Acknowledgment & disclaimer

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Special thanks to the team members on this project for their contributions to this presentation:

- Richard Knight, Project Manager, Gas Technology Institute
- Jim Patel, Project Manager, Carbona/Andritz
- Jesper H. Jensen, Project Manager, Haldor Topsoe A/S
- Kip Walston, Project Manager, Phillips 66
- Pekka Jokela, Project Manager, UPM-Kymmene

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Wood to green gasoline project

U.S. Department of Energy
Golden Field Office

DOE Award No.
DE-EE0002874

DOE Program Manager:
Paul Grabowski

Government share:
$ 25,000,000

Cost share:
$ 9,388,775

Period of performance:
12/28/09 through 12/31/14
Project partners

Haldor Topsoe is a leading worldwide supplier of catalysts and catalytic technology for fuel conversion and upgrading. Provides: TIGAS process, syngas cleanup including tar reforming and conversion; overall project management.

Phillips 66 Company is a leading oil refiner & contributor to TIGAS. Provides: Liquids fuels handling, transportation and marketing, sample characterization, pilot plant design, construction, operation and scale-up assistance.

UPM is one of the world’s largest pulp and paper companies, with over 100 facilities. Provides: gathering, handling and transporting of wood; 1st commercial plant site.

Carbona is a supplier of biomass gasification and gas cleanup plants. Provides: fluidized-bed gasification, tar reforming, commercialization support.

GTI is the developer of gasification technology, licensor of acid gas removal process, and owner/operator of pilot plant test facility. Provides: design, construction, and operation of pilot plant plus modeling, data analysis, commercialization support.
# Project Go/No-Go Points

<table>
<thead>
<tr>
<th>Decision point</th>
<th>Basis</th>
<th>Month/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Complete preliminary design package</td>
<td>Preliminary HAZOP - <em>completed</em></td>
<td>Nov 2010</td>
</tr>
<tr>
<td>2. Complete detailed design package</td>
<td>Final HAZOP - <em>completed</em></td>
<td>Apr 2011</td>
</tr>
<tr>
<td>3. Proceed with BP-2</td>
<td>Final design review, capital cost update - <em>completed</em></td>
<td>May 2011</td>
</tr>
<tr>
<td>4. Proceed with procurement</td>
<td>Major bids received and evaluated - <em>completed</em></td>
<td>Sep 2011</td>
</tr>
<tr>
<td>5. Proceed with shakedown</td>
<td>Feedstock received in acceptable condition - <em>completed</em></td>
<td>Nov 2012</td>
</tr>
<tr>
<td>6. Proceed with Test Campaign</td>
<td>Independent Engineer Test approval - <em>completed</em></td>
<td>Oct 2013</td>
</tr>
</tbody>
</table>
TIGAS skid fabrication at Zeton
Construction at GTI – TIGAS module A1 lift
Process flow sheet of demonstration unit

Gasifier
145 psig/1600°F

Scrubber

Morphysorb
1015 psig/105°F

TIGAS
920 psig/430-750°F

Off-gas
Gasoline
Water

Wood pellets
Oxygen steam

Tar reformer
Syngas compressor
Guard bed
Separator
Carbona gasifier

BIOMASS

FLUIDIZED BED

GRID

FEEDING SCREW

ASH REMOVAL SCREW

Oxygen

ASH

ASHER REMOVAL SCREW

CYCLONE

GASIFICATION REACTOR

FEED HOPPER

HOT PRODUCT GAS
Topsoe TIGAS synthesis

CO + 2H₂ = CH₃OH
2CH₃OH = CH₃OCH₃ + H₂O
CH₃OCH₃ = 2 -CH₂- + H₂O
Shakedown testing

- Conducted 3 shakedown tests

- Stepwise full-scale operation of each major plant section at process conditions:
  - Gasification section (Nov 2012)
  - Gasification + AGR sections (Dec 2012)
  - Gasification + AGR + TIGAS (Jan 2013)

- Final commissioning of feedstock delivery system, CO$_2$ supply and purge system, syngas compressor, AGR upgrades, and TIGAS plant operation

- Total 200 hours of gasification, 103 hours AGR, and 56 hours TIGAS operation

- First gasoline production (100 gal)
Test #1 (March 5 - 22, 2013)

