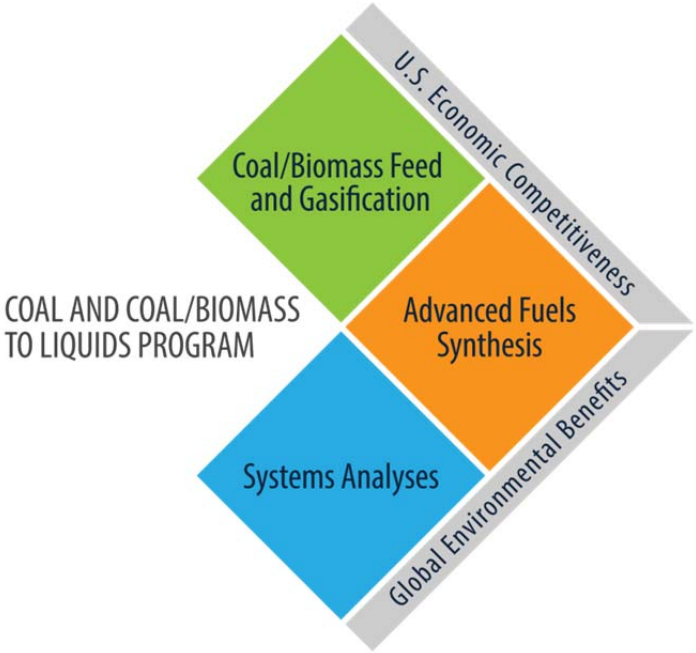
Coal Liquefaction Technology Short Course



January 27, 2014
NETL Pittsburgh, PA

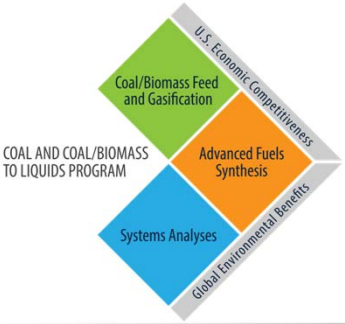
Coal Liquefaction Short Course Agenda

27 January 2014

1) Introduction and Overview
2) Coal Liquefaction Fundamentals
   a) Direct Liquefaction
   b) Indirect Liquefaction
3) Chronology of Liquefaction Technology Developments
   a) History of direct and indirect coal liquefaction
   b) Findings from those activities
   c) More recent developments (DCL - Shenhua and Accelergy)
4) Coal Liquids Refining
   a) Product characteristics
   b) Upgrading strategies

   BREAK

5) Overview of Economics of Coal Liquefaction
6) Climate Change Impacts of Coal Liquefaction
   a) Mitigation of GHG emissions
   b) Regulatory and policy drivers
7) Hybrid CTL Concept
8) Alternative Coal Liquefaction Approaches
9) Barriers and Requirements for Commercialization
10) Closing Remarks and Discussion



Short Course on Coal Liquefaction

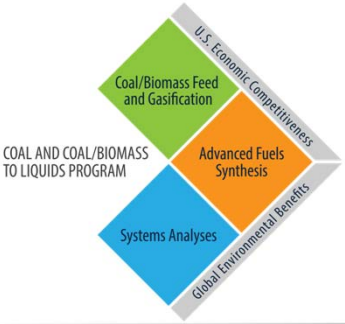
David Gray and John Marano
Noblis/JM Energy Consulting Inc

January 27, 2014

U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

Presentation Content

- Introduction & Overview
- Fundamentals of Coal Liquefaction
  - Direct Coal Liquefaction (DCL)
  - Indirect Coal Liquefaction (ICL)
- Chronology of Coal Liquefaction Activities
  - History of direct and indirect coal liquefaction
  - Findings from those activities
  - More recent developments (DCL – Shenhua and Accelergy)
- Coal Liquefaction – Product Refining
  - Petroleum Refining
  - Transportation Fuel Specifications
  - Upgrading Options for Coal Liquids
- Comparative Economics of DCL and ICL
- Climate Change Impacts of Coal Liquefaction
  - Relative GHG Emissions
  - Mitigation of GHG Emissions for CTL
  - Renewable & Low-Carbon Fuel Standards
  - DOD Alternative Fuels Initative
- Hybrid CTL Concept
- Alternative Coal Liquefaction Approaches
- Barriers and Requirements for Commercialization
- Closing Remark and Discussion



Coal Conversion – Direct Liquefaction

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Fundamentals of Direct Coal Liquefaction (DCL)

- Initially solubilized coal products are non-distillable (high molecular weight)
- Extended thermal and catalytic reaction is needed to produce distillates
- Products are light hydrocarbon gases, heterogases, distillates and non-distillable liquids
  - Oils are pentane soluble
  - asphaltenes (benzene soluble-pentane insoluble)
  - pre-asphaltenes (pyridine soluble-benzene insoluble)

Fundamentals of DCL (Continued)

- **Solvents**
  - provide transport medium
  - heat transfer
  - dispersion medium
  - hydrogen donor
  - typically the solvent is generated in the DCL process either in the liquefaction reactors or in a separate hydrotreater
  - heavy oils can also be used as solvents (coal/oil co-processing)

Fundamentals of DCL (Continued)

- **Hydrogen Donor Solvents**
  - they have a partially hydrogenated aromatic structure
  - the hydroaromatic hydrogen is transferred from the solvent to cap the "coal free radicals" and a stable aromatic solvent is produced
  - when recycled the solvent is rehydrogenated so that it can again donate its hydrogen to the coal radicals formed during the liquefaction process
  - partially saturated compounds like dihydropyrene in the donor solvent are much better donors than fully saturated compounds like decahydronaphthalene
- **Polycyclic aromatic compounds are easily hydrogenated and dehydrogenated. Pyrene is converted to dihydropyrene during coal liquefaction particularly when catalysts are present**

Fundamentals of DCL (Continued)

- **Coal conversion is considered to occur in two phases**
  - first coal is rapidly converted with low H_2 consumption (0.2 - 0.5 wt% of coal) at about 400 °C (coal structure dependent)
  - further conversion is gradual and consumes more hydrogen (dependent on H-donor concentration in solvent). If solvent is poor, condensation reactions can occur reducing the overall coal conversion
  - high solvent:coal ratios (1.5-2.0) can inhibit condensation by providing dilution and more H-donor capacity
  - this has led to liquefaction configurations usually accomplished in two reactor stages at different conditions

Fundamentals of DCL (Continued)

- **Other solvent effects**
  - coal-derived solvents are highly complex mixtures some benefit and others inhibit reaction
  - H-donors can be augmented by strong solvents like phenols
  - high boiling hydrocarbon fractions enhance liquefaction whilst heterocyclic fractions can inhibit
  - some components tend to char and this increases insoluble material and reduces conversion
  - certain heterocyclic nitrogen compounds can enhance liquefaction (tetrahydroquinoline for example)

Fundamentals of DCL (Continued)

- **Effect of coal composition**
  - suitability for liquefaction is governed by rank, petrographic composition, and inorganic matter content
  - vitrinite and liptinite macerals are generally reactive whilst inertinite (fusinite) is less reactive
  - mid rank coals (83-88% maf carbon) are best candidates whilst very high rank coals are inert
- **Bituminous coal**
  - correlation between coking properties and ease of liquefaction
  - lower molecular weight hydrogen-rich bitumens in the coal can serve as in-situ H-donors and solvents for the molecular species first liberated
- **Low-rank coals**
  - generally convert slower than bituminous and formation of water from high oxygen content consumes more hydrogen
  - although yield usually decreases with decreasing rank, proportion of low boiling distillate product increases
  - high oxygen content associated with absence of plastic properties they behave more like interlinked polymers
  - higher yields can be obtained using mixture of water and CO or synthesis gas

Fundamentals of DCL (Continued)

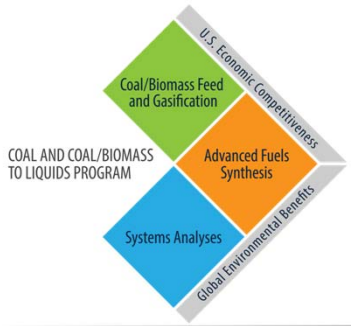
- **Gaseous hydrogen**
  - high pressure hydrogen (1500-3000 psi) provides stabilizing H_2 and H_2 for H-Donors
  - H_2 can react directly with the coal and hydrogenate depleted H-donor compounds in the solvent
  - overall hydrogen consumption including refining of raw products can be 8-10 wt % on an maf coal basis

Fundamentals of DCL (Continued)

- **Catalysts**
  - added catalysts are essential for providing a viable high conversion liquefaction process
  - catalyst can enhance production of H-donors in the solvent
  - they can enhance the reaction of gaseous H_2 with the coal
  - can facilitate removal of heteroatoms in the coal and in primary coal dissolution compounds
- **Disposable catalysts**
  - they are not recovered and must be inexpensive and effective at low concentration
  - compounds of iron like pyrites, tin and highly dispersed molybdenum have been used
  - more recent configurations use microcat-type catalysts

Fundamentals of DCL (Concluded)

- **Supported catalysts**
  - extrudates used in fixed, fluid, or ebullating bed reactors
  - these catalysts are assumed to catalyze conversion of the primary products and the solvent rather than the actual coal
  - they can be added and withdrawn to maintain activity
  - these catalysts can be deactivated by coking and metal deposition
  - catalyst requirements are similar for heavy resid upgrading



Coal Conversion – Indirect Liquefaction

Topics:

1) Feedstock Chemistry
2) Syngas Generation & Clean-Up
3) Synthesis Options
   - Fischer-Tropsch
   - Methanol

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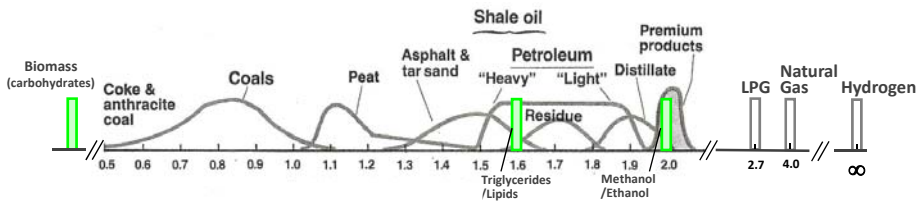
Conversion of Carbon-Based Materials to Premium Liquid Fuels



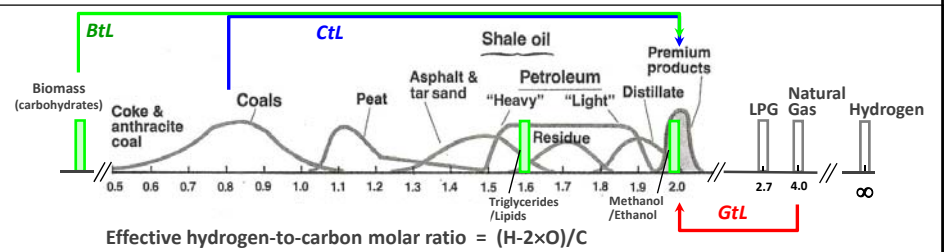
Effective hydrogen-to-carbon molar ratio = (H-2×O)/C

John J. Moreno Ph.D.

