2013 DOE Bioenergy Technologies Office (BETO) Project Peer Review

WBS 3.2.5.12 - Validation of the RTI Therminator Syngas Cleanup Technology in an Integrated Biomass Gasification/Fuel Synthesis Process

Date: May 20, 2013

Gasification Technology Area

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RTI International

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Syngas Cleanup Goals

Feed Processing & Handling → Biomass Gasification → Syngas Cleanup → Syngas Conditioning → Catalytic Fuel Synthesis → Next Generation Biofuels

Crystallized light tars in IC engine intake manifold (courtesy Dahlman)

Targets

Tar < 0.1 g/Nm^3

NH_3 < 10 ppm

H_2S < 100 ppb

HCl < 10 ppb

Heavy tar accumulation (courtesy ECN)

Technical Goals

- Reduce syngas cleanup process complexity
- Validate technology with biomass-derived syngas

Economic Target

- Reduce syngas cleanup/conditioning capital and operating costs to achieve biofuel production cost goals

Process Advantages

- Thermally efficient
- Cleaner and reduced-volume water product
- Process intensification (i.e., fewer unit operations)

Quad Chart Overview

Timeline

- Project selected: 12/7/2007
- Conditional project award date: 9/30/2008
- Project award date: 3/12/2009
- Project start date: 9/30/2008
- Phase 1 Completion date: 9/30/2011
- Stage Gate Review: 12/14/2011
- Decommissioning complete: 12/15/2012
- Project end date: 9/30/2013
- Percent complete: 100%

Budget

- $3.1MM Total project funding
  - $2MM DOE share
  - $1.1MM Contractor share
- $600,000 received in FY09
- $503,296 received in FY10
- $896,704 received in FY11
- No ARRA funding

Barriers Addressed

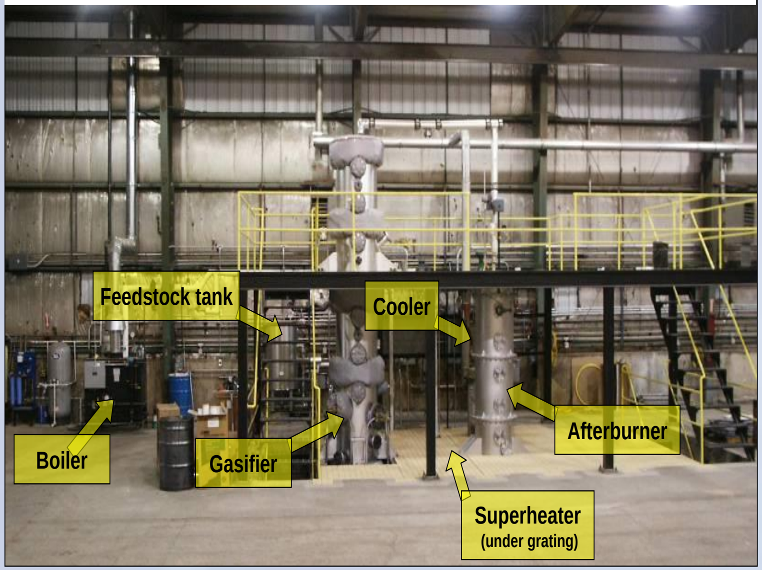
- Gt-C High-Temperature Gas Production from Biomass
- Gt-F Gas Cleanup and Conditioning
- Gt-H Validation of Syngas Quality

Partners

- RTI – project lead, gas cleanup and fuel synthesis technology, project management
- University of Utah – pilot-scale biomass gasification facility
- North Carolina State University – feedstock provider and process modeling
- Golden Leaf Foundation – pilot-scale lignin-rich feedstock production
- Biofuels Center of North Carolina

Project Overview

University of Utah's Industrial Combustion and Gasification Research Facility



- Woody biomass and lignin-rich torrefaction residues
- Indirect biomass gasification
- RTI's Tar cracking gas cleanup technology
- Catalytic fuel synthesis

Biomass Gasification

- Long-term, steady-state operation
- Tar sampling
- Effect of biomass torrefaction on syngas quality and tar formation

Tar Cracking Reactor Sub-system

- Successful cold flow testing
- Successful commissioning with biomass-derived syngas
- Demonstrate feasibility of continuous reaction-regeneration process
- Complete 300 hours of integrated biomass gasification/gas cleanup
- Achieve gas cleanup targets for tar and sulfur removal

