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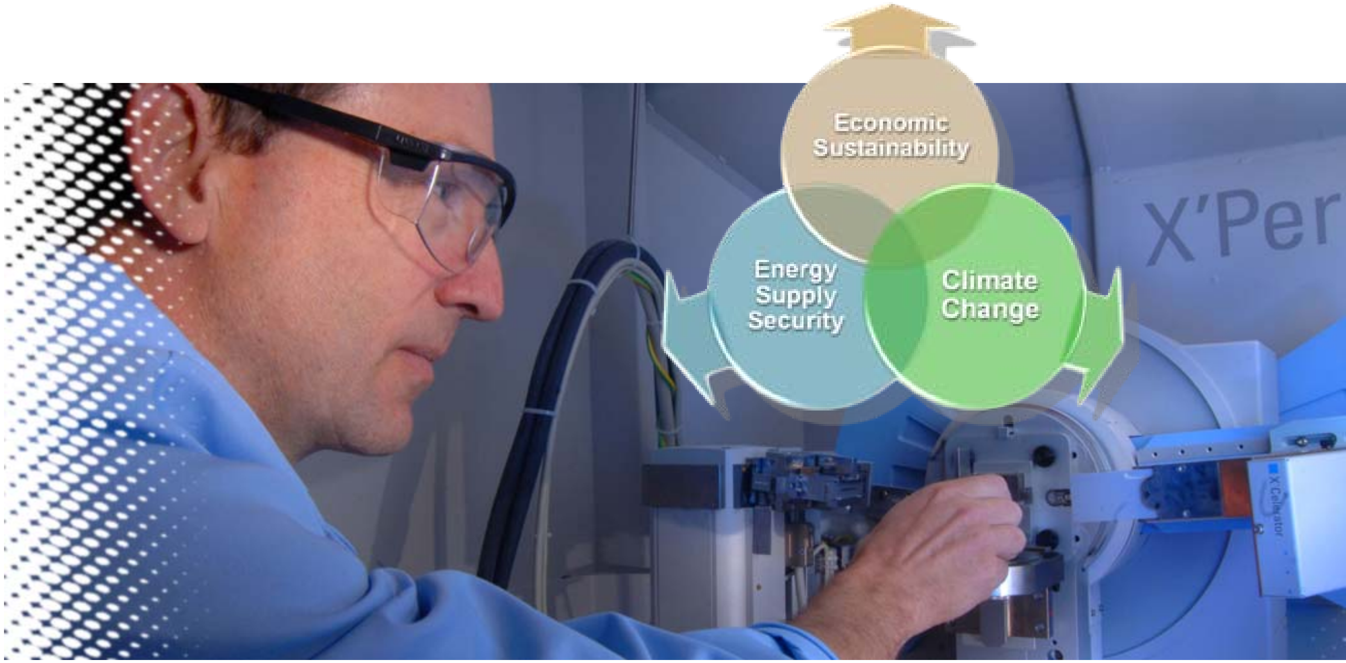

# Direct Coal Liquefaction Overview Presented to NETL

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Leonardo Technologies, Inc.

U.S. DEPARTMENT OF ENERGY

# Direct Liquefaction Presentation Outline

- What is Direct Coal Liquefaction (DCL)? And How does it Differ from Indirect Liquefaction (ICL)?
- History of U.S/Foreign DCL Processes
- Comparison of Results from DOE DCL Technology Support
  - EDS; H-Coal; HRI
- Overall Findings
- DOE Previous DCL Designs and Potential Vendors
- Environmental Considerations/Fuel Specifications
- Current DCL Technology Developments
  - Shenhua; Accelergy
- LTI Thoughts and Comments/Recommendations
  - Analysis
  - R&D

**Details are found in supporting presentations**

# Direct Liquefaction Presentation Summary

- DOE support for direct coal liquefaction occurred mainly over the period 1976-2000.
  - About 90% of total DOE funding of $3.6 billion was spent for the large scale demo program (1976-82) referred to as Phase I, which showed the overall engineering feasibility and applicability of direct liquefaction to a wide range of coals.

  - Processes demonstrated included SRC (both I and II), EDS and H-Coal. Supporting research paved the way for process improvements

- Three main components:
  - Phase I to accelerate the technology as a short-term response to ‘70s energy crisis;

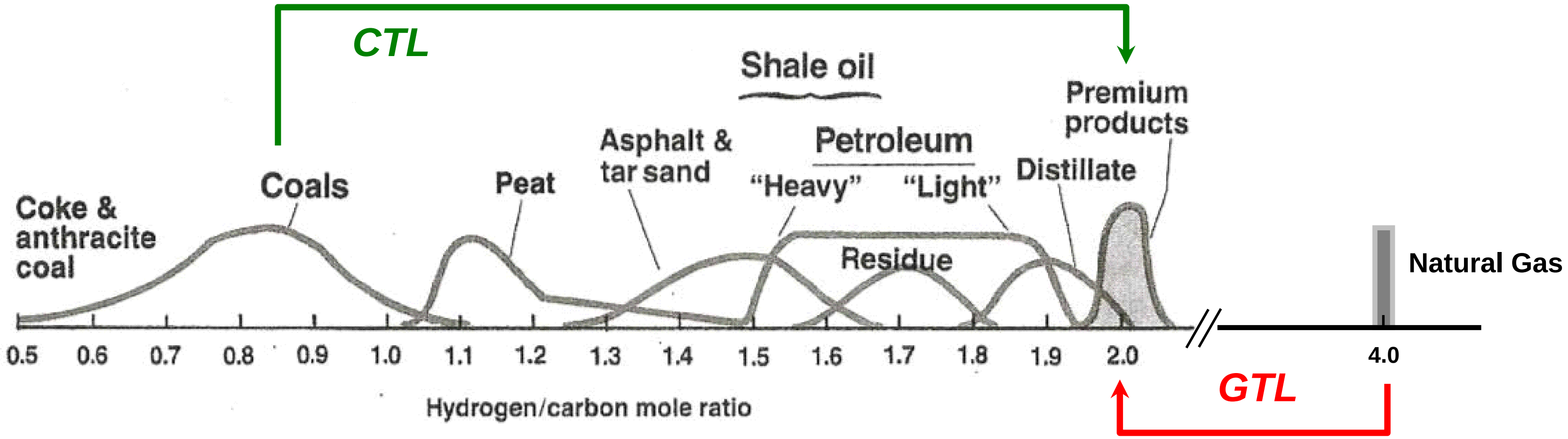
  - Fundamental research to develop improvements and identify alternatives;

  - Phase II bench/pilot-scale program to overcome technical and economic deficiencies in Phase I (Lummus, HTI and Wilsonville facility)

# Direct Liquefaction Presentation Summary (2)

- Accomplishments of Phase II
  - Higher distillate yields…naphtha, mid-distillate and gas oil (~ 70% vs. ~50%)
  - Higher quality liquids…no resid and metals and low heteroatom content; naphtha can be processed in conventional refineries
  - Higher hydrogen content and lower product boiling point end point alleviated carcinogenity concerns
  - Applicability to low rank coals and mixed feedstocks ..coprocessing with petroleum resides, heavy oils, waste plastics
  - Valuable chemicals can be produced…cresylics, wax, BTX, argon, krypton; suggests possible advantage of direct liquefaction with IGCC
  - Burke, etal concluded that radical departures from the DOE-supported direct liquefaction program are unlikely to result in substantially improved processes

# Fuels H/C Ratios



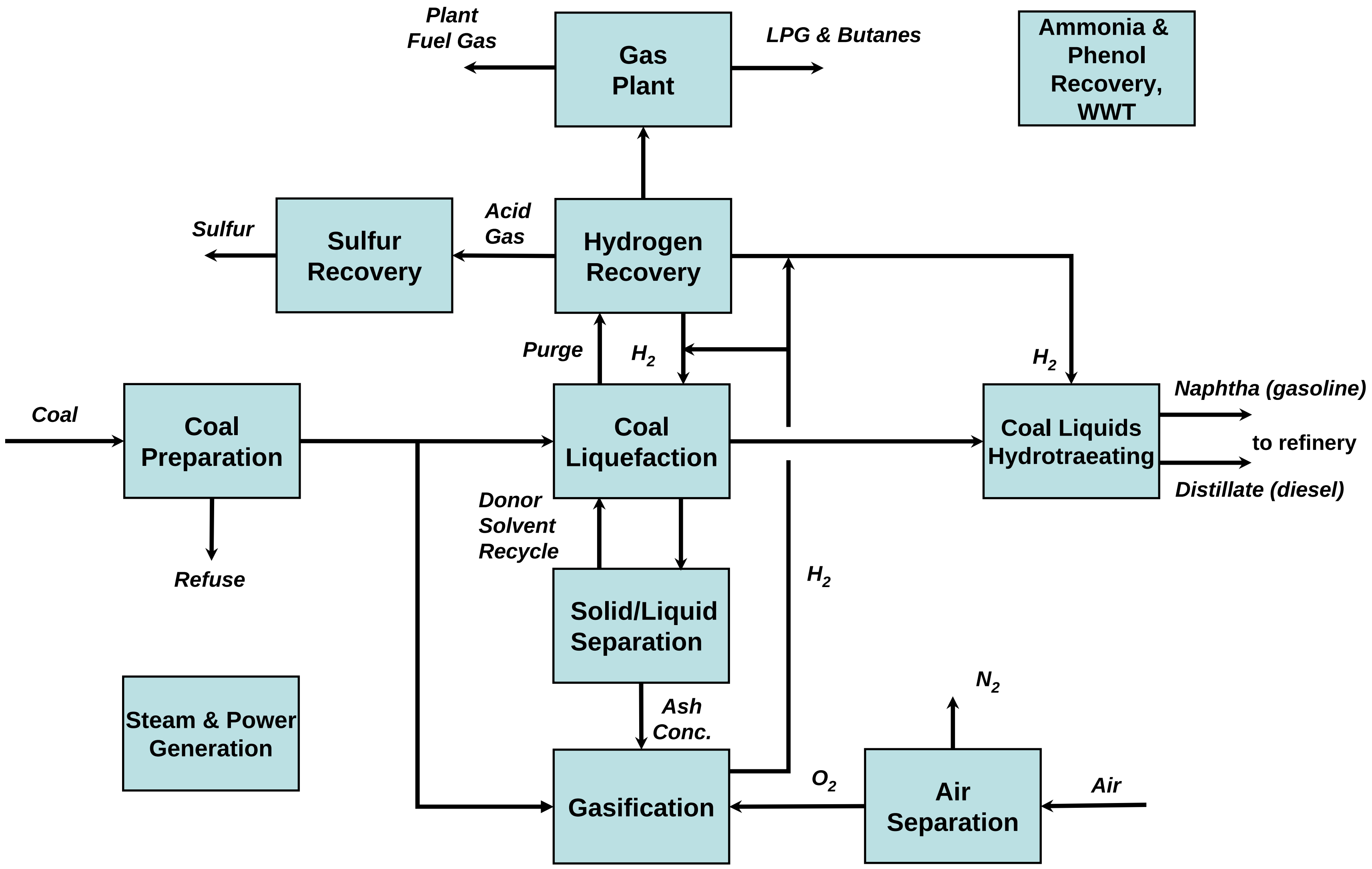
- To make liquid fuels from coal - need to add hydrogen or reject carbon
- To make liquid fuels from natural gas - need to reject hydrogen or add carbon
- Adding hydrogen and rejecting carbon (or vice versa) may be equivalent:

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

Water Gas Shift (WGS) Reaction

John Marano, April 2006, presentation to NETL

# Direct Liquefaction Block Flow Diagram



John Marano, April 2006, presentation to NETL

# Direct Liquefaction Defined

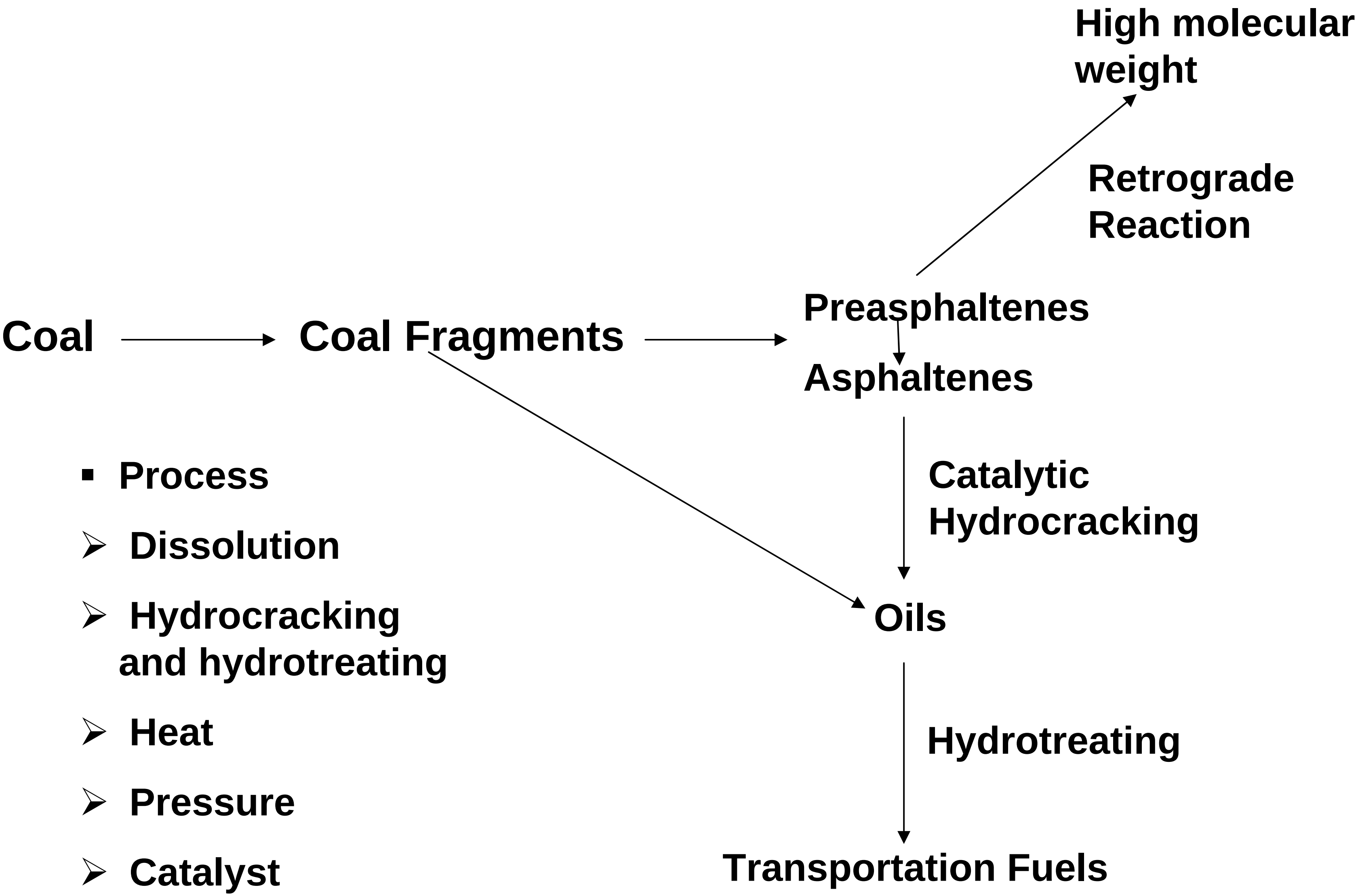
- Direct liquefaction processes add hydrogen to the hydrogen deficient organic structure of the coal, breaking it down only as far as is necessary to produce distillable liquids.
- Coal dissolution is accomplished under high temperature (~400 $^{0}$C) and pressure (~1500-3000 psi) with hydrogen and a coal-derived solvent.
- The coal fragments are further hydrocracked to produce a synthetic crude oil.
- This synthetic crude must then undergo refinery upgrading and hydrotreating to produce acceptable transportation fuels.

# Comparing Direct and Indirect Liquefaction

- **In Direct Liquefaction (DL) pressure, heat and catalyst are used to crack the coal to make liquids**
  - theoretical efficiency can be high…roughly 70-75%
  - “sledge hammer” approach
- **In Indirect Liquefaction (IL) coal is first gasified to form syngas. Syngas is then converted to liquids by means of a catalyst and Fischer Tropsch (FT) chemistry**
  - Synthesis Gas or Syngas – mixture of CO, $H_2$, $CO_2$, $H_2O$
  - theoretical efficiency is lower…roughly 60-65%
  - “engineered” approach

John Marano, April 2006, presentation to NETL

# The Direct Conversion Process Basics



High molecular weight

Retrograde Reaction

Coal

Coal Fragments

Preasphaltenes

Asphaltenes

Catalytic Hydrocracking

Oils

Hydrotreating

Transportation Fuels

- Process
  - ➢ Dissolution
  - ➢ Hydrocracking and hydrotreating
  - ➢ Heat
  - ➢ Pressure
  - ➢ Catalyst

# Direct Liquids Quality

- **Liquid Products are much more aromatic than indirect**
  - DCL Naphtha can be used to make very high octane gasoline component; however aromatics content of Reformulated Gasolines is now limited by EPA
  - DCL Distillate is poor diesel blending component due to high aromatics which results in low cetane versus U.S. average of about 46
- **Raw DCL Liquids still contain contaminants: Sulfur, Nitrogen, Oxygen, possibly metals and require extensive hydrotreatment to meet Clean Fuels Specifications**

# Direct Liquefaction Process

- A single-stage direct liquefaction process gives distillates via one primary reactor. Such processes may include an integrated on-line hydrotreating reactor, which is intended to upgrade the primary distillates without directly increasing the overall conversion.
- A two-stage direct liquefaction process is designed to give distillate products via two reactor stages in series. The primary function of the first stage is coal dissolution and is operated either without a catalyst or with only a low-activity disposable catalyst. The heavy coal liquids produced in this way are hydrotreated in the second stage in the presence of a high-activity catalyst to produce additional distillate.