Solid ← → "Tar" ← → Liquid ← → Gas

- For hydrocarbons molar ratio of hydrogen to carbon indicative as to whether material is gas, liquid or solid at ambient conditions
- For organic materials containing elements oxygen, nitrogen or sulfur, effective hydrogen-to-carbon ratio serves same function:
  - reduce hydrogen by twice the oxygen, twice the sulfur and thrice the nitrogen

Conversion of Carbon-Based Materials to Premium Liquid Fuels

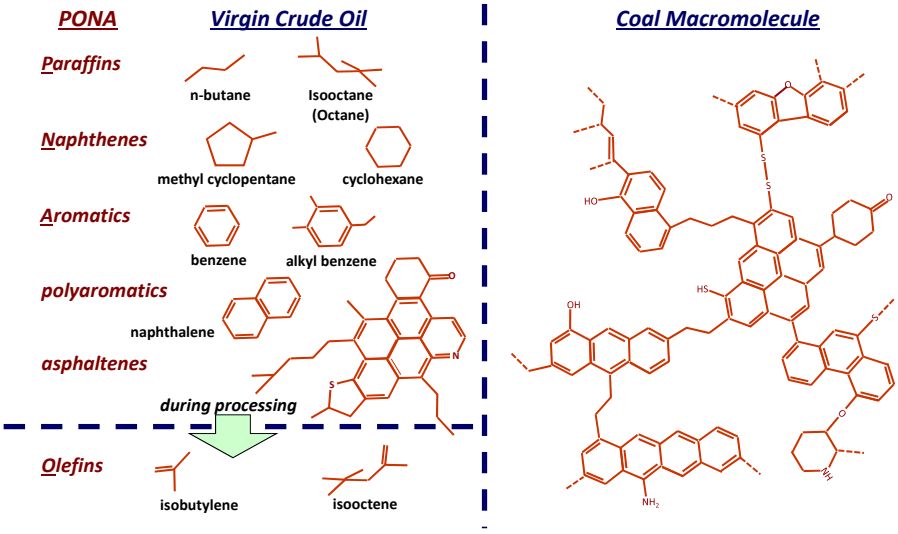


- To make liquid fuels from: petroleum/coals/biomass need to add H_2 or reject C
  natural gas need to reject H_2 or add C
  triglycerides either add H_2 or CH_3OH (methanol)
- Adding hydrogen and rejecting carbon (or vice versa) may be equivalent:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

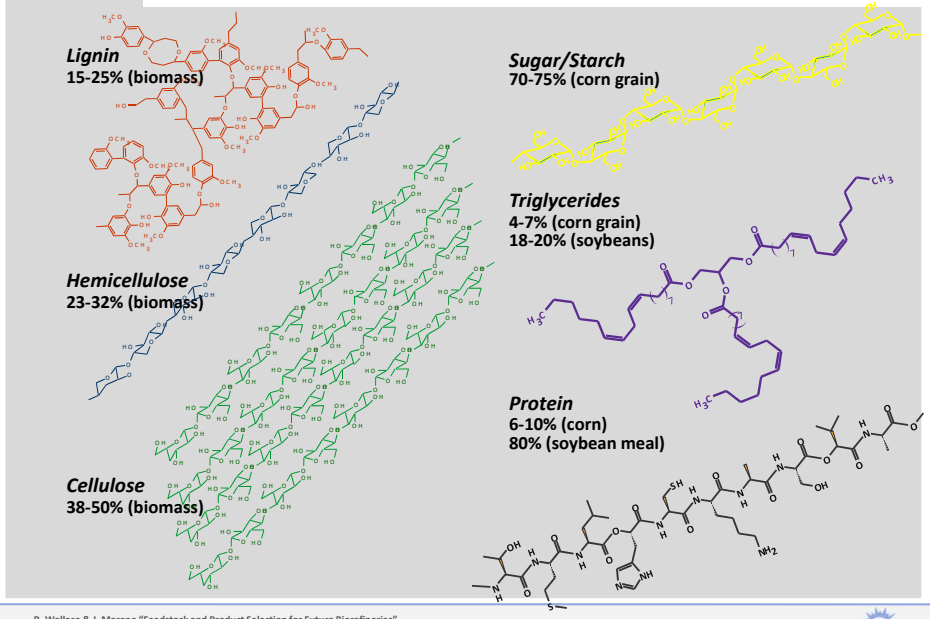
Water Gas Shift (WGS) Reaction

Constituents Molecules of Petroleum & Coal



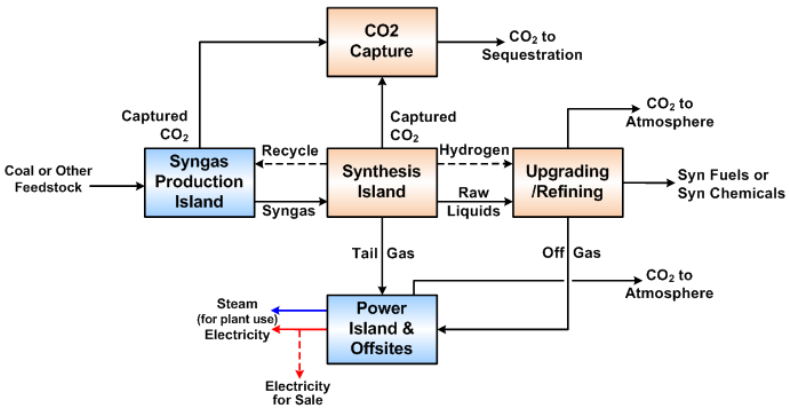
John J. Marano "Options for Upgrading & Refining Fischer-Tropsch Liquids"
2nd International Freiberg Conference on IGCC & XtL Technologies Freiberg, Germany May 8-12, 2007

Constituents Macromolecules of Biomass

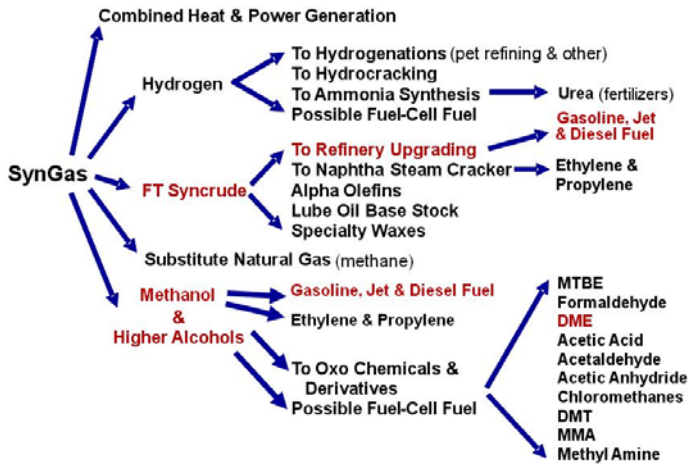


R. Wallace & J. Marano "Feedstock and Product Selection for Future Biorefineries"
World Congress on Industrial Biotechnology and Bioprocessing Orlando, FL March 22, 2007

XtL Block Flow Diagram



Products that can be made from syngas



Molecules H_2 and CO contained in synthesis gas are building blocks
can be used to synthesize wide variety of complex hydrocarbons & organic compounds

Fischer-Tropsch Chemistry

- **FT synthesis over Fe catalyst:**

$$2n\ CO + n{+}1\ H_2 \rightarrow C_nH_{2n+2} + n\ CO_2 \quad \text{(n-paraffins)}$$

$$2n\ CO + n\ H_2 \rightarrow C_nH_{2n} + n\ CO_2 \quad \text{(α-olefins)}$$

$$2n\ CO + n\ H_2 \xrightarrow{+H_2O} C_nH_{2n+1}OH + n\ CO_2 \quad \text{(n-alcohols)}$$

Water-Gas-Shift Reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

  - desired H_2/CO feed ratio ~0.5
- **And over Co catalyst:**

$$n\ CO + 2n{+}1\ H_2 \rightarrow C_nH_{2n+2} + n\ H_2O \quad \text{(n-paraffins)}$$

  - desired H_2/CO feed ratio ~2.0
- **Synthesis conditions:** 200 - 300°C 1 - 30 bar

Fischer-Tropsch Chemistry

- **FT synthesis classical polymerization mechanism:**
  - can't make single product
  - Follow Anderson-Shultz-Flory product distribution based on chain-growth probability factor α
  - on molar basis methane is main product
  - to maximize distillate want to make high carbon number wax and crack molecules
- **Iron (Fe) catalyst preferred for coal-derived syngas with low H_2/CO ratio**
- **Cobalt (Co) catalyst preferred for natural gas-derived syngas with high H_2/CO ratio**
- **However, Fe provides flexibility to upgrading raw FT liquids**

Fischer-Tropsch Reactor Technology

1st Generations

Fixed bed tubular reactors
- Gulf/Badger, Sasol (1950s)
- Shell Bintulu GTL (1990s)
- High wax yield

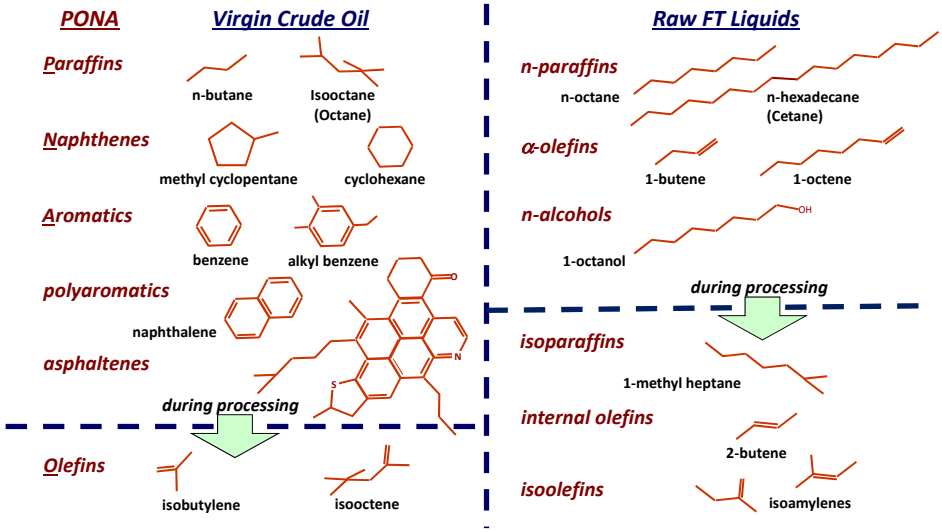
Moving fluidized bed reactors
- Synthol™, Sasol (1980s)
- No wax/low diesel yield

2nd Generations

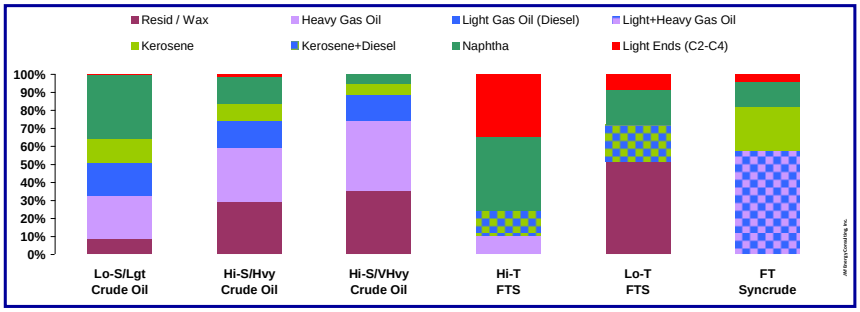
Fixed fluidized bed reactors
- Adv. Synthol™, Sasol (1990s)
- Mossel Bay GTL (1990s)

Slurry bubble column reactors
- Sasol/others pre-commercial
- Focus of DOE (1990s)
- Three-phase reactor
- High wax yield

Constituents Molecules of Petroleum & FTL



Assays for Petroleum & FT Liquids



°API	39.5		27.4		14.7		N/A		53		57	
Sulfur	0.4%		2.8%		2.7%		nil		nil		nil	
Nitrogen	0.1%		0.2%		0.5%		nil		nil		nil	
Oxygen	nil		nil		nil		N/A		1%		nil	
RON[1]	N/A		50		65		~20		~20		~40	
CN[2]	50		N/A		39		>70		>70		>70	
Asphalt.	0.2%		N/A		8.7%		nil		nil		nil	

[1]Naphtha Cut [2]Diesel Cut

Methanol Synthesis Chemistry

- **Methanol synthesis over Cu/Zn catalyst:**

$$CO + 2\,H_2 \leftrightarrow CH_3OH$$

$$CO_2 + 3\,H_2 \leftrightarrow CH_3OH + H_2O$$

Water-Gas-Shift Reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

  - desired $(H_2\text{-}CO_2)/(CO+CO_2)$ feed ratio 2.05
  - synthesis conditions: 350 - 400°C 300 - 500 bar (Hi-*P* process)
    250 - 275°C 50 - 100 bar (Lo-*P* process)

- **Commercial Lurgi gas-phase fixed-bed tubular reactors**
- **Slurry-bubble column reactor development by Air Products/DOE (1990s)**

Methanol Conversion Chemistry

- **Mixed alcohols synthesis over modified Cu/Zn catalyst:**

$$n\,CO + 2n\,H_2 \rightarrow C_nH_{2n+1}OH + n\text{-}1\,H_2O \quad \text{(C2-C4 alcohols)}$$