Project Work Plan

Phase 1

- Task 1: Biomass Feedstock Selection and Analysis
- Task 2: Commission University of Utah Gasifier with Selected Feedstock
- Task 3: Integration of Gasifier with Therminator
- Task 4: Process Modeling for Selection of Fuel Synthesis Process
- Task 5: Accelerated Fuel Synthesis Catalyst Poisoning Studies
- Task 6: Integrated Gasification/Gas Cleanup Testing
- Task 7: Stage Gate Review

Phase 2

- Task 8: Modification and Commissioning of Fuel Synthesis Reactor System
- Task 9: Procurement and Commissioning of Clean Syngas Compressor To Compress the Syngas to 1,000+ psi
- Task 10: Integration of Gasifier, Two-Stage Therminator, Compressor, and Fuel Synthesis Reactor
- Task 11: Integrated 500-h Testing of University of Utah Gasifier, RTI Therminator, and RTI Fuel Synthesis Reactor, and Data Analysis

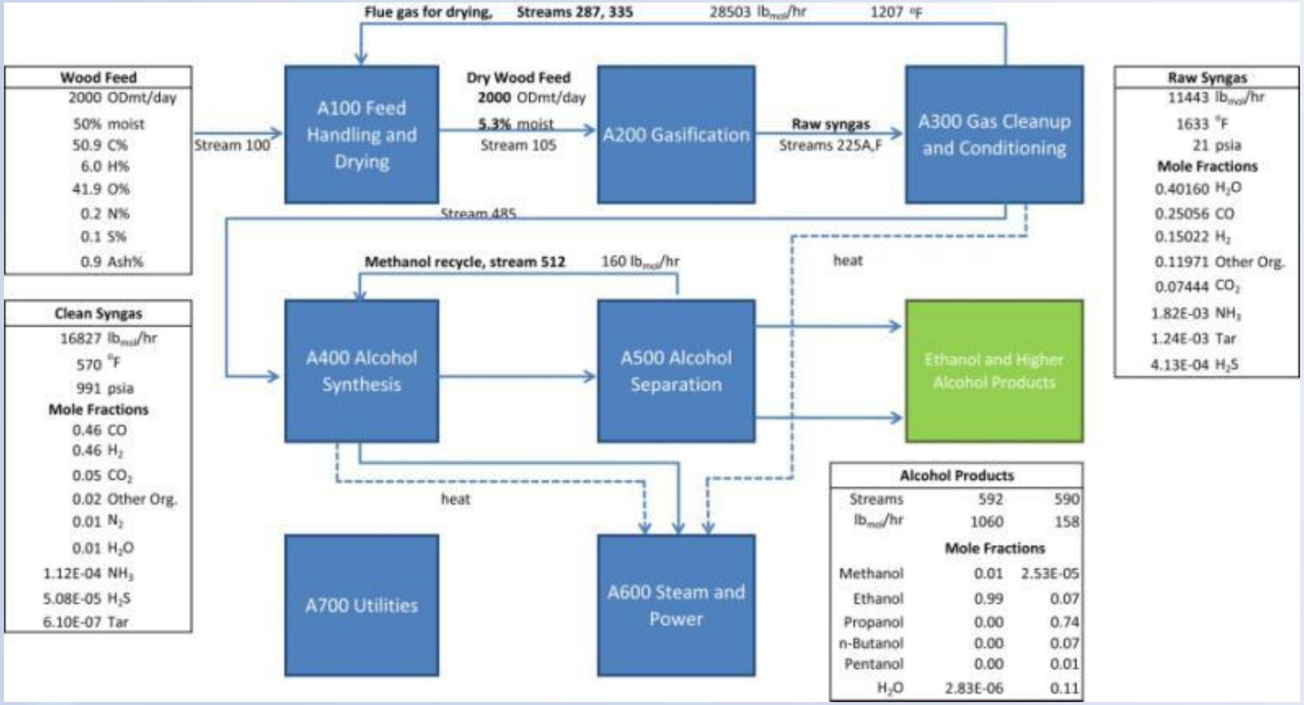
Biomass Feedstock Selection and Analysis