# Direct Liquefaction Benefits

- Direct liquefaction efficiency may be higher than indirect technology. One ton of a high volatile bituminous coal can be converted into approximately three barrels of high quality distillate syncrude for refinery upgrading and blending

- Direct Liquefaction provides high octane, low sulfur gasoline and a distillate that will require upgrading to make an acceptable diesel blending stock

- Development of direct liquefaction technology could lead to hybrid (direct/indirect) processes producing high quality gasoline and diesel

- The NCC, others suggest that direct liquefaction may have a better carbon footprint than indirect technology

# Direct Liquefaction Challenges

- **Uncertainty in World Oil Prices**
- **High Capital Costs**
- **Investment Risk**
- **Technical Challenges**
  - First technology (since 2nd World War) is being commercialized in the PRC (Shenhua) – need other first-of-kind large scale operation (with carbon management) to verify baselines and economics
  - R&D activity should focus on remaining process issues such as further improvement in efficiency, product cost and quality, reliability of materials and components* and data needed to better define carbon life cycle
  - The timelines for demonstration and development of direct liquefaction technology and carbon capture and storage must be integrated.
  - Hybrid technology needs development including integrated demonstration
- **Environmental Challenges**
  - $CO_2$ and criteria pollutants
  - Water use
- **Concerns with increased coal use in U.S.**

*** The Shenhua commercial plant will provide new information on reliability and performance**

# U.S. Direct Liquefaction Process History

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

# Non-U.S. Direct Liquefaction Processes

| Country | Facility | Capacity Tons/Day | Status |
|---|---|---|---|
| Germany | BOTTROP Plant<br>– I.G. Farben Variant | 200 | Shut Down |
| Japan | Brown Coal Liquefaction Plant<br>– ITSL Variant<br>– Victoria, Australia | 50 | Shut Down (~1990) |
| Japan | Nedol Plant<br>– ITSL Variant<br>– BIT. and SUBBIT. Coals | 150 | Shut down (Late 1990s) |
| U.K. | Point-of-AYR Plant<br>– ITSL Variant | 2.5 | Shut Down (~1990) |
| China | Inner Mongolia | 7,000 | Start-up 2008 |

# Comparison of Results for DOE Direct Liquefaction Program

# DOE Sponsored Programs
# 1968-1995

- **Phase I processes**
  - SRC-II
  - Exxon Donor Solvent (EDS)
  - H-Coal
- **Phase II process campaigns**
  - Lummus Integrated Two-Stage Liquefaction (ITSL)
  - Wilsonville Two-Stage Liquefaction
  - HRI/HTI Catalytic Multi-Stage Liquefaction (CMSL)
  - U. Ky./HTI/CONSOL/Sandia/LDP Advanced Liquefaction Concepts (ALC)

# EDS Process

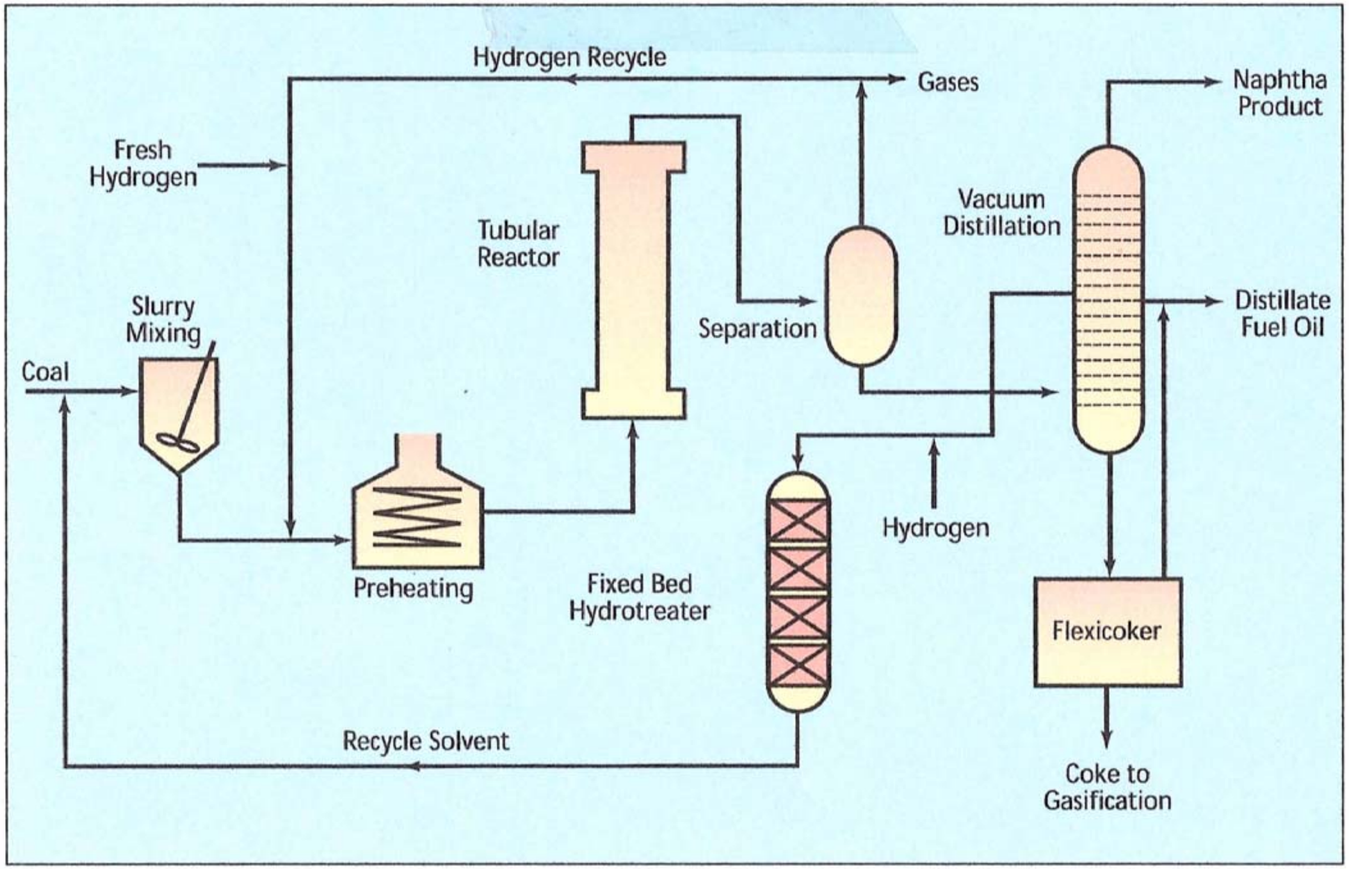


*Figure 6. Schematic diagram of the EDS process*

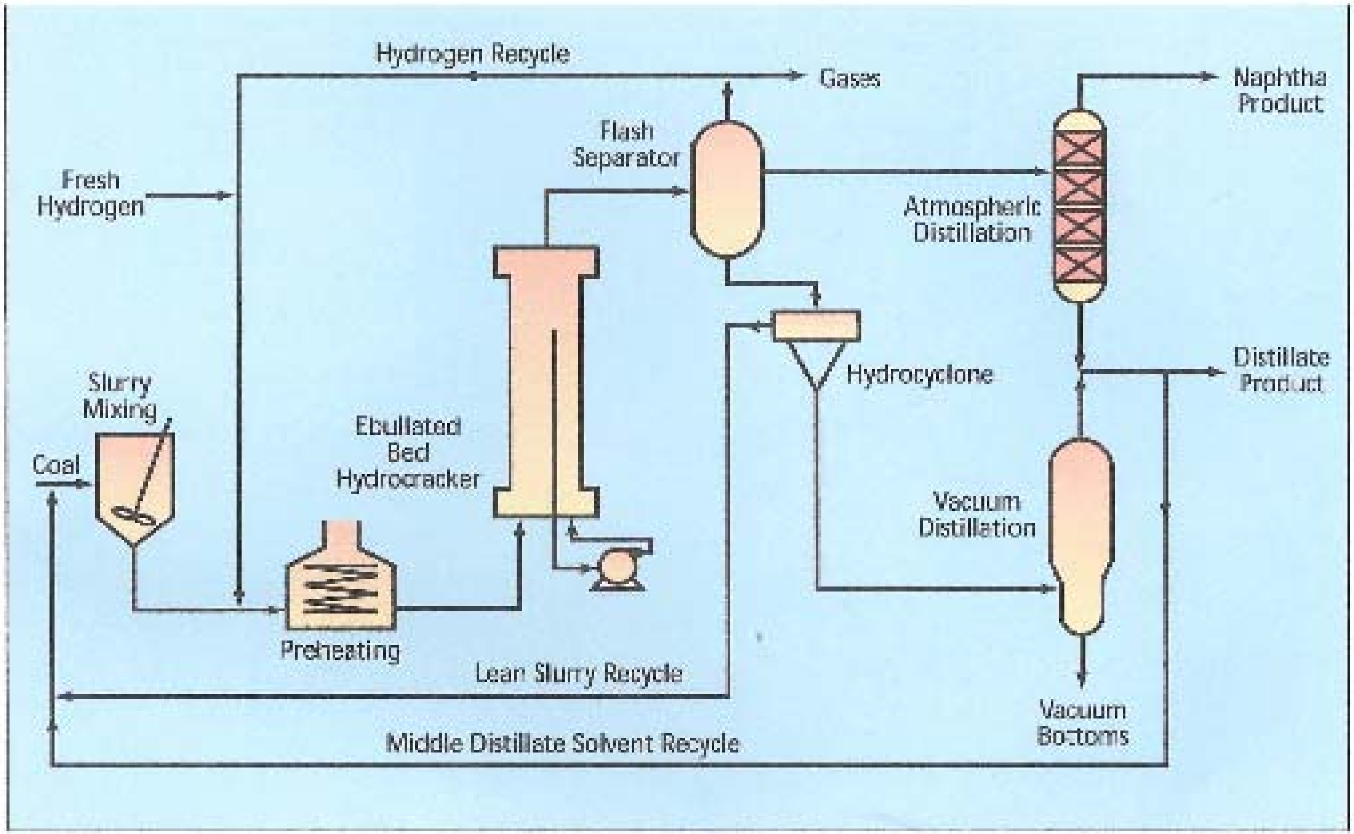
Dept. of Trade and Industry (U.K.), October, 1999

# EDS Process Specifications and Conditions

- Coal is slurried with a distillable recycled solvent that has been rehydrogenated to restore its hydrogen donation capacity
- The slurry is mixed with $H_2$, preheated and fed to a simple up-flow tubular reactor that operates at 425-450 ºC and 2575 psig .
- No catalyst is added to liquefaction reactor
- Naphtha and middle distillate products are recovered, although a portion of the middle distillate is recombined with the heavy distillate to form the basis for the recycle solvent.
- Rehydrogenation of the recycle solvent is carried out in a fixed-bed catalytic reactor, using either nickel-molybdenum or cobalt-molybdenum on an alumina support.
- The hydrogenation reactor is operated at conditions in the region of 370 ºC / 1600 psig, although conditions are varied to control the degree of hydrogenation of the solvent and thus maintain its quality.
- Yields of up to 47% for lignites, 50% for sub-bituminous coals and 60% for bituminous coals could be achieved.

Dept. of Trade and Industry (U.K.), October, 1999

# H-Coal Process Schematic



*Schematic diagram of the H-Coal process*

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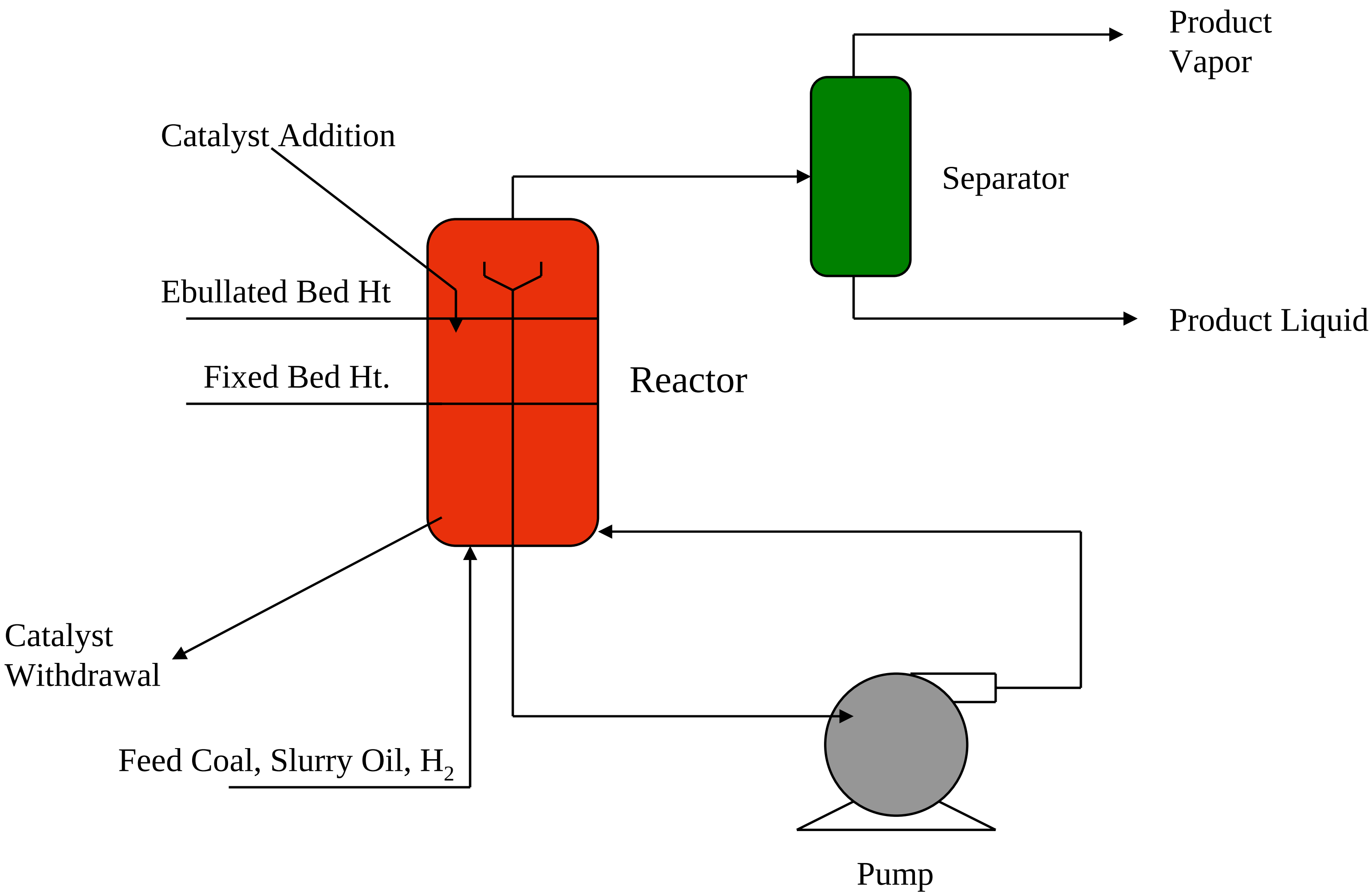
# H-Coal Ebullated-Bed Reactor



# H-Coal Process Specifications and Conditions

- Coal is slurried with a recycle solvent that consists of a mixture of a solids containing hydrocracker product with heavy and middle distillates obtained by product fractionation.
- $H_2$ is added and the mixture is preheated and fed to an ebullated bed hydrocracker, which is the distinguishing feature of the process.
- This reactor operates at temperatures of 425-455°C and a pressure of 2900 psig.
- A conventional supported hydrotreating catalyst, either Ni-Mo or Co-Mo alumina is used. The catalyst is fluidized by $H_2$ and a pumped internal recycle stream, for which the intake is positioned above the upper limit of the expanded bed of catalyst but still within the reactor liquid zone. This recycle stream contains unreacted coal solids.
- The ebullated-bed reactor system offers substantial advantages over fixed-bed reactors - the reactor contents are well mixed and temperature monitoring and control are more easily effected.

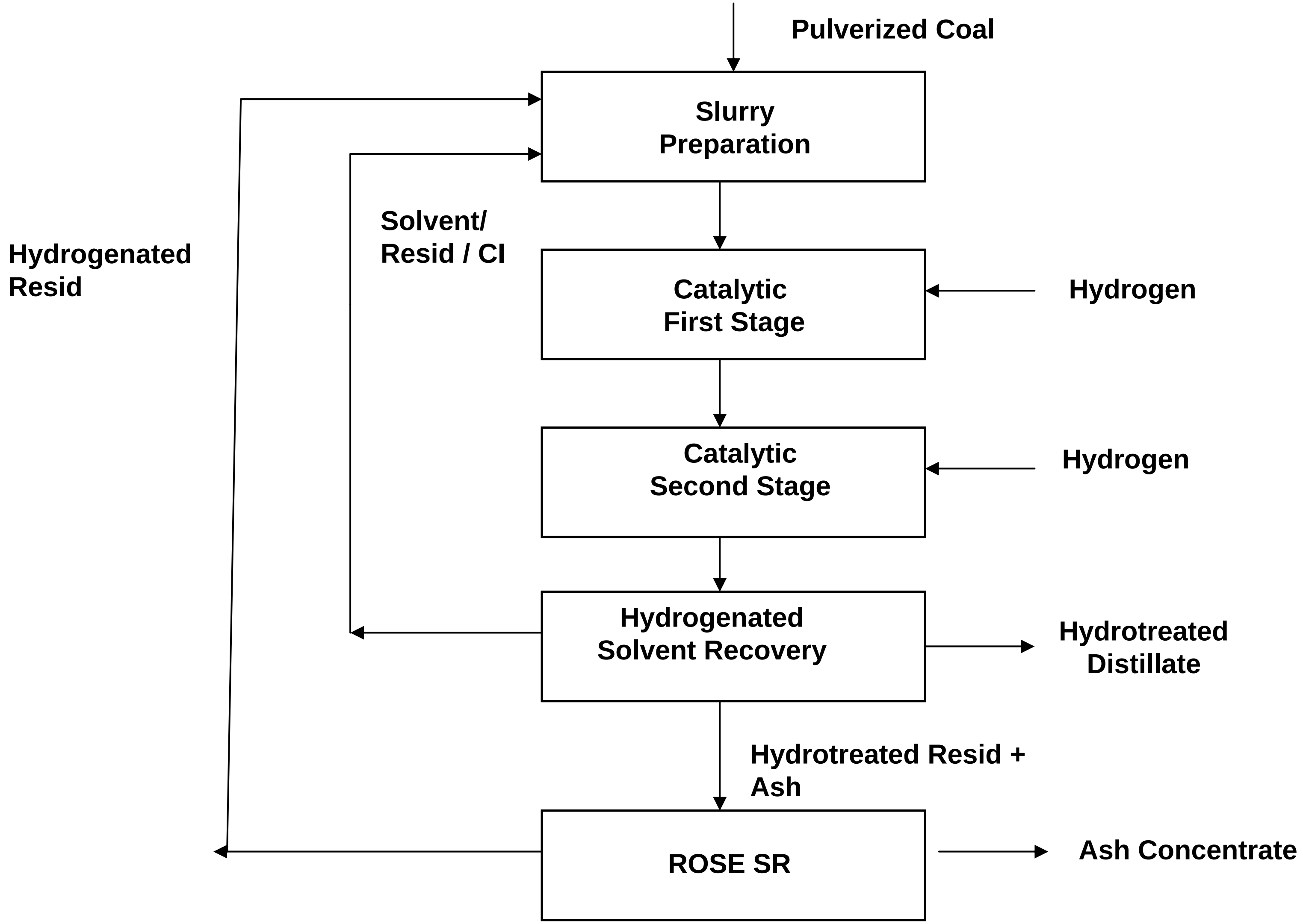
Dept. of Trade and Industry (U.K.), October, 1999

# H-Coal Process Specifications and Conditions (2)

- Ebullated-bed reactors allow catalyst to be replaced while the reactor remains in operation, enabling a constant catalyst activity to be maintained
- The reactor products pass to a flash separator. Liquids in the overheads are condensed and routed to an atmospheric distillation column, producing naphtha and middle distillate.
- The flash bottoms are fed to a bank of hydrocyclones. The overheads stream, which contains 1-2% solids, is recycled to the slurrying stage. The underflow is routed to a vacuum distillation column. Solids are removed with the vacuum column bottoms, while the vacuum distillate forms part of the product for export
- As with other processes, yields are dependent on the coal. >95% overall conversion can be obtained with suitable coals, with liquid yields up to 50% (dry basis).