- Successful processing of wood feedstock from bulk trucks, to storage silo, and through the pressurized metering system into the gasifier at >75% capacity throughout the test.
- Stable, steady-state wood gasification at >75% capacity with 95% carbon conversion to syngas.
- Operation of tar reformer at varying conditions to optimize tar and hydrocarbon reforming, H₂:CO ratio, and energy efficiency.
- Reliable startup and sustained operation of syngas compressor at >75% design rate.
- Reliable AGR system extended operation, delivering decarbonized syngas at >75% capacity.
- Sustained 96% CO₂ capture from syngas with Morphysorb® solvent.
Test #1 (continued)

- 99.9%+ methanol conversion in TIGAS section
- Produced gasoline-range product at steady-state conditions for a total of 47 hours
- Produced 13.6 bbl of product
- Gasoline octane consistently above target
- Identified key steps to improve performance in next test
  - Hot gas filter durability and stability
  - Naphthalene control with stable catalyst performance
  - Minimization of N\(_2\) in syngas
  - Recycle of tail gas to gasification section
  - Optimization of TIGAS section conditions (P, T, internal recycle)
Test #1 technical data

<table>
<thead>
<tr>
<th>Syngas production and cleanup (entire test)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total biomass fed (6% moisture)</td>
<td>212 tons</td>
</tr>
<tr>
<td>Biomass feed rate</td>
<td>1450 lb/h</td>
</tr>
<tr>
<td>Hours of operation</td>
<td></td>
</tr>
<tr>
<td>Gasification</td>
<td>299 hours</td>
</tr>
<tr>
<td>TAR reformer</td>
<td>299 hours</td>
</tr>
<tr>
<td>Compressor</td>
<td>222 hours</td>
</tr>
<tr>
<td>AGR</td>
<td>215 hours</td>
</tr>
</tbody>
</table>

Front-end of the demonstration plant to produce clean syngas operated very well and was on stand-by for several days in readiness to provide syngas to the TIGAS synthesis section of the plant.
## Test #1 technical data (continued)

<table>
<thead>
<tr>
<th>Integrated TIGAS operation periods</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total biomass fed (6% moisture)</td>
<td>34 tons</td>
</tr>
<tr>
<td>Biomass feedrate</td>
<td>1450 lb/h</td>
</tr>
<tr>
<td>Hours of operation</td>
<td></td>
</tr>
<tr>
<td>TIGAS unit</td>
<td>56 hours</td>
</tr>
<tr>
<td>Gasoline production Period 1 (03/12-13)</td>
<td>9 hours</td>
</tr>
<tr>
<td>Gasoline production Period 2 (03/18)</td>
<td>15 hours</td>
</tr>
<tr>
<td>Gasoline production Period 3 (03/21-22)</td>
<td>23 hours</td>
</tr>
<tr>
<td>Total gasoline production time</td>
<td>47 hours</td>
</tr>
<tr>
<td>Gasoline produced</td>
<td>573 gal (13.6 bbl)</td>
</tr>
<tr>
<td>Octane number (R+M)/2</td>
<td>96.3</td>
</tr>
</tbody>
</table>

After initial mechanical start-up issues the TIGAS synthesis section of the demonstration plant operated very well at steady reactor temperature profiles.
Test #2 (October 18 – November 1, 2013)

- Operated the integrated demonstration plant at up to 100% load
- Verified successful performance of the new hot gas filter and other minor modification introduced post Test #1
- Conducted the Independent Engineer (IE) Test
- Introduced syngas recycle to gasifier to maximize yield
- Produced TIGAS gasoline for the emission test at SouthWest Research Institute in San Antonio, Texas
## Test #2 technical data

<table>
<thead>
<tr>
<th>Syngas production and cleanup (entire test)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total biomass fed (6% moisture)</td>
<td>182 tons</td>
</tr>
<tr>
<td>Maximum biomass feed rate</td>
<td>1689 lb/h</td>
</tr>
</tbody>
</table>

### Hours of operation

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification</td>
<td>248 hours</td>
</tr>
<tr>
<td>TAR reformer</td>
<td>248 hours</td>
</tr>
<tr>
<td>Compressor</td>
<td>235 hours</td>
</tr>
<tr>
<td>AGR</td>
<td>235 hours</td>
</tr>
</tbody>
</table>

