HHC</td>
<td>Heavy hydrocarbon</td>
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<tr>
<td>HP</td>
<td>High pressure</td>
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<tr>
<td>HT</td>
<td>High temperature</td>
</tr>
<tr>
<td>IGCC</td>
<td>Integrated gasification combined cycle</td>
</tr>
<tr>
<td>IMPCA</td>
<td>International methanol producers and consumers association</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>Kr</td>
<td>Krypton</td>
</tr>
<tr>
<td>LAR</td>
<td>Liquid argon</td>
</tr>
<tr>
<td>LiN</td>
<td>Liquid nitrogen</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
</tr>
<tr>
<td>LOX</td>
<td>Liquid oxygen</td>
</tr>
<tr>
<td>LP</td>
<td>Low pressure</td>
</tr>
<tr>
<td>LP3</td>
<td>Low pressure fatty alcohols production</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied petroleum gas</td>
</tr>
<tr>
<td>LTGT</td>
<td>Lurgi tailgas treatment</td>
</tr>
<tr>
<td>MA</td>
<td>Methylacrylate</td>
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<tr>
<td>MDEA</td>
<td>Methyl diethanolamine</td>
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<tr>
<td>MDI</td>
<td>Methylenediphenyl disocyanate</td>
</tr>
<tr>
<td>MEGE</td>
<td>Monoethyle glycol</td>
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<tr>
<td>MeOH</td>
<td>Methanol</td>
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<tr>
<td>MP</td>
<td>Medium pressure</td>
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<tr>
<td>MPG</td>
<td>Multi-purpose gasifier</td>
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<tr>
<td>MTG</td>
<td>Methanol-to-Gasoline</td>
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<tr>
<td>MTP</td>
<td>Methanol-to-Propylene</td>
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<tr>
<td>NaOH</td>
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<td>Neon</td>
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<td>N-methylpyrrolidone</td>
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<td>NO</td>
<td>Nitrous oxide</td>
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<tr>
<td>NOx</td>
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<td>NRU</td>
<td>Nitrogen removal unit</td>
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<tr>
<td>OpEx</td>
<td>Operating expenditures</td>
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<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbon</td>
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<td>PC</td>
<td>Polycarbonate</td>
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<tr>
<td>PDH</td>
<td>Propane dehydrogenation</td>
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<tr>
<td>PDP</td>
<td>Preliminary design package</td>
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<tr>
<td>PIMS</td>
<td>Proprietary simulation software</td>
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<td>PIP</td>
<td>Performance improvement program</td>
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<tr>
<td>POX</td>
<td>Partial oxidation</td>
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<tr>
<td>PSA</td>
<td>Pressure swing adsorption</td>
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<tr>
<td>PSD</td>
<td>Prevention of significant deterioration</td>
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<tr>
<td>PTSA</td>
<td>Para-toluene sulfuric acid</td>
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<tr>
<td>RBD</td>
<td>Reformed, bleached and deodorized</td>
</tr>
<tr>
<td>RSH</td>
<td>Carbon-bonded sulfhydryl or thiol</td>
</tr>
<tr>
<td>SMR</td>
<td>Steam methane reforming or reformer</td>
</tr>
<tr>
<td>SNG</td>
<td>Synthetic natural gas</td>
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<tr>
<td>SO2</td>
<td>Sulfur dioxide</td>
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<tr>
<td>SOx</td>
<td>Sulfur oxides</td>
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<td>SRU</td>
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<td>TDI</td>
<td>Toluene disocyanate</td>
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<tr>
<td>USD</td>
<td>United States dollar</td>
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<tr>
<td>VDU</td>
<td>Vacuum distillation unit</td>
</tr>
<tr>
<td>VSA</td>
<td>Vacuum Swing Adsorption</td>
</tr>
<tr>
<td>WHRS</td>
<td>Waste heat recovery system</td>
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<td>Xe</td>
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**AIR LIQUIDE LABORATORY SOLUTIONS**

**Cryogenics Lurgi**