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Institute of Energy Process
Engineering and Chemical Engineering
Chair EVT

XtL: Development of synthesis fuels in Europe and South Africa

Prof. Dr.-Ing. Bernd Meyer

IEA-MOST Workshop
“Advances in deployment of fossil fuel technologies”

Beijing, June 24–25, 2014

Outline

I Introduction

- **Global boundary conditions for synthetic fuels applications**
- **Indirect vs. direct coal liquefaction**

II Direct coal liquefaction and ist commercial applications

III Development trends

Global boundary conditions for synthetic fuels applications

Germany/Europe:

- No CtL (still very limited activities for shale gas) or GtL applications in Germany or Europe
- Conceptual studies on annex CtL blocks attached to conventional power plants in Germany
  → Option for reduction of investment costs
  → Potential to include renewable hydrogen (storage of excess renewable electricity)
- Visible trend towards underground coal gasification in Poland and UK (but not for CtL)
- *Politically driven development and demonstration of BtL routes*

Africa:

- No new CtL developments in South Africa
- GtL development for flare gas utilization in particular in Nigeria (compact GtL)
- Trend towards underground coal gasification (but not for CtL)

Asia:

- Continuous development/demonstration/commercialization of CtL and CtG technologies

Northern America:

- Shale gas-to-liquids in the U.S.

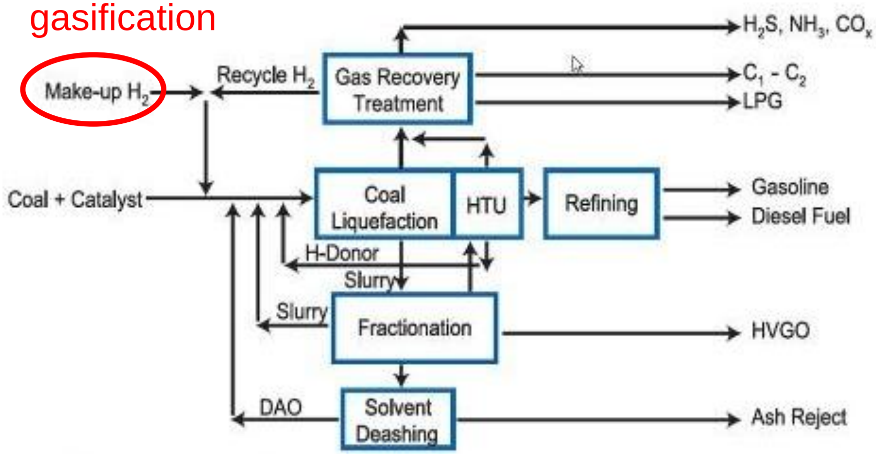
Russia:

- GtL for flare gas reduction and consideration of CtL in remote areas

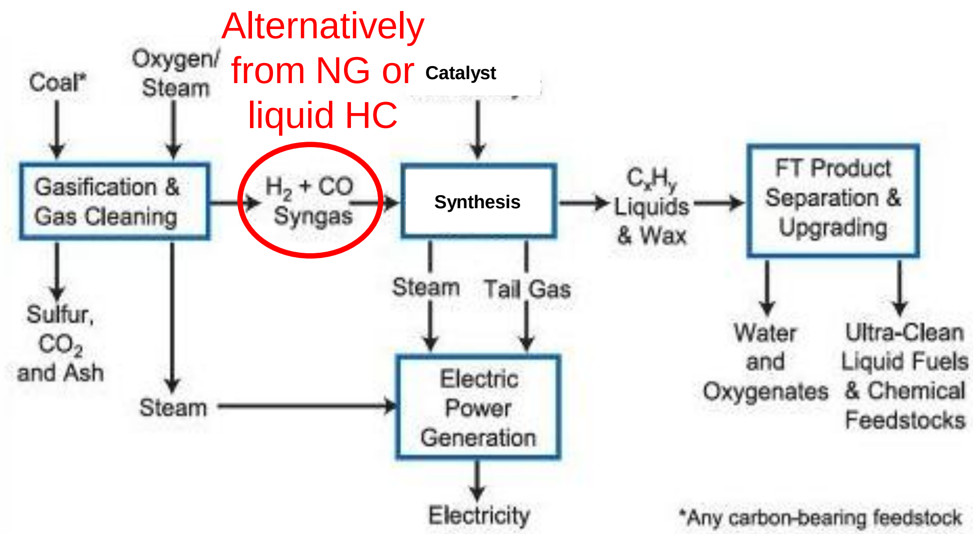
Coal liquefaction technologies for synthetic fuels

Direct coal liquefaction

Provided by gasification



Indirect coal liquefaction (example: Fischer-Tropsch synthesis)



- High efficiency potential
- 1 commercial plant (Shenhua Direct Coal Liquefaction Plant located in Ordos/Inner Mongolia)
- 24,000 bpd (1 mill. t/a)

- More mature and established technology
- About 10 commercial plants with vaious synthesis technologies (FT, MtG etc.)
- Production capacity of >390,000 bpd (with the largest plant being operated in South Africa)

Source: IEA Coal Industry Advisory Board workshop 2006

Outline

I Indirect vs. direct coal liquefaction

II Indirect coal liquefaction and its commercial applications

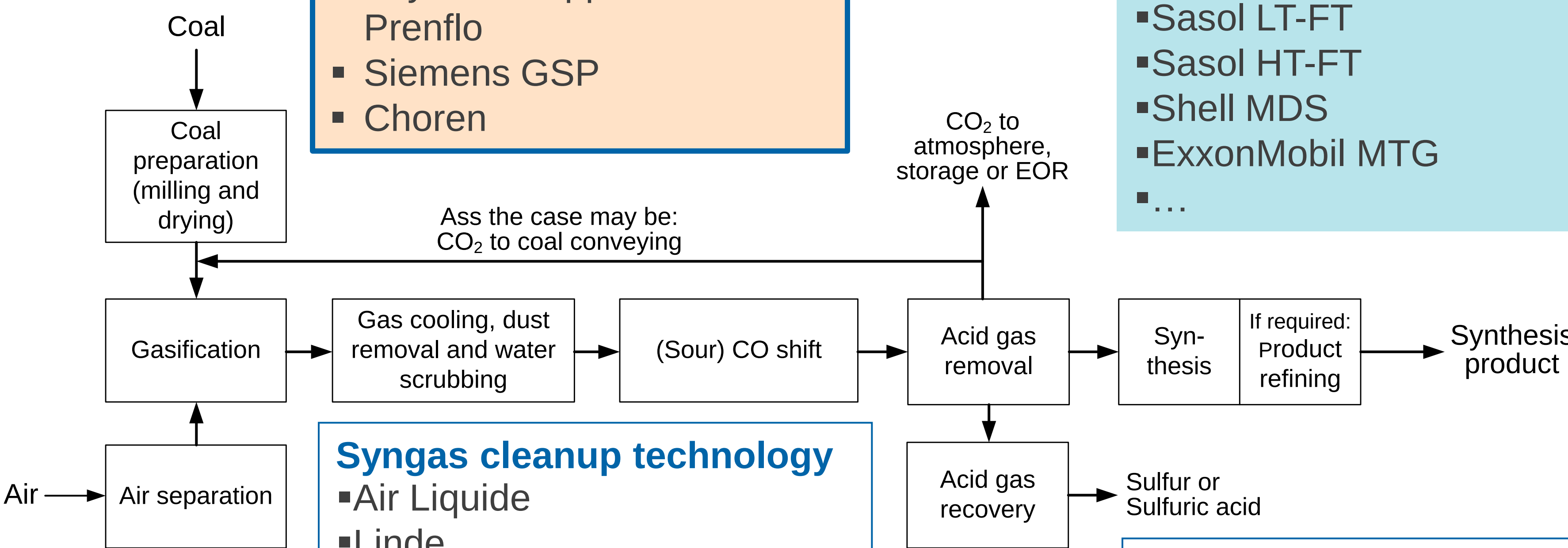
- **Introduction to the process chain**
- **Major European process development in gasification**
- **Major European process development in hydrocarbons syntheses**
- **Examples of European BtL projects**

III Development trends

Indirect coal liquefaction

Gasification technology
- Shell
- Lurgi/Air Liquide
- ThyssenKrupp Uhde Prenflo
- Siemens GSP
- Choren

Hydrocarbon synthesis
- Sasol LT-FT
- Sasol HT-FT
- Shell MDS
- ExxonMobil MTG
- …

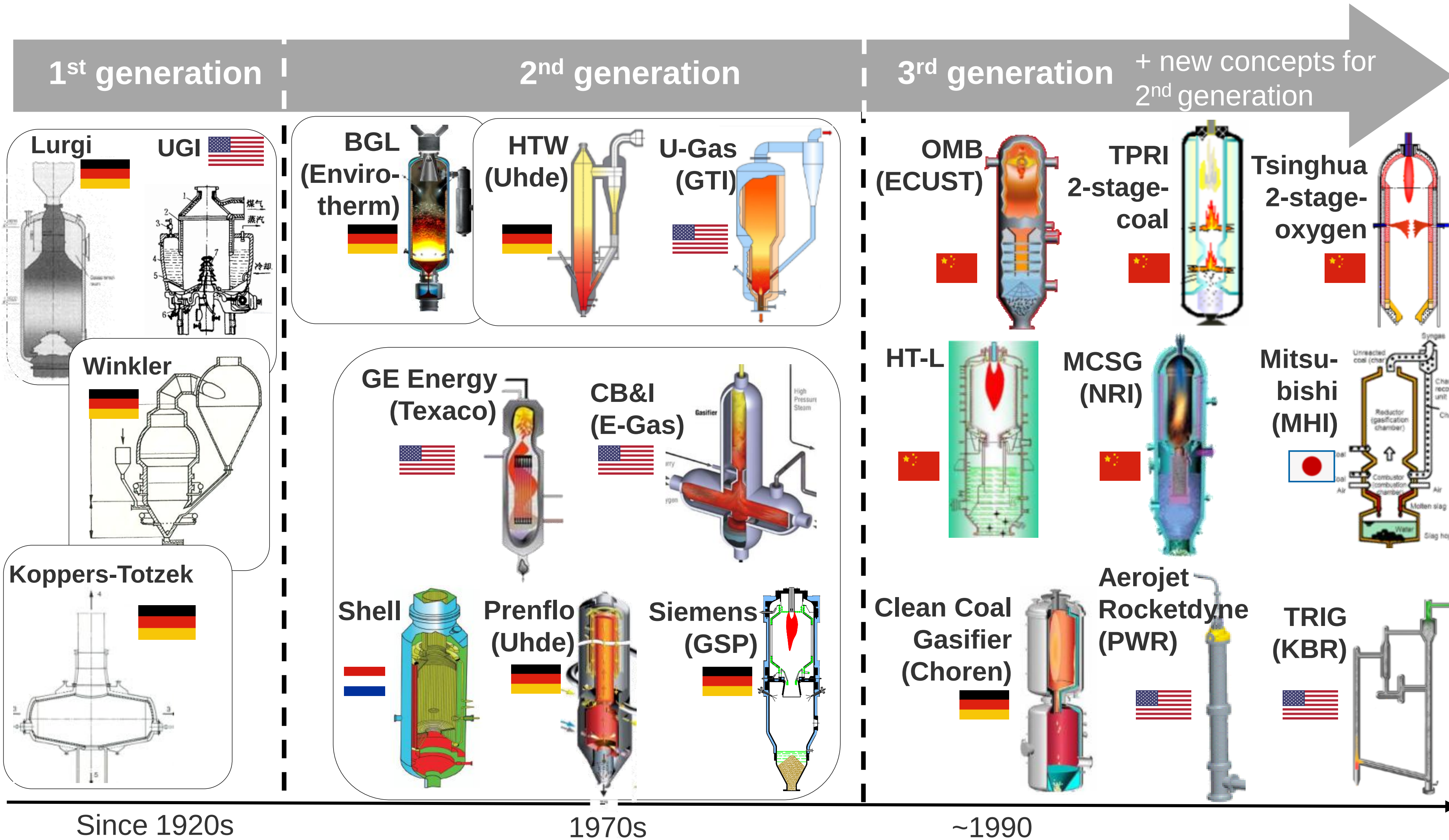


Syngas cleanup technology
- Air Liquide
- Linde
- UOP Honeywell
- ThyssenKrupp Uhde
- …