Front-end of the demonstration plant to produce clean syngas operated very well and produced syngas for TIGAS unit within specifications.
## Test #2 technical data (continued)

<table>
<thead>
<tr>
<th>Integrated TIGAS operation periods</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total biomass fed (6% moisture)</td>
<td>150 tons</td>
</tr>
<tr>
<td>Maximum biomass feedrate</td>
<td>1689 lb/h</td>
</tr>
<tr>
<td>Hours of operation</td>
<td></td>
</tr>
<tr>
<td>Gasoline production Period 1 (10/22-26)</td>
<td>73 hours</td>
</tr>
<tr>
<td>Gasoline production Period 2 (10/27 -11/01)</td>
<td>121 hours</td>
</tr>
<tr>
<td>Total gasoline production time</td>
<td>194 hours</td>
</tr>
<tr>
<td>Gasoline produced</td>
<td>3954 gal (94.1 bbl)</td>
</tr>
<tr>
<td>Octane number (R+M)/2</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>

The TIGAS synthesis section operated very well at steady reactor temperature profiles, stable product distribution, very low methanol slip, and an increasing gasoline yield.
Independent Engineer (IE) Test

Objectives:

- Demonstrate that all of the instrumentation and analytical equipment is in place and operating satisfactorily – **PASSED**
- Demonstrate that all of the mechanical, electrical and environmental control systems are complete and capable of operating safely and within the permit limitations – **PASSED**
- The facility has operated continuously throughout the IE Test at a minimum average feed rate of 1,430 lb/h of wood pellets for 72 hours – **PASSED (actual was 1,601 lb/h)**
- The product gasoline produced during the IE Test is a liquid hydrocarbon product in 4 to 12 carbon range with a minimum average of research and motor octane ((R+M)/2) of 83 – **PASSED (actual average was 90.2)**
- The methanol content of the water condensate produced during the IE Test is less than one weight percent – **PASSED (actual was 0.0106 wt-%)**

*During the IE Test the plant produced about 1700 gallons of gasoline*
Test #3 (March 3 – 16, 2014)

- Operated the integrated demonstration plant at up to 100% load with recycle.
- Produced more than 8000 gallons of TIGAS gasoline for the fleet test at test site in Ohio
TIGAS gasoline testing

- Engine emissions testing at SwRI
  - Tested a 80/20 high biomass TIGAS/gasoline blend
  - Emission level better than conventional gasoline
  - Phillips 66 will prepare EPA application for this blend

- Moderate Fleet Testing (planned for spring/summer 2014)
  - 8 vehicles over ~ 4 months
  - Accumulate ~ 600,000 miles
Innospec Fuel Specialties performed corrosion evaluation of the raw TIGAS gasoline product using the NACE TM01-72 Corrosion Test.

With a low treat rate of 2 ptb DCI-6A the raw TIGAS gasoline meets the typical Pipeline Specification of B+ (<5% corrosion).

The actual test data showed much less corrosion corresponding to a B++ (<0.1% corrosion).

A blend of the raw TIGAS gasoline and ethanol (E10 Blend) meets the B+ rating even before adding any corrosion inhibitors.
Process efficiency in commercial plant

- **Energy efficiency***
  - 45% input energy (biomass) converted to finished products (gasoline + LPG)

- **Carbon efficiency***
  - 32% input carbon (biomass) converted to finished products (gasoline + LPG)

* Based on original proposed design basis
Project economics

Gasoline retail price prediction – example California

Crude prices year 2020

Crude at $155/barrel

Crude at $106/barrel

Crude at $69/barrel

Areas for further development & demonstration

1. Total installed cost
   - Processing biomass is more expensive than using natural gas
   - Consider co-feeding biomass and natural gas (shale gas)

2. Optimization of the biomass gasifier system

3. Optimization of gas recycling
   - Back to gasifier for conversion of hydrocarbons
   - Back to Methanol/DME reactor for increased conversion of syngas

4. Continued optimization of catalysts
   - Increased yield and selectivity
   - Increased resistance towards poisoning (deactivation)