	Untreated	Mildly Torrefied	Severely Torrefied
Bulk Density, kg/m^3	300	250	200
Proximate Analysis, wt% (dry basis)			
Volatile matter	85.0	78.6	60.0
Fixed Carbon	12.4	20.8	38.6
Ash	2.6	0.6	1.4
Ultimate Analysis, wt% (dry basis)			
Carbon	49.3	55.0	65.8
Hydrogen	6.3	5.9	4.9
Oxygen	44.0	39.0	29.0
Nitrogen	0.4	0.1	0.3

- 19.7 tonnes of mixed softwood (primarily loblolly pine) supplied by Weyerhaeuser
- 45 wt% moisture, as received
- Biomass Preparation: screened to separate > 3/8” pins and fines
- Air dried over three weeks to 30 wt% moisture (Untreated feedstock)
- 500 lbs each of lignin-rich biomass generated using torrefaction at two different temperatures
  - Mildly torrefied biomass: 300ºC
  - Severely torrefied biomass: 400ºC

Process Modeling

- A Comparison of Two Modeled Syngas Cleanup Systems and Their Integration with Selected Fuel Synthesis Processes based on NREL Thermochem Mixed Alcohols ASPEN Model

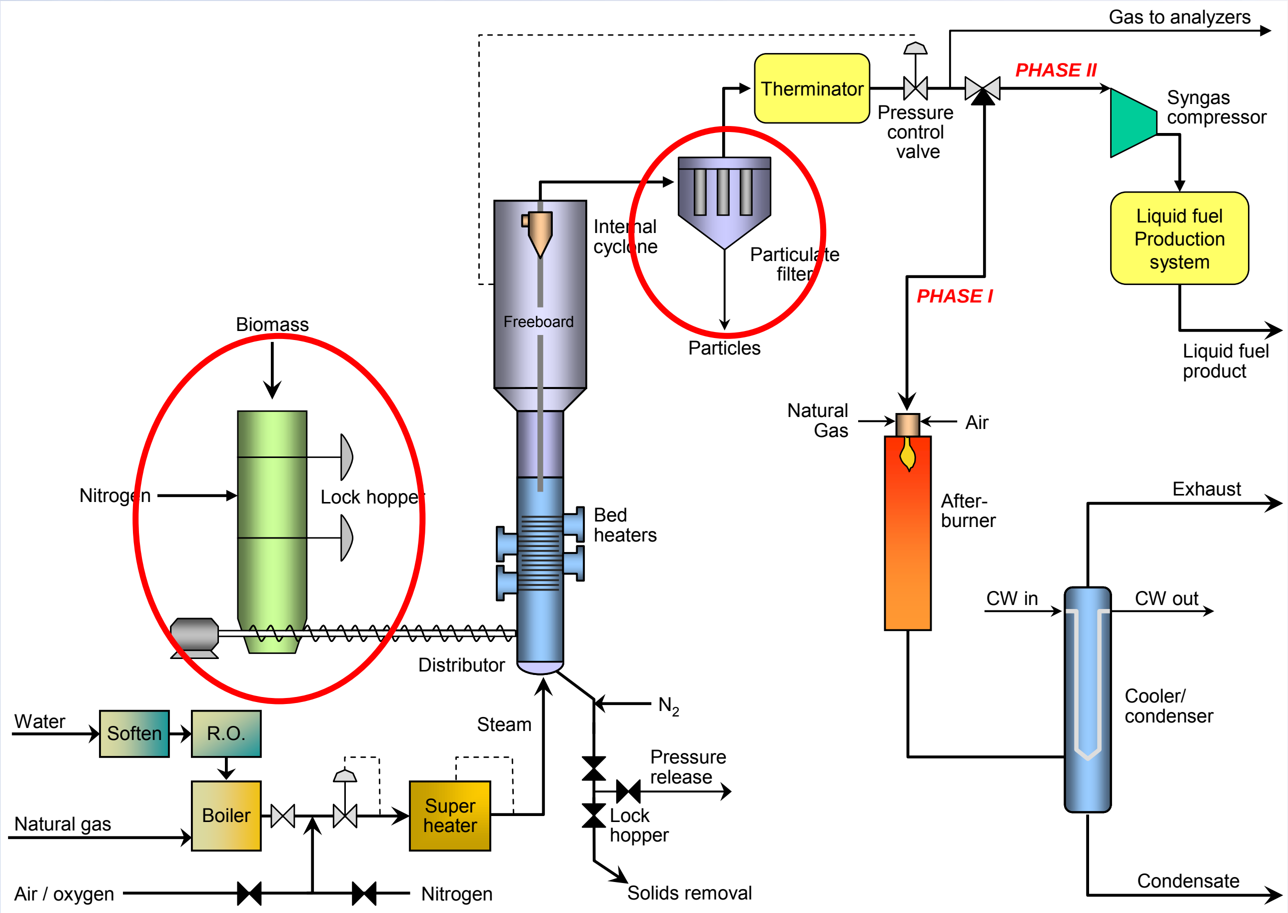


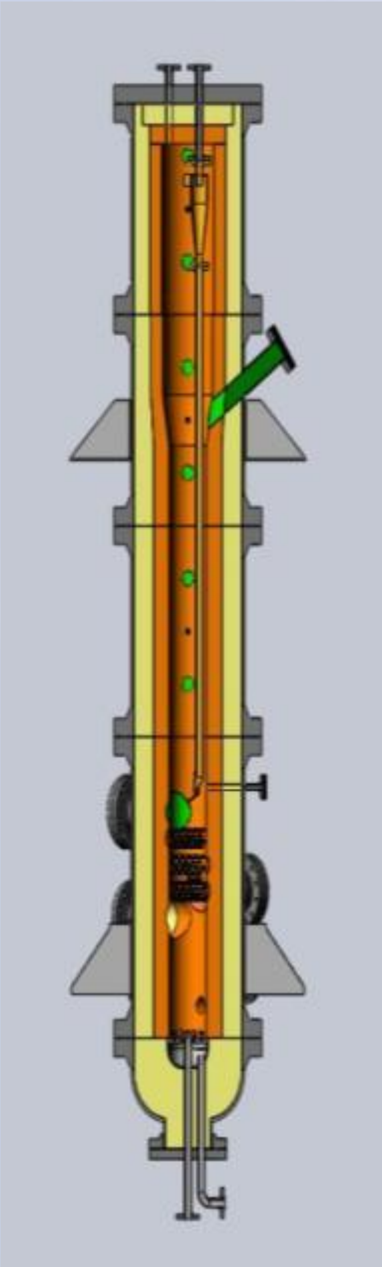
- NREL model combines H_2S removal with acid gas (CO_2) removal
- RTI Gas Cleanup unit has no CO_2 removal section
- Methane reforming generates more H_2