  - gasoline blendstock alternative to ethanol

- **Dimethyl Ether synthesis over Cu/Zn with co-catalyst:**

$$2\,CH_3OH \leftrightarrow CH_3OCH_3 + H_2O \quad \text{(DME)}$$

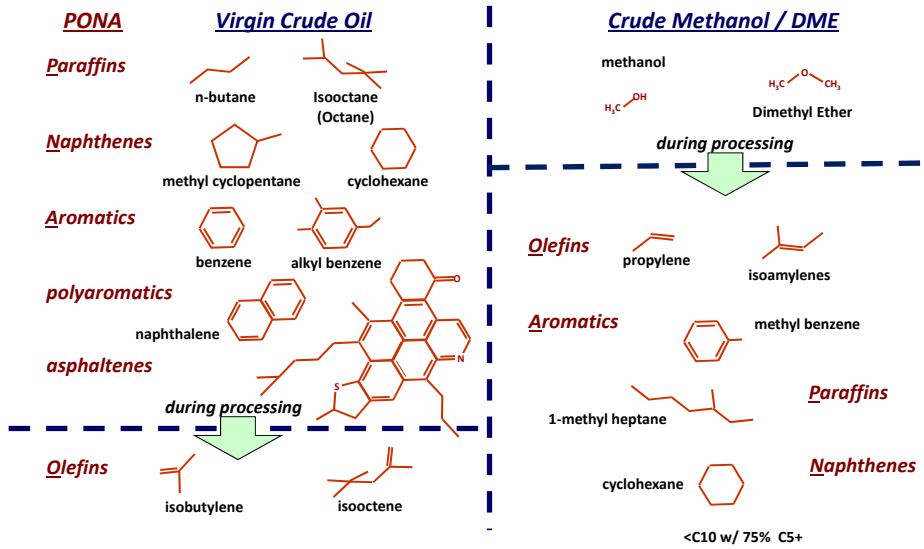
  - alternative diesel fuel with physical properties similar to LPG

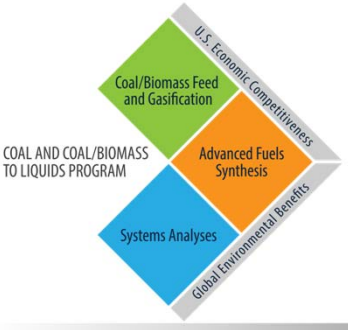
- **DME can be converted to gasoline and distillate over zeolite catalyst:**

$$CH_3OCH_3 \rightarrow \text{lower olefins} \rightarrow \text{higher paraffins \& aromatics}$$

  - basis for commercial methanol-to-olefins (MTO), methanol-to-gasoline (MTG), methanol-to-distillate (MTD) processes
  - fixed or fluidized-bed reactors

Constituents Molecules of Petroleum & MTG





Chronology of Coal Liquefaction Technology Developments

Topics:

1) History of DCL & ICL
2) Activities Findings
3) More Recent Developments
   - Shenhua
   - Accelergy

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Early Development of DCL

YEAR	EVENT/PROCESS
1868	First coal hydrogenation – Berthelot Hydroiodic acid 270 °C for 24 hours 67% oil yield
1913	First direct liquefaction patent – Bergius Single stage 450 °C, 3,000 psi H_2, Fe catalyst, Low quality products produced
1927	First commercial plant in Leuna Germany – I.G. Farben 1st stage 480 °C, 10,000 psi H_2, Fe catalyst 2nd stage 450 °C, 3,000 psi H_2, Mo/Zn/Mg catalyst Feed brown coal and coal tar, 2,500 BPD Product gasoline and diesel fuel
1935	Commercial plant in Billingham, UK – ICI – variant of I.G. Farben process Bituminous coal, Sn and Fe catalysts, 120,000 tons per year of products
1944	Peak production in Germany during WWII 12 plants producing 100,000 BPD of aviation gasoline and diesel oil

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U.S. Direct Liquefaction Process History

source: Consol Energy and Mitretek Systems July 2001

Year	Process	Coal Capacity (TPD)
1945-1953	Bergius – Louisiana, MO	100
1962-early 1980s	Solvent Refined Coal (SRC) – Pott-Broche	50
1963-1972	Consol Synthetic Fuels (CSF) – Two-Stage, Catalytic	20
1970s-early 1980s	SRC-I and SRC II (Gulf Oil Fort Lewis) – One-Stage, Non-catalytic	50
1965-early 1980s	H-Coal (Catlettsburg KY, HRI) – One-Stage, Catalytic	250
Late 1960s-early 1980s	EXXON Donor Solvent (Baytown, TX)	250
Early 1980s-late 1980s	Integrated Two-Stage Liquefaction (ITSL) – Lummus – Wilsonville (Southern Company) – HRI	6
1990-1995	Multi-Stage Slurry Phase Liquefaction HTI	3 (proof of concept)

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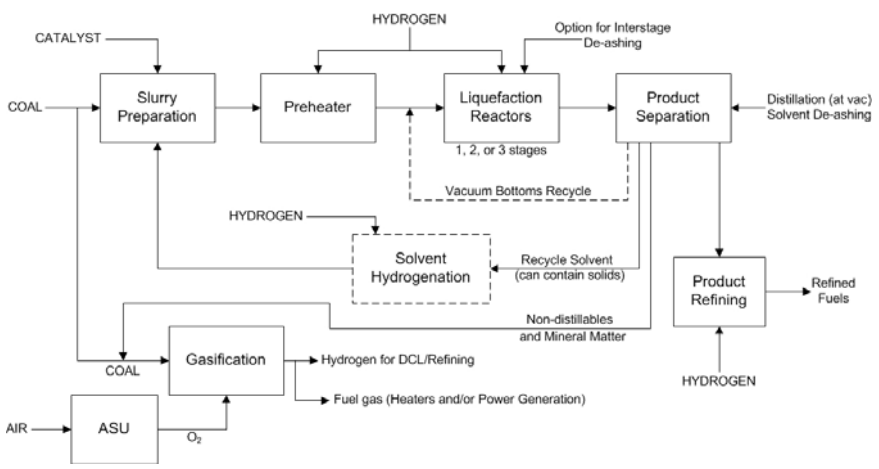
Non-U.S. Direct Liquefaction Processes

source: Consol Energy and Mitretek Systems July 2001

Country	Facility	Capacity (TPD)	Status
Germany	BOTTROP Plant – I.G. Farben Variant	200	Shut down
Japan	Brown Coal Liquefaction Plant – ITSL Variant – Victoria, Australia	50	Shut down (~1990)
Japan	Nedol Plant – ITSL Variant – Bit. and Subbit. Coals	150	Shut down (late 1990s)
U. K.	Point-of-AYR Plant – ITSL Variant	2.5	Shut down (~1990)
China	Inner Mongolia	7,000	Start-up 2008

Generic Configuration for DCL



U.S. Pilot Plant/PDU Facilities for DCL Overview

	EDS	H-COAL	CC-ITSL	CMSL
Year of operation	Late 1970s	Early 1980s	1982	1994
Number of reactors	1	1	2	3
Reactor type	Plug flow	Ebullated bed	Ebullated beds/ Back mixed slurry	Back mixed slurry and fixed bed
Temperature (°F)	800-900	800-850	810	755
Pressure (psi)	2500	2900	2800	2500
2nd reactor Temp (°F)	-	-	750-800	844
2nd reactor Pressure (psi)	-	-	2500-2700	2500
Plant size (TPD coal)	250	200	6	3 PDU
Catalyst	none	Co/Mo	Supported or dispersed	HTI developed dispersed Fe cat (GelCat)
Other characteristics	External Rec solvent hydrogenation Co/Mo cat 700F/1600psi	Addition & withdrawal of catalyst		In-line hydrotreater

Summary of Representative DCL Process Yields

source: Consol Energy and Mitretek Systems July 2001

PROCESS	EDS	H-COAL	CC-ITSL	CMSL
	Yields (weight % MAF coal)			
Heterogases	17.4	11.3	15.2	15.2
C1-C4 gases	19.0	12.8	5.4	11.4
Naphtha (IBP-350 °F)	22.8	22.9	14.5	20.7
Middle distillate (350-650 °F)	17.0	20.0	21.7	39.1
Gas oil (650 °F+)	4.4	7.6	29.6	12.5
Total liquids	44.2	50.5	65.8	72.3
Hydrogen consumption	5.9	6.0	6.0	7.5
Hydrogen efficiency (lb Distillate/lb H_2 consumed)	7.5	8.4	11.0	9.7

More Recent Developments for DCL

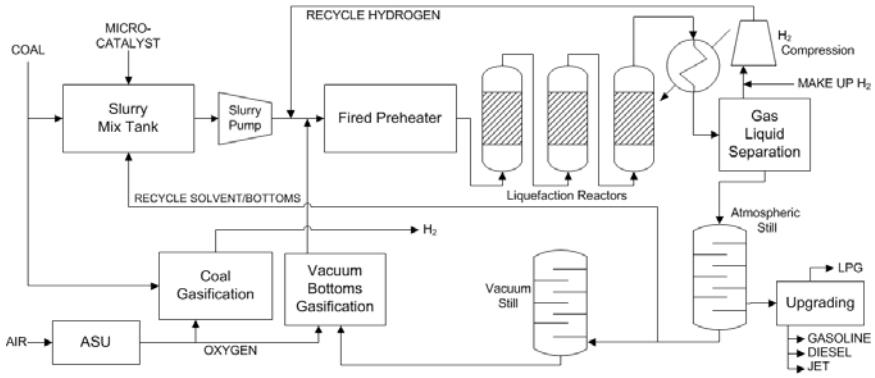
- Shenhua
- Accelergy

Shenhua DCL Plant in China

- Only operating commercial DCL plant worldwide
- Commissioned in 2008 and located in Erdos City, Inner Mongolia
- First DCL train produces ~20,000 BPD of LPG, naphtha, and diesel from 6,000 TPD of coal. Two more trains will be brought on line.
- Based on H-Oil/H-Coal ebullated bed reactor technology developed by HRI now licensed by Axens. H_2 production uses Shell gasification.
- Recycle solvent is hydrotreated in H-Oil reactor
- Shenhua developed an active disposable micro iron catalyst for initial coal dissolution
- Ebullated bed catalysts are supported
- Recently FT unit added – see Hybrid Plant Concept

Accelergy MCL Simple BFD

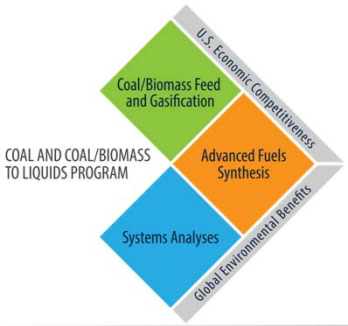
Source: Accelergy Permission granted



Accelergy MCL

Chemical Species In Accelergy's MCL Fuel Products

	DIESEL %	JET %	GASOLINE %
AROMATICS	2	0	0
NAPHTHENES	90	89	86
PARAFFINS	8	11	14



Chronology of Coal Liquefaction Technology Developments – Indirect Liquefaction

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Early Development of ICL (1902-1950)

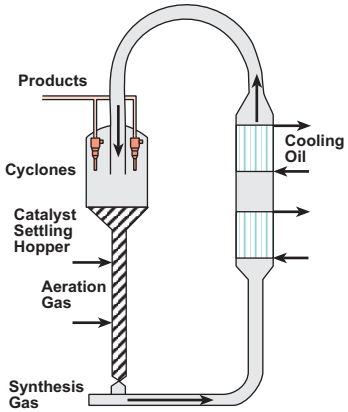
YEAR	EVENT/PROCESS
1902	Sabatier and Senderens hydrogenated CO over Ni to produce methanol
1913	BASF awarded patent to produce hydrocarbons and oxygenates using Co to hydrogenate CO
1923	Franz Fischer and Hans Tropsch hydrogenated CO using Fe catalysts at 100 atmospheres and 750F. They called the product “synthol”
1936	Four German FT plants started producing 200,000 TPY of hydrocarbons using a Co catalyst
1939-1944	German R&D to perfect Fe catalysts and fixed and slurry bed reactors for FT synthesis. By 1944 nine FT plants were operating in Germany producing 700,000 TPY
1947-1950	Ruhrchemie and Lurgi formed Arbeitsgemeinschaft (ARGE) and developed the tubular fixed bed reactor using precipitated alkaline Fe catalyst for high wax yields

Developmental History of ICL (1950-present)