Air separation
- Linde
- Air Liquide
- Air Products
- …

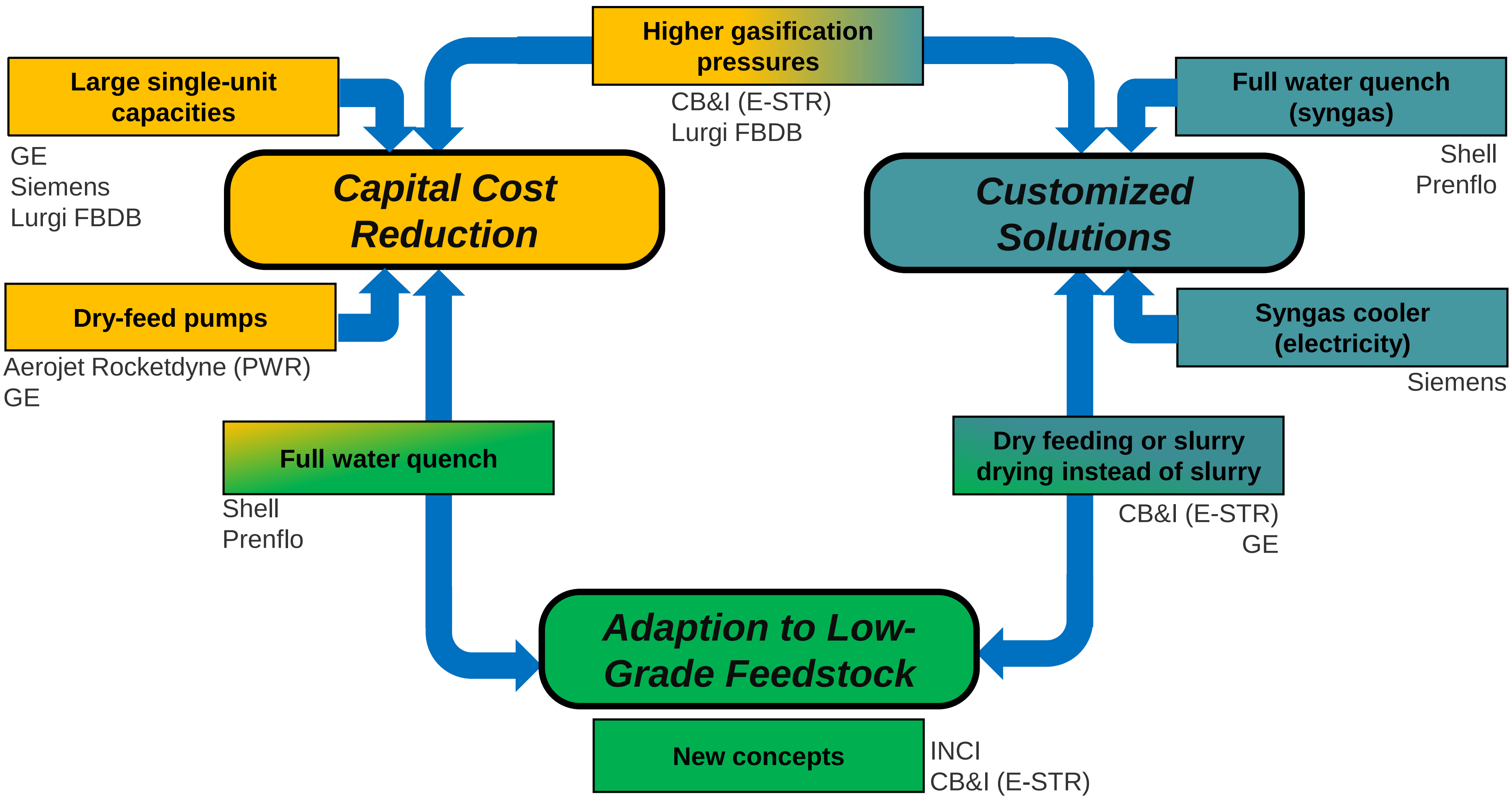
Hydrocarbon upgrading
- Shell
- Chevron
- Haldor Topsøe
- …

Developments in coal gasification from European perspective



Adapted from Gräbner, M. and Meyer, B.: Coal Gasification - Quo Vadis?, World of Mining, Volume 62, Issue 6, pp. 355-362, 2010

3rd Generation Gasification – Development Drivers



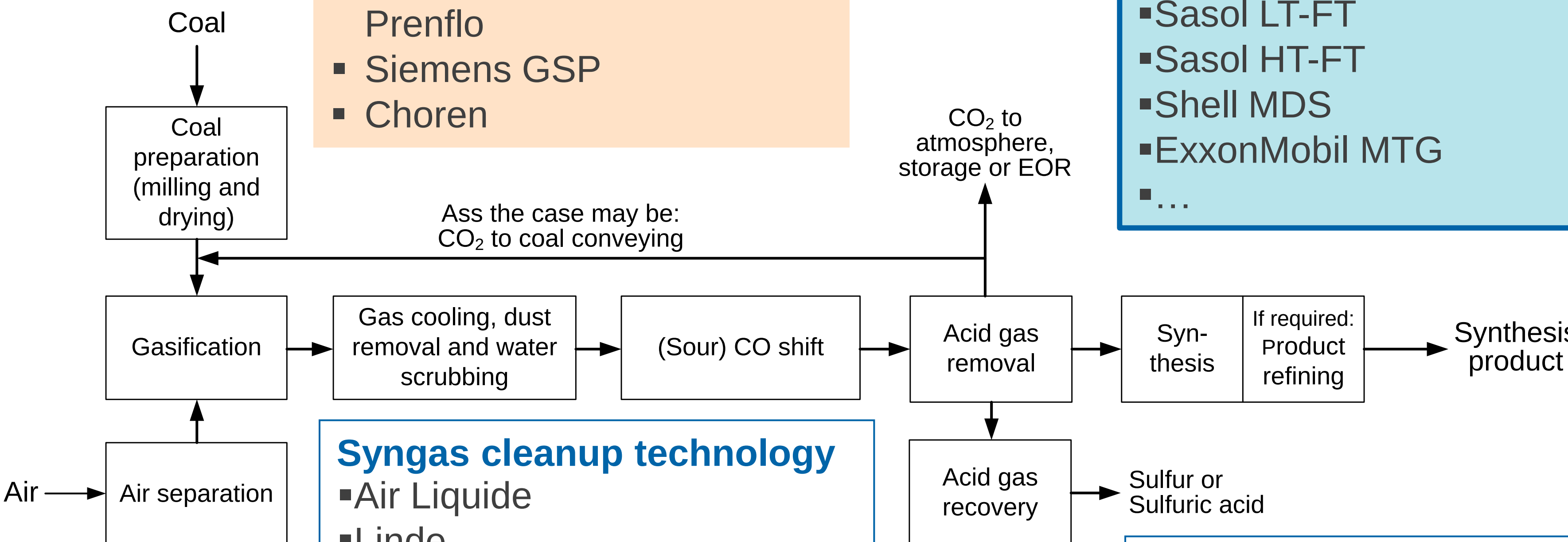
Status of commercially important European gasification technologies

Technology	Lurgi	BGL	Siemens	Shell	Prenflo	Choren
Max. realized capacity in t(coal)/d	1800 (Mark V Secunda)	1550 (Shriram Project)	1800 (NCPP Project)	2700 (e.g. Datang; Anning Yuntianhua)	2400 (Puertollano)	1500 (400 MW(th) GuiZhou-Province)
Max. planned capacity in t(coal)/d	2500 (Mark+) (=500 MW(th) for very low quality coal) * Turna, DGMK Tagung, 2012	1750 *Olschar, Gasification Course FG, 2012	2500 (currently only 2000 t/d = 850MW(th))	4000 (=1200MWth)	4000	2000
Number of gasifiers in operation	131 (excl SEDIN gasifiers)	4	9 (32)	20 plants with ca. 23 GW(th)	1	2
Major developments	Increase of single unit capacity, pressure and reduction of waste water yield	Adaptation to wider fuel range and customizing to application (fuel gas or syngas)	Increase of single unit capacity, feeding system and syngas cooling development	New syngas cooling concept (partial quench and convective cooling)	New syngas cooling concept (quench) and changed reactor layout	-/-

Indirect coal liquefaction

Gasification technology
- Shell
- Lurgi/Air Liquide
- ThyssenKrupp Uhde Prenflo
- Siemens GSP
- Choren

Hydrocarbon synthesis
- Sasol LT-FT
- Sasol HT-FT
- Shell MDS
- ExxonMobil MTG
- …



Syngas cleanup technology
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- …

Air separation
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- …

Hydrocarbon upgrading
- Shell
- Chevron
- Haldor Topsøe
- …

Fischer-Tropsch synthesis

Major chemical reactions:

Paraffins: $n\,CO + (2n+1)\,H_2 \leftrightarrow C_nH_{(2n+2)} + n\,H_2O$

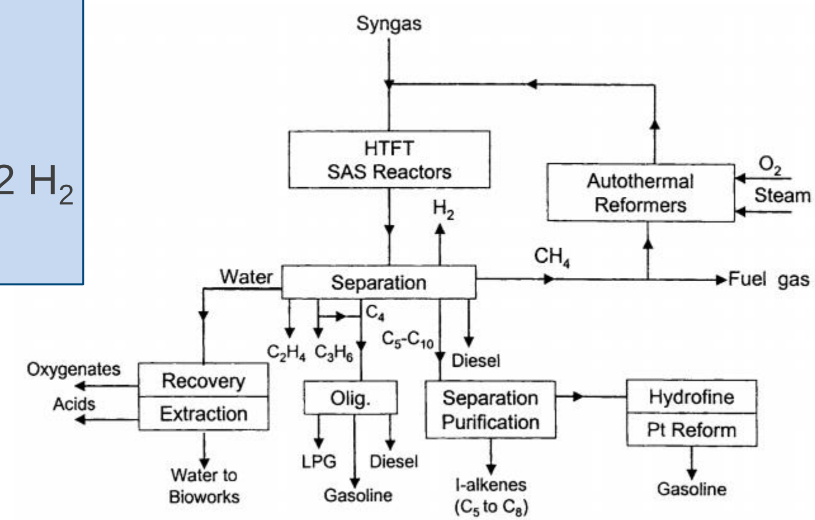
Olefins: $n\,CO + 2n\,H_2 \leftrightarrow C_nH_{2n} + n\,H_2O$

Alcohols: $n\,CO + 2n\,H_2 \leftrightarrow C_nH_{(2n+1)}OH + (n-1)\,H_2O$

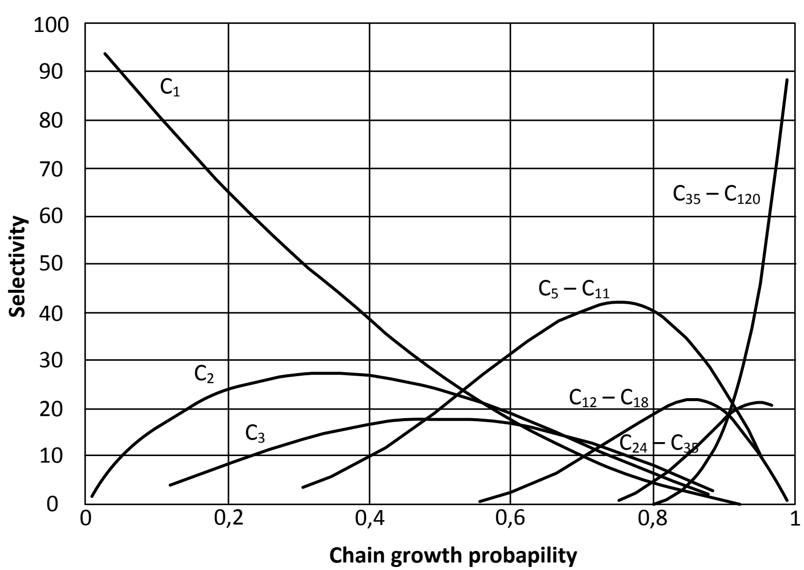
Acids: $C_nH_{(2n+1)}OH + H_2O \leftrightarrow C_{(n-1)}H_{(2n-1)}COOH + 2\,H_2$

Aldehydes: $C_nH_{(2n+1)}OH \rightarrow C_{(n-1)}H_{(2n-1)}COH + H_2$

HT-FT process layout



FT product spectrum dependent on catalyst properties



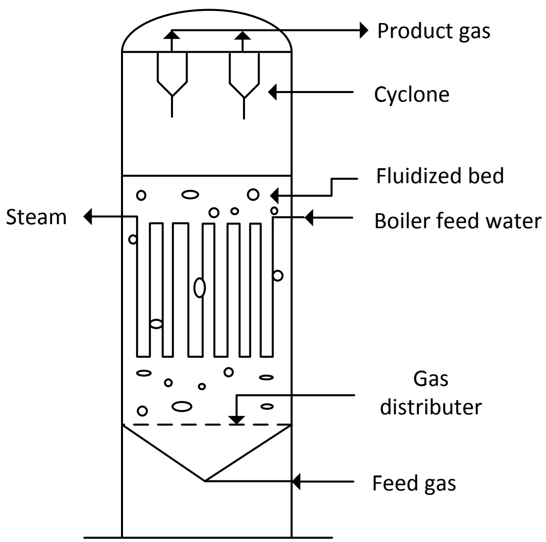
FT product spectrum dependent on temperature

Process	Temperature	Catalyst	Prefered product
HT-FT	ca. 350° C	Iron based	Gasoline/olefines
MT-FT	ca. 275 ° C	Iron based	Diesel
LT-FT	ca. 230 ° C	Cobalt based	Diesel/waxes

Source: Vertes, A. et al. „Biomass to Synfuels“ Wiley 2010
Steynberg, A., Dry, M. „Fischer-Tropsch Technology“ Elsevier 2004

SAS high-temperatue FT synthesis (Sasol)

SAS reactor scheme



Process characteristics:

- High-temperature FT synthesis
- Fluidized-bed reactor with iron-based catalyst
- Temperature: 330–350 °C
- Pressure: max. 40 bar
- Diameter: 10 m
- Internal cyclones for catalyst recirculation

Products:

- Lighter components up to C_{20} olefins and aromatics for gasoline and chemicals

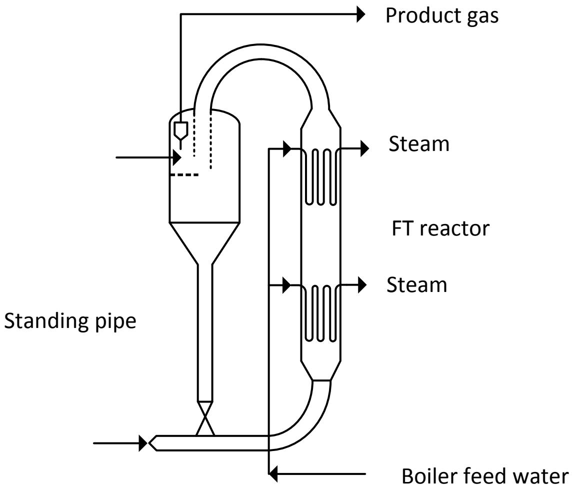
References:

- Secunda Sasol II and Sasol III, total capacity 160,000 bpd

Source: „Sasol: an industrial perspective“ UKZN 2013
Steynberg, A., Dry, M. „Fischer-Tropsch Technology“ Elsevier 2004

Synthol HT-FT reactor (Sasol)

SAS reactor scheme



Process characteristics:

- High-temperature FT
- Circulating fluidized-bed reactor
- Iron catalyst
- Tempartue/pressure: 340 ° C, 20 bar
- Syngas conversion of 80–90 %
- Capacity of 2500 bpd per reactor
- In Secunda: reactors later replaced by SAS reactors

Products:

- Mainly for gasoline production

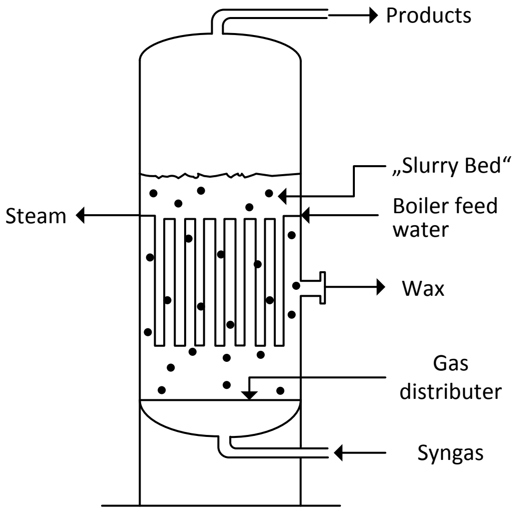
References:

- PetroSA: 45,000 bpd GtL facility in Mossel Bay (SA)

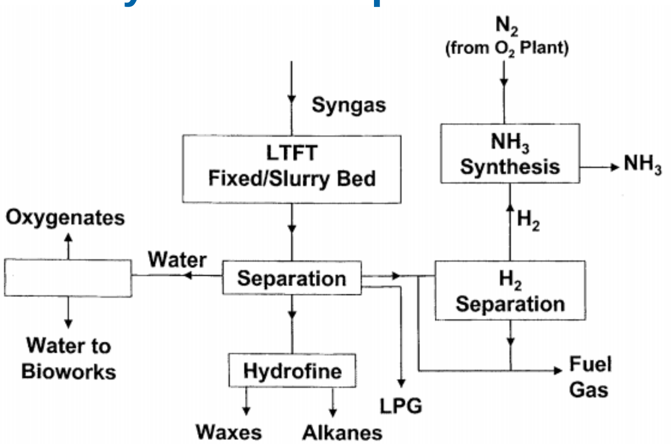
Source: PetroSA
Steynberg, A., Dry, M. „Fischer-Tropsch Technology“ Elsevier 2004

Slurry-phase LT-FT reactor (Sasol)

Slurry-phase reactor scheme



LT-FT synthesis loop



Source: „Sasol: an industrial perspective“ UKZN 2013
Steynberg, A., Dry, M. „Fischer-Tropsch Technology“ Elsevier 2004

Process characteristics:

- Low-temperature FT synthesis
- Slurry-phase reactor
- Mainly cobalt-based catalyst
- Temperature: 200–240 ° C
- Pressure: 20–30 bar
- Diameter: 5 m
- 2,500 bpd per reactor

Products:

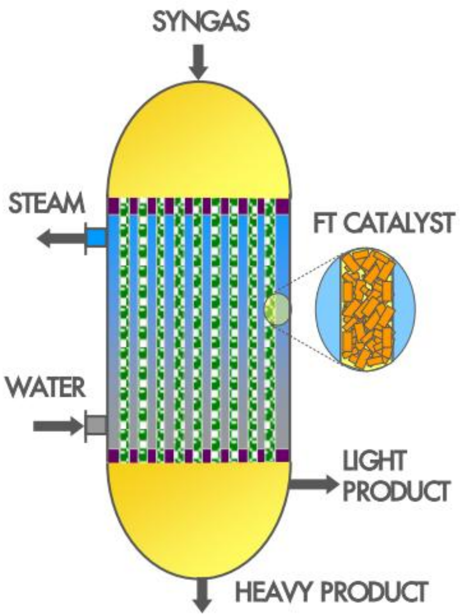
- Mainly wax and paraffines for diesel production

References:

- Sasolburg
  - 5,600 bpd
  - Switched from coal to natural gas in 2005
- ORYX GTL in Qatar (cooperation with Qatar Petroleum) 34,000 bpd

Shell Middle Distillate (SMD) LT-FT synthesis

SMD reactor scheme



Process characteristics:

- Low-temperature FT
- Fixed-bed multi-tubular reactors (similar to Sasol's ARGE)
- Cobalt-based catalyst

Products:

- Heavy Paraffin Synthesis (HPS)
- Maximal chain growth

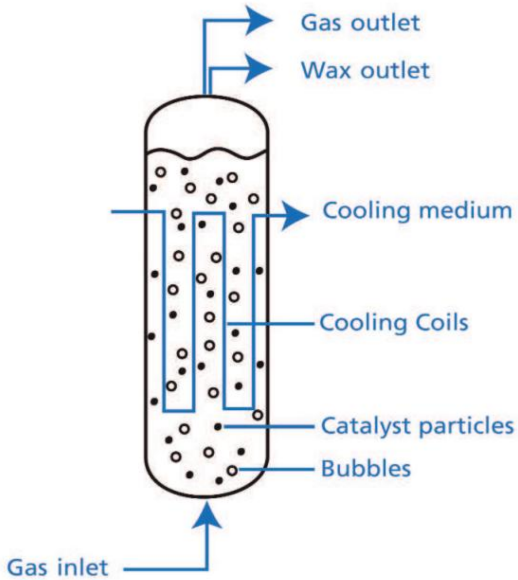
References:

- Pearl GTL Qatar: 140,000 bpd
- Bintulu GTL Malaysia: 12,500 bpd

Source: Volk, J. „INNOVATION IN GASIFICATION " Gasification Technologies Conference 2011

GTL.F1 LT-FT synthesis (Air Liquide)

LT-FT reactor scheme



Process characteristics:

- Joint venture by PetroSA and Air Liquide
- Low-temperature FT synthesis
- Slurry bubble column reactor
- Cobalt-based catalyst

Products:

- Naphtha, diesel and LPG from waxes

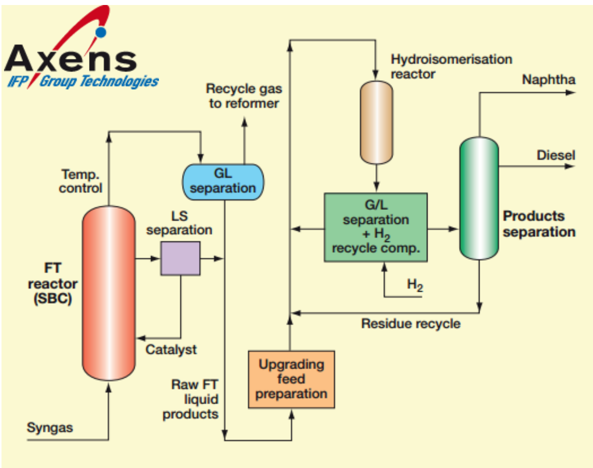
References:

- Semi-commercial demo plant in Mossel Bay (SA) (1,000 bpd oil or wax)

Source: „GTL.F1 Technology“ Air Liquide Website June 2014

Other LT-FT syntheses

Gasel (Axens & ThyssenKrupp)



Process characteristics:

- Low-temperature FT-synthesis
- Slurry bubble column reactor
- Cobalt-based catalyst

Product:

- Diesel

References:

- 20 bpd Pilot Plant in Sannazarro, Italy (20 bpd)
- Planned BioTfueL project for production of Biodiesel

Source: „Conversion of syngas to diesel“ Axens Website June 2014

BP & JM Davy fixed-bed FT synthesis

Process characteristics:

- Low-temperature FT process
- Fixed-bed multi-tubular reactor
- Cobalt-based catalyst

References:

- Pilot plant in Nikiski (Alaska)

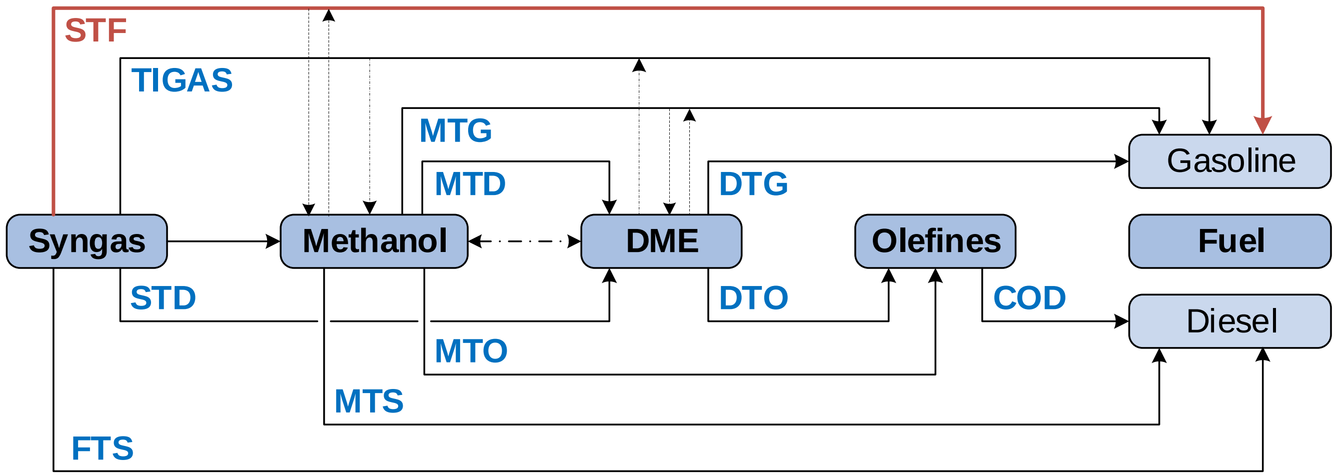
Source: „Fischer-Tropsch Technology“ BP website June 2014

Fischer-Tropsch plants

Plant	Technology		Capacity (bpd)	Owner	Production start
Secunda	CTL	SAS	160,000	Sasol	1980/1984
Pearl	GTL	Shell MDS	140,000	Shell	2011
Mossel Bay	GTL	Synthol	45,000	PetroSA Statoil Lurgi	1992
Oryx	GTL	SPD	34,000	Qatar Petroleum Sasol	2007
Bintulu	GTL	Shell MDS	12,500	Shell	1993
Sasolburg	GTL	SPD	5,600	Sasol	1955
Ordos	CTL	Synfuels China MT-FT	4,000	Yitai	2009
ChangZhi	CTL	Synfuels China MT-FT	4,000	ShanXi LuAn	2009
Ordos	CTL	Synfuels China MT-FT	5,000	Shenhua	2009

Source: Anantharaman et al. “Consider coal gasification for liquid fuels production” Hydrocarbon Processing Dec 2012, pg 47-53

Methanol-based fuel production



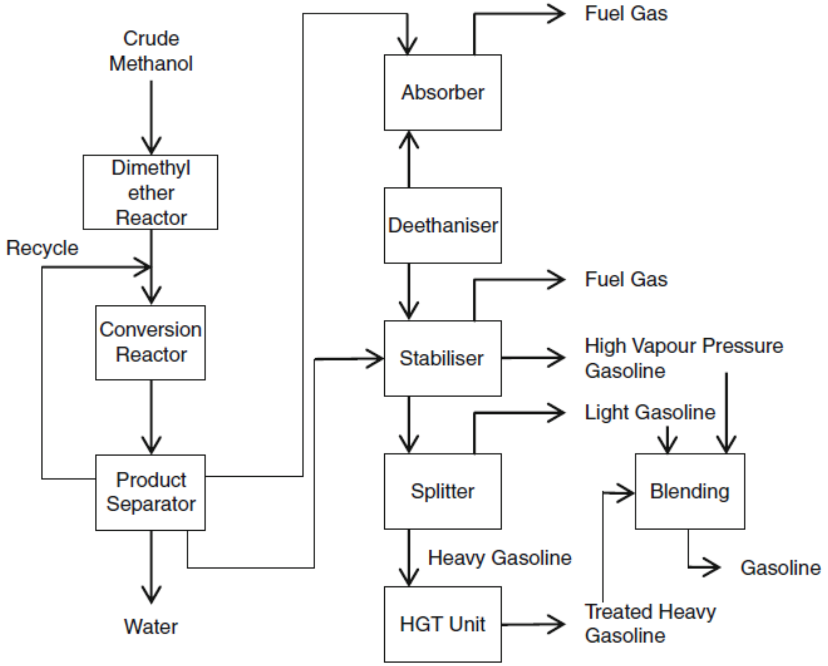
TIGAS	Topsøe Integrated Gasoline Synthesis	StF	Syngas-to-Fuel (CAC, TU Freiberg)
MtG	Methanol-to-Gasoline (i.e. g. ExoxonMobil (Uhde))	MtD	Methanol-to-Dimethylether (e. g. Lurgi/ Air Liquide)
DtG	Dimethylether-to-Gasoline (e. g. Karlsruhe Institut für Technology)	StD	Syngas-to-Dimethylether (e. g. JFE)
DtO	Dimethylether-to-Olefins (e. g. Karlsruhe Institut für Technology)	COD	Conversion of Olefins to Distillates (e. g. Lurgi/ Air Liquide)
MtO	Methanol-to-Olefins (e. g. UOP, MtP® by Lurgi/ Air Liquide)	MtS	MtSynfuels® by Lurgi/ Air Liquide

$2\ CH_3OH \leftrightarrow CH_3OCH_3 + H_2O$
$CH_3OH, CH_3OCH_3 \rightarrow$ Light Olefins, H_2O
Light Olefins $\rightarrow C_{5+}$ Olefins
C_{5+} Olefins $\rightarrow$ Paraffins, Naphthenes, Aromatics