Dept. of Trade and Industry (U.K.), October, 1999

# Wilsonville PDU
# Block Diagram of CC ITSL Process



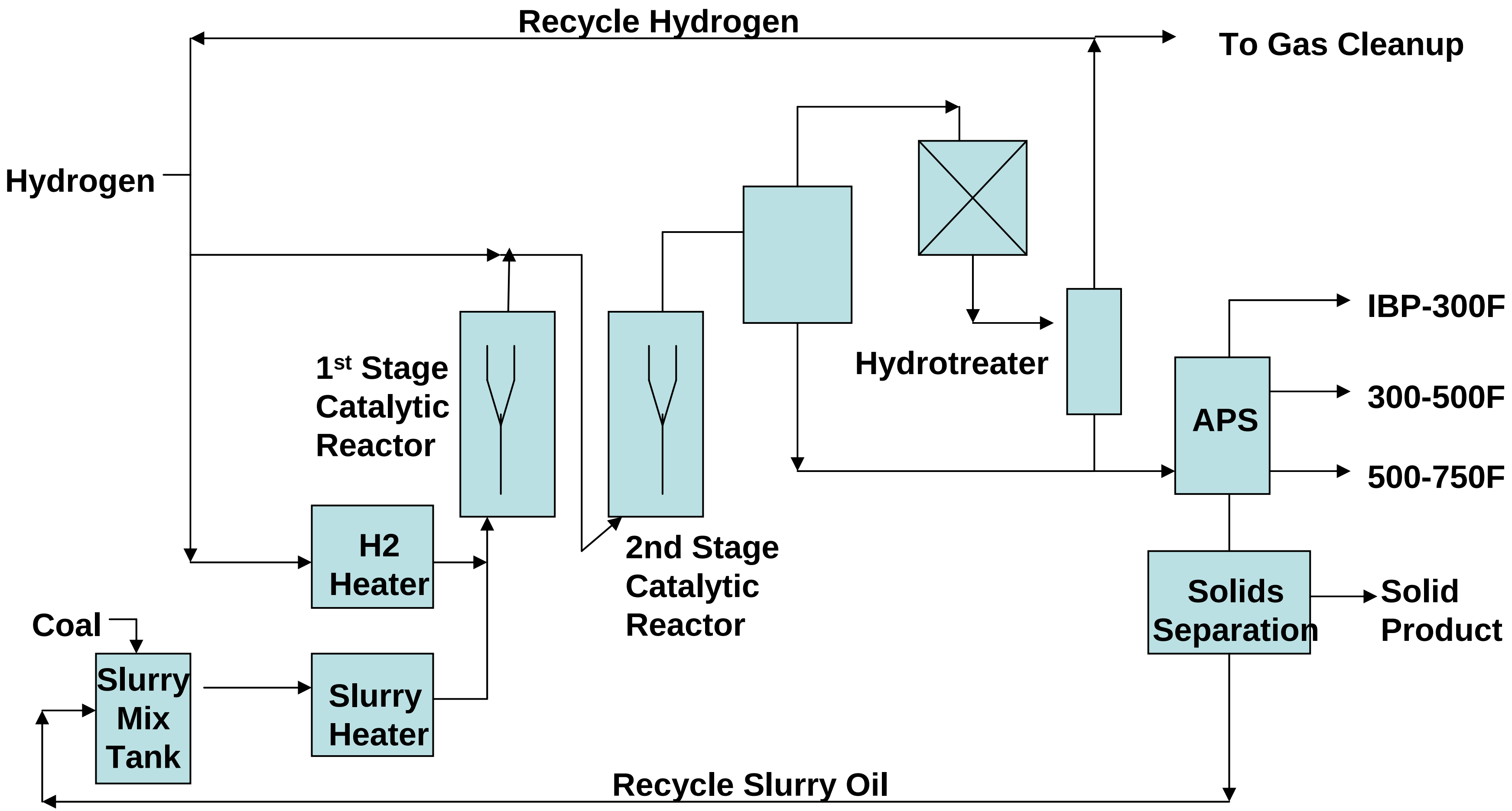
Consol Energy Inc. and Mitretek Systems, July 2001

# HRI/HTI
# Two Stage Liquefaction

**Catalytic Multi-stage Liquefaction (CMSL) System**

- In 1993, the two-stage liquefaction system evolved into the catalytic multi-stage liquefaction (CMSL) system.
- In 1993, the Department of Energy awarded HRI a contract to conduct demonstrations of direct coal liquefaction in the 3 t/d PDU. This program was known as the Proof of Concept (POC) Program.
- The PDU was modified to incorporate an in-line hydrotreater, a new second-stage reactor and reactor structure, a ROSE-SR$^{TM}$ solid separation unit, a new pulverized coal storage and handling system, new preheaters, new flare system, and a computerized automated data collection and control system.

# HRI/HTI
# Two Stage Liquefaction (2)



HTI 3 TPD PDU

# HRI/HTI
# Two Stage Liquefaction (3)

**Catalysts**

- The role of catalyst in the first stage of the CMSL process
  - promote hydrogenation of the solvent
  - stabilize the primary liquefaction products
  - hydrogenate the primary and recycle resid
- In the second stage
  - promote heteroatom removal and thus product quality improvement,
  - convert resid to distillate,
  - promote secondary conversion to lighter products, and aids in avoiding dehydrogenation.
- Catalyst Types evaluated
  - Supported catalysts (Co/Mo, Co/Ni)
  - Dispersed Catalyst (Fe, Mo)
  - HTI proprietary catalyst (GelCat – iron-based)

# HRI/HTI
# Two Stage Liquefaction (4)

**Proprietary Catalysts**

- HTI developed several proprietary dispersed iron catalysts.
- In microautoclave tests with these sulfate-modified iron-based catalysts, coal conversions based on THF solubility of a Black Thunder Mine subbituminous Wyoming coal were greater than that obtained at the same loadings (5000 ppm iron) with a commercially available dispersed iron catalyst (ca.83- 86 wt % vs 76-81 wt %).
- The addition of a small amount of Mo (100 ppm) improved the conversion further (ca. 87-90 wt %).
- In tests made in the CMSL system with the proprietary catalyst in both reactors (all-dispersed mode of operation) and Mo loadings of 50-100 ppm, coal conversion in the range of 93-96 wt %, resid conversion of 83-92 wt % and C4-524 $^0$C distillate liquid yields of 60-66 wt % were obtained.
- The level of performance achieved was better than that obtained with any other catalyst system.

# Sample Process Conditions: One and Two Stage Liquefaction Processes

| **Process**<br>**Year** | **SRC-II**<br>1980 | **H-Coal**<br>1981 | **EDS**<br>Late 1970's | **ITSL**<br>1989 | **CMSL**<br>1994 |
|---|---|---|---|---|---|
| Reactor Number | 1 | 1 | 1 | 2 | 2 |
| Reactor Temperature, $^{O}$F | 835-870 | 800-850 | 800-932 | 840-850 | 755 |
| Reactor Pressure, psig | 2000 max | 3000 | 2000-3000 | 2500 | 2500 |
| 2nd Reactor Temperature, $^{O}$F | | | | 760-810 | 829-845 |
| 2nd Reactor Pressure, psig | | | | 2500 | 2500 |
| Reactor Residence Time, hours | 0.75-1.0 | | | | |
| Solids Concentration, wt % | 48 | | | 33 | |
| Coal Ton per day | 30 | 200 | 250 | ~ 6 | 3 |
| Catalyst | iron pyrite | Co-Mo | | Multiple | Multiple |

Consol Energy Inc. and Mitretek Systems, July 2001

# Comparison of One and Two Stage Liquefaction Process Yields

| **Process** | **SRC-II** | **H-Coal** | **EDS** | **ITSL** | **CMSL** |
|---|---|---|---|---|---|
| **Year** | 1980 | 1981 | Early 1980's | 1989 | 1994 |
| **Yield, wt% MAF Coal** | | | | | |
| Heterogases | 12.9 | 11.3 | 17.4 | 15.2 | 15.2 |
| C1-C3 gas | 14.5 | 12.8 | 19* | 5.4 | 11.4 |
| naphtha | 19.3 | 22.9 | 22.8 | 14.5 | 20.7 |
| middle distillate | 25.2 | 20 | 17 | 21.7 | 39.1 |
| gas oil | 4.9 | 7.6 | 4.4 | 29.6 | 12.5 |
| total distilate | 49.4 | 50.5 | 44.2 | 65.8 | 72.3 |
| H consumption, wt% | 5 | 6 | 5.9 | 6 | 7.5 |
| H efficency, lb dist/lb H consumed | 9.5 | 8.4 | 7.5 | 11 | 9.7 |

* C1-C4 gas

# Illinois Basin Coal Syncrudes

| | H-Coal 1981 | ITSL 1991 | CMSL 1994 | Typical Crude |
|---|---|---|---|---|
| **Carbon, %** | 86.6 | 85.7 | 86.6 | 85.8 |
| **Hydrogen, %** | 10.5 | 11.5 | 13.1 | 13.0 |
| **Nitrogen, ppm** | 5000 | 4900 | 44 | 2000 |
| **Sulfur, %** | 0.19 | 0.07 | 0.06 | 1.00 |
| **Oxygen, %** | 2.13 | 2.24 | 0.44 | |
| **Vanadium, ppm** | nil | nil | nil | 200 |
| **% 650 $^0$F$^-$** | 83 | 79 | 80 | 53 |
| **% 975 $^0$F$^+$** | 0 | 0 | 0 | 20 |
| **API Gravity** | 27 | 22 | 38 | 32 |
| **Premium** | 1.00 | 1.07 | 1.20 | 1.00 |

# Comparison of Naphtha Quality Among One and Two Stage Liquefaction Processes

| | Illinois Basin Coal | | | | |
|---|---|---|---|---|---|
| **Process** | **SRC-II** | **H-Coal** | **EDS** | **CMSL** | **CMSL*** |
| **Year** | 1980 | 1981 | Late 1970's | 1996 | 1996 |
| Naphtha Properties | | | | | |
| boiling Point, °F | 100-400 | 180-380 | 158-392 | i.b.p.-350 | 70-350 |
| °API | 39 | 35 | 31.1 | 49.9 | 53.5 |
| H. wt% | 11.5 | 11.6 | 10.9 | 14 | 14.7 |
| S, wt% | 0.2 | 0.2 | 0.5 | 0.04 | 0.02 |
| N, wt% | 0.4 | 0.31 | 0.2 | 0.02 | 0.002 |
| O, wt% | 3.9 | 3 | 2.8 | 0.3 | <0.1 |

* PRB Coal On-line hydrotreater

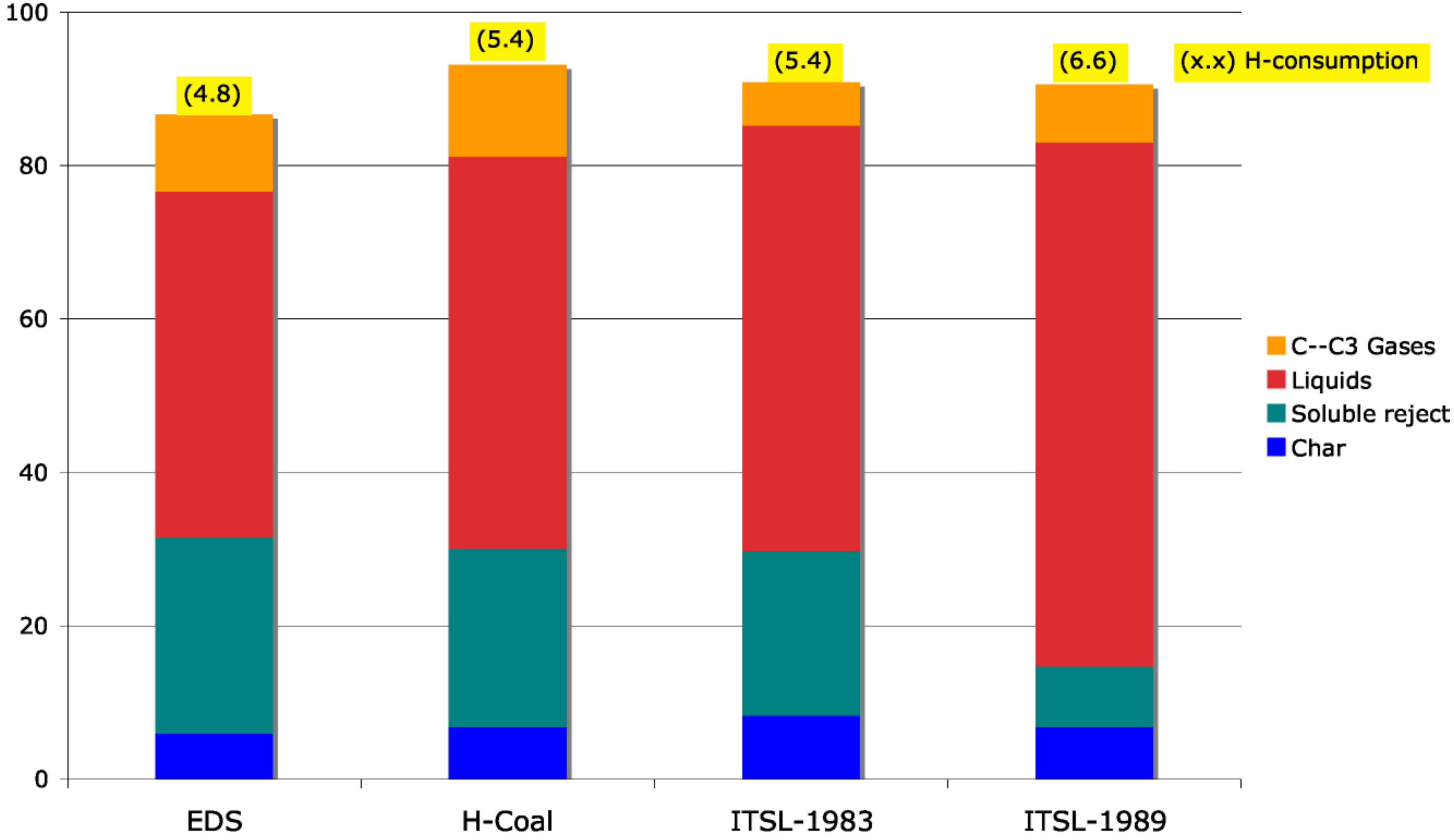
# Technology Applies to Wide Range of Coals

## PRB COAL

| Yield, wt % MAF Coal | H-Coal<br>1980 | ALC/CMSL<br>1996 |
|---|---|---|
| **$C_1$-$C_3$ gas** | 11.0 | 12.4 |
| **naphtha** | 24.3 | 23.0 |
| **total distillate** | 50.7 | 66.1 |
| **H efficiency, lb dist./lb H consumed** | 9.0 | 9.7 |

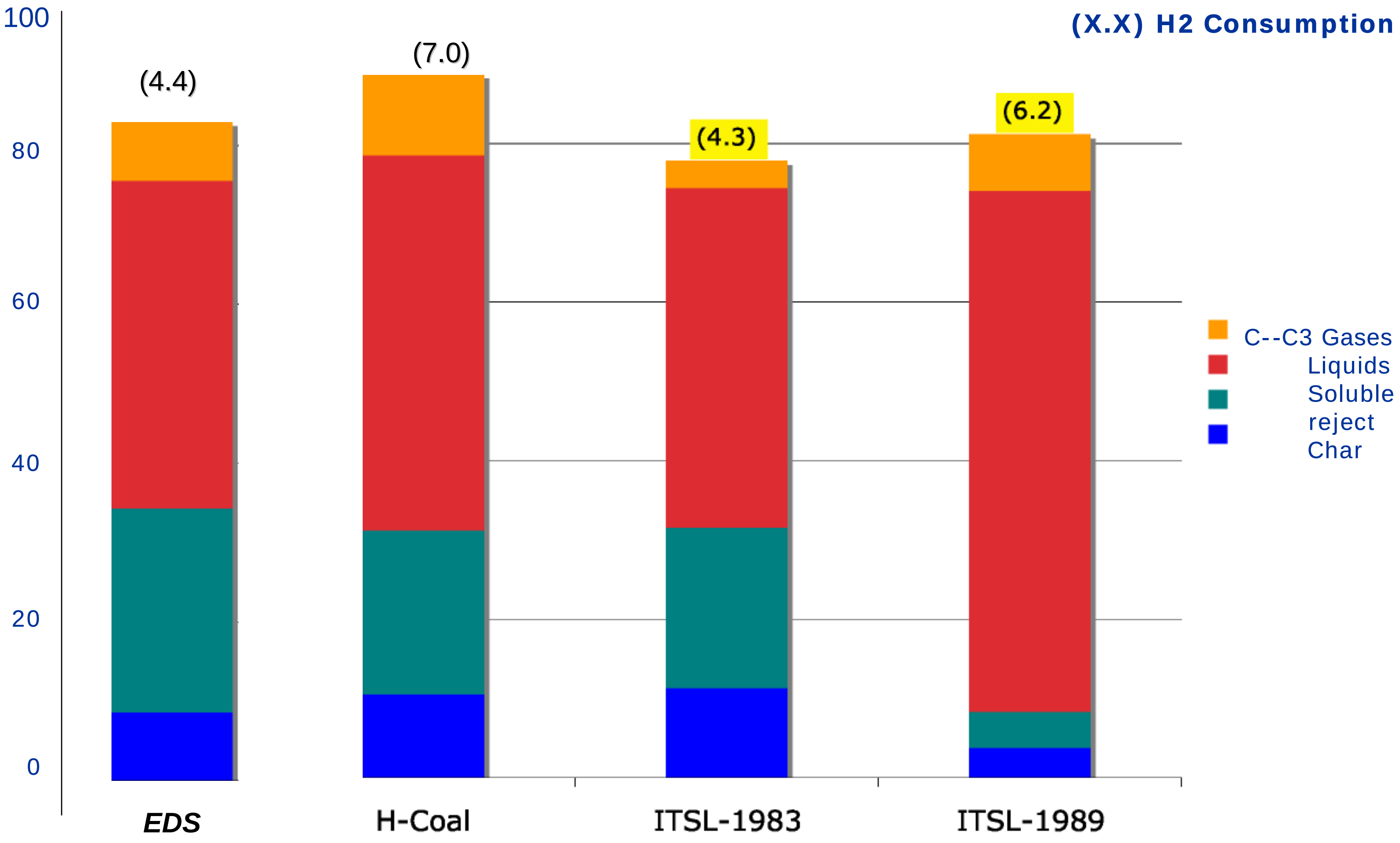
Consol Energy Inc. and Mitretek Systems, July 2001