- More biofuel yield with reforming but revenue from fuel plus electricity is comparable for both cleanup options

Biomass Gasifier Commissioning

System Modifications

- Install Pressurized biomass feed system
- Install hot gas particulate filter
- Baseline biomass gasification tests
- Interconnections for tar cracking unit





Industrial Combustion and Gasification Research Facility (ICGRF) – U of Utah

- Indirect gasifier
- Refractory lined bubbling fluidized bed (BFB)
- Air or steam blown
- Bed: 1.5m x 25cm
- Freeboard: 3m x 36cm
- Max. press.: 7 bar
- Max. temp.: 870°C
- Boiler: 116 kW and 130 kg/hr
- Steam superheater: 35 kW
- Bed heaters: 32 kW total
- Bed solids removal via lock-hopper

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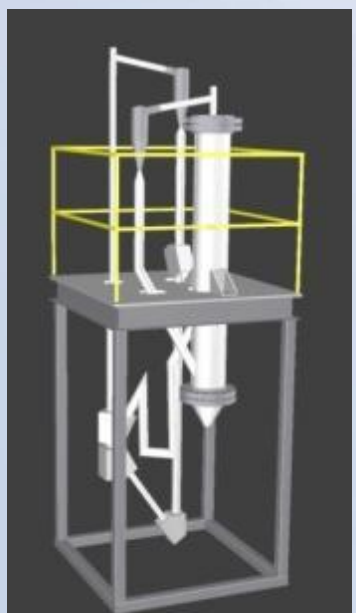
Gas Cleanup Technology Development Approach

Catalyst Development
- Productivity
- Attrition resistance
- Stability

Process Development
- Reaction kinetics
- Integration strategy

Catalyst Development
- Catalyst scale-up

Process Development
- Reactor scale-up
- Continuous operation
- Performance evaluation
- Pilot-plant testing