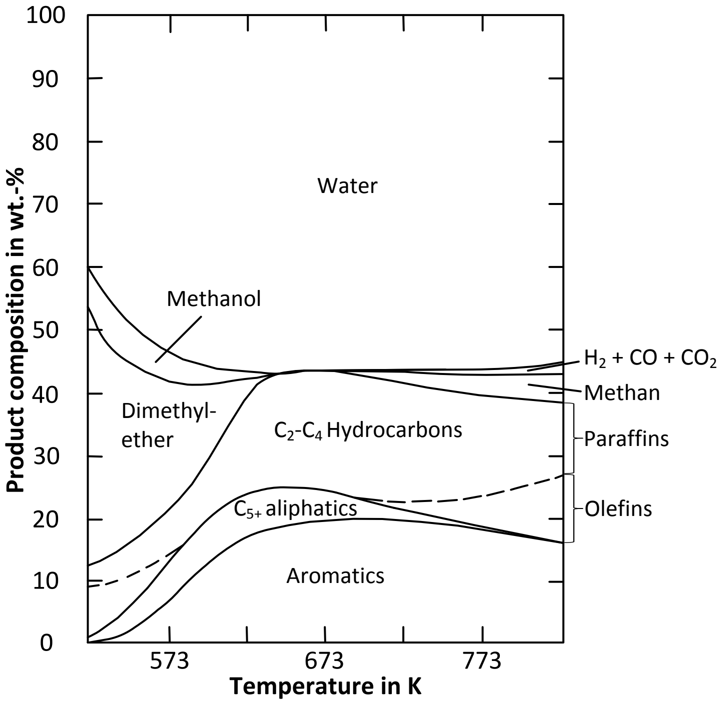
Source: Bertau, M. et al. „Methanol: The Basic Chemical and Energy Feedstock of the Future " Springer 2014,
Stahlschmidt, R. „Concepts for XtL-Routes based on a technical proven Gasoline Synthesis Process" IFC 2014
Methanol to Gasoline (MTG)" ExxonMobil website June 2014

Fixed-bed MTG (ExxonMobil & TK Uhde)

Fixed-bed MtG process layout



Fixed-bed MtG product spectrum



Process characteristics:

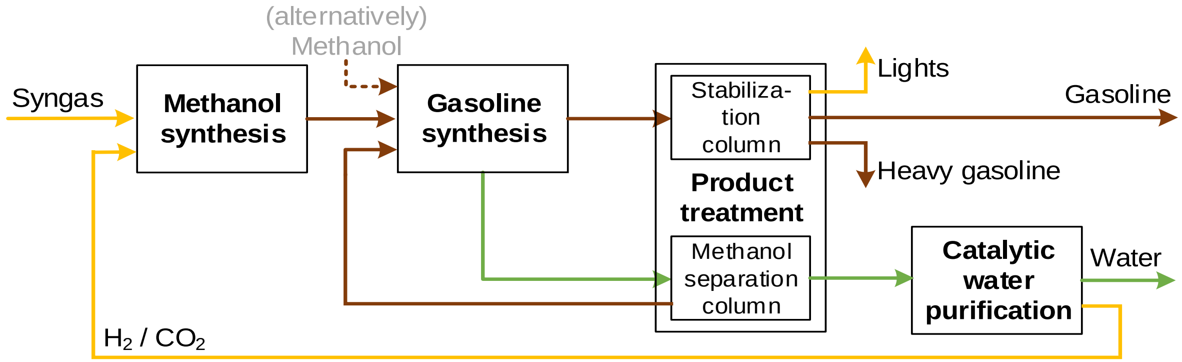
- 1^{st} stage: adiabatic fixed-bed reactor for DME production (300–420 ° C, 26–27 bar, alumina-based catalyst)
- 2^{nd} stage adiabatic fixed-bed reactor, ZSM-5 catalyst, (350-420 ° C, 19–23 bar), to be discontinuously regenerated

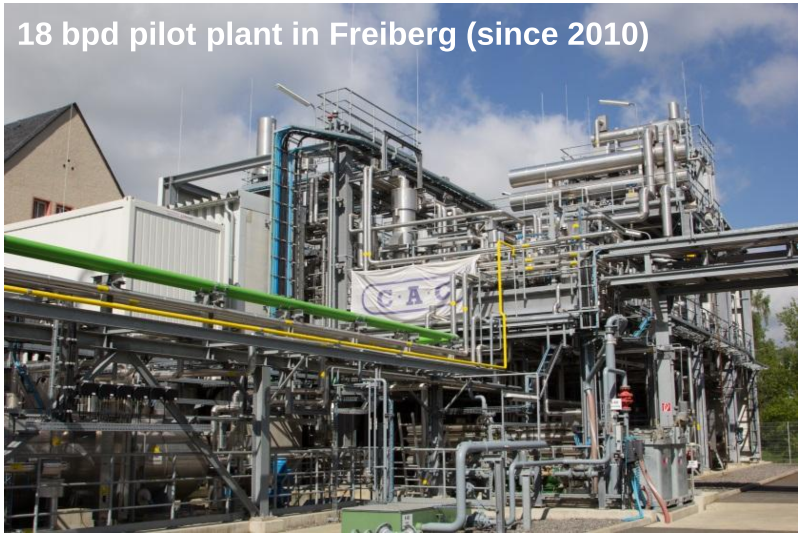
References: - Jincheng MtG plant (China): 2,500 bpd
- Planed: Medicine Bow project (USA): 15,000 bpd

Source: Bertau, M. et al. „Methanol: The Basic Chemical and Energy Feedstock of the Future " Springer 2014, „ Methanol to Gasoline (MTG)" ExxonMobil website June 2014

Syngas-To-Fuel (CAC & TU Bergakademie Freiberg)

Fixed-bed MtG process layout



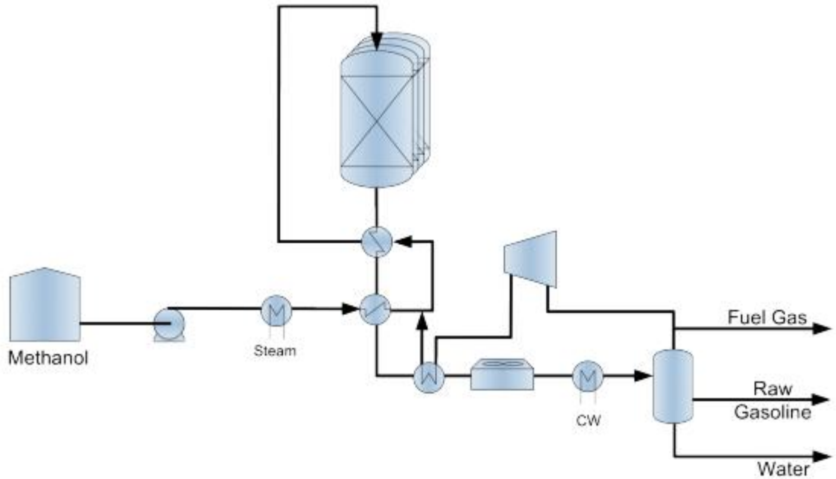


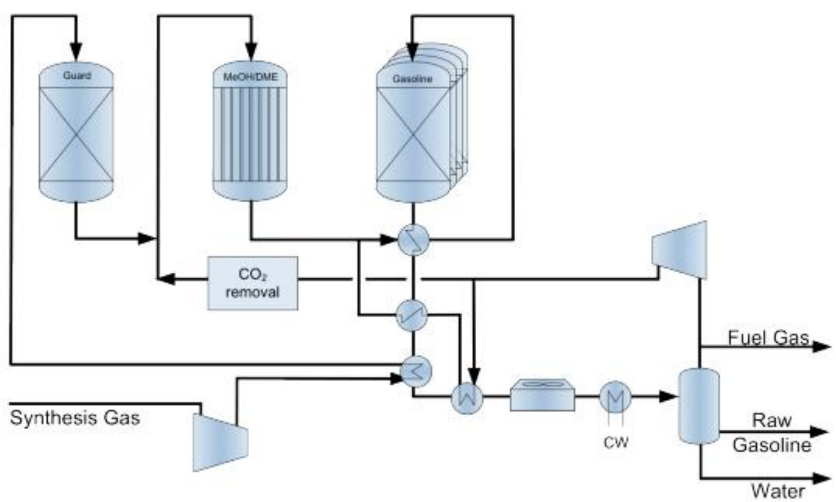
STF characteristics:

- Syngas → Methanol → Gasoline (direct processing of raw methanol from 1st stage)
- Isothermal gasoline synthesis reactor layout → improved stability and product quality
- Application of newly developed catalysts for gasoline production and treatment of process water (formed in process) → higher product yields and reduced waste water yield
- Reduced amount of circulation gases in combination with isothermal plant operation

Source: Stahlschmidt, R. „Concepts for XtL-Routes based on a technical proven Gasoline Synthesis Process” IFC 2014

TIGAS (Haldor Topsoe)





Process modifications

MTG process:

- Methanol as isolated intermediate, directly converted to raw gasoline
- Parallel adiabatic fixed-bed reactors
- Zeolite type catalyst GSK-10

STG process:

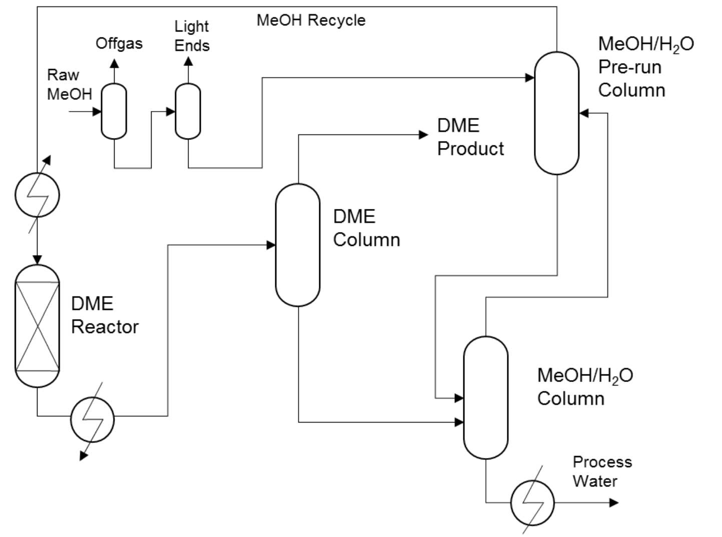
- Simultaneous formation of Methanol and DME without separation
- Especially suitable for syngas with H_2:CO near 1 (from coal, biomass)

Source: „TIGAS Technologies for gasoline production“ Haldor website June 2014

DME production (Diesel substitute)

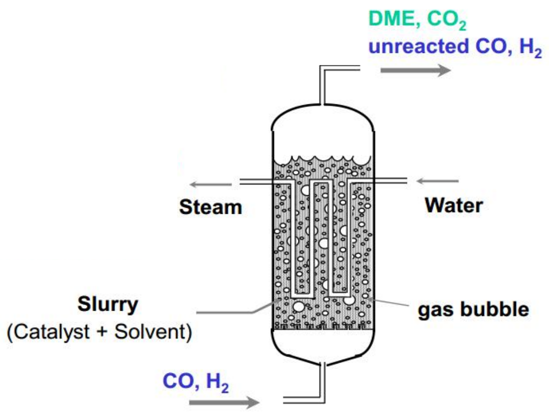
Two-stage technology

- Addition of the dehydration stage to methanol production, e.g. Lurgi MegaDME, Topsøe's DME
- Problem: costs for cryogenic DME separation



Single-stage technology:

- Application of multifunctional catalysts (methanol synthesis and dehydration, water gas shift)
- Slurry reactor technology
- No commercial applications
- OEMs: JFE and Air Products



Source: Bertau, M. et al. „Methanol: The Basic Chemical and Energy Feedstock of the Future " Springer 2014,
Zwiefelhofer, U., Liebner, W. „Monetisation of Gas and Coal as Feedstok for Petrochemicals through MtC" Gastech 2008 Bangkok
Ohno, Y. „New Clean Fuel DME"DeWitt Asia Pacific Global Methanol & MTBE Conference 2008

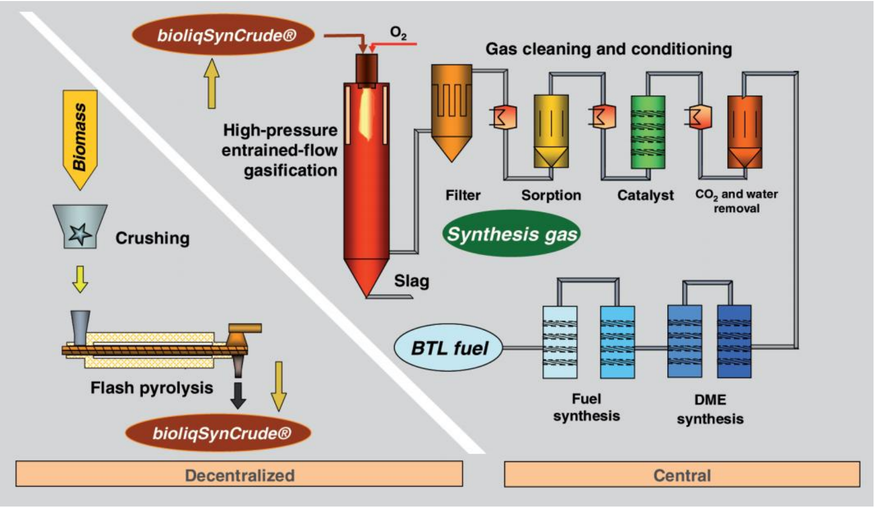
Bioliq (KIT & Lurgi)

Decentralized:

- Fast pyrolysis (sand as heating agent) of dry biomass at 500 °C
- 500 kg/h pilot plant

Centralized:

- Lurgi MPG-based gasification (1200 °C, up to 80 bar)
- HT gas cleaning
- **Two-stage gasoline synthesis** (DME as intermediate) with CAC
  - First stage: 250 °C, 55 bar
  - Second stage: 350 °C, 25 bar, zeolitic catalyst
- 2MW(th) pilot plant at KIT in Karlsruhe (Germany)