# Liquefaction Product Yields, Illinois # 6



R. Malhotra, SRI International, GCEP Advanced Workshop, BYU, Provo, UT, March 2005

# Liquefaction Product Yields, Wyodak



R. Malhotra, SRI International, GCEP Advanced Workshop, BYU, Provo, UT, March 2005

# Economic Competitiveness Greatly Improved

## ILLINOIS BASIN COAL

| | H-Coal<br>1981 | CMSL<br>1997 |
|---|---|---|
| **Yield, bbls/day** | 50,000 | 51,500 |
| **Coal feed, T/D AR** | 26,370 | 18,090 |
| **Plant cost, $MM** | $4,592 | $2,914 |
| **Coal cost, $MM/yr** | $178 | $122 |
| **Required Selling Price (RSP)** | $63.69 | $38.06 |
| **Premium** | 1.00 | 1.20 |
| **Equiv. Crude RSP** | $63.69 | $31.78 |

Consol Energy Inc. and Mitretek Systems, July 2001

# Differences Between Phase I and Phase II Technologies

| **Issue/Variable** | **Phase I** | **Phase II** |
|---|---|---|
| Minimize reactor volume | Yes | No |
| Maximize distillate yields | No | Yes |
| Space velocity | Higher | Lower |
| Reaction temperature | Higher | Lower |
| Reactor staging | Generally No | Yes |
| Dispersed catalyst | Generally No | Yes |
| Solids recycle | No | Yes |
| Product recycle | Yes | No |
| Donor solvent concerns | Yes | No |

# Overall Findings – DOE Program

- While the H-Coal and EDS programs (Phase I) demonstrated the technical and engineering feasibility of direct coal liquefaction, many issues were not satisfactorily resolved, including those of process yield, selectivity, product quality, and, ultimately, economic potential.
- Process development research had identified a number of options for process improvement that were further developed and demonstrated (Phase II) at the bench and pilot plant scale, principally at Lummus-Crest, HRI (later, HTI) and the Wilsonville facility, during the 1980s and early 1990s.
- Improvements in distillate yields and quality were shown in HTI bench scale program with dispersed catalysts.  Low sulfur and nitrogen were achieved with in-line hydrotreating.  Need PDU verification, which may have been done.

Consol Energy Inc. and Mitretek Systems, July 2001; LTI Revision

# Overall Findings – DOE Program (2)

**High Yields of Distillate Fuels Demonstrated**

- One of the most important accomplishments of the Phase II work was a substantial increase in liquid yields compared to the Phase I processes. High liquid yield is important, because direct liquefaction is capital-intensive. Therefore, increasing liquid yields greatly reduced the capital cost component of the process on a dollars/barrel/stream day basis. Liquid fuel yields were increased from 45% to 50% (MAF coal basis) for Phase 1 processes to about 75% (more than 4.5 bbl/t of MAF coal) for Phase 2 processes, while the yields of less valuable gaseous and non-distillate fuels were reduced commensurately for mid-western U.S. (Illinois Basin) coal.

Consol Energy Inc. and Mitretek Systems, July 2001

# Overall Findings – DOE Program (3)

**High-Quality Liquids Produced**

- The liquids made in the Phase I processes were intended to be crude oil replacements, but they were unstable, highly aromatic, and had high heteroatom (sulfur, nitrogen, oxygen) contents. This prompted concern about refinability, storage stability, and human health, principally related to carcinogenicity.
- In the Phase II work, considerable attention was paid to improving liquid fuel quality. The Phase II process produces liquid fuels containing no resid, no metals, and low levels of heteroatoms.
- These primary products can be refined in conventional refineries to meet current specifications for motor and turbine fuels. Product quality evaluations, which were an important element of the Phase II work, ensured that acceptable transportation fuels can be produced by direct coal liquefaction.

# Overall Findings – DOE Program (4)

**High-Quality Liquids Produced**

- The Phase ll processes make a quality naphtha that can be processed in conventional refineries into high-quality gasoline.
- No undesirable blending interaction with conventional gasolines and naphthas is expected. Direct coal liquefaction middle distillates can serve as blend stocks for the production of diesel fuel and kerosene.
- The low heteroatom content with accompanying higher hydrogen contents of Phase 2 process products alleviate the carcinogenicity concerns related to Phase 1 process products.

# Overall Findings – DOE Program (5)

**Process Scale-Up Demonstrated**

- The Phase I work demonstrated successful continuous operation of plants as large as 200 t/d of coal feed (Ashland Synthetic Fuels, Inc., Catlettsburg, KY)
- The Phase II processes are sufficiently similar to the Phase I processes, in terms of process equipment and unit operations, that this experience is directly applicable.
- In addition, some of the key process equipment, such as the ebullated bed reactor, is used in petroleum refineries around the world.
- Materials of construction and equipment designs were found to overcome corrosion, erosion, and fouling problems experienced in Phase 1 plants; these new materials and designs were demonstrated to be suitable.
- As a result, we can approach the scale-up of the Phase II processes to commercial scale with reasonable confidence.

# Overall Findings – DOE Program (6)

**Direct Liquefaction Shown to Apply to a Wide Range of Coals**

- One emphasis of the Phase II work was to apply direct liquefaction to low-rank coals. This is important, because it proved that the huge reserves of inexpensive western U.S. subbituminous coals make excellent liquefaction feedstocks.
  - Lignite, subbituminous, and bituminous coals from the eastern, mid-western, and western U.S. were shown to be suitable feedstocks. These represent the vast majority of U.S. coal resources.
- The Phase 2 work showed that direct liquefaction is a flexible process for sub-bituminous and other low rank coals.
- It was shown that direct liquefaction could be applied to a mixed feedstock containing coal and petroleum resids, heavy oil, or bitumen ("coprocessing"), and to coal and waste polymers. This allows a single plant to operate with the most economical feedstock available at a given place and time.

# Overall Findings – DOE Program (7)

- Some specific issues that were originally significant problem areas, but that were moderated by improved materials, equipment, or process design during the development program include:
  - Overall plant reliability
  - Deashing
  - Product compatibility with conventional fuels
  - Let-down valve erosion
  - Preheater coking
  - Corrosion in distillation columns

Modified from Consol Energy Inc. and Mitretek Systems, July 2001

# Direct Coal Liquefaction Previous Designs

# Direct Liquefaction Design Information

- **During the late 1970's and early 1980's designs were prepared for the one stage liquefaction processes**
  - Pilot Plants: H coal, EDS, SRC
  - Demonstration Plants: SRC-I, SRC-II, H-Coal
- **Baseline Design for Direct Liquefaction Plant**
  - May 1990 to February 1995
  - Bechtel / Amoco Contractors
  - Two Stage Liquefaction based on Wilsonville PDU
  - Plant capacity of roughly 60,000 barrels per day of liquid products plus C1 – C4 gases.
  - Considered both Bituminous and sub-bituminous coals

# Direct Liquefaction Design Information (2)

- Development of the cost estimate and economics for
  - the base-line design
  - alternates for the coal liquefaction facility
  - compilation of equipment lists and utilities summary
  - development of scaling factors for equipment size and plant cost
  - development of the estimates for capital equipment, working capital, and owner's costs.
  - The economic analyses includes manpower requirements and operating costs
- Development of mathematical algorithms and models for equipment sizing, scaleup, costing, train duplication for incorporation into the ASPEN/SP simulation program.

# Direct Liquefaction Design Information (3)

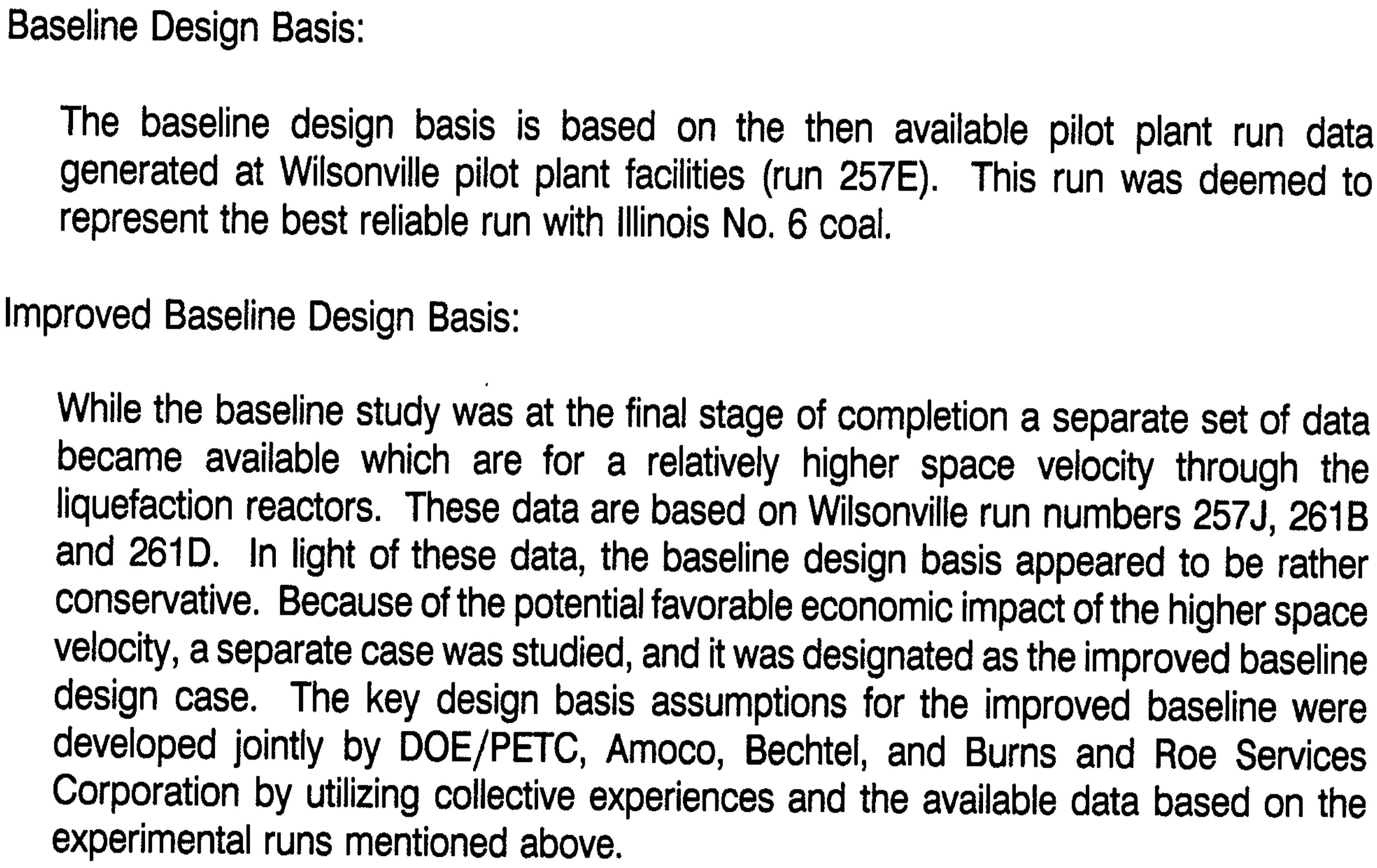
- **Development of an ASPEN/SP process simulation model of the baseline design.**
  - The model produces complete heat and material balances, elemental balances around each plant and the entire process complex,
  - a major equipment list and outline specifications for the plant sections, utility requirements, capital cost for all plants sections
  - a discounted cash flow economics model for the total complex.
  - The model is suitable for studying technology advances and options in a case study approach. The model does not feature optimization capabilities.

# Direct Liquefaction Design Information (4)

**Design information beyond Bechtel Study**

- HRI Two stage CMSL liquefaction design
- NEDO pilot plant design and operation
- Shenhua Commercial plant design
- Headwaters conceptual designs for India and Indonesia
- Information in public domain is minimal

# Comparison of Baselines



Baseline Design Basis:

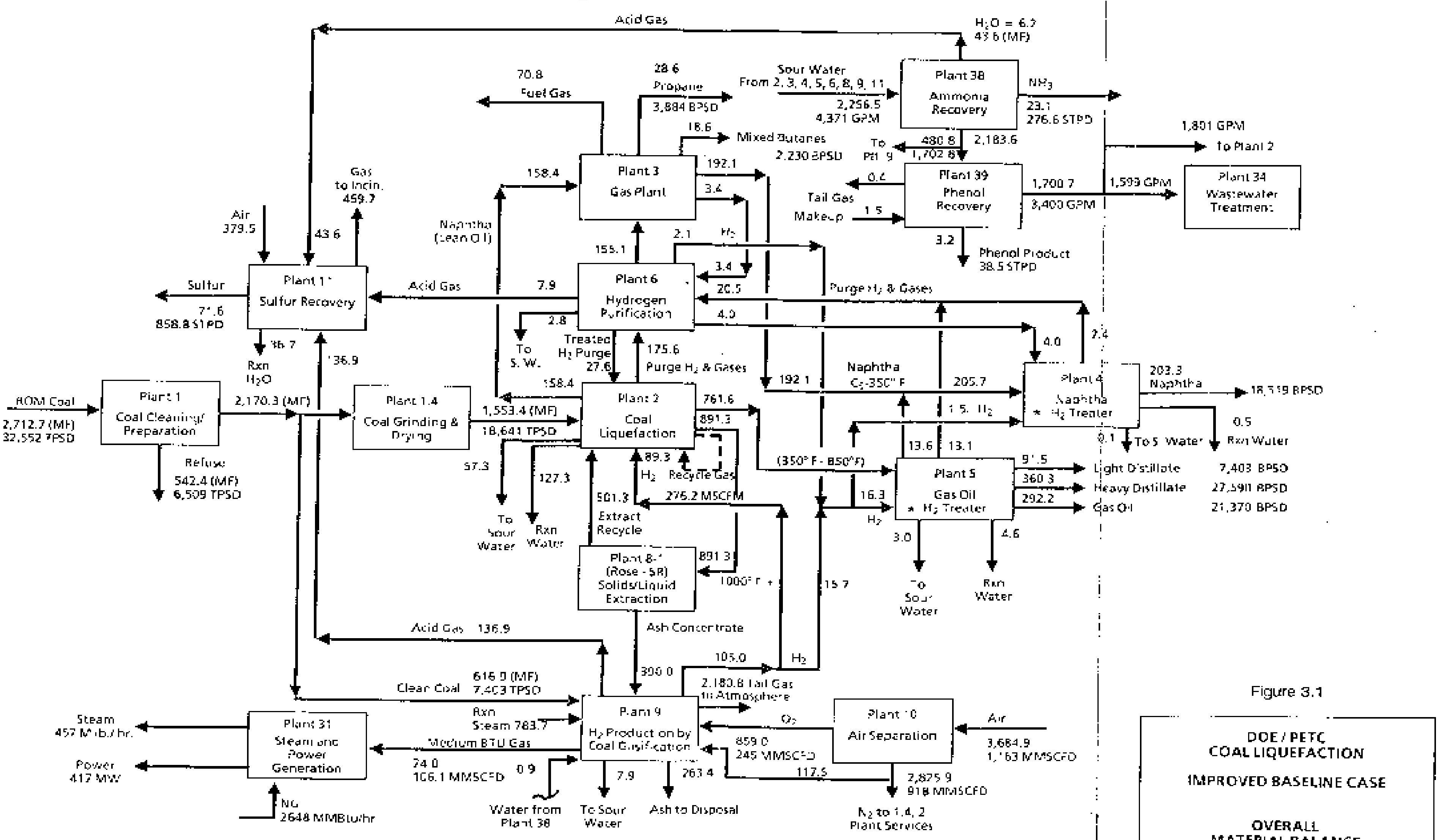
The baseline design basis is based on the then available pilot plant run data generated at Wilsonville pilot plant facilities (run 257E). This run was deemed to represent the best reliable run with Illinois No. 6 coal.

Improved Baseline Design Basis:

While the baseline study was at the final stage of completion a separate set of data became available which are for a relatively higher space velocity through the liquefaction reactors. These data are based on Wilsonville run numbers 257J, 261B and 261D. In light of these data, the baseline design basis appeared to be rather conservative. Because of the potential favorable economic impact of the higher space velocity, a separate case was studied, and it was designated as the improved baseline design case. The key design basis assumptions for the improved baseline were developed jointly by DOE/PETC, Amoco, Bechtel, and Burns and Roe Services Corporation by utilizing collective experiences and the available data based on the experimental runs mentioned above.