Catalyst development and testing
- Tar cracking catalysts
- Lab-scale fluidized bed testing

Process design and development
- Process modeling; material and energy balances
- Detailed engineering design; Fabrication; Installation and hot testing

Biomass feedstock preparation and pretreatment (torrefaction)

Biomass gasifier modifications

Pilot-scale (20 kg/hr) integrated biomass gasification/gas cleanup/catalytic fuel synthesis

Tar Cracking Catalyst Development Catalyst Screening-RTI

Objectives

- Measure tar cracking rates and activity in a laboratory-scale fluidized bed reactor system
- Determine carbon deposition rates
- Develop operating conditions for pilot-scale system

Reaction conditions: 1 atm, 600-700 ° C

Feed composition: 30% H_2,15% CO, 5% CO_2, 40% H_2O, 10% N_2, 35 g/Nm^3 Tar, 100 ppm H_2S

Tar Composition: Phenol, cresol, naphthalene and methyl naphthalene in toluene

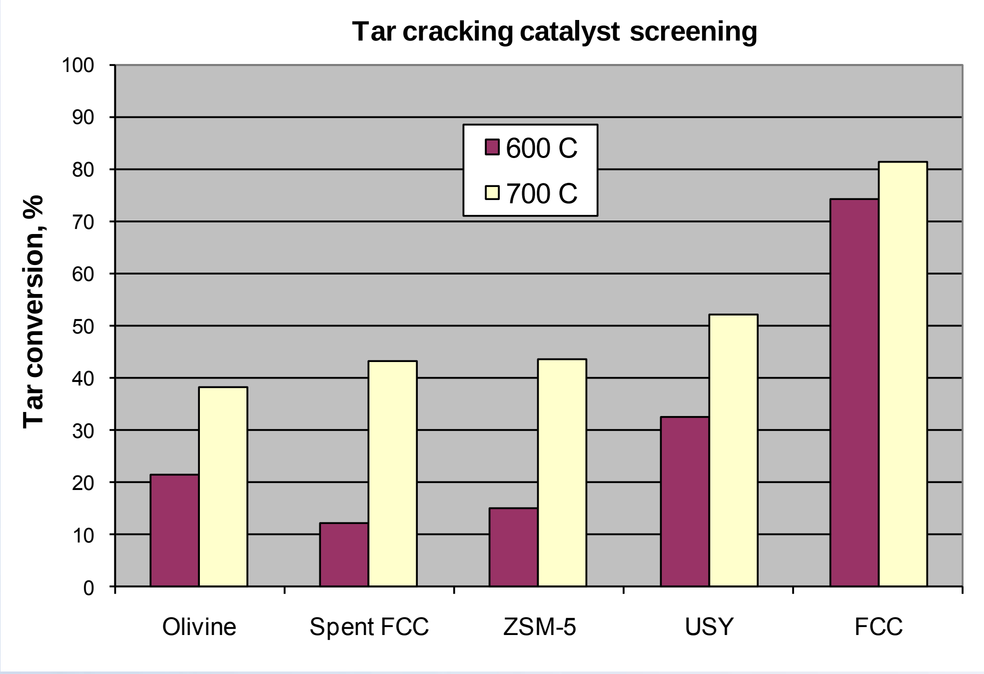
Flow rate: ~20 slpm

Solid loading: ~500 g

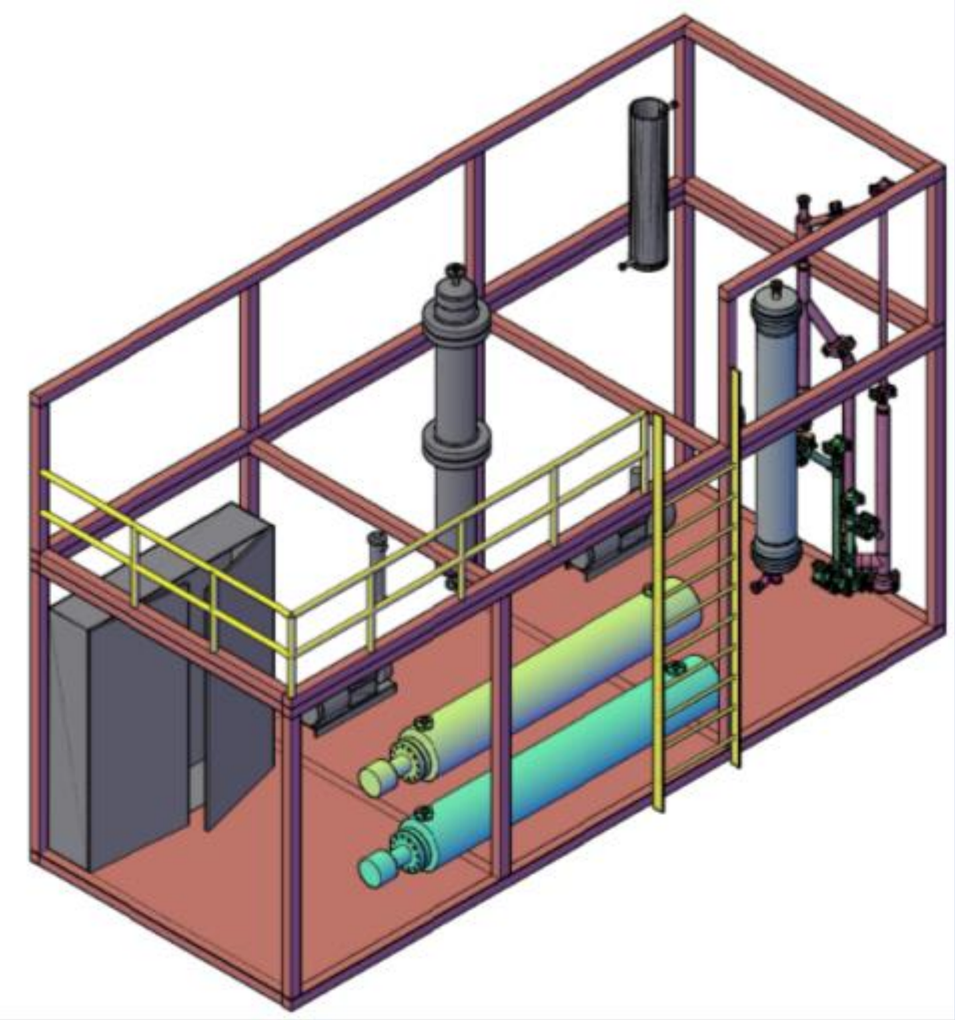
Catalyst screening experiments conducted in nitrogen

- Olivine is a well known tar reforming catalyst
- Zeolite catalysts provide the acidity required for hydrocarbon cracking
- USY was identified as an active catalyst in previous work

- Significant increase in tar conversion at higher temperature
- FCC Catalyst supplied by Inprocat Inc. (EnlightenMax®) had the best tar cracking activity for pilot-scale testing