Source: www.bioliq.de June 2014

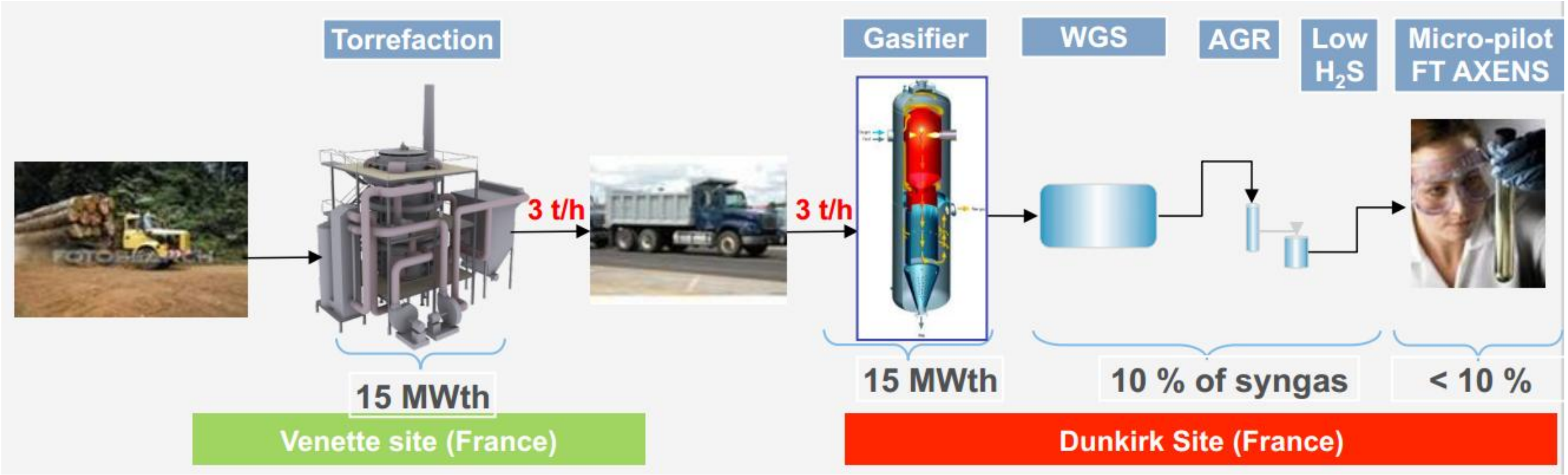
BioTfueL

- Joint project of:
  ThyssenKrupp Uhde, Axens, CEA, IFP Energies nouvelles, Sofiprotéol, Total

- Pilot plant in Venette and Dunkirk
  (3 t/h biomass torrefaction,
  15 MW(th) gasifier),
  production scheduled for 2014

Process steps:

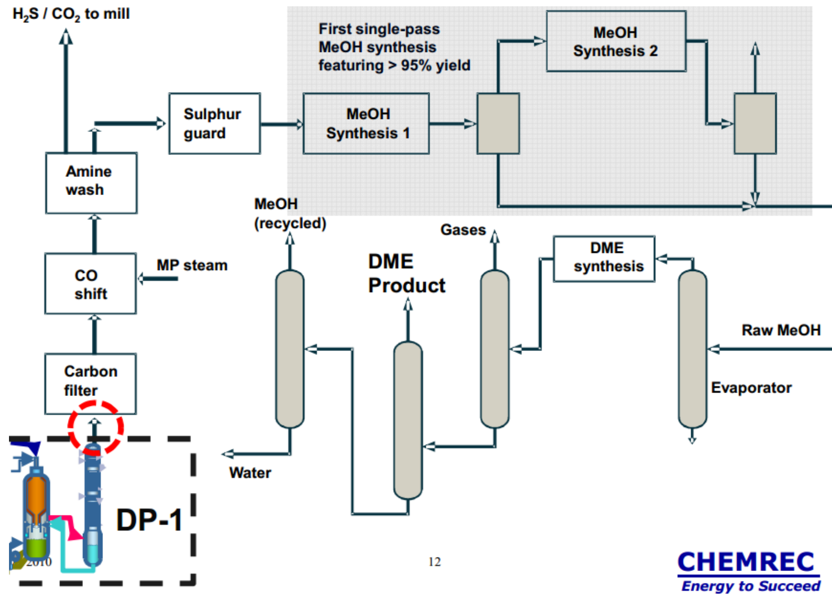
- Biomass pre-treatment and torrefaction at 250–300 ° C
- Prenflo PDQ gasification (1200–1600 ° C, 30–42 bar)
- Syngas cleanup
- Gasel **Fischer-Tropsch** by Axens (1st pilot-scale demonstration)

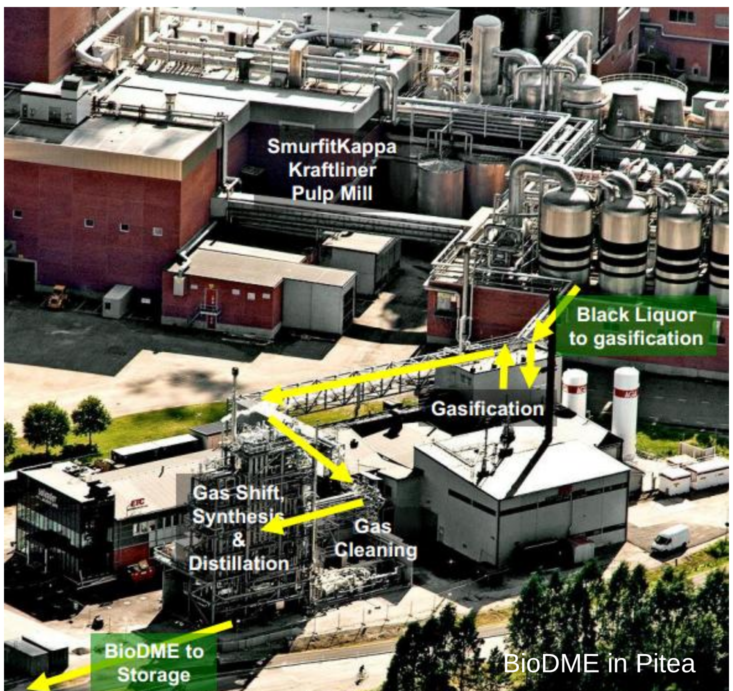


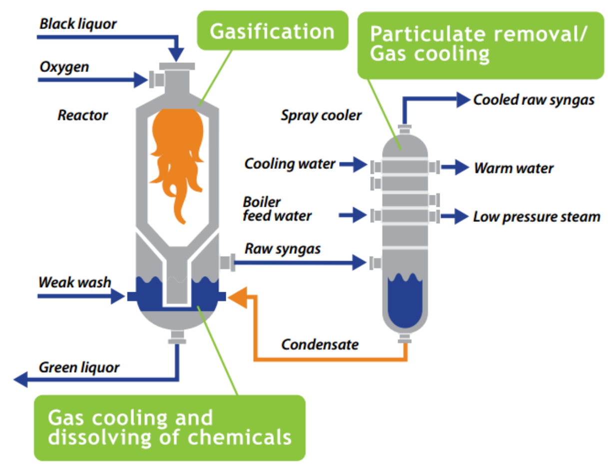
Source: Vigué, J.-C. et al. „ BioTfueL Project" Oil & Gas Science & Technology Vol. 68 (2013) ppn. 935-946

BioDME (Chemrec & Haldor Topsoe)

- DME production from pulp mill residuals
- Chemrec black liquor Gasification (entrained flow, top-fired, 30 bar, 1050 ° C)
- Haldor Topsoe **two-stage DME** technology
- 38 bpd plant in Pitea, Sweden (2011)







Source: Salomonsson, P. „Final Report of the European BioDME Project" 5th Int. DME Conference 2013
Chemrec Company Presentation 2010

Outline

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II Direct coal liquefaction and ist commercial applications

III Development trends

Development trends – Coal gasification technology

- **Reduction of investment costs:**
  - Simplification of technology
  - Increase of unit size

- **New gasifiers and components:**
  - Compact gasifiers (Aerojet Rocketdyne (former PWR))
  - Mild Gasification (INCI)
  - Solid feed pumps (Aerojet Rocketdyne (former PWR), GE)
  - Advanced refractory materials

- **Increase of efficiency and matching raw gas composition to application:**
  - Increase carbon conversion
  - Tendency to dry feed systems (slurry drying or solid feed pumps)
  - Flexibilization of heat recovery systems

Besides: Significant increasing efforts to further develop gas-to-syngas technologies (e.g. for flare gas or smaller-scale shale gas application)

Development trends – Synthesis routes

- FT routes for diesel production and methanol-based routes for gasoline
- In western countries only consideration of synthesis products competing with oil products
- Strong trend for GtL in the U.S. and upcoming trend for small-scale technologies for flare gas and associated gas utilization

- Synthesis development requirements:
  - Tailored products pectrum (catalyst and operation conditions) → reduction of refining efforts
  - Optimized reactor concepts → reduction of cooling effort → reduction of equipment effort
  - Reduction of waste water yield
  - Scale-down of single unit size allowing for off-shore or small-scale applications for flare gas/associated gas utilization

Thank you for your attention!

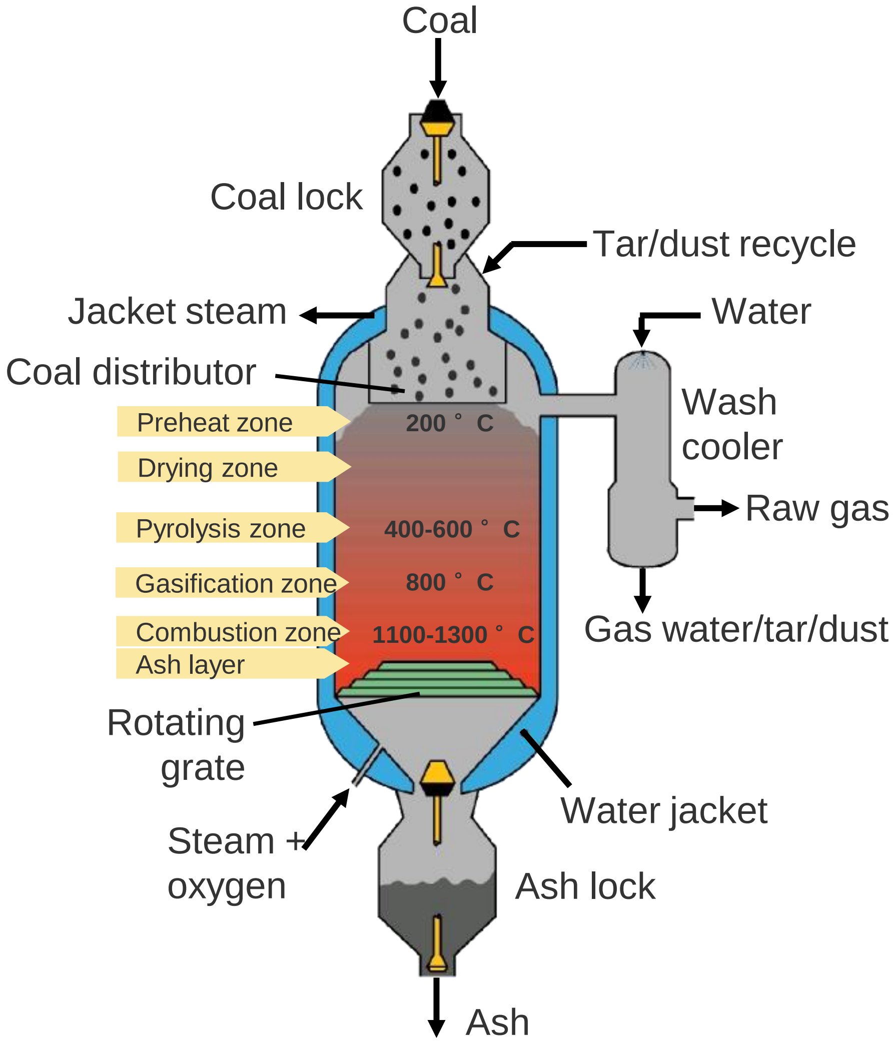
Backup

Fixed Bed Dry Bottom Gasifier (FBDB) – Air Liquide (Lurgi), Sasol

Features:

- Semi-continuous feeding via sluice system (optional coal distributer)
- Water jacket with outer steel pressure shell and inner temperature shell (for corrosive ashes SiC-lined)
- 10–15 % of gasification agent steam generated in water wall
- Inner diameter 2.6–4.7 m, height 5-9 m
- O_2/H_2O injection by rotating grate while ash is cooled to 300–400 °C
- Gas exit temperature 370-600 °C
- Production of tar/dust/water mix in wash cooler

→ 7 Plants (153 gasifiers) operating
17.9 GW (th)
FT-fuels; SNG; Fertilizer; MeOH; Reduction gas



Source: Peter Modde und Steffen Krzack. Die Veredlung und Umwandlung von Kohle, Technologien und Projekte 1970 bis 2000 in Deutschland, Chapter: Gaserzeuger mit Drehrost, Seiten 307–309. DGMK, 2008; Weiss, M.-M.: Update on New Project & Design Developments with Lurgi's FBDB Gasifier, CCT 2011.