Bechtel Baseline reports

# The DCL Process is More Complex Than a Simple Schematic



Notes:

1. Flow rates are in MLB/HR unless noted and on dry basis
2. Minor streams including steam, water, sour water, and make up amine are not shown on this diagram
3. Flow rates around plants #38, 39, 34 are shown on wet basis

* H2 Treater = Hydrotreater

Figure 3.1

DOE / PETC
COAL LIQUEFACTION
IMPROVED BASELINE CASE

OVERALL
MATERIAL BALANCE

# DCL Reactor Operating Conditions

Key Operating Conditions for the Coal Liquefaction Reactor

| | Wilsonville 257-J | Improved Baseline | Baseline |
|---|---|---|---|
| Coal SV, lb MAF/hr/lb Catalyst | 2.17 | 1.95 | 1.12 |
| Temp, °F | | | |
| Reactor 1 | 809 | 810 | 790 |
| Reactor 2 | 760 | 760 | 760 |
| Catalyst addition | 3/1.5 | 3/1.5 | 3/1.5 |
| Lbs/ ton MF coal each stage | | | |
| Solvent/MAF Coal | 2.25 | 2.26 | 2.46 |
| Resid in Solvent, wt% | 50 | 50 | 50 |

Bechtel Baseline reports

# DCL Product Yields

Overall Liquefaction Product Yields

| Yields, wt%, MAF | Wilsonville 257-J | Improved Baseline | Baseline |
|---|---|---|---|
| $H_2S + H_2O + CO_x + NH_3$ | 15.1 | 13.9 | 14.0 |
| C1 – C3 | 5.4 | 5.5 | 4.8 |
| C4 – 350 °F | 14.5 | 15.8 | 16.9 |
| 350 – 450 °F | 7.1 | 7.3 | 7.5 |
| 450 – 850 °F | 44.2 | 48.1 | 46.8 |
| C4+ Liquids | 65.8 | 71.2 | 71.2 |
| Resid | 1.2 | 0.0 | 0.0 |
| Organics in ash-concentrate | 18.5 | 15.7 | 16.3 |
| $H_2$ | (6.0) | (6.3) | (6.2) |

Bechtel Baseline reports

# Bechtel Capital Cost

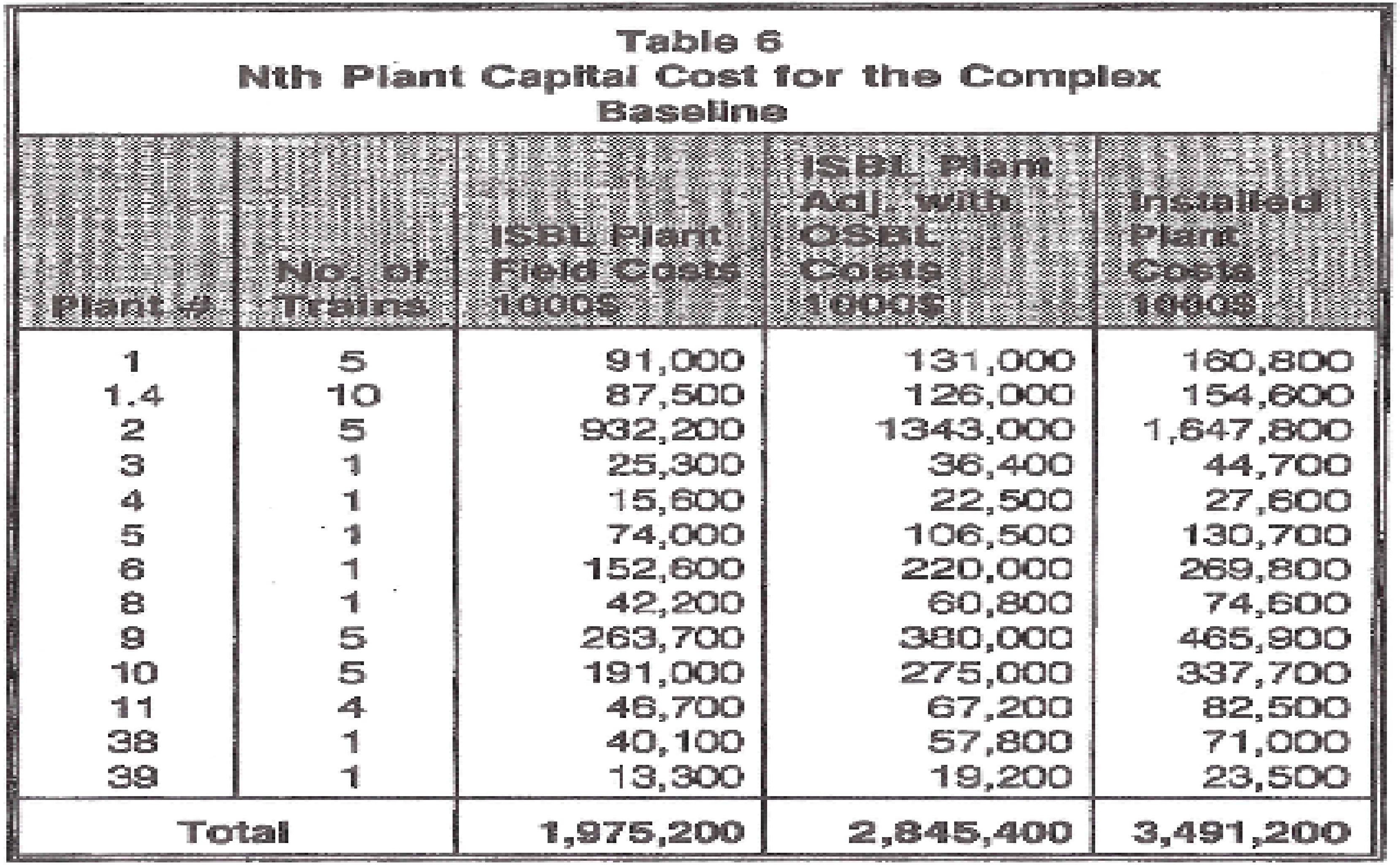


Table 6
Nth Plant Capital Cost for the Complex
Baseline

| Plant # | No. of Trains | ISBL Plant Field Costs 1000$ | ISBL Plant Adj. with OSBL Costs 1000$ | Installed Plant Costs 1000$ |
|---|---|---|---|---|
| 1 | 5 | 91,000 | 131,000 | 160,800 |
| 1.4 | 10 | 87,500 | 126,000 | 154,600 |
| 2 | 5 | 932,200 | 1343,000 | 1,647,800 |
| 3 | 1 | 25,300 | 36,400 | 44,700 |
| 4 | 1 | 15,600 | 22,500 | 27,600 |
| 5 | 1 | 74,000 | 106,500 | 130,700 |
| 6 | 1 | 152,600 | 220,000 | 269,800 |
| 8 | 1 | 42,200 | 60,800 | 74,600 |
| 9 | 5 | 263,700 | 380,000 | 465,900 |
| 10 | 5 | 191,000 | 275,000 | 337,700 |
| 11 | 4 | 46,700 | 67,200 | 82,500 |
| 38 | 1 | 40,100 | 57,800 | 71,000 |
| 39 | 1 | 13,300 | 19,200 | 23,500 |
| Total | | 1,975,200 | 2,845,400 | 3,491,200 |

**Capital Cost Mid 1991 dollars**

Bechtel Baseline reports

# Bechtel Capital Cost (2)

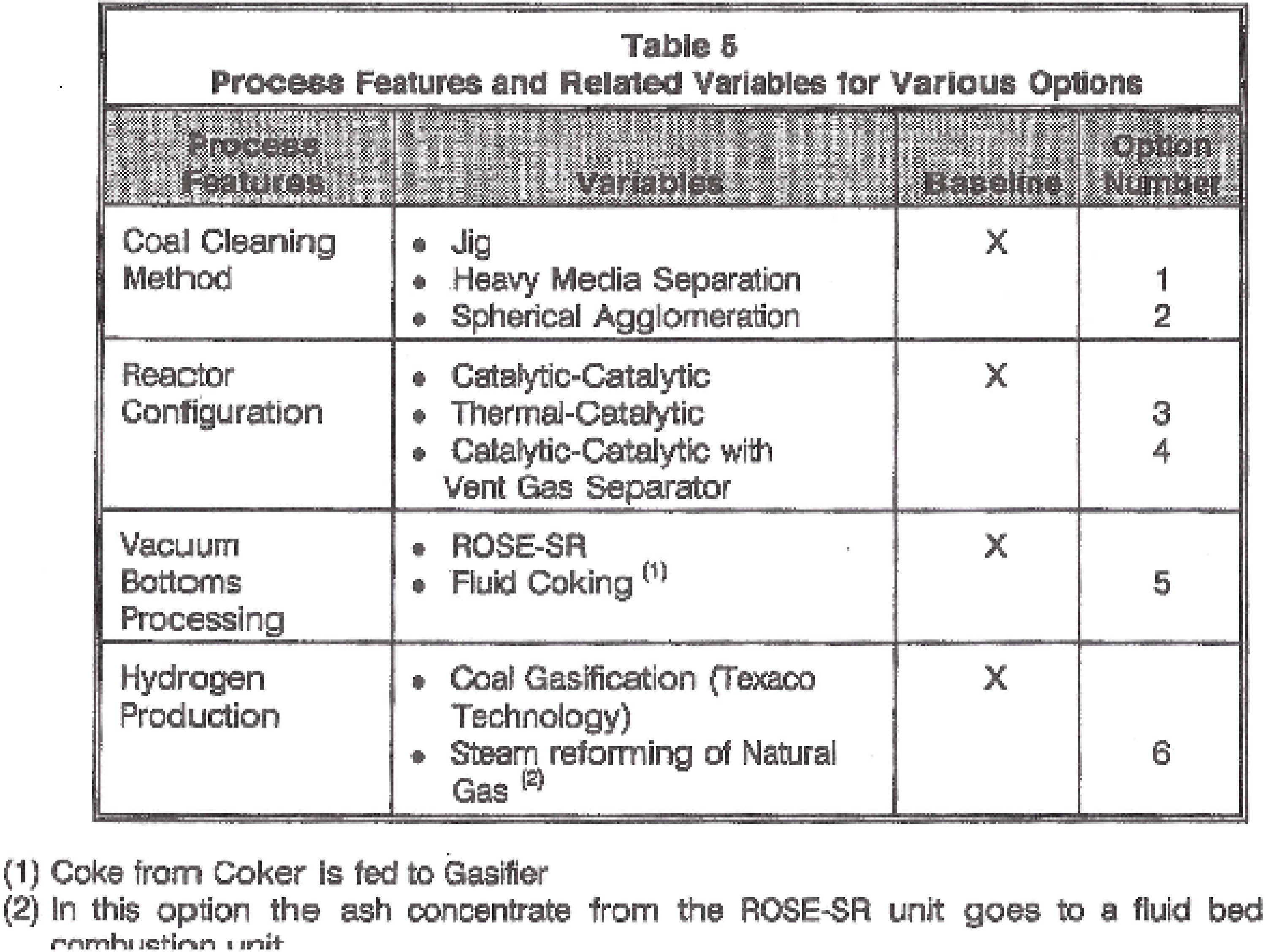


**Table 5**
**Process Features and Related Variables for Various Options**

| Process Features | Variables | Baseline | Option Number |
|---|---|---|---|
| Coal Cleaning Method | • Jig<br>• Heavy Media Separation<br>• Spherical Agglomeration | X<br><br> | <br>1<br>2 |
| Reactor Configuration | • Catalytic-Catalytic<br>• Thermal-Catalytic<br>• Catalytic-Catalytic with Vent Gas Separator | X<br><br> | <br>3<br>4 |
| Vacuum Bottoms Processing | • ROSE-SR<br>• Fluid Coking (1) | X<br> | <br>5 |
| Hydrogen Production | • Coal Gasification (Texaco Technology)<br>• Steam reforming of Natural Gas (2) | X<br> | <br>6 |

(1) Coke from Coker is fed to Gasifier

(2) In this option the ash concentrate from the ROSE-SR unit goes to a fluid bed combustion unit

Bechtel Baseline reports

# Bechtel Capital Cost (3)

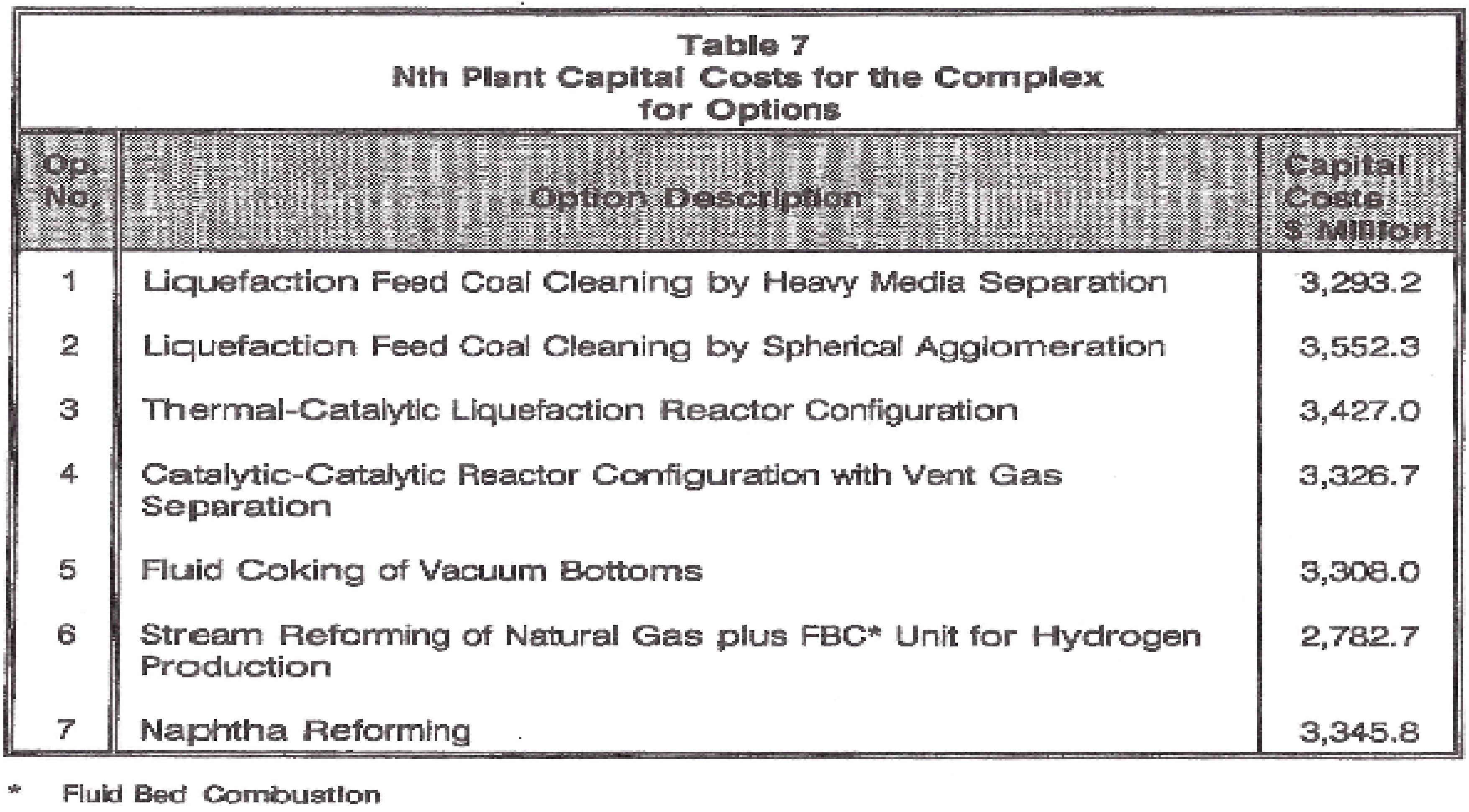


**Table 7**
**Nth Plant Capital Costs for the Complex for Options**

| Op. No. | Option Description | Capital Costs $ Million |
|---|---|---|
| 1 | Liquefaction Feed Coal Cleaning by Heavy Media Separation | 3,293.2 |
| 2 | Liquefaction Feed Coal Cleaning by Spherical Agglomeration | 3,552.3 |
| 3 | Thermal-Catalytic Liquefaction Reactor Configuration | 3,427.0 |
| 4 | Catalytic-Catalytic Reactor Configuration with Vent Gas Separation | 3,326.7 |
| 5 | Fluid Coking of Vacuum Bottoms | 3,308.0 |
| 6 | Stream Reforming of Natural Gas plus FBC* Unit for Hydrogen Production | 2,782.7 |
| 7 | Naphtha Reforming | 3,345.8 |

* Fluid Bed Combustion

Bechtel Baseline reports

# Bechtel Capital Cost (4)

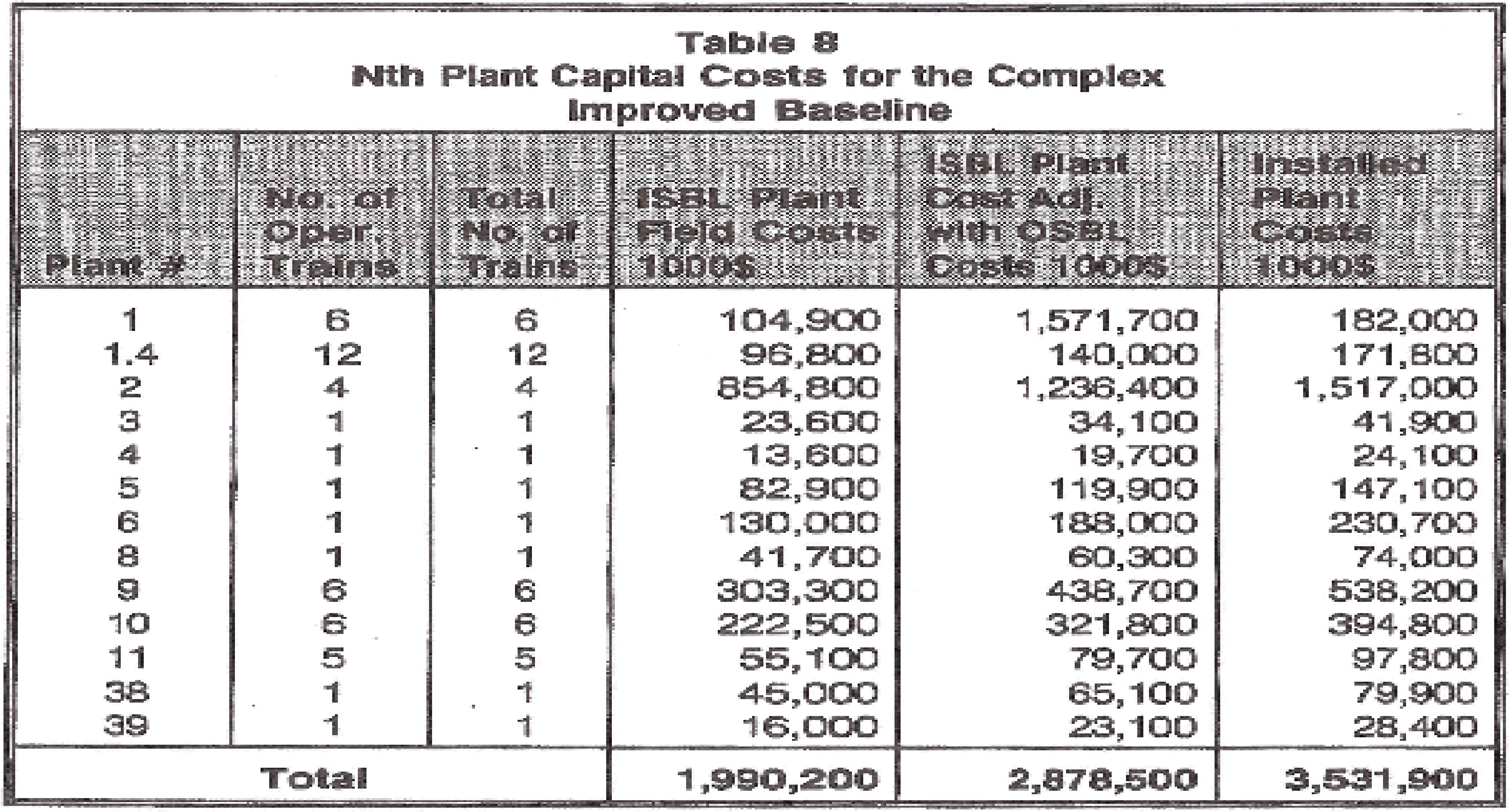


**Table 8**
**Nth Plant Capital Costs for the Complex**
**Improved Baseline**

| Plant # | No. of Oper. Trains | Total No. of Trains | ISBL Plant Field Costs 1000$ | ISBL Plant Cost Adj. with OSBL Costs 1000$ | Installed Plant Costs 1000$ |
|---|---|---|---|---|---|
| 1 | 6 | 6 | 104,900 | 1,571,700 | 182,000 |
| 1.4 | 12 | 12 | 96,800 | 140,000 | 171,800 |
| 2 | 4 | 4 | 854,800 | 1,236,400 | 1,517,000 |
| 3 | 1 | 1 | 23,600 | 34,100 | 41,900 |
| 4 | 1 | 1 | 13,600 | 19,700 | 24,100 |
| 5 | 1 | 1 | 82,900 | 119,900 | 147,100 |
| 6 | 1 | 1 | 130,000 | 188,000 | 230,700 |
| 8 | 1 | 1 | 41,700 | 60,300 | 74,000 |
| 9 | 6 | 6 | 303,300 | 438,700 | 538,200 |
| 10 | 6 | 6 | 222,500 | 321,800 | 394,800 |
| 11 | 5 | 5 | 55,100 | 79,700 | 97,800 |
| 38 | 1 | 1 | 45,000 | 65,100 | 79,900 |
| 39 | 1 | 1 | 16,000 | 23,100 | 28,400 |
| **Total** | | | **1,990,200** | **2,878,500** | **3,531,900** |