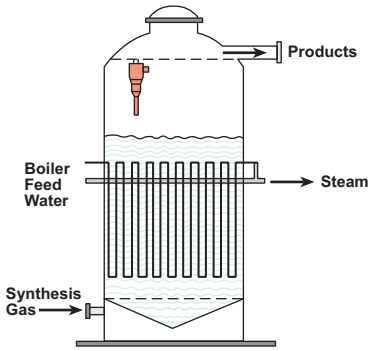
YEAR	EVENT/PROCESS
1950	Hydrocarbon Research (Trenton NJ) developed a fixed fluid bed reactor to produce hydrocarbons from natural gas (Carthage Hydrocol) located in Brownsville Texas
1953	Koelbel and Ackerman at Rheinpreussen, Germany operated a 10 TPD pilot scale slurry phase bubble column FT reactor with precipitated Fe catalyst
1955	Sasol I plant commissioned in South Africa. This plant used ARGE reactors and circulating entrained flow reactors developed by M.W. Kellogg. The Kellogg reactors did not function well until 1960 after Sasol modifications. The circulating reactors were called Synthol.
1975	Sasol built a larger plant at Secunda South Africa (Sasol II) that came on line in 1980.
1979	Sasol decided to construct Sasol III at Secunda, a mirror image of Sasol II
	Since then FT synthesis has been improved through GTL. Sasol built the Oryx plant and Shell built Pearl both at Ras Laffan, Qatar. Also Velocys has developed the micro-channel FT reactor for small plant applications

High Temperature FT Reactors (250-350C)

Source: NETL/CTL Seminar 2006



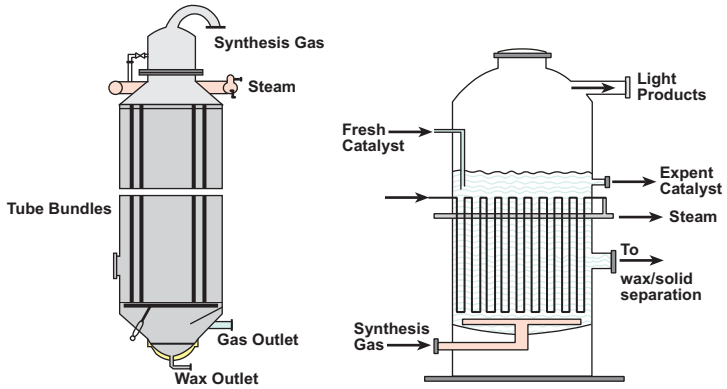
SYNTHOL REACTOR



SASOL ADVANCED FLUIDIZED REACTOR

Low Temperature FT Reactors (180-240C)

Source: NETL/CTL Seminar 2006



ARGE REACTOR

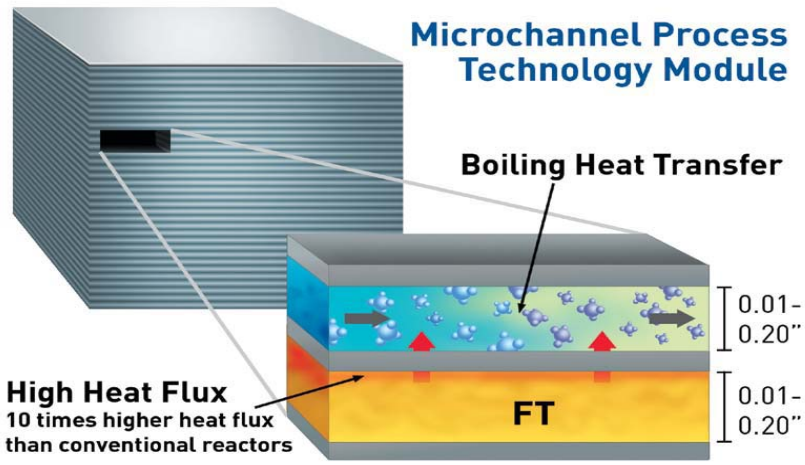
SLURRY BED REACTOR (SSBP)

More Recent Developments for ICL FT Reactor Technology

Velocys Micro-Channel FT Reactor System

Velocys Micro-Channel FT Reactor

Source: Velocys permission granted



Velocys

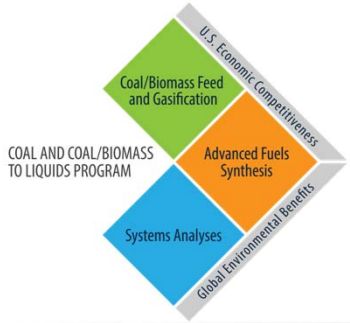
Source: Velocys permission granted

- **Principles of design and operation**
  - High activity proprietary Co-based particulate catalyst in small channels results in very high volumetric productivity
  - High catalyst volume fraction (~50%)
  - Syngas down flow, products exit bottom
  - Cross-flow coolant water/steam generation
  - Heat removal by steam generation
  - Velocys microchannel technology combines the best of fixed and slurry bubble column reactor performance with very few of the negatives Isothermal performance without catalyst/wax separation issues
  - High on-stream factor without complicated and expensive regeneration unit
  - High upset and shutdown robustness
  - Very low recycle to fresh feed ratio requirements while achieving high conversion
  - Velocys microchannel technology uniquely suitable for plants <15,000 BPD
  - High per pass syngas conversions

Velocys GTL Projects

Source: Velocys permission granted

- 6 BPD demonstration plant for Petrobas, Brazil
- Selected as FT technology provider for a 1,000 BPD capacity plant at Calumet's Karns City site in Pennsylvania. Calumet proposes to convert Marcellus gas into specialty products such as lubricants, solvents and waxes
- Selected as FT provider for Pinto Energy's proposed 2,800 BPD plant in Ashtabula OH to produce solvents, lubricants, waxes and transportation fuels from Marcellus and Utica shale gas



Coal Liquefaction – Product Refining

Topics:

1) Petroleum Refining
2) Transportation Fuel Specifications
3) Characterization of Raw Coal Liquids
4) Upgrading Options for Coal Liquids

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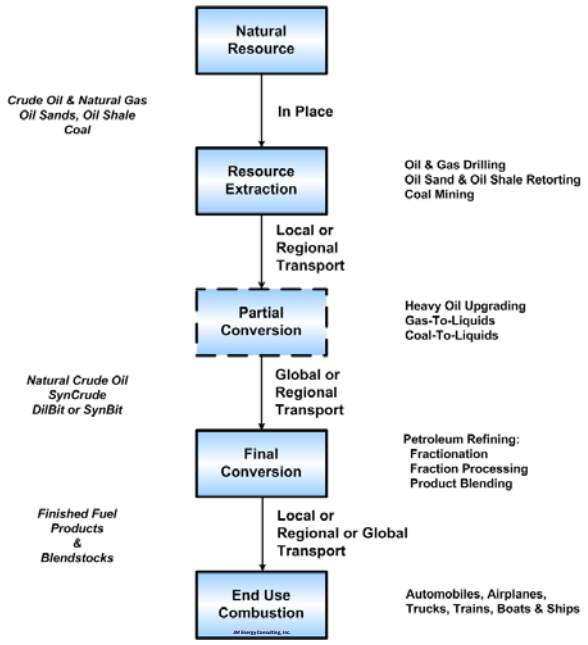
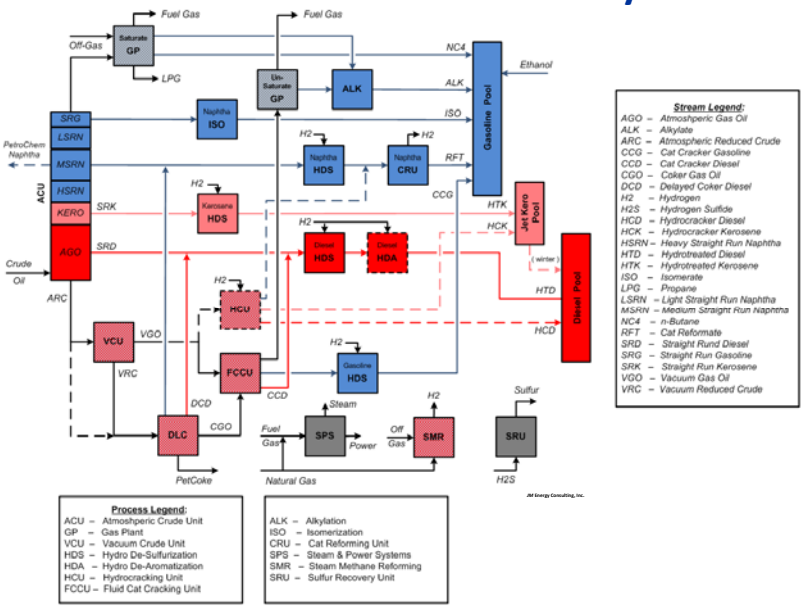
Transportation Fuel Supply Chain



Notional U.S. Petroleum Refinery BFD

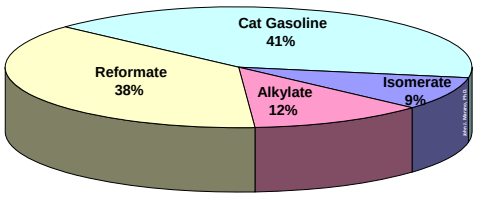


Petroleum Refining

In-A-Nutshell

Crude Distillation Unit (ACU+VCU)	***crude oil fractionation***
Delayed Coking Unit (DLC)	***incremental product volume***
Fluid Catalytic Cracking Unit (FCCU)	***gasoline-making machine***
Hydrocracking Unit (HCU)	***gasoline-jet-diesel fuel switch***
Hydrotreating Units (HDS+HDA)	***"contaminant removal"***
Catalytic Reforming Unit (CRU)	***gasoline "octane valve"***
Isomerization Unit (ISO)	***octane improvement***
Alkylation Unit (ALK)	***gasoline synthesis from offgas***
Steam Methane Reforming Unit (SMR)	***hydrogen production***

Gasoline



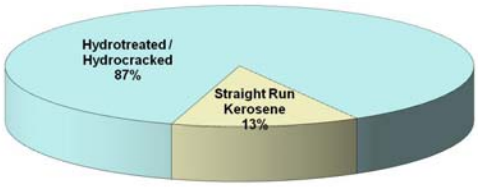
Typical U.S. Conventional Gasoline Blend
"RBOB & CBOB"

U.S. Gasoline is boutique fuel

- >10 grades nationally
- Specs dependent on more than forty fuel-related props
- Blending with 10% bioethanol now the norm (at "blendwall")

- **Blended to meet performance**
  - has and continues to evolve to meet environmental requirements
- **Critical specifications:**
  - Octane Rating (R+M)/2 — best source reformate & alkylate
  - Vapor Pressure (RVP) — limited by n-butane & isomerate
  - Sulfur Content (ppm levels) — dominant source cat gasoline
  - VOCs & Toxicity
    - Lower Benzene — dominant source reformate
    - Lower Aromatics — dominant sources reformate & cat gasoline
    - Lower Reactive Olefins — dominant source cat gasoline

Jet Fuel



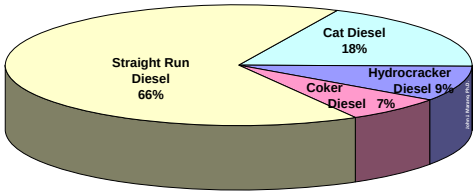
Typical U.S. Jet Fuel Blend

U.S. KeroJet Fuel

- Blend of kerosene & other light distillates
- Only premium transportation fuel that is not low sulfur
- Currently 1-2% of global demand supplied by renewable jet fuel (as blend)

- **Blended to meet performance**
  - Average sulfur content declining due to lower sulfur requirements for gasoline & diesel fuel
- **Specifications vary for commercial (Jet A & Jet A-1) and military (USN JP-5 & USAF JP-8) jet fuels**
- **Critical specifications:**
  - Aromatics Content — typically higher in hydrocrackate
  - Flash Point — related to distillation cut points
  - Density — typically higher for more aromatic fuels

Diesel Fuel



Typical U.S. Diesel Blend

U.S. Diesel Fuel

- Blend of middle & light distillates
- All blending components require hydrotreatment
- Currently >2% of U.S. demand supplied by biodiesel & renewable diesel (as blend)