Fixed Bed Dry Bottom – Sasol/Lurgi

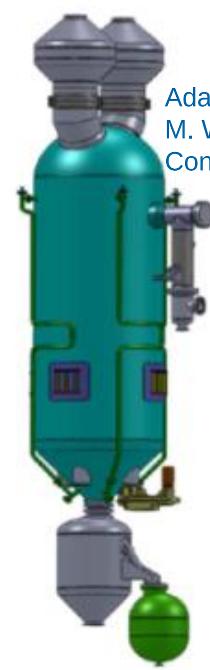
- Commercial plants:
  131 gasifiers in operation (excl. domestic Chinese (SEDIN) FBDB gasifiers)

– Vresova	26	Power
– Sasol Synfuels, Secund, SA	80+4	Liquid fuels & chemicals
– Dakota Gasification Company, Dakota, USA	14	SNG
– Shanxi-Tianji Coal Chemical Company, CHN	5	Ammonia
– Yima, CHN	2	MeOH

- Current activities – Lurgi FBDB™:
  – Jindal Steel & Power, Angul plant
  225,000 Nm^3/hr syngas from 7 gasifiers, start up 2013

- Projects under developments – Lurgi FBDB™:
  8x Coal to SNG 7x Coal to Liquids
  3x Coal to Chemicals 1x Coal to MeOH
  4x Coal to Fertilizer 1x Coal to Power

- Next technology steps – Lurgi FBDB™:
  – **Lurgi FBDB™ Mk Plus™** (60 bar, twin coal lock, 5.05m outer diameter)
  – Reduction of water consumption (e.g. dry ash handling)

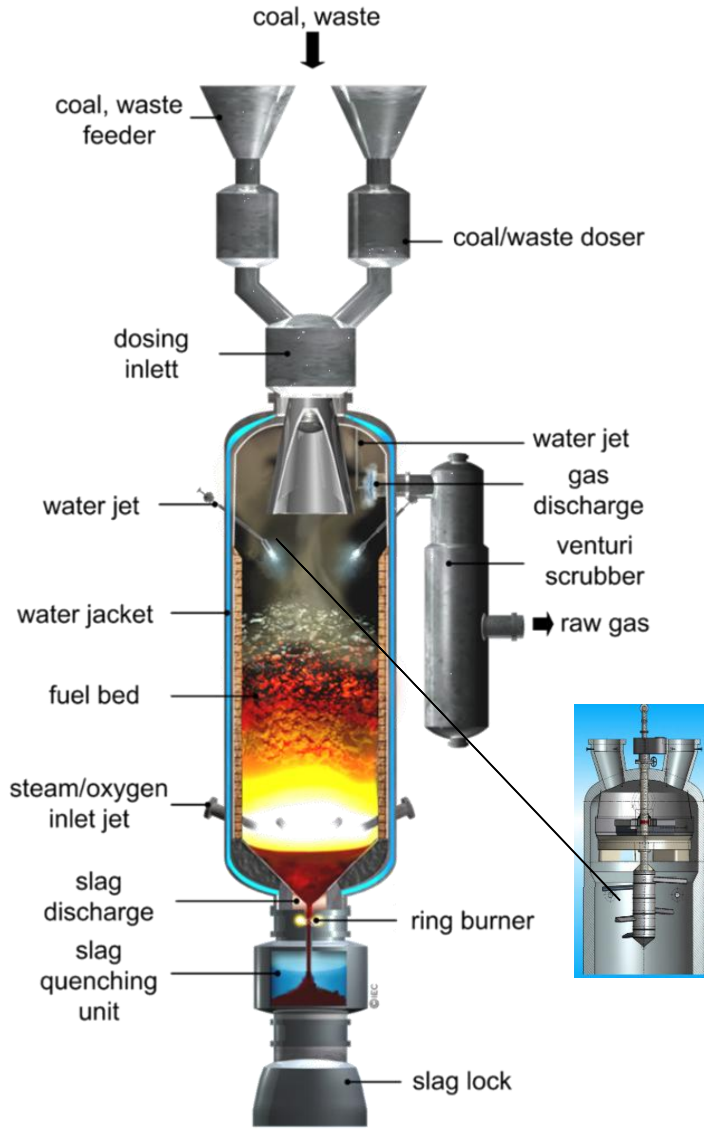


Adapted from:
M. Weiss; GTC
Conference; 2011

British Gas/Lurgi Gasifier (BGL) – Envirotherm, ZEMAG, Advantica

Features:

- Upper part like Sasol-Lurgi-FBDB
- Semi-continuous feeding via a double sluice system
- Water jacket with outer steel pressure shell and inner shell with refractory lining (MgO, SiC)
- Slag bath (1250-1500° C) with cooling tubes and protective solid slag layer
- Inner diameter 3.6 m, height 12-13 m
- O_2/H_2O injection by 6 tuyere nozzles
- Natural gas ring burner to keep slag tap open
- Gas exit temperature 500-800 ° C
- Production of tar/dust/water mix in wash cooler
- References plants location:
  SVZ Schwarze Pumpe (GER), Hulunbeier (CHN), Luoyang (CHN), Orissa (IND), Ordos Tuke (MNG)



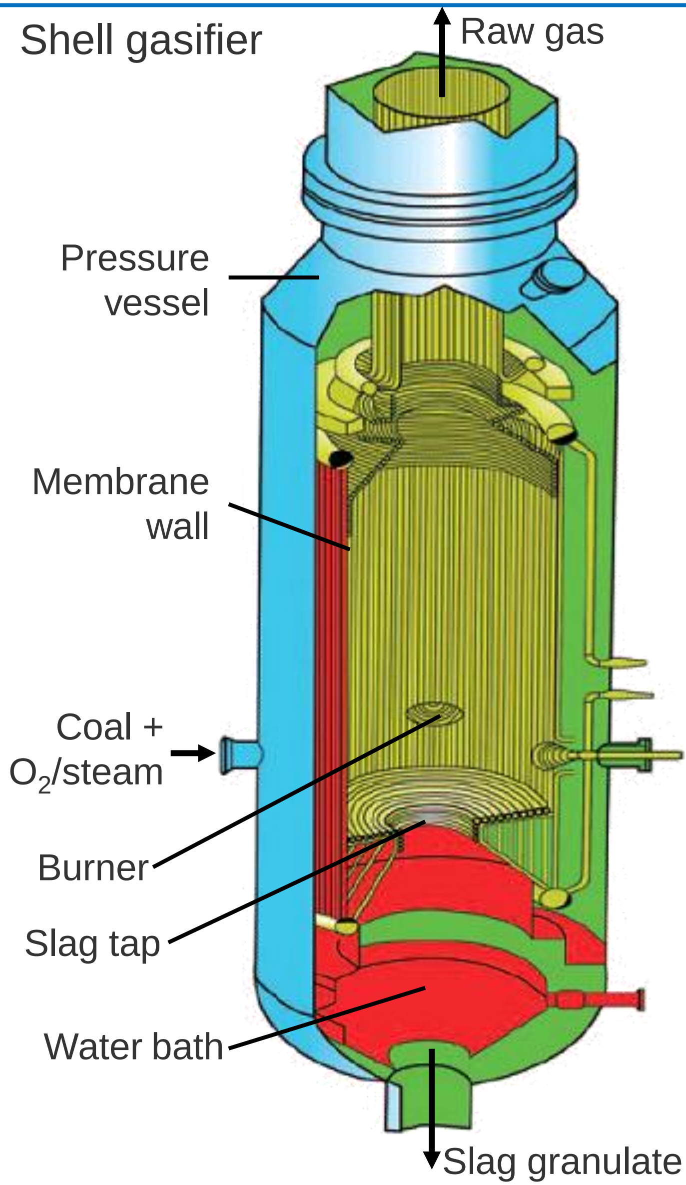
Source: Turna, O. et al.: Die Veredlung und Umwandlung von Kohle, Technologien und Projekte 1970 bis 2000 in Deutschland, Chapter British Gas/Lurgi-Schlackebad-Vergaser (BGL), Seiten 363–391. DGMK, 2008. M. Olschar,5th International Freiberg Conference, 2012

Shell Gasifier (Prenflo Gasifier)

Features:

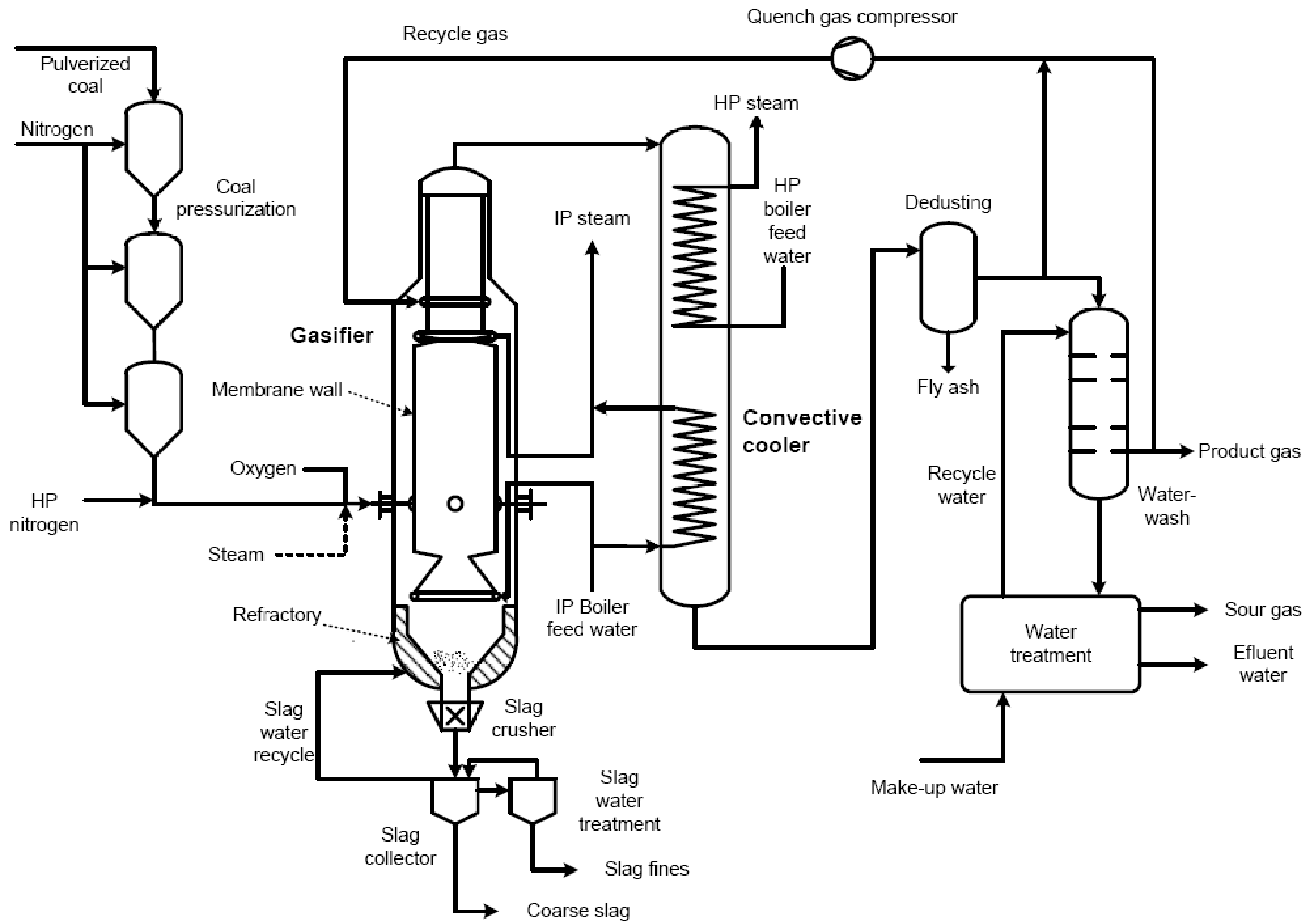
- Upward single-stage pressurized entrained-flow gasification (24-40 bar)
- Dry feeding via lock hoppers + dense-phase conveying
- Outer steel pressure vessel with inner membrane wall (2–4 % loss LHV input)
- Gas residence time: 0.5–4 s
- Coal + O_2/H_2O injection typically four two-flow burners in boxer arrangement
- Direct dust recycle by cyclone
- Gas exit temperature 1500 °C
- Raw gas cooling by cold recycle gas quench to 900 °C (50 % gas recycle necessary)

→ 20 Plants operating on solid feedstocks approx. 23 GW (th)



Source: Radtke, K., Rich, J.W. Jr., Hoppe, R.: Indirect Coal Liquefaction - Shell Coal Gasification with Fischer-Tropsch Synthesis. 1st International Freiberg Conference on IGCC & XtL Technologies, 2005.
S. van Paasen, Technology Development for Shell coal gasification, IFC, 2012

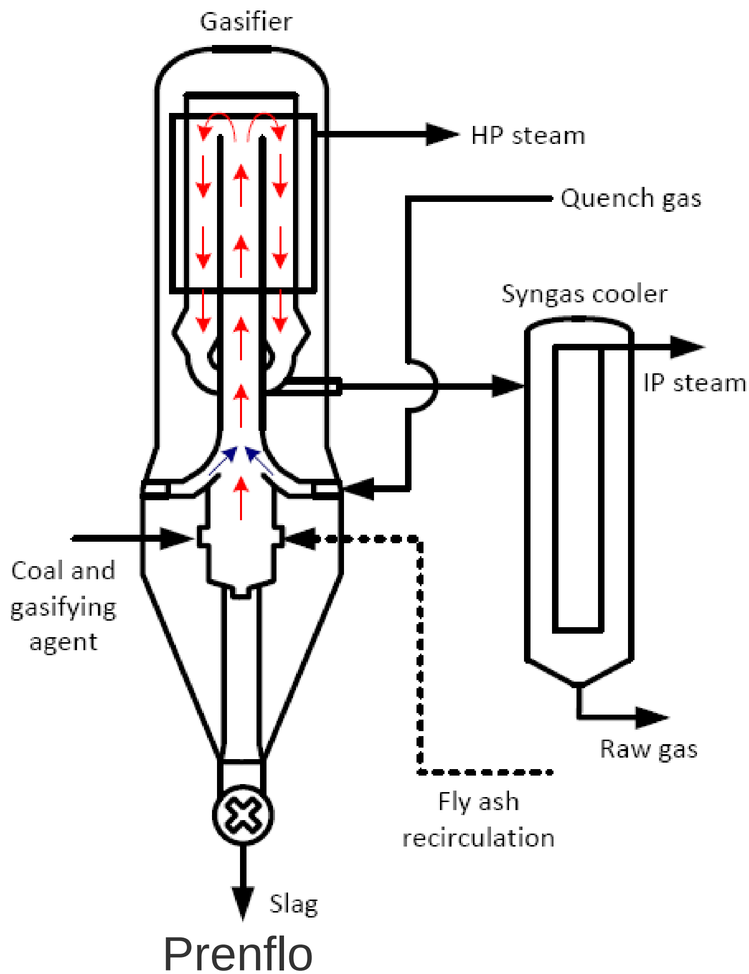
Shell Gasifier (Prenflo Gasifier)