Bechtel Baseline reports

# Bechtel Capital Cost (5)

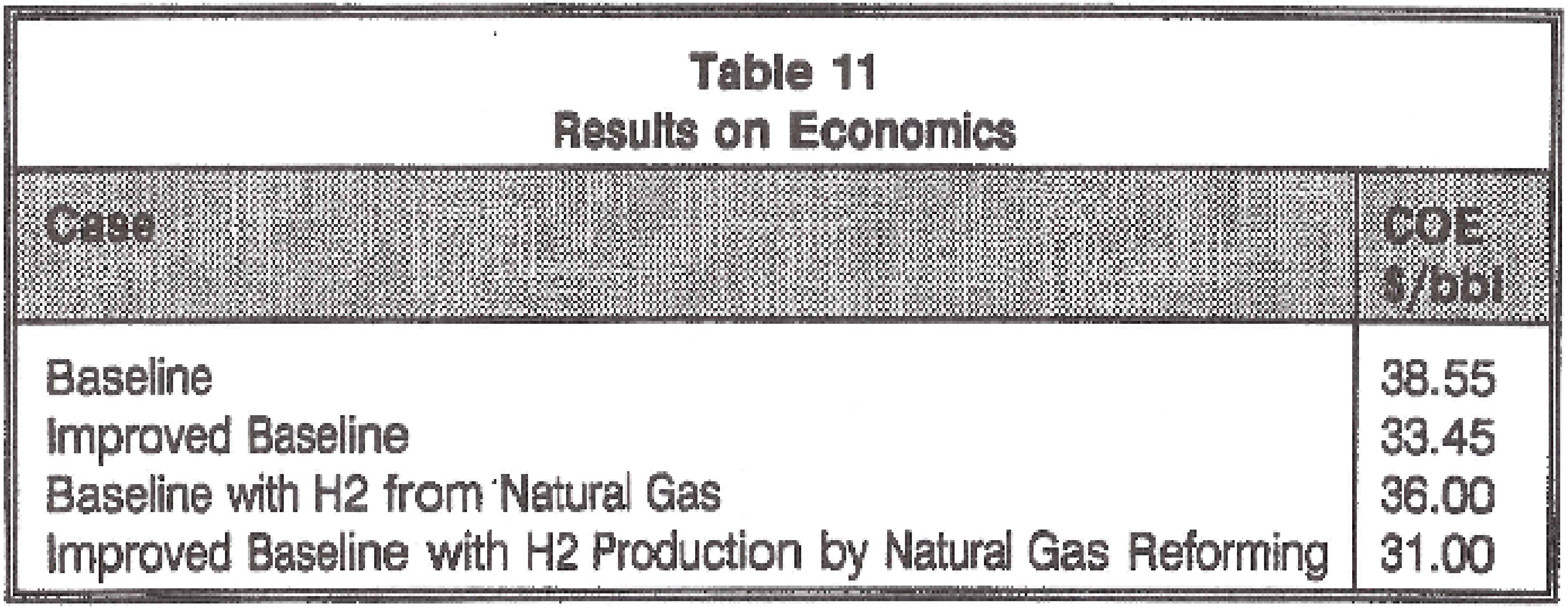


**Table 11**
**Results on Economics**

| Case | COE $/bbl |
|---|---|
| Baseline | 38.55 |
| Improved Baseline | 33.45 |
| Baseline with H2 from Natural Gas | 36.00 |
| Improved Baseline with H2 Production by Natural Gas Reforming | 31.00 |

Bechtel Baseline reports

# Bechtel Sub-bituminous Coal

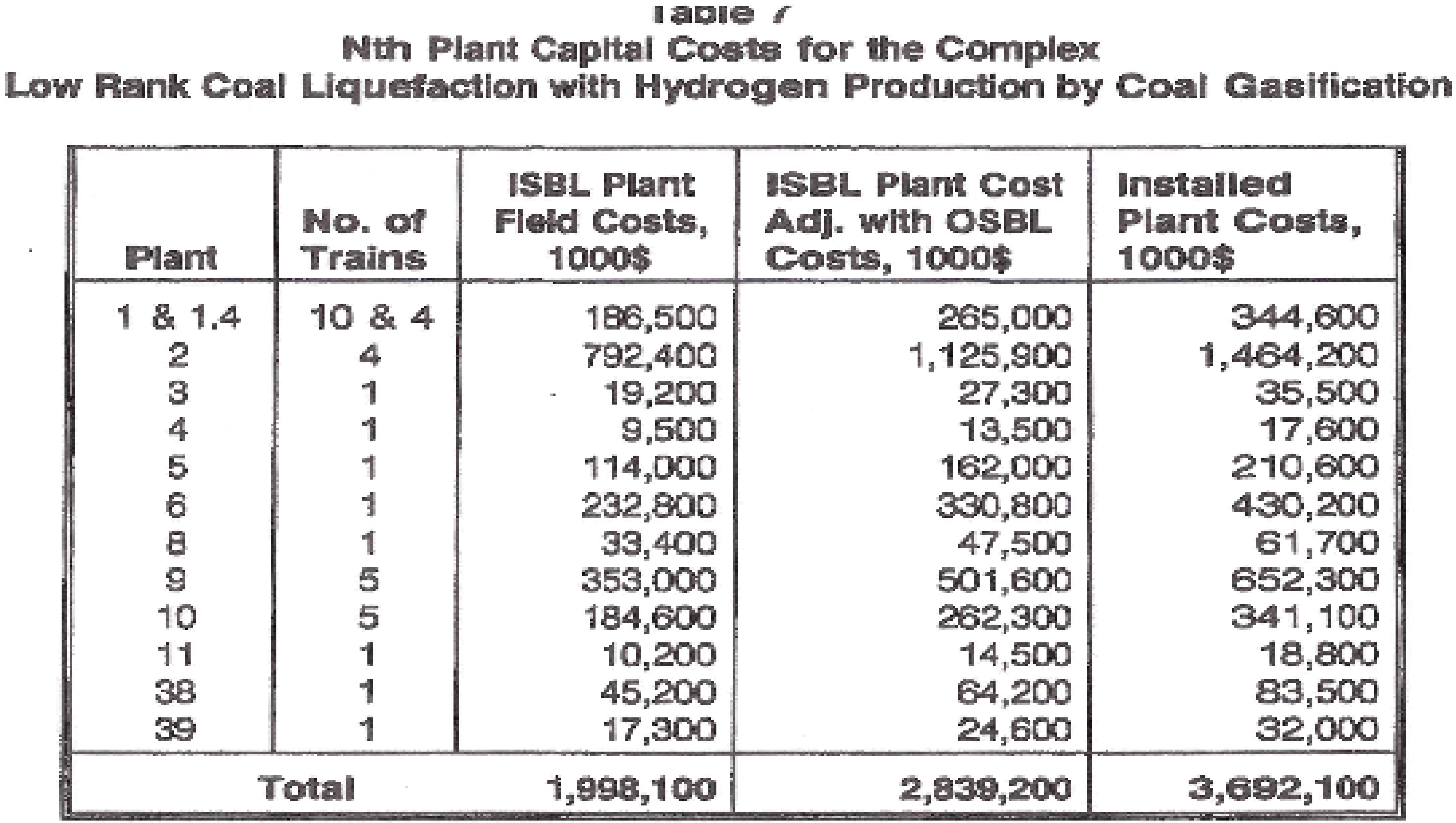


Table 7

Nth Plant Capital Costs for the Complex

Low Rank Coal Liquefaction with Hydrogen Production by Coal Gasification

| Plant | No. of Trains | ISBL Plant Field Costs, 1000$ | ISBL Plant Cost Adj. with OSBL Costs, 1000$ | Installed Plant Costs, 1000$ |
|---|---|---|---|---|
| 1 & 1.4 | 10 & 4 | 186,500 | 265,000 | 344,600 |
| 2 | 4 | 792,400 | 1,125,900 | 1,464,200 |
| 3 | 1 | 19,200 | 27,300 | 35,500 |
| 4 | 1 | 9,500 | 13,500 | 17,600 |
| 5 | 1 | 114,000 | 162,000 | 210,600 |
| 6 | 1 | 232,800 | 330,800 | 430,200 |
| 8 | 1 | 33,400 | 47,500 | 61,700 |
| 9 | 5 | 353,000 | 501,600 | 652,300 |
| 10 | 5 | 184,600 | 262,300 | 341,100 |
| 11 | 1 | 10,200 | 14,500 | 18,800 |
| 38 | 1 | 45,200 | 64,200 | 83,500 |
| 39 | 1 | 17,300 | 24,600 | 32,000 |
| Total | | 1,998,100 | 2,839,200 | 3,692,100 |

**Capital Cost 4th Q 1993 dollars**

Bechtel Baseline reports

# Bechtel Sub-bituminous Coal (2)

**Economics**

| Case | COE $/bbl |
|---|---|
| Low Rank Coal with H2 Production by Coal Gasification | 32.75 |
| Low Rank Coal with H2 production from natural gas | 33.85 |

Bechtel Baseline reports

# Potential Technology Vendors

EPCs: Bechtel, Fluor, Kellogg, Parsons

| Technology | Licensor | Process |
|---|---|---|
| **Coal Liquefaction** | **Axens**<br>**Accelergy**<br>**Chevron**<br>**Headwaters/HTI** | **H-Coal**<br>**EDS**<br><br>**CMSL** |
| **Bottom solid-liquid separation** | **Kerr McGee, ConocoPhillips, Exxon** | **ROSE™ de-asphalting**<br>**Delayed Coking**<br>**Fluid Coking** |
| **H2 (NG Reforming)** | **Foster Wheeler, Kellogg, ICI, Kvaerner, etc.** | |
| **H2 (coal Gasification)** | **GE, ConocoPhillips, Shell, Siemens, Lurgi, Southern Co.** | |
| **H2 Purification** | **UOP** | **PSA/Membrane** |
| **LPG Treating** | **UOP** | **Merox** |
| **Ammonia Removal** | **USX** | **Phosam-W** |
| **Phenol Removal** | **Koch-Glitsch** | **Dephenolization** |

# Design Thoughts and Issues

- **Bechtel design does not include updated information for HTI PDU activities and post DOE work**
- **Carbon footprint was not considered**
- **Technical information and more recent designs probably done by Headwaters and Axens which would be helpful to update the baseline.**
  - Verification of data may be difficult without independent experimentation
- **Active technology developers Headwaters and Axens (subsidiary of IFP)**
- **Other Technology Developers are working on advanced direct liquefaction technology – not public knowledge**

# Environmental Considerations

# Illinois No. 6 Coal Analysis

| **Proximate Analysis** | **wt.%** |
|---|---|
| Volatile Matter | 33.0 |
| Fixed Carbon | 38.3 |
| Ash | 20.0 |
| Moisture | 8.7 |

| **Ultimate Analysis** | **wt.% Dry** |
|---|---|
| Carbon | 61.5 |
| Hydrogen | 4.2 |
| Nitrogen | 1.2 |
| Sulfur | 5.1 |
| Chlorine | 0.1 |
| Ash | 21.9 |
| Oxygen (by difference) | 6.0 |

Burning Star Mine, ROM Coal Analysis

# Illinois No. 6 Coal Analysis (2)

| **Sulfur Forms** | |
|---|---|
| Pyrite | 38.3 |
| Sulfitic | 20.0 |
| Organic | 8.7 |

| **Ash Composition** | |
|---|---|
| P2O5 | 0.1 |
| SiO2 | 43.8 |
| Fe2O3 | 24.1 |
| Al2O3 | 17.1 |
| TiO2 | 0.6 |
| CaO | 5.6 |
| MgO | 1.0 |
| SO3 | 4.1 |
| K2O | 2.1 |
| Na2O | 0.6 |
| Undetermined | 0.7 |

Burning Star Mine, ROM Coal Analysis

# Other Coal Constituents

**Besides PAHs, coal also contains many toxic inorganic elements such as cadmium (Cd), arsenic (As), lead (Pb), selenium (Se), and mercury (Hg) that might be carried over into liquid fuel products.**

# U.S. Fuel Specifications (only a sample)

| Spec | Calif. RFG (Average)<br>http://www.arb.ca.gov/enf/fuels/phase3dates.pdf | On-Road Diesel<br>http://0301.netclime.net/1_5/0/H/K/Effect%20of%20Gen49D%20on%20.pdf | JP-8<br>ConocoPhillips |
|---|---|---|---|
| Sulfur (PPMW) | 15 | 15 | 3,000 |
| Aromatics (% Vol.) | 22 | 35 | 25 |
| Benzene (% vol.) | 0.7 | ---------------------- | --------------------- |
| Olefins (% vol.) | 4 | ---------------------- | --------------------- |
| Cetane Number (Min) | ---------------------- | 40(ASTM) (Engine Manufacturers: 42-45) | ---------------------- |
| Flash Point (°F, Min) | ---------------------- | ---------------------- | 100 (JP-5: 140) |
| Freeze Point (°C, Max) | ---------------------- | ---------------------- | -47 (JP-5: 46) |

# Comparison of DCL and ICL Final Products

| | **Direct** | **Indirect** |
|---|---|---|
| **Distillable product mix** | 65% diesel<br>35% naphtha | 80% diesel<br>20% naphtha |
| **Diesel cetane** | 42-47 | 70-75 |
| **Diesel sulfur** | <5 ppm | <1 ppm |
| **Diesel aromatics** | 4.8% | <4% |
| **Diesel specific gravity** | 0.865 | 0.780 |
| **Naphtha octane (RON)** | >100 | 45-75 |
| **Naphtha sulfur** | <0.5 ppm | Nil |
| **Naphtha aromatics** | 5% | 2% |
| **Naphtha specific gravity** | 0.764 | 0.673 |

**Final coal to liquid products meet stringent standards**

# Environmental Considerations

- **Baseline meets environmental standards as of 1990**
- **Waste streams addressed include:**
  - Solid waste
  - Waste water (organics including phenols)
  - Acid gases
- **Process equipment to meet the environmental standards included in baseline designs**
- **Solid waste and waste water use mainly standard equipment for petroleum processing or coal power plants – some novel processing**

# National Coal Council Report

| Plant Type | DCL | ICL Recycle | Hybrid |
|---|---|---|---|
| Coal Consumption<br>STPD dry basis | 23,044 | 32,305 | 25,514 |
| Liquid Products | | | |
| Diesel | 45,812 | 47,687 | 46,750 |
| Naphtha | 18,863 | 22,313 | 20,591 |
| LPG | 5,325 | 0 | 2,660 |
| Total | 70,000 | 70,000 | 70,001 |
| Electric Power | | | |
| Import | 282 | | |
| Export | | 1,139 | 45 |
| Overall Efficiency (%) | 60.1 | 47.4 | 58.7 |
| Plant CO2 Generation<br>(lbs/barrel) | 783 | 1,972 | 1,010 |

National Coal Council – June 2007

# National Coal Council Report (2)

| Plant Type | DCL | iCL Recycle | Hybrid | Spec/Typical<br>Conventional ULS Diesel |
|---|---|---|---|---|
| **Diesel** | | | | |
| Specific gravity | 0.865 | 0.78 | 0.821 | 0.82-0.85 |
| Cetane | 42-47 | 70-75 | 56-61 | > 40 |
| Sulfur (ppm) | < 5 | < 1 | < 3 | < 15 |
| Aromatics (%) | 4.8 | < 4 | < 4.4 | < 35 |
| Heating Value (Btu/Gal) | 138,100 | 129,800 | 133,950 | 138,700 |
| **Naphtha** | | | | |
| Specific gravity | 0.764 | 0.673 | 0.717 | 0.72-0.78 |
| Octane (RON) | > 100 | 45-75 | 75-95 | 85-95 |
| Sulfur (ppm) | < 0.5 | Nil | < 0.3 | < 30 |
| Aromatic (%) | 5 | 2 | 3.5 | < 27 |
| Heating Value (Btu/Gal) | 133,000 | 116,690 | 124,845 | 124,800 |

National Coal Council – June 2007

# LTI Review of NCC Data

## Preliminary for Discussion only

| **Plant Type** | **DCL** | **iCL Recycle** | **iCL Once-through** | **Hybrid** |
|---|---|---|---|---|
| Coal Consumption<br>STPD dry basis | 23,044 | 32,305 | 37,974 | 25,514 |
| Liquid Products | | | | |
| Diesel | 45,812 | 47,687 | 47,687 | 46,750 |
| Naphtha | 18,863 | 22,313 | 22,313 | 20,591 |
| LPG | 5,325 | 0 | 0 | 2,660 |
| Total | 70,000 | 70,000 | 70,000 | 70,001 |
| Electric Power | | | | |
| Import | 282 | | | |
| Export | | 1,018 | 1,139 | 45 |
| Overall Efficiency (%) | 60.1 | 48.4 | 47.4 | 58.73 |
| Plant CO2 Generation<br>(lbs/barrel) | 783 | 1,557 | 1,972 | 1,010 |
| **Plant CO2 Generation with sequestration for gasification** | 369 | 217 | 275 | |