Tar Cracking Process Development

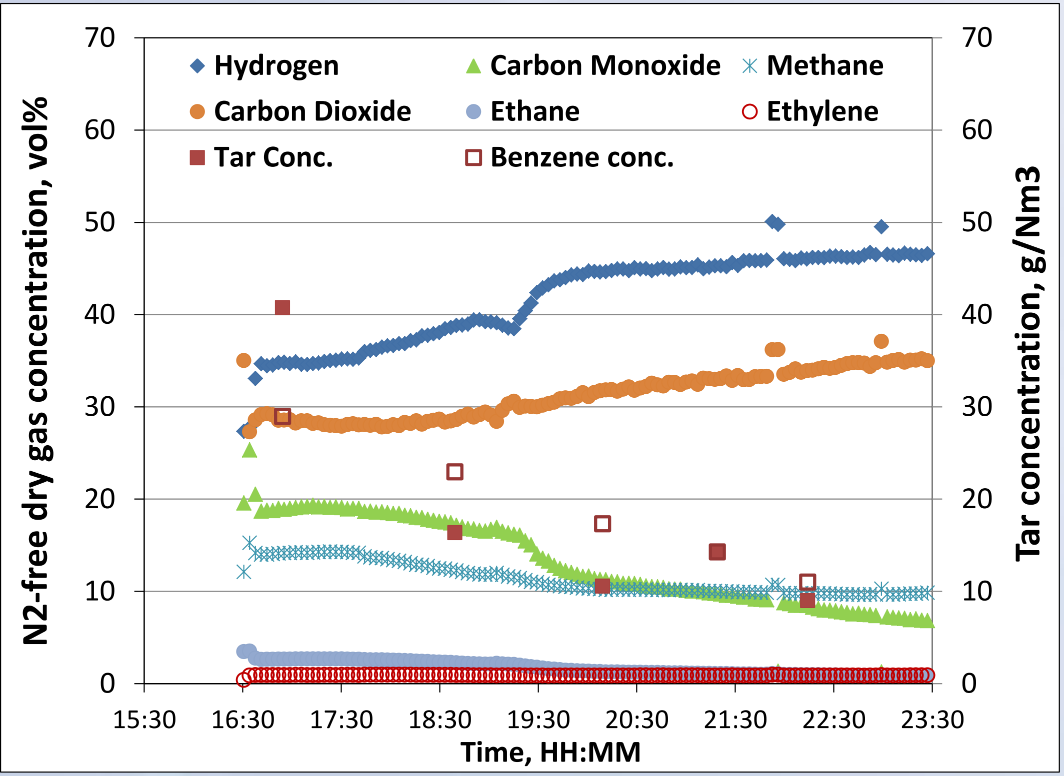


- Design for 20 kg/hr indirect biomass gasifier (2,900 SCFH syngas)
- Design basis: 22 psig, 600 °C
- Design limits: 150 psig, 650 °C, 3,400 SCFH syngas
- Bubbling bed absorber
- Circulating regeneration loop for continuous operation
- Solids circulation rate: 636 lb/hr

Therminator-Fabrication & Installation

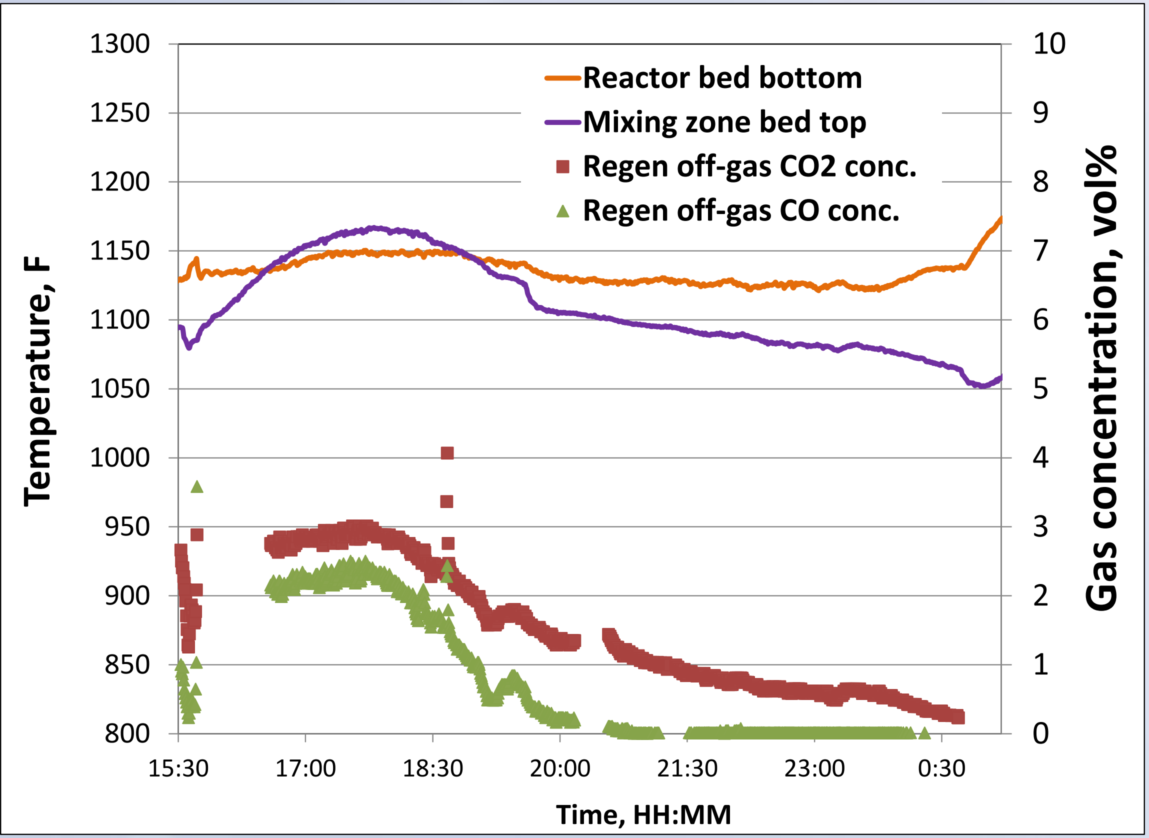
- Therminator fabrication completed July 2010
- Factory acceptance test completed July 2010
- Shipped to Utah September 2010
- Installation and commissioning October 2010 – January 2011
  - Inlet and outlet syngas lines and bypass valves installed
  - All mechanical connections (compressed air, process nitrogen, chilled water, and vent lines)
  - Electrical connections
  - Control system installation and testing