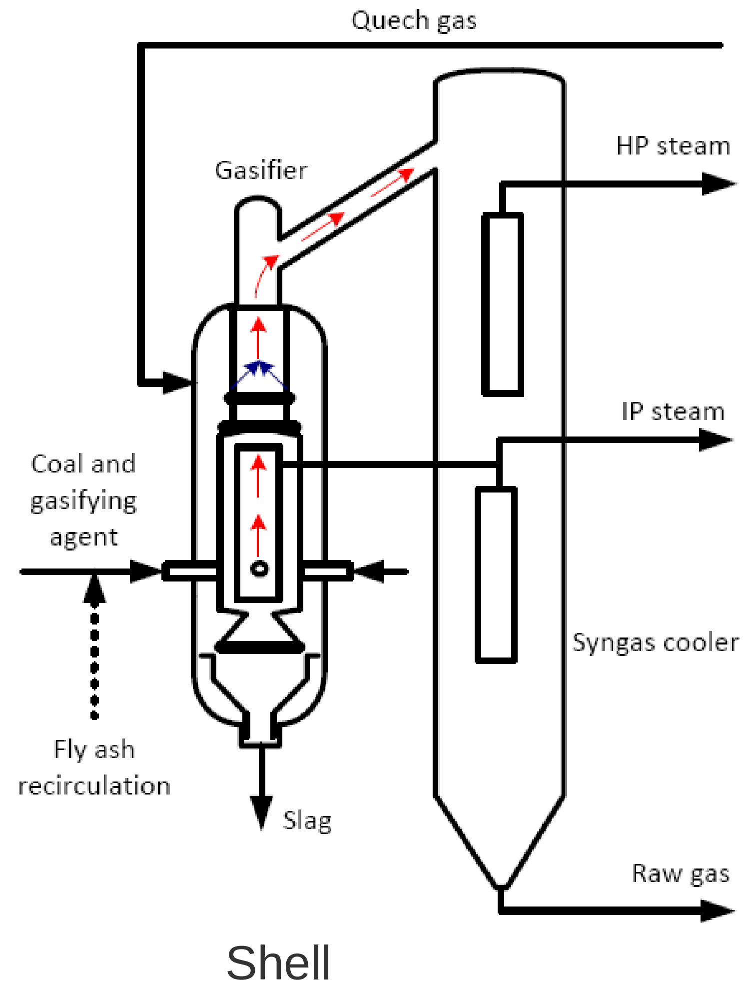


Adapted from: Higman, C. and van der Burgt, M.: Gasification. Elsevier Science, New York, 2003. ISBN 978-0-75-067707-3; Radtke, K., Rich, J.W. Jr., Hoppe, R.: Indirect Coal Liquefaction - Shell Coal Gasification with Fischer-Tropsch Synthesis. 1st International Freiberg Conference on IGCC & XtL Technologies, 2005. and Volk, J.: Coal Gasification: Delivering Performance in Chinese Operations & Developing Technology Deployment Solutions. Gasification Technologies Conference, 2010.

Shell Gasifier (Prenflo Gasifier)

Differences between Shell and Prenflo plant setup

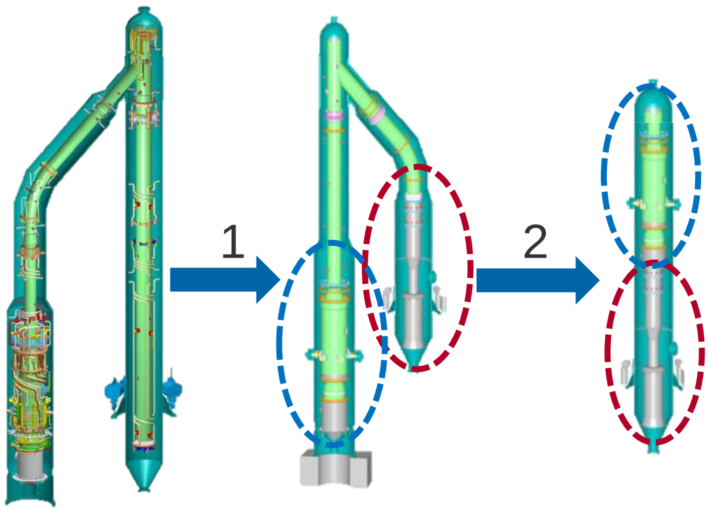


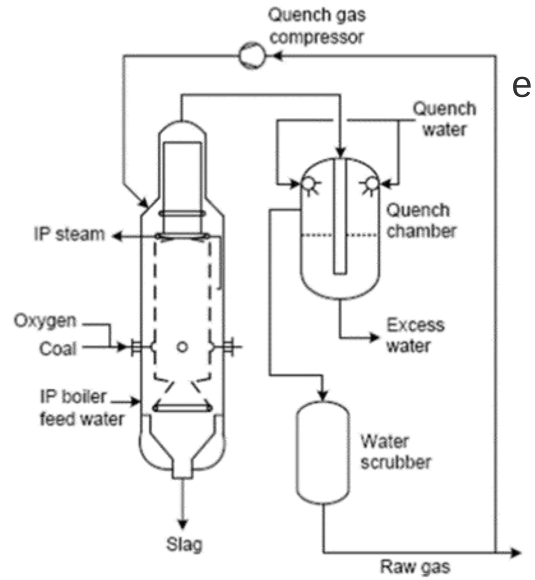


Adapted from: Eurlings, J. and Ploeg, J.: Process Performance of the SCGP at Buggenum IGCC. Gasification Technology Conference, 1999.; Radtke, K.: Uhde Biomass and Coal Gasification: Applying Fluidized Bed and Entrained Flow Gasification. Gasification Technologies Conference, 2010.; Mendez-Vigo et al.: The Puertollano IGCC Plant: Status Update. 1998.; Volk, J.: Coal Gasification: Delivering Performance in Chinese Operations & Developing Technology Deployment Solutions. Gasification Technologies Conference, 2010

Shell Gasifier (Prenflo Gasifier)

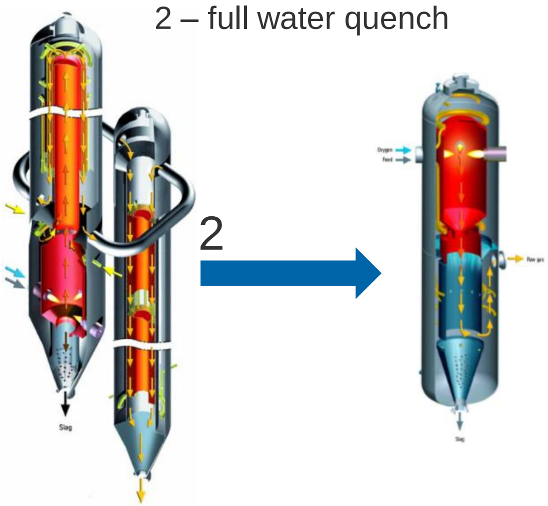
Development directions

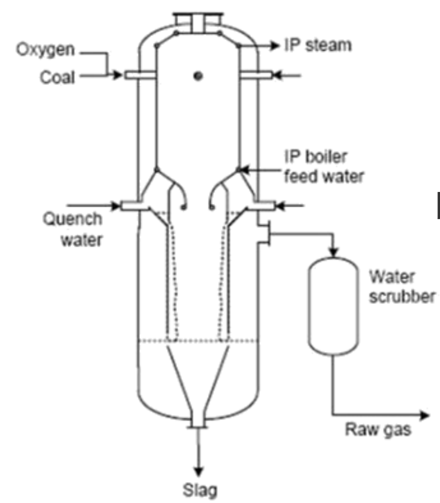




e.g. Shell design with cold gas quench and subsequent water quench

1 – cold gas quench & partial water quench
2 – full water quench





e.g. Prenflo direct water quench (PDQ) (comparable to Shell bottom water quench)

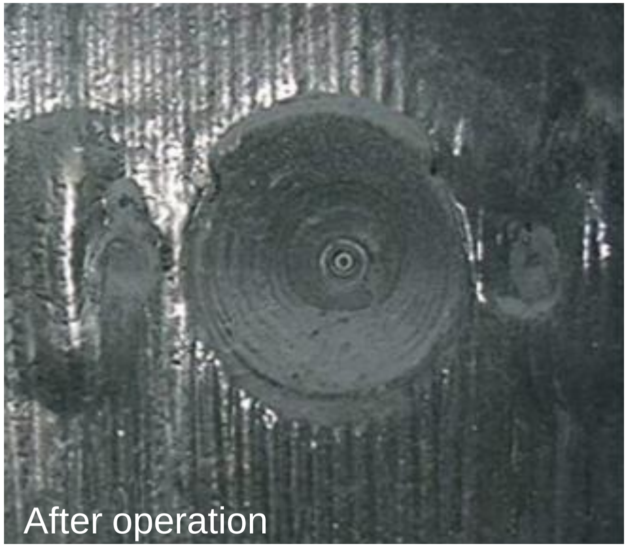
Sources: Chhoa, T.: Radtke, K. and Heinritz-Adrian, M.: PRENFLO PSG and PDQ. Gasification Technology Conference, 2008.; Volk, J.: Coal Gasification: Delivering Performance in Chinese Operations & Developing Technology Deployment Solutions. Gasification Technologies Conference, 2010.

Shell Gasifier (Prenflo Gasifier)

Illustrative Material

2000 t/d Shell gasifier before installation in pressure vessel

Membrane wall of Prenflo coal gasifier



After operation

After assembly

Membrane wall of Prenflo coal gasifier

Sources: Chhoa, T.: Shell Gasfication business in action. Gasification Technologies Conference, 2005.; Radtke, K., Rich, J.W. Jr., Hoppe, R.: Indirect Coal Liquefaction - Shell Coal Gasification with Fischer-Tropsch Synthesis. 1st International Freiberg Conference on IGCC & XtL Technologies, 2005.; Radtke, K. and Heinritz-Adrian, M.: PRENFLO PSG and PDQ. Gasification Technology Conference, 2008.

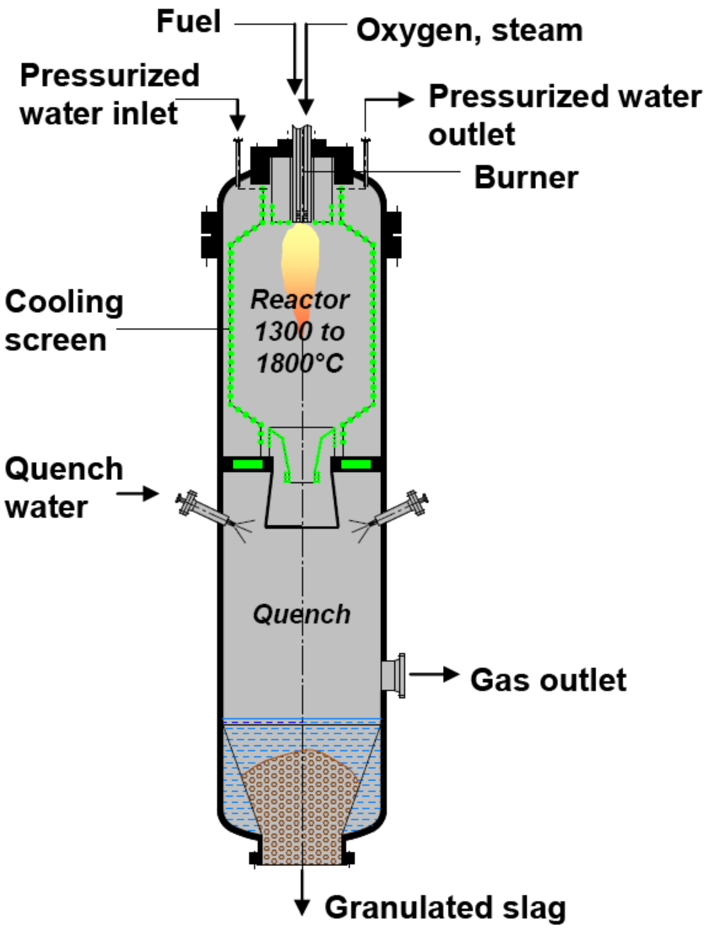
Siemens Gasifier (SFGT or GSP)

Features:

- Downward single-stage pressurized entrained-flow gasification (5-25 bar)
- Dry feeding via lock hoppers + dense-phase conveying by N_2, CO_2 or natural gas
- Outer steel pressure vessel with inner coiled cooling screen (2.5 % loss LHV input)
- Refractory lined gasifier for low ash coals available (e.g. Vresova IGCC)
- Gas residence time: 2-4 s
- Coal + O_2/H_2O injection through one top central burner with integrated pilot burner
- Integrated spray water quench from 1300-1800 ° C to saturation temperature (240 ° C)
- Slag granulation in water bath