National Coal Council – June 2007; Additional information LTI

# Current Technology Developments

# Shenhua DCL Project

# DCL Scale-up and Commercial Development

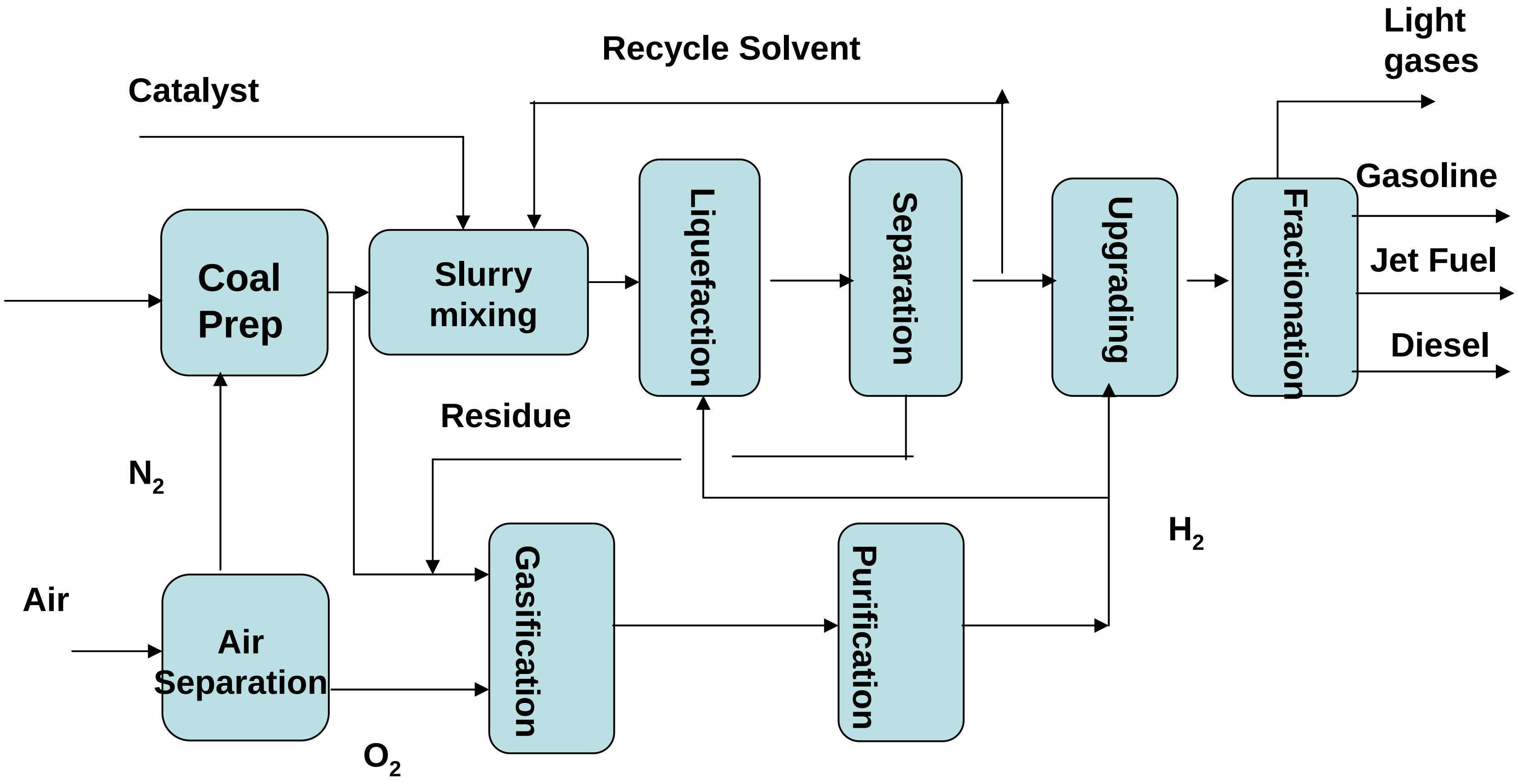
**Lawrenceville, NJ**
**30 bpd**

**Catlettsburg, KY**
**1800 bpd**

**Inner Mongolia, China**
**17,000 bpd**

Lepinski, Overview of Coal Liquefaction November 2005

# Shenhua DCL Project



Recycle Solvent

Light gases

Catalyst

Gasoline

Jet Fuel

Diesel

Coal Prep

Slurry mixing

Liquefaction

Separation

Upgrading

Fractionation

Residue

$N_2$

$H_2$

Air

Air Separation

Gasification

Purification

$O_2$

- Shenhua Direct Coal Liquefaction Process
- First Train: 1 MT/a Liquefaction oil

Shenhua Group, 2006

# Axens H-Oil and Coal Liquefaction Reactors

H-Oil Reactors in Poland

Shenhua Liquefaction Reactors

CTLtec Americas 2008

# Shenhua Plant

China Daily, S. Tingting, January 22, 2009

# Speculations About Shenhua DCL Plant

- **Direct liquefaction**
  - Conversion and hydrocracking to oils
    - Two reactors in series
    - Purpose: conversion and hydrocracking to oils
    - slurry catalyst
    - Expanded bed reactors (probably slurry)
  - Solvent Hydro-treating (?) and upgrading
    - Ebullated Bed (H-Oil)
    - Hydrotreating
    - Recycle solvent hydro-treating (?)
    - Manufactured petroleum catalyst (Co-Mo or Ni-Mo)

# Shenhua Patent

- According to a preferred embodiment of the invention, a test of direct coal liquefaction is performed using a low rank bituminous coal as feedstock, and the operation conditions and test results are as follows:
- Test operation conditions:
  - Reactor temperature: 1st reactor 455°C, 2nd reactor 455°C;
  - Reactor pressure: 1st reactor 19.0MPa, 2nd reactor 19.0MPa;
  - Slurry coal concentration: 45/55(dry coal/solvent, mass ratio);
  - Catalyst addition rate: Liquefaction catalyst: 1.0 wt %(Fe/dry coal);
  - Sulfur addition rate: S/Fe=2(molar ratio);
  - Gas/liquid: 1000NL/Kg slurry;
  - Hydrogen in the recycle gas: 85vol %.

***A PROCESS FOR DIRECT LIQUEFACTION OF COAL,*** *European Patent EP1783194*

# Shenhua Patent (2)

The results of direct coal liquefaction of a low rank bituminous coal in a CFU test unit of the invention is shown in Table 1, wherein the figures in the table are based on MAF coal. The results of the same kind of coal tested in another direct coal liquefaction CFU is shown in Table 2, wherein the figures in table 2 are also based on MAF coal.

**Table 1. Direct coal liquefaction results of a low rank bituminous coal in a CFU unit**

| | Conversion % | Oil yield % | Gas yield % | $H_2O$ yield % | Organic residue % | $H_2$ consumption % |
|---|---|---|---|---|---|---|
| Process of the invention | 91.22 | 57.17 | 13.11 | 12.51 | 23.99 | 6.8 |

**Table 2. Direct coal liquefaction results of a low rank bituminous coal in a CFU unit**

| | Conversion % | Oil yield % | Gas yield % | $H_2O$ yield % | Organic residue % | $H_2$ consumption % |
|---|---|---|---|---|---|---|
| Process of the prior art | 89.69 | 52.84 | 17.89 | 7.3 | 28.1 | 6.75 |

***A PROCESS FOR DIRECT LIQUEFACTION OF COAL,*** *European Patent EP1783194*

# Shenhua Information on PDU

- **Coal to liquid fuels product data**
  - – Naphtha product: 0.748-0.758 g/cm3
  - – N < 0.5 ppm (wt)
  - – Jet fuel: smoke point, 25mm, minimum
  - – Naphthene < 0.1wt%
  - – High density
- **Table of diesel product results**

| | **Diesel A** | **Diesel B** |
|---|---|---|
| **Density** | 0.866 | 0.86 |
| **S (mg/g)** | 1.8 (< 5ppm) | < 5 ppm |
| **Aromatics %** | 4.5 | 4.6 |
| **Carbon %** | 86.66 | 86.67 |
| **Cetane #** | 43.3 | 43.9 |

*U.S. DOE, M. Ackiewicz, Notes 2009*

# The Brown Coal Liquefaction Process

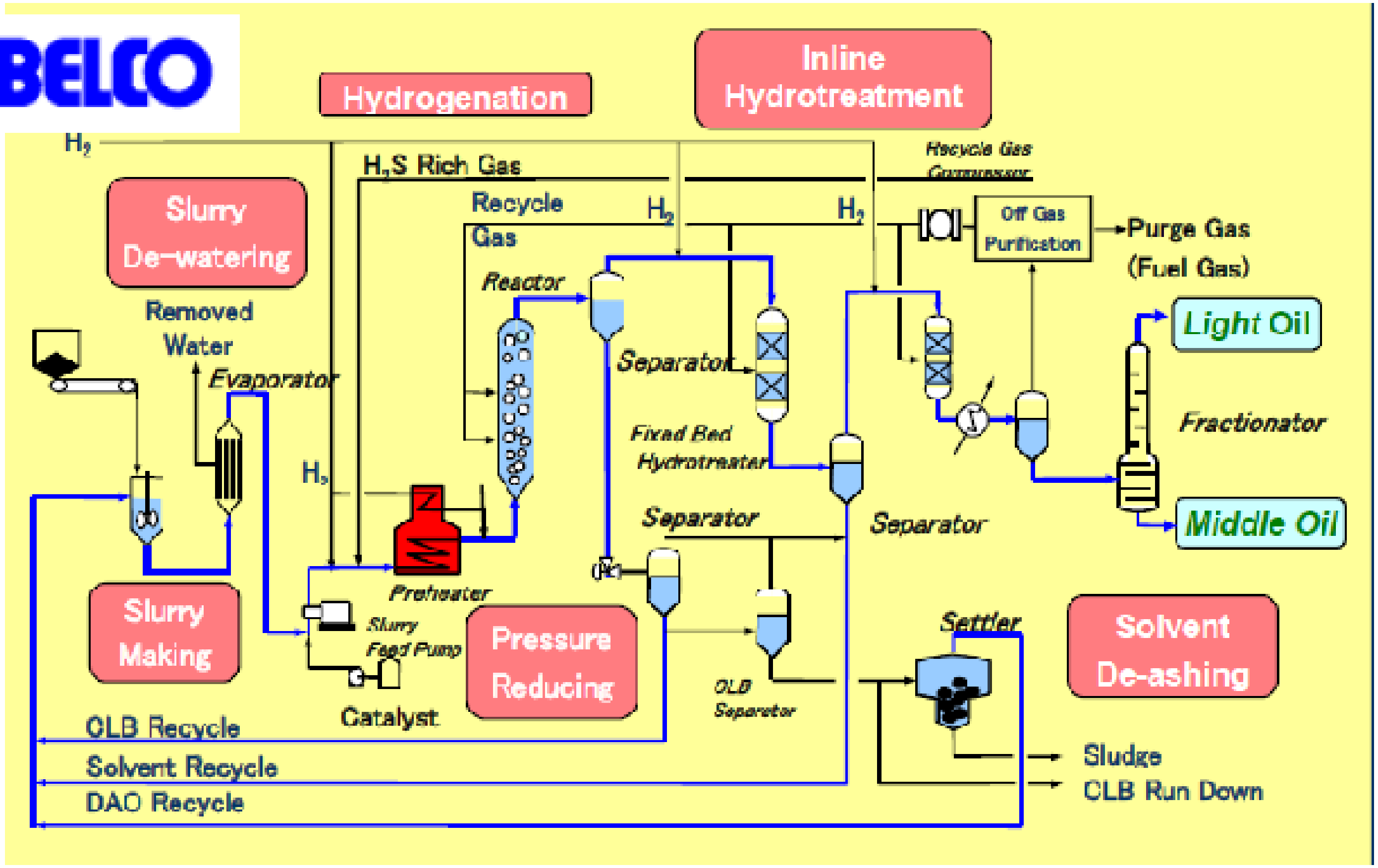
Centre for Management Technology®
Into our 24th year

CTLtec Americas 2008
23 - 24 JUNE
PITTSBURGH
USA

sojitz

# Improved Brown Coal Liquefaction (BCL) Process

KOBELCO



Source: Sojitz, CTLtec 2008

# Brown Coal Liquefaction Process

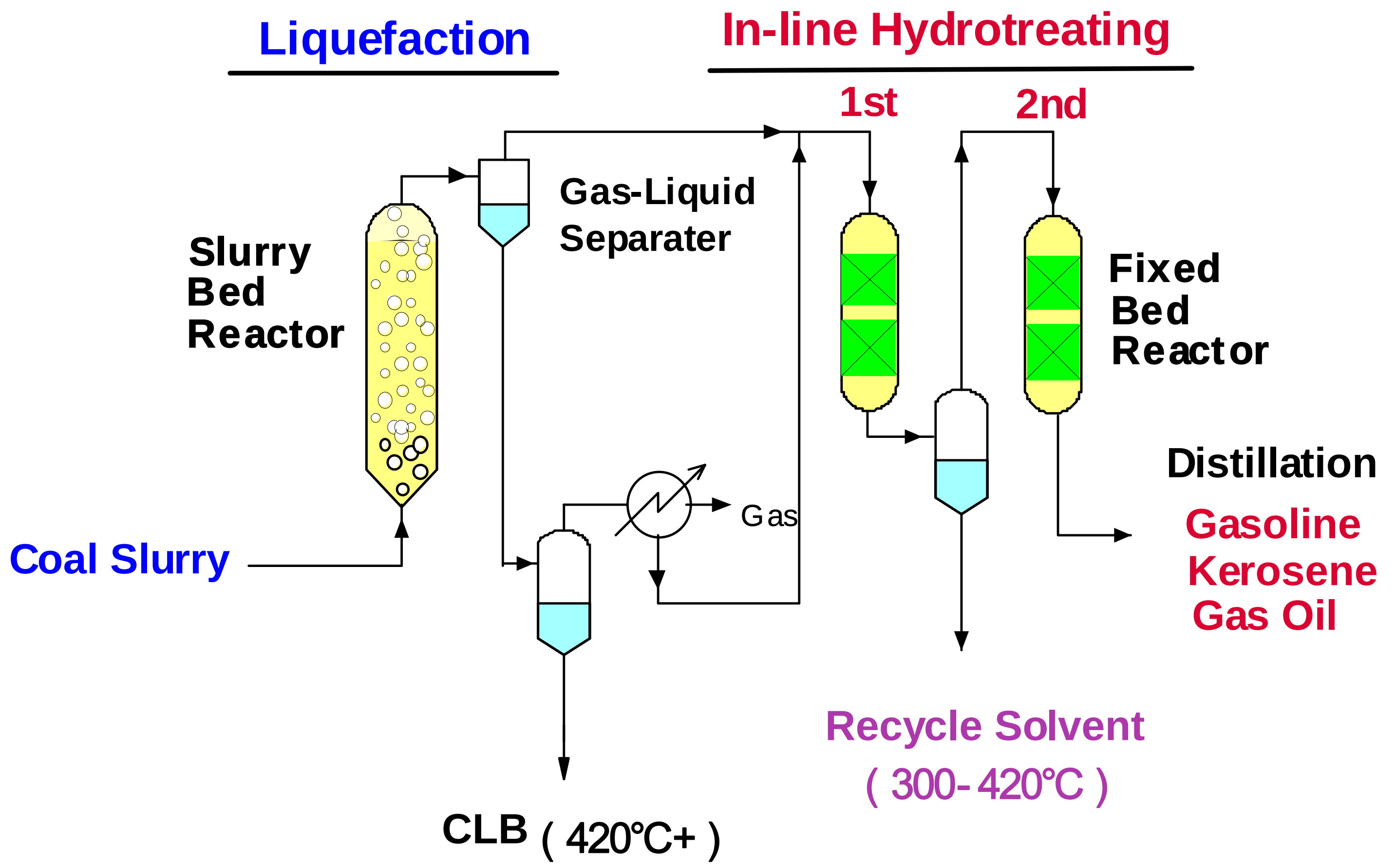


Fig. Conceptual flow of In-line hydrotreating section

Source: Sojitz, CTLtec 2008

# Brown Coal Liquefaction Process (2)

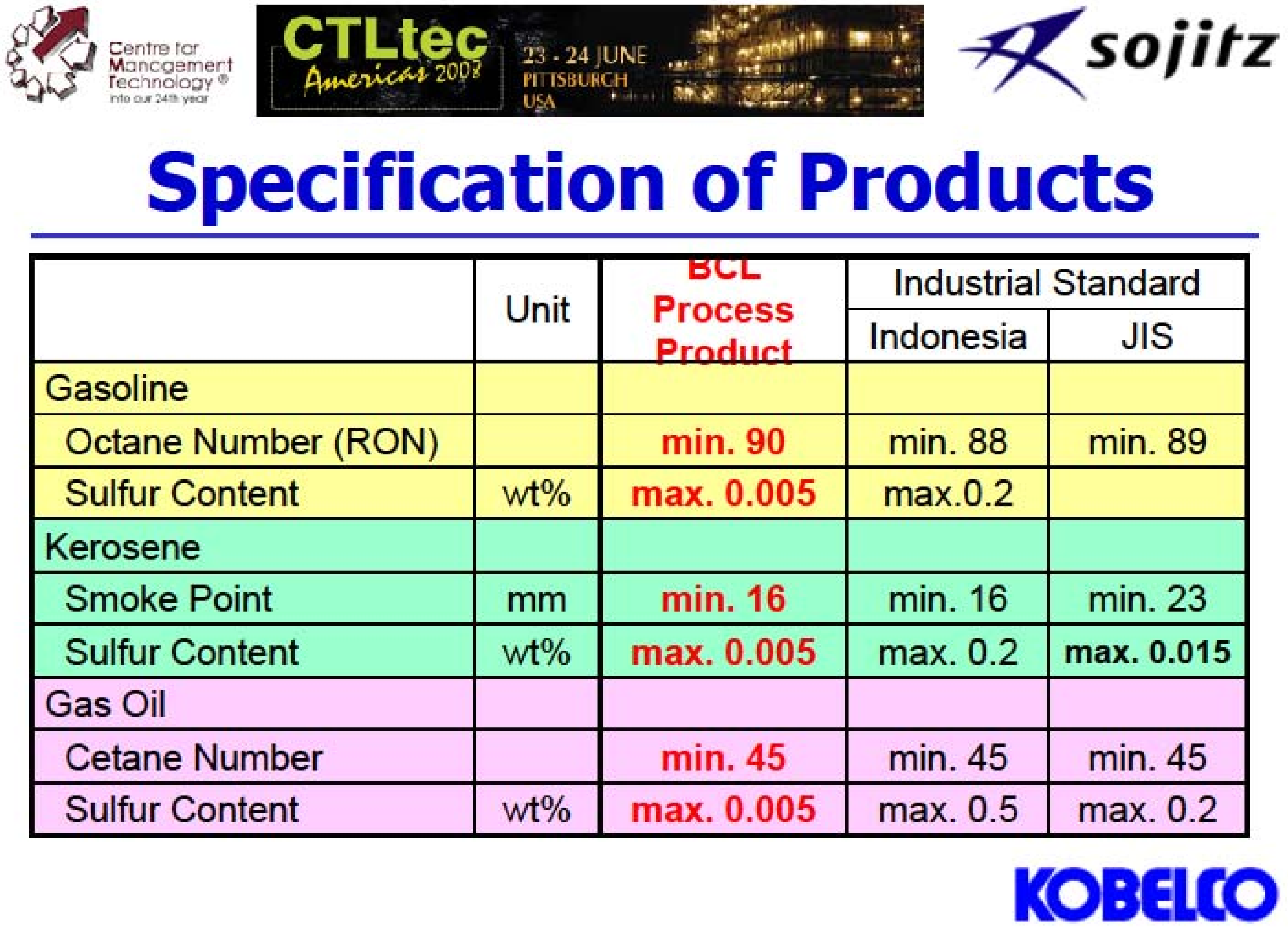
- The BCL process was developed by NEDO of Japan to a 50 tonnes/day pilot-plant scale, constructed at Morwell in Victoria, Australia.
- The process is designed specifically to handle very low-rank coals such as those found in the Latrobe Valley of Victoria, which may contain >60% moisture.
- It was operated over the period 1985-1990, processing a total of ~60,000 tonnes of coal. Operations ceased in October 1990.
- The plant was decommissioned in 1991 and demolished in 1992.
- A crucial aspect is the efficient drying of the coal. The 50 tonnes/day rated throughput of the pilot plant required ~170 tonnes/day of raw coal to be processed.
- Following extensive pilot plant operation, R&D using a 0.1 tonnes/day bench-scale continuous liquefaction test facility and related equipment was carried out until 1997 to improve the reliability, economics and environmental compatibility of the coal liquefaction process.