- **Blended to meet performance**
  - has and continues to evolve to meet environmental requirements
- **Critical specifications:**
  - Cetane Rating — best source hydrocrackate & straight run
  - Cloud or Pour Point — problem w/severely hydroprocessed blendstocks
  - Sulfur Content (ppm levels) — highest levels in coker & cat diesels
  - Lower Aromatics (in CA) — dominant sources coker & cat diesels
    - Lower Polyaromatic Hydrocarbons (PAH) — dominant source coker & cat diesels
  - Lubricity & Seal Swell — problem w/severely hydroprocessed blendstocks

Relative Value of Fuel Blendstocks

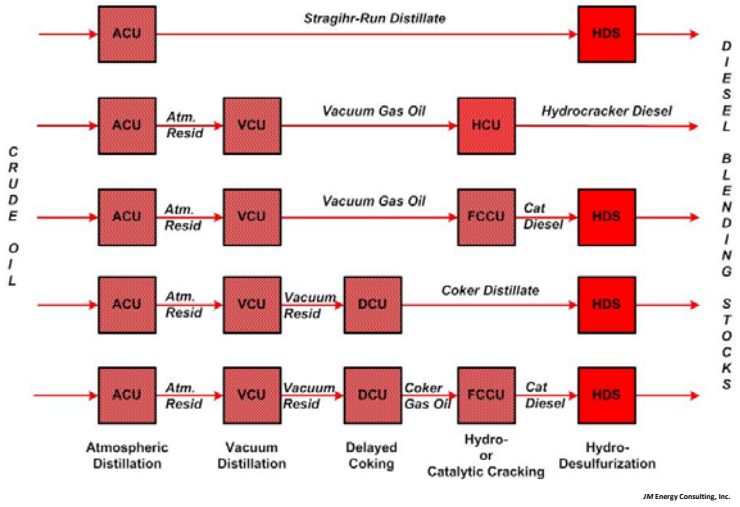
decreasing value

Gasolines		Distillate Fuels
Bioethanol*	BLENDSTOCKS	Hydrocracker Distillate
High-Octane Reformate		Hydrotreated Distillate (high-severity operation)
Alkylate		➢ Ultra-Low-Sulfur Diesel Fuel
➢ Premium-Grade Gasoline		Hydrotreated Distillate (low-severity operation)
Cat Gasoline		➢ High-Sulfur Distillate Fuel Oil (Home Heating Oil)
Low-Octane Rerformate		
➢ Regular-Grade Gasoline	FEEDSTOCKS	
Isomerate		
Hydrocracker Naphtha		Straight-Run Distillate
Straight-Run Naphtha		Cat Cracker Distillate
Coker Naphtha		Coker Distillate

*bioethanol blending mandated—price set by market conditions

Refinery Pathways for Producing Diesel

A Different View



Distillates from Benchmark Crude Oil

High Sulfur Light (HL)
1.8 wt % 33.4°API

Product	Kerosene		Light Gas Oil					Diesel
Process	Straight Run	Hydro-cracking	Straight Run	Hydro-cracking	Cat-Cracking	Cat Cracking	Delayed Coking	Blend
Feed	Crude Cut	Vacuum Gas Oil	Crude Cut	Vacuum Gas Oil	Vacuum Gas Oil	Coker Gas Oil	Vacuum Resid	-
Yield on Crude Oil	10.4%	10.5%	19.1%	10.8%	4.9%	6.2%	3.3%	33.51%
Cetane Number	48	50	52	60	35	35	25	44
Specific Gravity	0.7973	0.8260	0.8437	0.8600	0.9304	0.9675	0.8753	0.8826
Wt% Carbon	86.2%	86.6%	86.7%	86.9%	88.0%	88.5%	87.2%	87.3%
LHV MJ/kg	43.2	42.8	42.8	42.5	41.7	41.3	42.3	42.3

JM Energy Consulting, Inc.

All streams sufficiently hydrotreated to make ULSD blend

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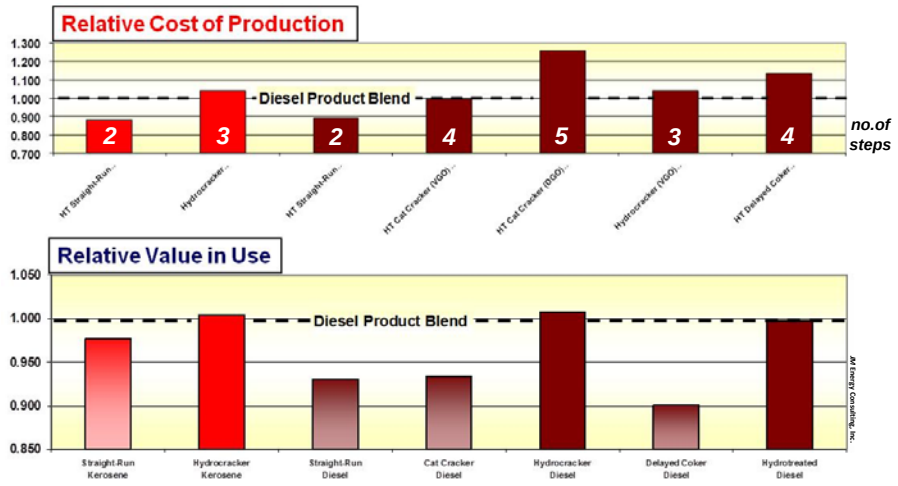
Refinery Distillate Streams

Relative Cost vs. Relative Value



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Trends for Transportation Fuel Regulation

On The Horizon

- **Tier 3 Rule for gasoline by 2017**
  - to address Mobil Source Air Toxics (MACTs)
    - from 30 to 10 ppm sulfur
    - potentially lower benzene, aromatics and olefins
    - emissions test fuel consisting of 15% ethanol
- **MARPOL mandated staged reduction in sulfur content of maritime fuels to less than 0.5% by 2020**
    - fuel switching distillate FO for residual FO
    - on-board sulfur removal systems
    - LNG … other options
- **Continued biofuels mandates but with changes**
    - bioethanol vs. biobutanol vs. drop-in biofuels
    - bioethanol in what blend: E10 vs. E15 vs. E20 vs…
    - biodiesel vs. renewable diesel
    - biojet & bio fuel oils

Transportation Fuel Regulations

Long Term Trends

- **Environment and Human Health & Safety driven**
  - ***Precautionary Principle*** holds that when a new technology carries suspected harm, scientific uncertainty about the scope of that harm should not necessarily prevent precautionary action; differs from risk assessment
- **Multiplication and fragmentation of regulations and jurisdictions**
  - averaging and geographic variation
- **Convergence of standards among different fuels used for same general application**
  - couple fuel to vehicle technology
  - all fuels will come under careful scrutiny (e.g., Jet, RR diesel)
  - units such as per passenger-miles driven

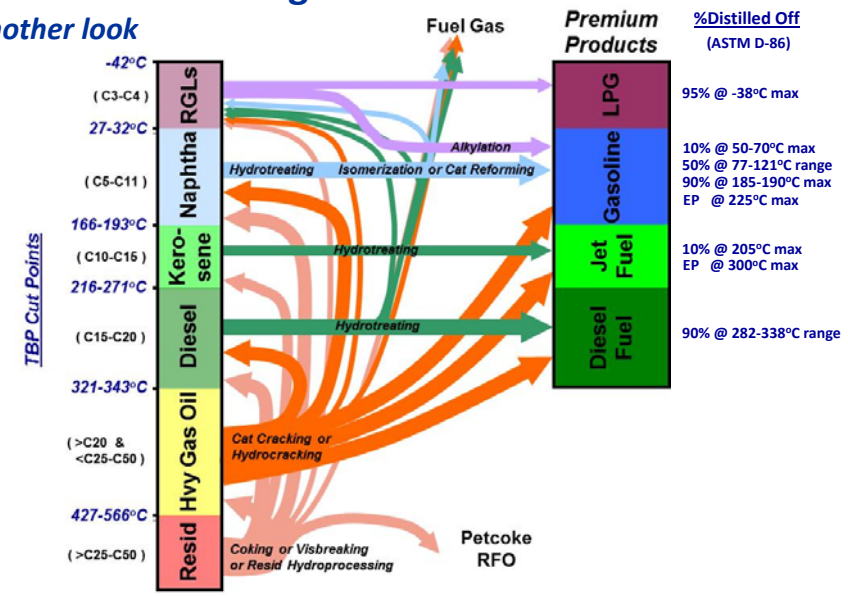
Transportation Fuel Regulations

Long Term Trends

- **Fuel Life-Cycle requirements to address:**
  - Sustainability (not just renewability)
  - Life-Cycle GHG Emissions
  - Other LC emissions
  - Fuel Economy (e.g., PNGV 80 mpg car)
  - Domestic vs. Imported Energy
  - Multiplicity of Alternative Fuels
  - Predictive Models vs. Product Blending Specs
- **Reduction Allowance & Credit driven:**
  - Emissions of X must be xx% lower in year *y* than they where in year *z*
  - Emission reductions must be in addition to what would occur otherwise in order to be credited toward emission allowance
  - Emission credits banking and trading
  - Requires enterprise-wide data reporting system to establish baselines, track reductions and validate credits

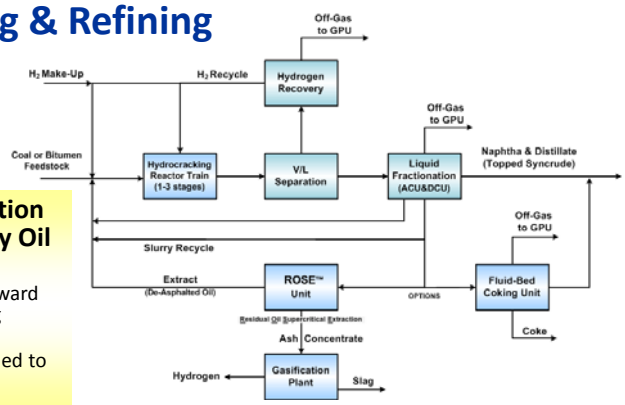
Petroleum Refining

another look



John J. Marano "Options for Upgrading & Refining Fischer-Tropsch Liquids"
2nd International Freiberg Conference on IGCC & XtL Technologies Freiberg, GermanyMay 8-12, 2007

DCL Upgrading & Refining



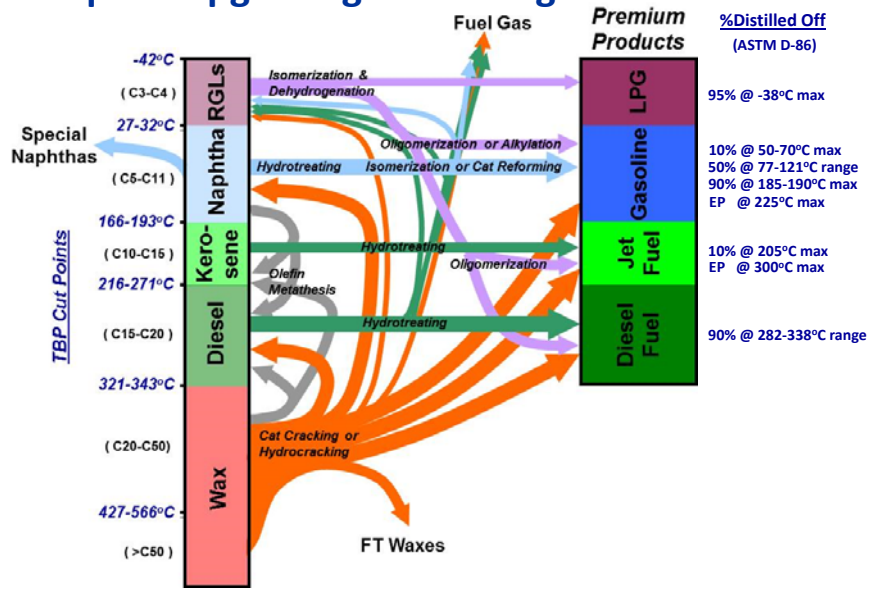
Direct Coal Liquefaction vary similar to Heavy Oil Upgrading

- Distillation skewed toward heavier, higher boiling fractions
- Heavy tail often recycled to extinction

Same refining options as petroleum—but different:

- DCL more aromatic as well as polyaromatic
- Higher nitrogen, oxygen and metals content
- Nitrogen & sulfur compounds more refractive
- Hydroprocessing operations more severe
  - higher pressure & temperature
  - custom catalyst formulations
  - greater hydrogen consumption per barrel