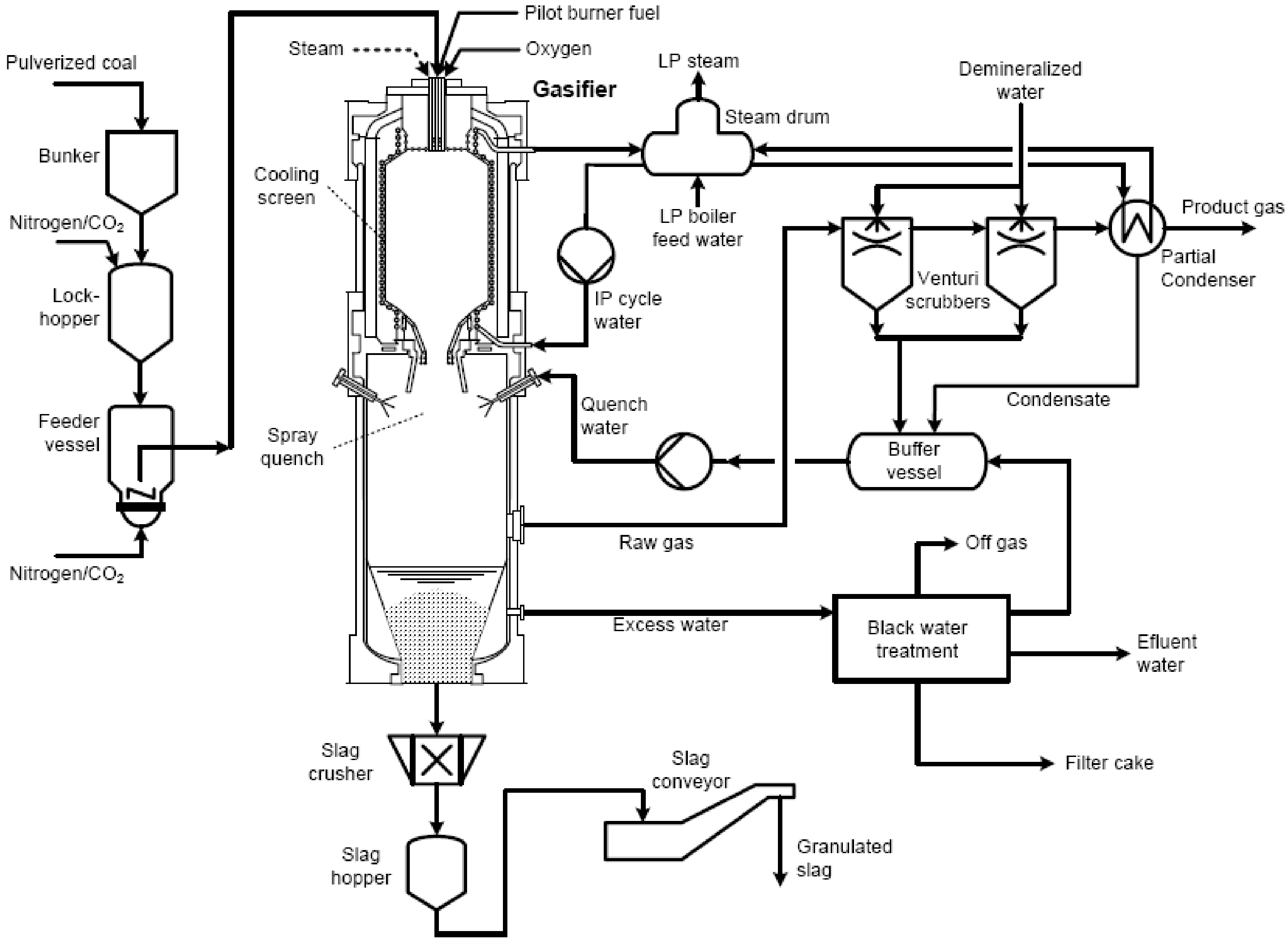
References:

- 9 x 500 MW gasifiers installed in 3 projects (2 plants operating)
- 32 gasifiers under manufacturing



Sources: F. Hannemann, The challenge: Economically attractive and environmentally friendly use of local energy sources, International Freiberg Conference 2014

Siemens Gasifier (SFGT or GSP)



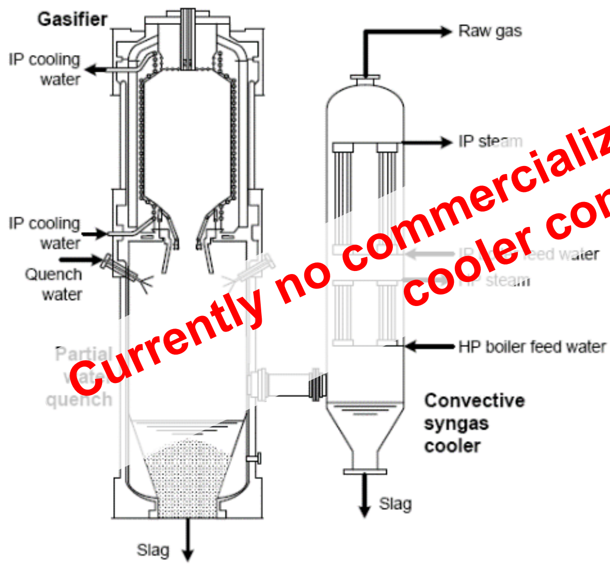
Sources: Morehead, H.: Siemens Technology Advances and Project Development Activities. Gasification Technologies Conference, 2010. Schingnitz, M.: Übersichtsvortrag zur Vergasungstechnik. Technische Universität Dresden, 2010.

Siemens Gasifier (SFGT or GSP)

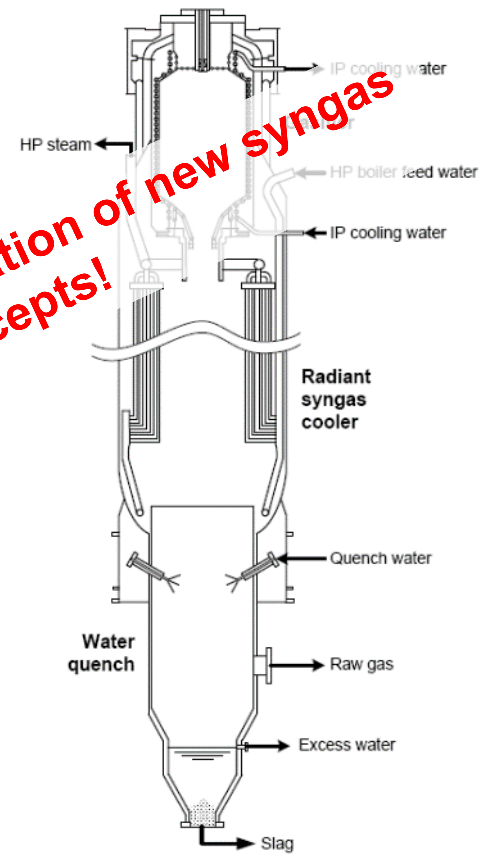
Development directions

- Scale up to 850 MW
- Raw gas cooling and heat recovery

Currently no commercialization of new syngas cooler concepts!



Siemens gasifier with partial water quench and convective syngas cooler



Siemens gasifier with radiant syngas cooler and water quench

Sources: Hannemann, F., Schingnitz, M. and Zimmermann, G.: Siemens IGCC and Gasification Technology - Today's Solution and Developments. 2nd International Freiberg Conference on IGCC & XtL Technologies, 2007.; Morehead, H.: Siemens Technology Advances and Project Development Activities. Gasification Technologies Conference, 2010.

Choren Clean Coal Gasifier (CCG)

Features:

- Roots back to GSP gasifier
- Multiple burners
- Two separate vessels

Projects:

- YanKuang project (GuiZhou, CHN)
  - Operating since 2013
  - 2+0 gasifiers (each 1,500 t/d coal)
  - 500,000 t/a ammonia
- Jarud project (CHN)
  - Start up 2015
  - 2+0 gasifiers (each 1,500 t/d coal)
  - 600,000 t/a ethylene glycol

Sources: Cai, N.: Development of Coal Gasification & Polygeneration in China. IEA-MOST Workshop on Fossil Fuel Technologies, 2010.; Blades, T.: Reducing the Carbon footprint with combined Carbo-V & CCG technologies. Gasification Technologies Conference, 2008.

Typical synthesis routes

Fischer-Tropsch (FT) synthesis

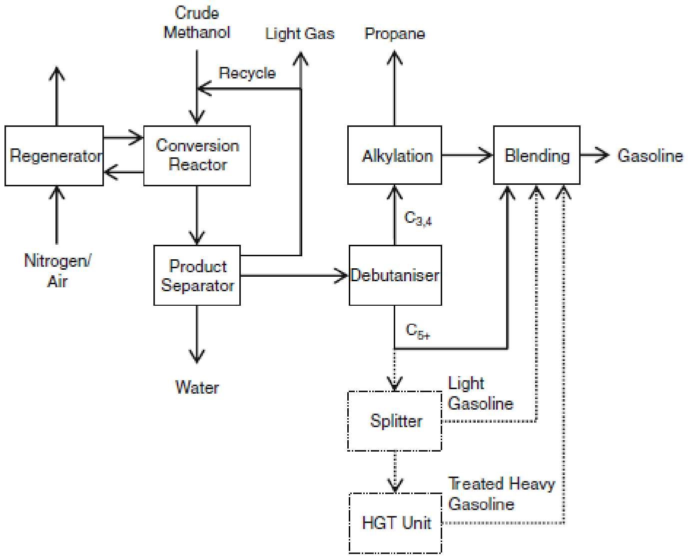
- Preferably for production of diesel or jet fuel
  ➔ Low-temperature FT synthesis with syncrude (wax upgrading)
- Gasoline and olefines only applied in two plants
  ➔ High-temperature FT synthesis
- Combined diesel and gasoline synthesis with reduced product purification effort
  ➔ New medium-temperature FT synthesis (Synfuels China Technology Ltd. & Co.)
- All FT syntheses with high refining effort for products

Methanol-based syntheses

- Production of:
  - Gasoline
  - Olefines / aromatics or
  - DME (diesel substitute)
- DME as intermediate product for most synthesis routes
- Reduced product refining effort because of higher selecivity compared to FT syntheses

Fluid-bed MTG (ExxonMobil & Uhde)

Fluid-bed MtG process layout



Process characteristics:

- Direct hydrocarbon formation in isothermal fluid-bed reactor with vaporized MeOH, continuous catalyst regeneration
- Recovery of high-pressure steam
- Improved economics because of lower investment costs

References:

- Demo plant in Wesseling (Germany): 4,000 tpy
- Never commercialized

Source: Bertau, M. et al. „Methanol: The Basic Chemical and Energy Feedstock of the Future " Springer 2014,

Olefines as intermediates

MtSynfuel (Lurgi/Air Liquide)

- Based on MTP process (consecutive DME and propene production on zeolite catalyst)
- Further oligomerization and processing to gasoline and diesel (COD by PetroSA)
- Developed up to pilot plant scale

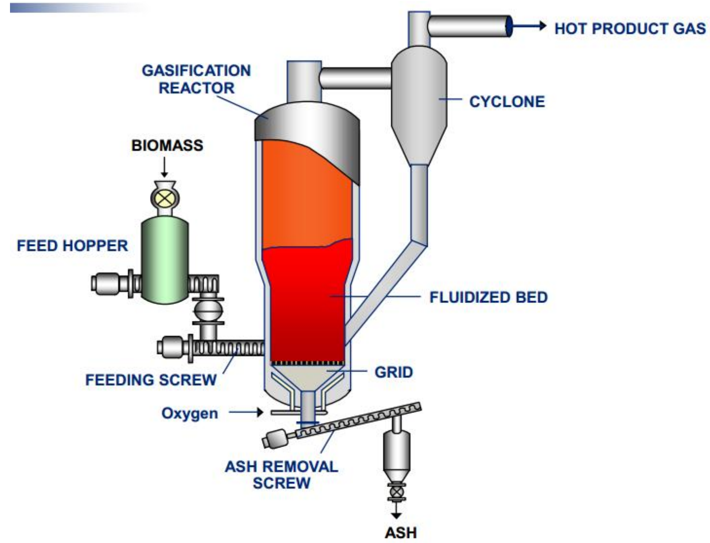
MOGD (ExxonMobil)

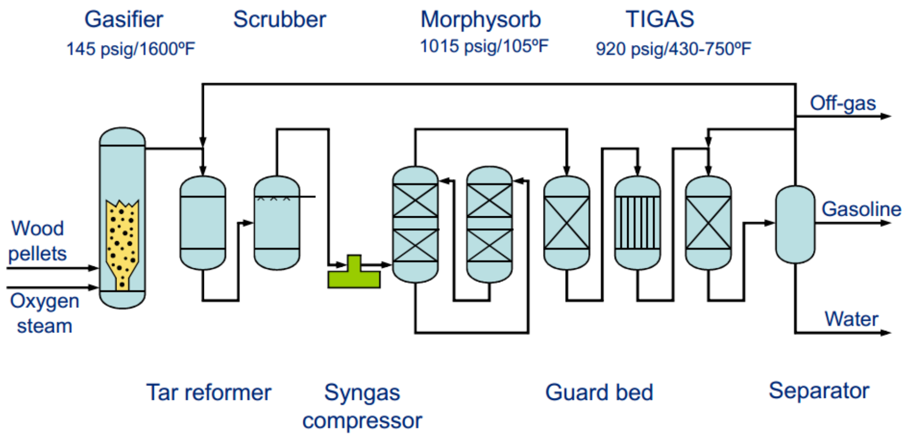
- Based on MTO process
- Products mainly i-olefins, need further hydrogenation
- Tested 1981 in a Mobil refinery

Source: Bertau, M. et al. „Methanol: The Basic Chemical and Energy Feedstock of the Future “ Springer 2014,

DOE Wood-to-Green-Gasoline

- Joint project of:
  UPM, Haldor Topsoe, Phillips66, Carbona, GTI
- Demonstration Plant at GTI in Des Plaines (IL), 20–25 bpd (2014)
- Process steps:
  - ANDRITZ/Carbona bubbling fluidized-bed gasification (10 bar, 850 ° C)
  - Syngas cleanup
  - TIGAS gasoline synthesis





Source: Udengaard, N. „Wood to green gasoline using Carbona gasification and Topsoe TIGAS processes“ Biomass IDL Workshop 2014
Joensen, F. “Biomass to Green Gasoline by TIGAS Technology” DTU International Energy Conference 2012