Dept. of Trade and Industry (U.K.), October, 1999

# Brown Coal Liquefaction Process (3)

- Based on the R&D results an improved BCL process was proposed. This comprises slurry de-watering, liquefaction, in-line hydrotreating, and de-ashing, with the following features:
  - use of a high-active and inexpensive catalyst such as limonite ore pulverized in oil
  - use of a heavy fraction solvent (bp 300-420ºC)
  - adoption of coal liquid bottom (CLB) bp>420ºC recycling
- Compared with the results of the pilot plant, the increase of oil yield, improvement of product oil quality and suppression of scale formation in reactors were proved using the bench-scale unit with <1% (dry ash-free coal) catalyst addition.
- It was estimated that the improved process could decrease the crude oil equivalent nominal price by 24% compared with the BCL process at the Australian pilot plant.
- Yields are stated to be 65% distillate.
- A new cooperation agreement was started between Japan (Sojitz) and Indonesia in 2005 to build a 27,000 BPD plant

Dept. of Trade and Industry (U.K.), October, 1999, Sojitz CTLtec -2008



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sojitz

# Specification of Products

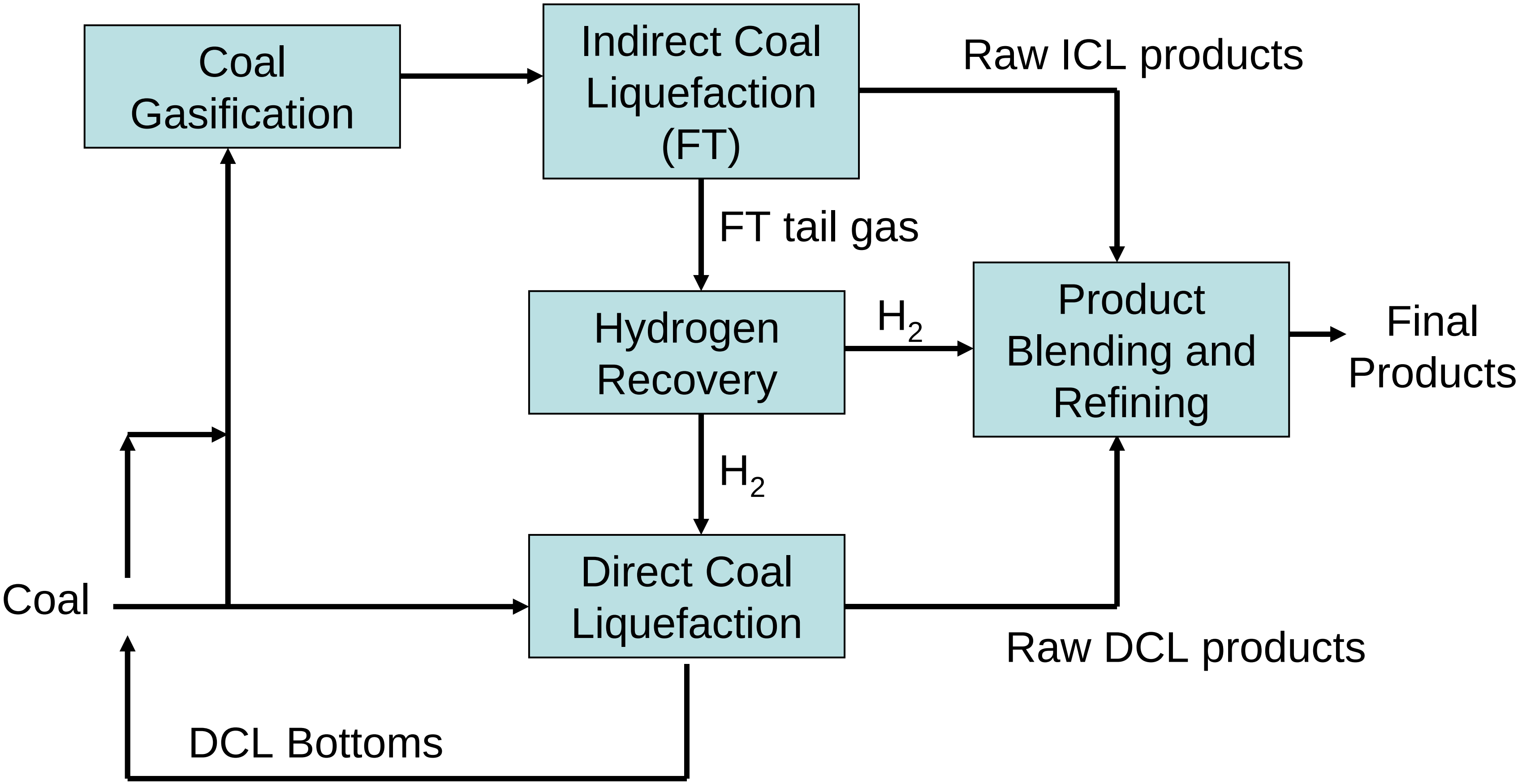
| | Unit | BCL Process Product | Industrial Standard | |
|---|---|---|---|---|
| | | | Indonesia | JIS |
| Gasoline | | | | |
| Octane Number (RON) | | min. 90 | min. 88 | min. 89 |
| Sulfur Content | wt% | max. 0.005 | max.0.2 | |
| Kerosene | | | | |
| Smoke Point | mm | min. 16 | min. 16 | min. 23 |
| Sulfur Content | wt% | max. 0.005 | max. 0.2 | max. 0.015 |
| Gas Oil | | | | |
| Cetane Number | | min. 45 | min. 45 | min. 45 |
| Sulfur Content | wt% | max. 0.005 | max. 0.5 | max. 0.2 |

KOBELCO

*Source: Sojitz, CTLtec 2008*

# Hybrid DCL/ICL Plant Concept

# Hybrid DCL/ICL Plant Concept



Coal Gasification

Indirect Coal Liquefaction (FT)

Raw ICL products

FT tail gas

Hydrogen Recovery

$H_2$

Product Blending and Refining

Final Products

$H_2$

Coal

Direct Coal Liquefaction

Raw DCL products

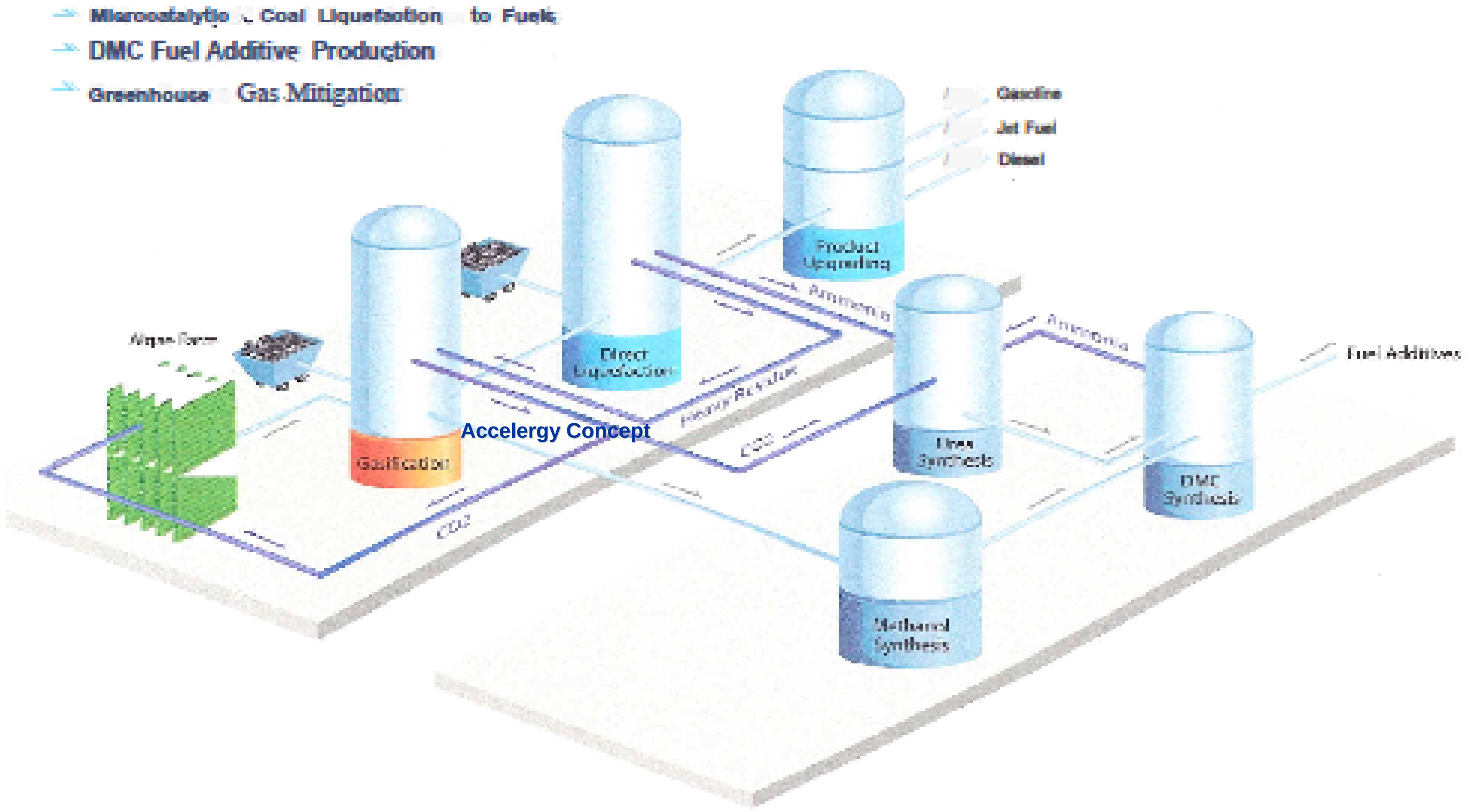
DCL Bottoms

# Hybrid Plant Theoretical Product Yields

| | |
|---|---|
| C3-C4 | 18 % |
| F-T naphtha | 19 % |
| DCL Naphtha | 26 % |
| F-T diesel | 22 % |
| DCL distillate | 10 % |
| DCL VGO | 5 % |

# Accelergy Concept

# Accelergy Concept



Accelergy Concept

Accelergy; http://www.accelergy.com/CTLprocess.php

# LTI
# Thoughts and Comments

# Potential Merits of Direct Coal Liquefaction

- DCL produces high octane gasoline
- DCL has higher thermal efficiency than indirect liquefaction
- Literature suggests that DCL with no CCS may have a lower carbon footprint
- Opportunity for combined coal and renewable energy processes with improved carbon footprint and carbon management
- Synergistic opportunities
  - Hybrid direct/indirect technology integration
  - Coprocessing with biomass (Hydrogen production)
  - Coprocessing with heavy oil/refinery bottoms/wastes(?)

# Thoughts and Issues

- LTI reviewed documents/analyses of direct liquefaction technology, design and current data where available
- General findings and conclusions
  - – Review of the past DOE R,D&D program generally agrees with the analysis and findings of Burke, Gray and Winschel, et al (2001)
  - – Significant progress has been made in achieving improved yield of distillate and product quality
  - – Reliability of operation of components has been increased

# Thoughts and Issues (2)

- Operation issues and readiness are still believed to be less than Indirect technologies and are a major concern
- Bechtel design for bituminous and sub-bituminous coals were thoroughly done and are authoritative
  - Were based on Wilsonville data and are still considered reasonably up to date, however:
    - Capital cost and economics must be revised
    - To the extent possible recent HTI and other data should be considered
    - Carbon footprint and carbon management were not considered

# Thoughts and Issues (3)

- HTI CMSL data with highest distillate results and later experimentation at the bench scale with coal and coal and other feedstocks (mixed plastics) needs further evaluation at the PDU scale to be considered highly reliable (this may have been done by HTI and others after the DOE program)
- Recent HTI results (for example) would meet current specifications for diesel and gasoline after significant hydrotreating

# Thoughts and Issues (4)

- Bechtel Baseline Design (1993) does not include updated information for HTI PDU activities and post DOE work
- Post Bechtel design information particularly CMSL provides hope for increased distillate but this is confounded by the many variables that effect yields and the small scale at which the data was generated
- The low sulfur and nitrogen content of the distillate achieved in the CMSL was due to in-line hydrotreating and lighter distillate
- Technical information and more recent designs probably done by Headwaters and Axens would be helpful to update the baseline.
  - Verification of data may be difficult without independent experimentation
  - Technology developers Headwaters and Axens (subsidiary of IFP) are actively seeking partners for direct liquefaction projects
  - It also appears that Shenhua, Sojitz as well as others are in some stage of planning or marketing their technology

# Thoughts on Present Concepts

- There is still competition for what is the preferred direct liquefaction Technology
- NEDO and Accelergy (possibly) are proposing single stage liquefaction through the primary use of a hydrogen donor solvent treated in a separate reactor
- Shenhua is supporting a combination of dispersed catalyst for liquefaction (single stage) and may be utilizing hydrogen donor solvent catalytically hydrotreated in separate reactors (H-Oil)
- HTI (and others?) are supporting two stage liquefaction (separate stages for coal dissolution and upgrading of the resulting oils). The technology likely incorporates use of either manufactured catalyst or dispersed catalyst
- Concepts are either providing a distillate crude for refinery upgrading or producing specification gasoline, diesel, jet fuel products. In either case, in-hydrotreating is being used in current technology.

# Thoughts on Present Concepts (2)

- It appears that current direct liquefaction distillate products can meet the existing fuel standards
- Concepts must have a strategy for waste product (liquefaction bottoms) use or disposal
- Configurations with liquefaction, upgrading, hydrotreating and ash separation will produce high yield, good quality products but are complex, highly integrated and capital intensive
- Need carbon management strategy, e.g. capture and sequestration of carbon produced during hydrogen production and/or use of renewable energy for hydrogen production or cofeeding

# Thoughts on Present Concepts (3)

- Other technology developers are working on advanced direct liquefaction technology – not public knowledge
- Similar to other complex conversion technologies, EPC contractors are available
  - Need track record in complex and large (multi $ billion) projects
- Specialized high pressure equipment vendors for reactors and components (slurry pumps, let-down values) are limited and probably foreign based (India/China)
- Shenhua could be useful source of information – material may not be available to public. WVU could facilitate obtaining information.

# Direct Liquefaction Technical Needs

- Advanced concepts
    - Reduce carbon footprint
    - Combination coal and renewable energy concepts
    - Co-feeding concepts
    - Less severe processing
        - Lower capital and process cost
- Product integration with refinery or finished distillate products
- Component material and reliability studies

# System Analysis Needs

- Perform carbon LCA for DCL using available data (Bechtel design study, e.g.) and compare with ICL
- Compare carbon LCA for two stage liquefaction with advanced one stage with separate reactor for hydrogenation of recycle hydrogen donor solvent
- Evaluate advanced concepts with reduced carbon footprint
  - Determine the benefits for producing hydrogen from non-carbon producing sources including biomass
  - Determine the benefits of hybrid concepts (combined direct and indirect liquefaction)
  - Determine the direct liquefaction opportunities for carbon capture and storage and other carbon management techniques

# System Analysis Needs (2)

- Direct Liquefaction Data Validation
  - Evaluate and confirm direct liquefaction data post DOE program
    - Two-stage liquefaction current concepts
    - Single stage
  - Compare catalyst and reactor types for direct liquefaction
    - Ebullated or slurry reactors
    - Manufactured or dispersed catalysts
  - Verify improved DCL product quality results (beyond that achieved in DOE program)

# System Analysis Needs (3)

- Shenhua Plant Operation
  - Confirm process operation (yields & quality)
  - Evaluate component reliability
  - Improve understanding of process configuration
  - Recognize that data may not be available in the public domain

# R&D Needs

- Verify by R&D Process and Product improvements
  - Verify improved DCL product quality results (beyond achieved in DOE program)
  - Hybrid Studies
    - Process and product optimization
    - Product characterization and compatibility
- Verify liquid products meet health and safety standards for commercial use
- Explore technologies to reduce water consumption
- Evaluate potential technologies that offer lower life cycle carbon footprint
  - Use of renewable feedstock or energy for hydrogen or synthesis
  - Integration with carbon management techniques

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