FT Liquids Upgrading & Refining



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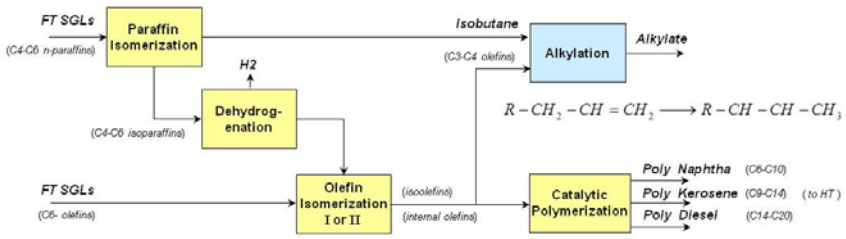
FT Light-Ends Work-Up



$$R-CH_2-CH=CH_2 \longrightarrow R-CH-CH-CH_3$$

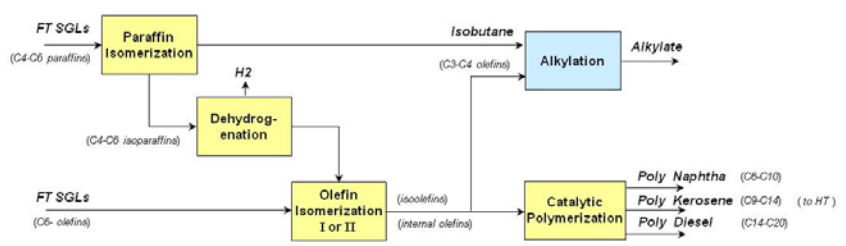
- **Paraffin Isomerization** $\quad R-CH_2-CH_2-CH_3 \xrightarrow[\text{acidic support}]{\text{NM on}} R-\underset{\underset{CH_3}{|}}{CH}-CH_3 + heat$
- **Dehyrogenation** $\quad R-CH_2-CH_2-R' + heat \xrightarrow[\text{acidic support}]{\text{NM on}} R-CH=CH-R' + H_2$
- **Olefin Isomerization I** $\quad R-CH_2-CH=CH_2 \xrightarrow{\text{Zeolite}} R-CH=CH-CH_3$
- **Olefin Isomerization II** $\quad R-CH=CH-CH_3 \xrightarrow{\text{Zeolite}} R-\underset{\underset{CH_3}{|}}{C}=CH_2 + heat$

NM – Noble Metal

Not typically found in pet refinery

FT Light-Ends Work-Up

(continued)



- **Alkylation**
  isobutylene alkylation

$$CH_3-\overset{\overset{CH_3}{|}}{C}=CH_2 + CH_3-\overset{\overset{CH_3}{|}}{C}H-CH_3 \xrightarrow[\text{or SA}]{\text{HF, SFA}} CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_2-\overset{\overset{CH_3}{|}}{C}H-CH_3 + heat$$

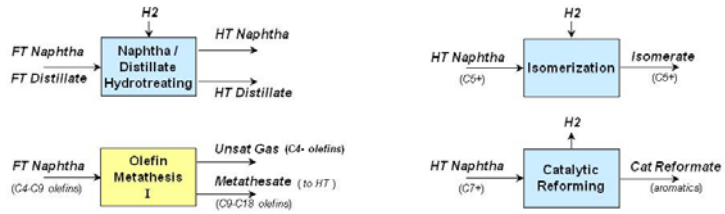
- **Catalytic Polymerization**
  isobutylene dimerization

$$2\,CH_3-\overset{\overset{CH_3}{|}}{C}=CH_2 \xrightarrow{\text{SPA}} CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_2-\overset{\overset{CH_3}{|}}{C}=CH_2 + heat$$

HFA – Hydrofluoric Acid, SFA – Sulfuric Acid, SA – Solid Acid, SPA – Solid Phosphoric Acid

Not typically found in pet refinery

FT Naphtha & Distillates Work-Up



- **Hydrotreating**
  olefin saturation

$$R-CH_1=CH_2+H_2 \xrightarrow[\text{acidic support}]{\text{BM on}} R-CH_2-CH_3+heat$$

NM – Noble Metal
BM – Base Metal

- **Isomerization**

$$R-CH_2-CH_2-CH_3 \xrightarrow[\text{acidic support}]{\text{NM on}} R-\underset{\underset{CH_3}{|}}{CH}-CH_3+heat$$

- **Catalytic Reforming**

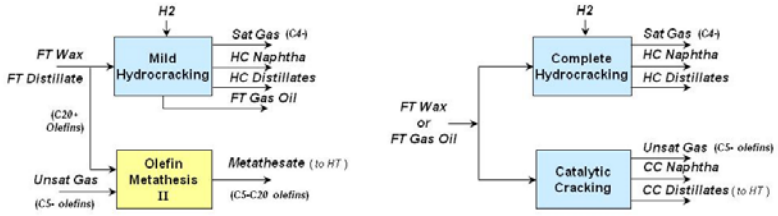
$$R-C_6H_{13}+heat \xrightarrow[\text{acidic support}]{\text{NM on}} 4H_2+R-C_6H_5\,[aromatic]$$

- **Olefin Metathesis I**

$$\underset{\underset{R_3}{|}}{R_1-CH}=\underset{\underset{R_4}{|}}{CH}-R_2+\underset{\underset{R_7}{|}}{R_5-CH}=\underset{\underset{R_8}{|}}{CH}-R_6 \xleftrightarrow{\text{W or Mo w/Pt}} \underset{\underset{R_5}{|}}{R_1-CH}=\underset{\underset{R_6}{|}}{CH}-R_2+\underset{\underset{R_7}{|}}{R_3-CH}=\underset{\underset{R_8}{|}}{CH}-R_4$$

4<CN<9 4<CN<9 9<CN<18 CN<4

FT Wax Work-Up



- **Hydrocracking**
  with olefin saturation

$$R-CH_2-CH=CH_2+2H_2 \xrightarrow[\text{acidic support}]{\text{NM or BM on}} RH+CH_3-CH_2-CH_3+heat$$

- **Hydrocracking**
  with isomerization

$$R'\text{–}CH_2-CH_2-CH_2-R''+H_2 \longrightarrow R'\text{–}\underset{\underset{CH_3}{|}}{CH}-CH_3+R''H+heat$$

- **Catalytic Cracking**

$$R'H-CH_2-CH_2-R''H+heat \xrightarrow{\text{Zeolite}} R'=CH_2+R''=CH_2+H_2$$

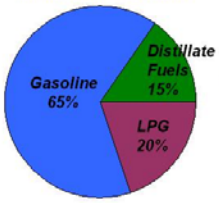
- **Olefin Metathesis II**

$$\underset{\underset{R_3}{|}}{R_1-CH}=\underset{\underset{R_4}{|}}{CH}-R_2+\underset{\underset{R_7}{|}}{R_5-CH}=\underset{\underset{R_8}{|}}{CH}-R_6 \xleftrightarrow{\text{W or Mo w/Pt}} \underset{\underset{R_5}{|}}{R_1-CH}=\underset{\underset{R_6}{|}}{CH}-R_2+\underset{\underset{R_7}{|}}{R_3-CH}=\underset{\underset{R_8}{|}}{CH}-R_4$$

CN<5 CN>20 5<CN<20 5<CN<20

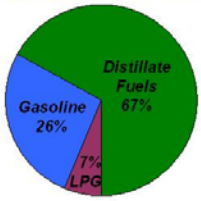
Estimated Product Distributions from Upgrading & Refining FTLs

Maximum Gasoline



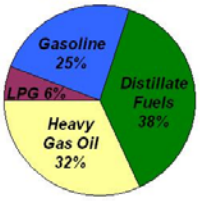
G/D = 4.2

Maximum Distillate Fuel



G/D = 0.4

Minimum Upgrading for Transport



The Current fuels market in U.S.
G/D = 0.91

Upgrading flexibility leads to higher utility for FT syncrude within petroleum refinery and thus higher premium

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Comparison of Diesel Alternatives

	Energy Density MJ/l (net)	Cetane No. -	Cloud Point °C	Pour Point °C	Viscosity 40°C mm²/s	Lubricity µm
U.S. Diesel						
specification	-	>40	-28-5	-	1.7-4.1	<520-560
typical ULSD	~36	42-53	-13	-24	2.5-3.5	450
Vegetable Oil						
as produced	~39	23-49	-4-13	-40- -7	27-54	500-1,500
hydro-processed	~34	>70	-10-20	-	2.0-4.0	570-680
biodiesel (FAME)	~34	45-65	-5-15	-	4.2-4.8	270-460
Biomass-Derived Pyrolysis Oil						
as produced (wet*)	~17	30-35*	-	<-9	13-80*	500-700
hydro-processed	~35	~45	-34	<-35	1.35**	-
Fischer-Tropsch Synthesis						
as produced (Fe)	~34	>70	>10	>0	1.2-3.5	-
hydro-processed	~34	>70	<-5	<-12	1.9-3.6	570-600

*15-30% H_2O *diluted *@ 50°C **@ 20°C

Relative Value of Fuel Blendstocks

- FTL equivalent
- MTG equivalent
- DCL equivalent

decreasing value

Gasolines				Distillate Fuels		
Bioethanol*			BLENDSTOCKS	Hydrocracker Distillate	+	
High-Octane Reformate	–	+		Hydrotreated Distillate (high-severity operation)	+	–
Alkylate	=	=		➢ Ultra-Low-Sulfur Diesel Fuel		
➢ Premium-Grade Gasoline				Hydrotreated Distillate (low-severity operation)		
Cat Gasoline	?	?	?	➢ High-Sulfur Distillate Fuel Oil (Home Heating Oil)		
Low-Octane Rerformate				Straight-Run Distillate	+	–
➢ Regular-Grade Gasoline				Cat Cracker Distillate	+	–
Isomerate	=	=	FEEDSTOCKS	Coker Distillate		=
Hydrocracker Naphtha	–					
Straight-Run Naphtha	–	+				
Coker Naphtha		=				

*bioethanol blending mandated—price set by market conditions

RD&D Challenges

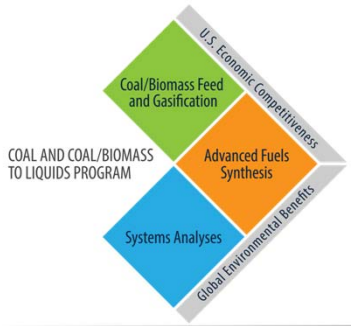
Direct Coal Liquefaction

- Deconstruct coal in more precise and efficient manner in order to:
  - reduce environmental challenges currently associated with DCLs & improve quality

Indirect Coal Liquefaction

- Reconstruct targeted fuels and chemicals from syngas more efficiently and in fewer steps in order to:
  - produce premium fuels and high-value co-product commodity & specialty chemicals

- Invent and apply new technologies to achieve lower costs and reduce effect of scale on capex
- Identify and co-process low-cost disadvantaged feedstocks such as:
  - waste coal, stranded petcoke, components of MSW, haz waste, agricultural residues



Comparative Economics of DCL and ICL

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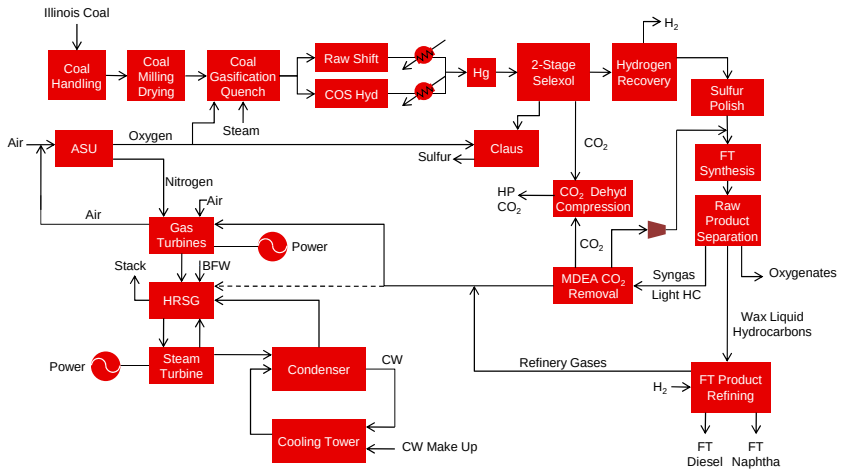
Economic Summary for DCL

- **Bechtel/Amoco TEA March 1993:**
  - Based on Wilsonville ITSL
  - Feed 29,000 TPD Illinois coal
  - Output 62,000 BPD
  - TPC $3,872 MM (1991$) FOAK
  - TPC $3,491 MM Nth plant
  - Estimated TPC in $2011 = $7,528 MM for FOAK
  - Estimated TPC in $2011 = $6,787 MM for Nth plant

Economic Summary for DCL (continued)

- **Mitretek TEA June 1986:**
  - Based on Wilsonville ITSL
  - feed 35,000 TPD Illinois coal
  - output 98,500 BPD
  - TPC $4,084 MM ($1981) FOAK
  - TPC $11,000 MM ($2011)
  - TPC $7,950 MM ($2011) equivalent output to Bechtel

Economic Summary for ICL
Baseline FT CTL Plant Configuration



Economic Summary for ICL

- **Noblis TEA May 2013:**
  - Based on conceptual design using Siemens gasification and low temperature slurry phase FT (Fe catalyst)
  - feed 22,500 TPD Illinois coal
  - output 50,000 BPD of naphtha and diesel
  - TOC $7,890 MM ($2011)

- **Caution: do not make too much of a comparison between DCL and ICL economics because of different product mix and value**

Coal Liquefaction – Climate Change Impacts & Drivers

Topics:
1) **Relative GHG Emissions**
2) **Mitigation of GHG Emissions for CtL**
3) **Renewable & Low-Carbon Fuel Standards**
4) **DOD Alternative Fuels Initiatives**

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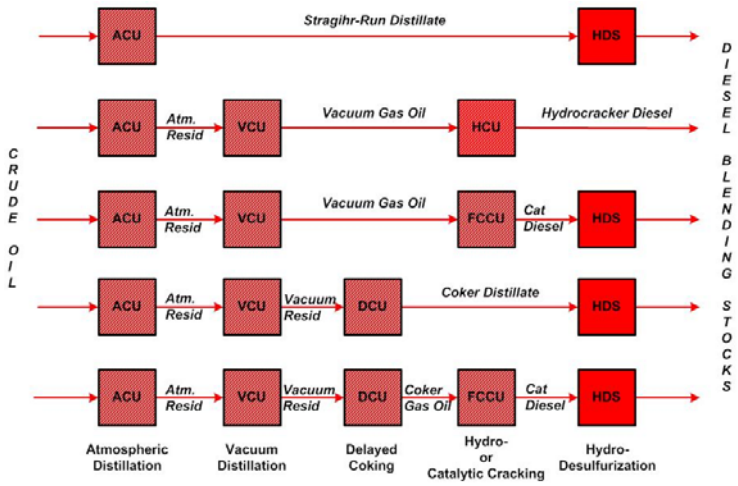
Refinery Pathways for Producing Diesel

A Different View



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Distillates from Benchmark Crude Oil

High Sulfur Light (HL)
1.8 wt % 33.4°API

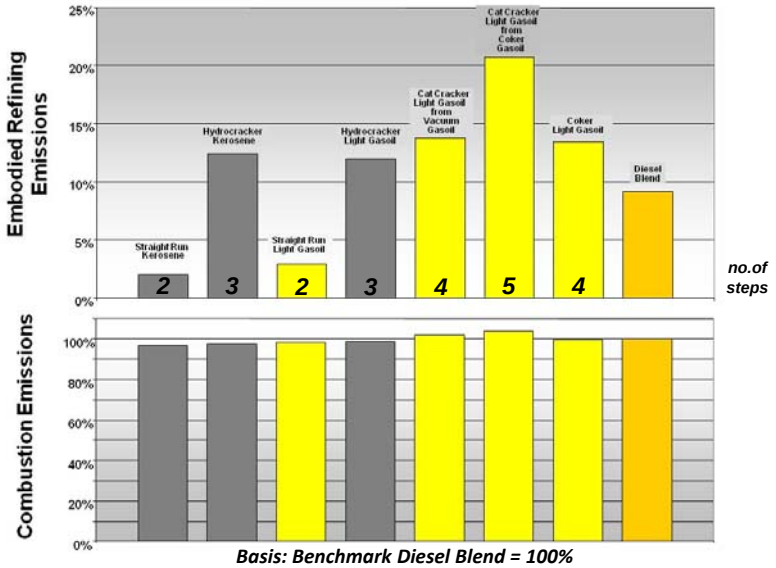
Product	Kerosene		Light Gas Oil					Diesel
Process	Straight Run	Hydro-cracking	Straight Run	Hydro-cracking	Cat-Cracking	Cat Cracking	Delayed Coking	Blend
Feed	Crude Cut	Vacuum Gas Oil	Crude Cut	Vacuum Gas Oil	Vacuum Gas Oil	Coker Gas Oil	Vacuum Resid	-
Yield on Crude Oil	10.4%	10.5%	19.1%	10.8%	4.9%	6.2%	3.3%	33.51%
Cetane Number	48	50	52	60	35	35	25	44
Specific Gravity	0.7973	0.8260	0.8437	0.8600	0.9304	0.9675	0.8753	0.8826
Wt% Carbon	86.2%	86.6%	86.7%	86.9%	88.0%	88.5%	87.2%	87.3%
LHV MJ/kg	43.2	42.8	42.8	42.5	41.7	41.3	42.3	42.3

JM Energy Consulting, Inc.

All streams sufficiently hydrotreated to make ULSD blend

Refinery Distillate Streams

Relative GHG Emissions



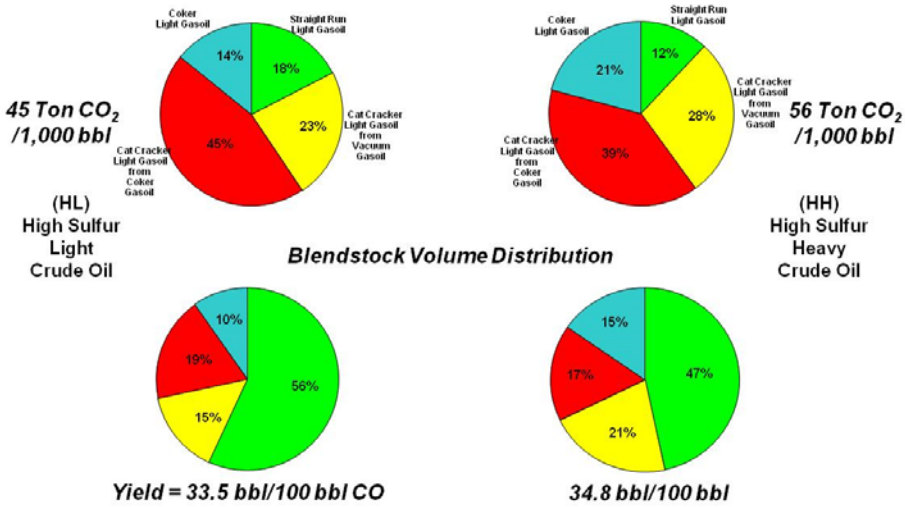
Basis: Benchmark Diesel Blend = 100%

81 Marano, J.J., "GHG Profiles for Refining & Upgrading Fossil Distillate Fuels," *9th International Conference on Greenhouse Gas Control Technologies*, Washington, DC, November 16-20, 2008.

GHG Profile for Petroleum-Derived Diesel Fuel

Effect of Crude Oil Quality

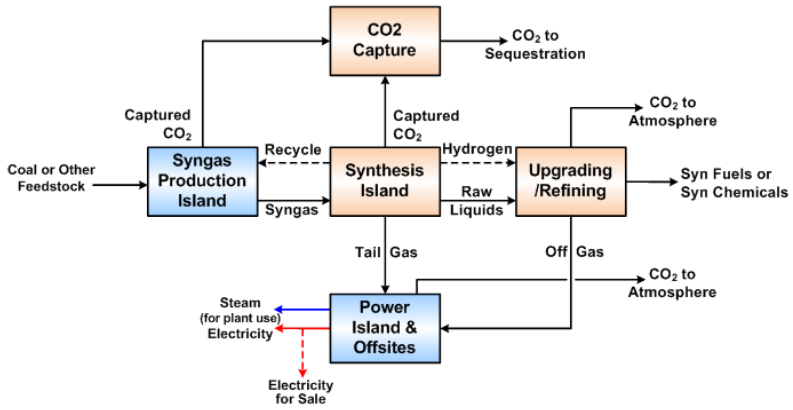
Embodied Refining GHG Emissions



Yield = 33.5 bbl/100 bbl CO *34.8 bbl/100 bbl*

82 Marano, J.J., "GHG Profiles for Refining & Upgrading Fossil Distillate Fuels," *9th International Conference on Greenhouse Gas Control Technologies*, Washington, DC, November 16-20, 2008

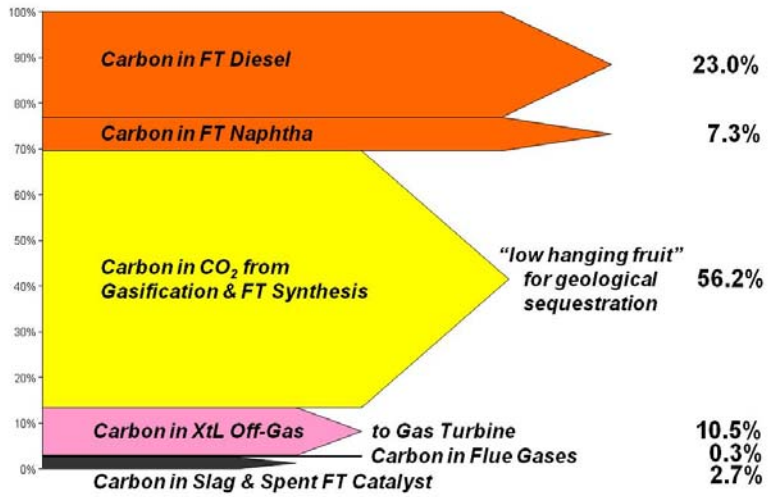
XtL Block Flow Diagram



Carbon Distribution

Rentech Natchez Co-Production XtL Plant

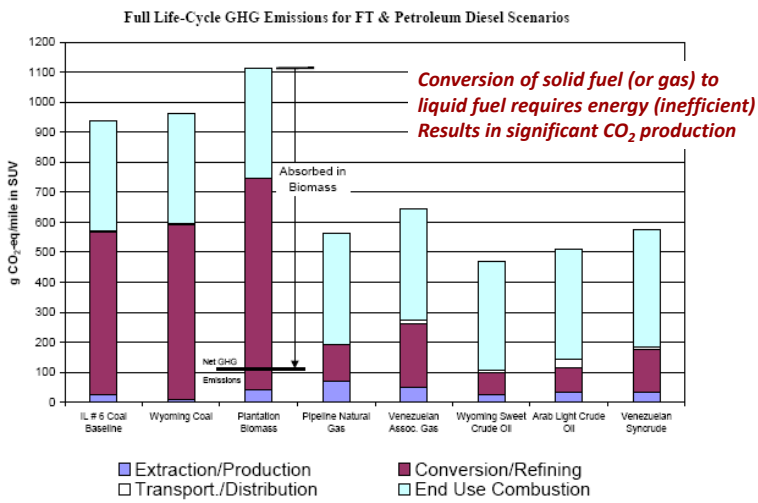
PetCoke Feedstock



R. Freerks & J. Marano "GHG Life-Cycle Inventory - Rentech Strategic Fuels & Chemicals Complex"
Seventh Annual Conference on Carbon Capture & Sequestration Pittsburgh PA May 5-8, 2008

Life-Cycle Greenhouse Gas Emissions

Comparison of Various Liquid-Fuel Pathways

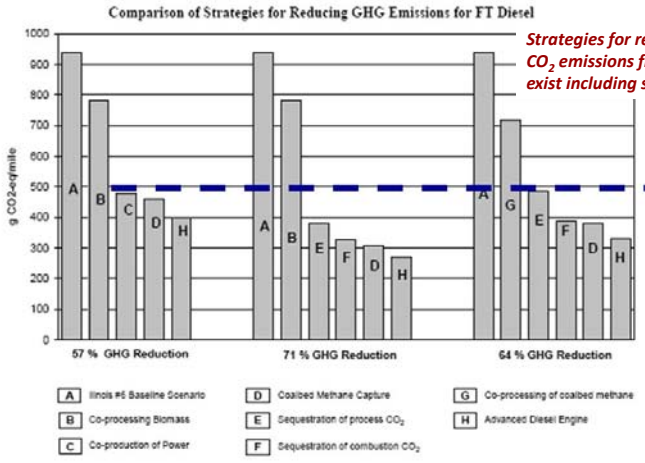


Conversion of solid fuel (or gas) to liquid fuel requires energy (inefficient) Results in significant CO_2 production

85 Marano & Ciferno *Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels,* NETL Report, June 2001

Life-Cycle Greenhouse Gas Emissions

Comparison of Several CtL Mitigation Scenarios



Strategies for reducing CO_2 emissions from CTL exist including sequestration

Imported ME Crude Oil

86 Marano & Ciferno *Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels,* NETL Report, June 2001

What About Direct Coal Liquefaction

- **Theoretical efficiency of DCL can be high…roughly 70-75%**
  - Compared to 60-65% for ICL
- **Therefore reasonable to assume GHG emissions for DCL could be 5-15% lower than for ICL**
  - This needs further examination to accurately quantify
- **DCL is hydrogen addition process**
  - Therefore primary GHG reduction option will be CO_2 capture from hydrogen production step either:
    - Ash Concentrate Gasification
    - Steam Methane Reforming

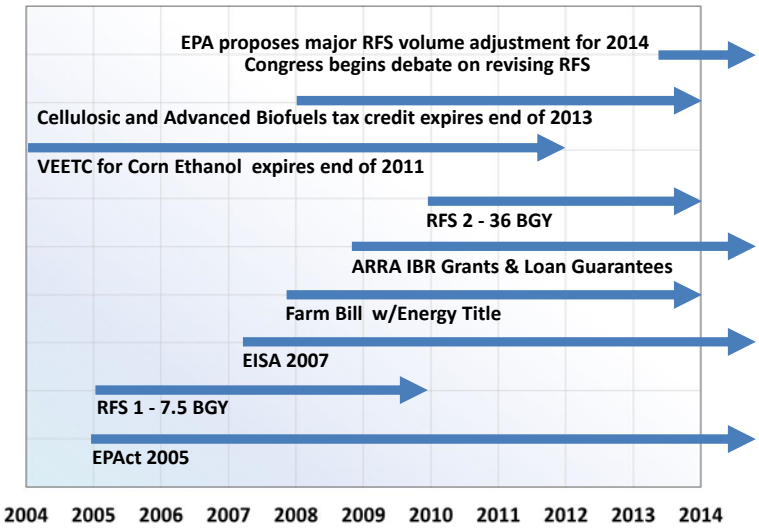
U.S. DOE NETL LCA Group

- **More extensive and up-to-date life-cycle analyses and related assessments can be found at:**

  http://www.netl.doe.gov/energy-analyses/refshelf/PubProductList.aspx

Federal Support for AltFuels

Executive & Legislative



Renewable & Low-Carbon Fuel Standards

- **Federal RFS established by EPAct legislation in 2005 with requirements expanded by EISA in 2007**
  - Establishes blending mandates for various types of biofuels based on life-cycle GHG emissions profiles for biofuel alternatives relative to petroleum products
  - Requirements increase from year to year through 2022
  - Program employs RIN trading program between biofuel producers and refiners & marketers
- **State of CA has promulgated its own LCFS**
  - Similar to RFS but more demanding
  - Considers indirect land-use changes (ILUC) on fuel LCA
  - Requirements increase from year to year through 2020

2014 RFS Requirements

	Baseline Reduction	Billion Gallons Ethanol Equivalent			
Categories	**ΔGHG**	**2013* (production)**	**2014 (statutory)**	**2014 (EPA proposal)**	**2022 (statutory)**
Other Renewable Fuel	-20%	14	14.400	13.010	15.0
Biomass-based Diesel	-50%	1.7	1.000	1.280	>1.0
Advanced Biofuel	-50%	-	3.750	2.200	4.0
Cellulosic Biofuel	-60%	0.007	1.750	0.017	16.0
Total Renewable Fuel	-	-	15.210	18.150	36.0

***estimated**

Examples:

- **Renewable Fuel** – Corn Ethanol/Butanol from efficient natural-gas fired facility
- **Biomass-derived Diesel** – Soy-Based Biodiesel; Biodiesel from Waste Grease/Oils/Fats; Diesel from Algal Oils
- **Advanced Biofuel** – Ethanol/Butanol from Cane, Sorgham; Unobligated Biomass-derived Diesel can be used to meet this category
- **Cellulosic Biofuel** – Cellulosic Ethanol/Butanol; BtL; Upgraded Biomass Pyrolysis Oils

In addition to examples above, other fuels such as bio jet fuel, locomotive diesel fuel and home heating oil can qualify as renewable fuel or advanced biofuel

U.S. DOD Alternative Fuels Initiatives

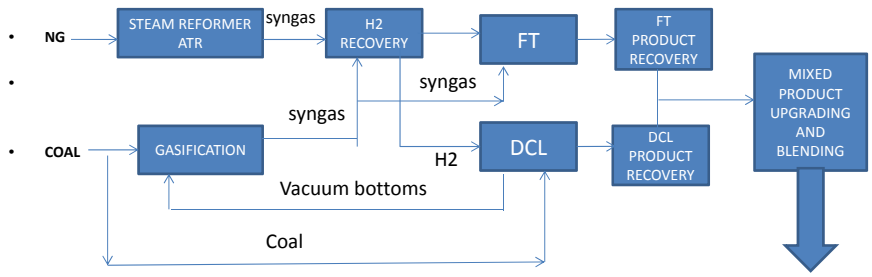
- **Drivers both national security & ultimately reduced carbon foot print**
- **Funding mechanism rests on Truman-era Defense Production Act Title III**
  - enables DOD to support RD&D
  - 2020 goal of replacing 50% of DOD energy consumption with cost-competitive alternatives
- **U.S. Navy taking lead followed by Air Force and Army**
  - procurement of 11 million gallons of fuel for Great Green Fleet RIMPAC demonstration in 2012
- **USN / USDA "Farm-to-Fleet" Program**
  - procure $4/gal drop-in-fuels (subsidized by USDA Commodity Credit Corporation)
    - JP-5 jet fuel & marine diesel fuel F-76
    - to be used to sail Great Green Fleet by 2016
    - requiring 77 million gallons of drop-in fuel per annum
  - 10-50% biofuels based (more is better)
    - must meet EISA 526 – same or better GHG emissions as petroleum fuels
  - $45 million RFP for initial fuel contracts – awarded spring 2014 with delivery by mid-year 2015

RD&D Challenges

- **Fossil-derived alternative fuels will ultimately be judged relative to targets established by RFS & LCFS**
  - to meet 2050 climate change goals, emissions from transportation will need to be much lower than today
- **Much more innovative liquefaction technologies will be required for coal-derived liquids to enter mix:**
  - Step changes in efficiency
  - CCUS beyond just EOR
  - Oxycombustion
  - Biomass co-feed
  - Hydrogen from renewables

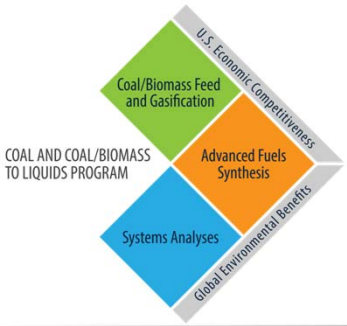
Coal Liquefaction – Hybrid CTL Concept

Hybrid Plant Concept Using Coal & Natural Gas



Generic Comparison of DCL and ICL Product Mix

	Direct	Indirect
Distillable product mix	65% diesel 35% naphtha	70% diesel 30% naphtha
Diesel cetane	42-47	70-75
Diesel sulfur	<5 ppm	<1 ppm
Diesel aromatics	5-20%	<2%
Diesel specific gravity	0.865	0.780
Naphtha octane (RON)	>100	45-60
Naphtha sulfur	<0.5 ppm	Nil
Naphtha aromatics	5-10%	<1%
Naphtha specific gravity	0.764	0.673



Alternative Coal Liquefaction Approaches

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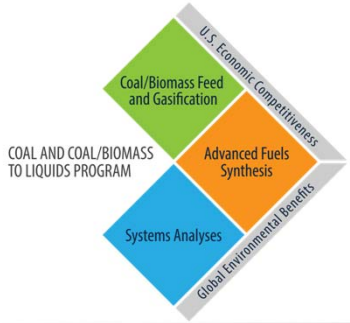
Other Approaches to Coal Liquefaction DCL

- Pyrolysis or Mild Gasification
- Hydropyrolysis
- Coal/Oil Co-processing
- Coal/Biomass Co-processing
- Solvent extraction (sub and supercritical)

Other Approaches to Coal Liquefaction
ICL

Coal → Syngas → Methanol → MTG → Gasoline

Methanol → MOGD → olefins, gasoline, diesel



Barriers and Requirements for Commercialization

Barriers and Requirements for Commercialization

- Uncertainty in future world oil prices
- Resource base for tight gas
- High capital costs
- Investment risk
- Technical challenges and plant complexity
- Environmental challenges
- Engineering capability
- Concerns with increased coal use in U.S.
- Government involvement with financial incentives
- Product off-take agreements

Summing Up

- Two major approaches to coal liquefaction to produce transport fuels – DCL and ICL
- DCL – partial disassembly of coal to smaller coal units followed by upgrading
- ICL – complete disassembly of coal to syngas followed by reassembly into hydrocarbons
- History and Milestones
  - DCL: 1913 Bergius, 1927 Leuna, 1944 Germany peak, 1970s and 80s H-Coal, EDS, ITSL pps in USA, 1990s CMS HTI, 2008 Shenhua and Accelergy MCL
  - ICL: 1923 Fischer and Tropsch, 1947 ARGE, 1950 Hydrocol, 1953 Koelbel, 1955 Sasol I, 1980 Sasols II and III, advances from GTL, 2000 Velocys

Summing Up (Continued)

- **Economics**
  - DCL Capital ~ $7-8B for 60K BPD plant
  - ICL Capital ~ $8B for 50K BPD plant
- **Hybrid plant – integrating DCL with ICL**
- **Other approaches to coal liquefaction**
- **Barriers and requirements**

Notes:

Notes:

Presenter Bios

Dr. David Gray

Dr. Gray was until recently Manager of the Energy Systems Analysis Group (ESAG) at Noblis where he had overall responsibility for the technical and management of the Energy Conversion Systems work. He has extensive experience in conversion of coal into fuels and chemicals. In that position he has provided R&D guidance to NETL in many coal conversion activities including both direct and indirect liquefaction. Prior to coming to the USA he worked in South Africa where he was an R&D manager operating pilot plants for alternative transportation fuels production. This included screening of South African coals for their suitability for production of transportation fuels from both direct, MTG, and Fischer-Tropsch liquefaction technologies. For direct liquefaction this included both donor solvent and hydropyrolysis techniques. He has served on the National Academies of Sciences Committee on America's Energy Future and has been asked to prepare the energy editorial for the G8 magazine for the last three years. He has recently served as a subject matter expert on the National Petroleum Council Study on Future Transportation Fuels.

Dr. John J. Marano

Dr. Marano is an independent consultant and principal of JM Energy Consulting, Inc. His practice specializes in:

- technology assessment and process evaluation of energy and environmental systems
- due diligence and transitioning of technologies form bench to pilot-scale to demonstration
- R&D program planning through technology demonstration

with a focus on conventional and alternative fuels and chemicals derived from petroleum, natural gas, coal and biomass resources, and on carbon dioxide capture, sequestration and beneficial re-use. Government-sector clients include: U.S. DOE national laboratories (NETL, NREL, ANL, PNL, LBNL), ARPA-E, DOE Policy Office and Energy Information Administration, and U.S. EPA. Private-sector clients include petroleum coke-to-liquids, biomass-to-liquids, and advanced hydrogen-separation membrane technology developers; and international consulting firms specializing in infrastructure advisory services for the energy and power sectors.

Prior to starting his consulting practice in 2003, he worked as a process engineer in the oil and gas industry and as an engineering contractor for the U.S. Department of Energy. Dr. Marano holds a Ph.D. degree from the University of Pittsburgh and M.S. and B.S. degrees from the University of Toledo; all in Chemical Engineering.