Raw Syngas Composition



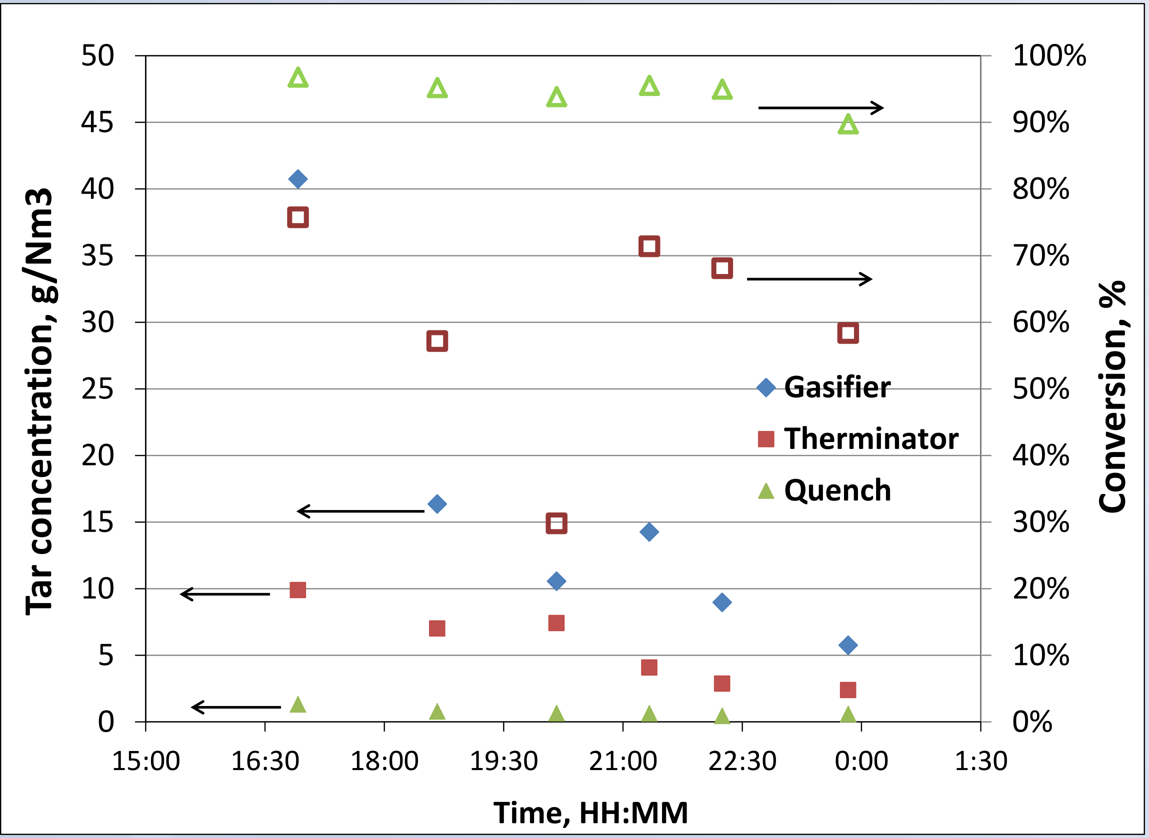
- Low temperature and insufficient mixing of gasifier bed leads to high methane and light hydrocarbons concentration at the start of the run
- Methane and light hydrocarbon concentration decreases with time
- Concentration of tar decreases with time on stream: from 40 to 9 g/Nm^3
- H_2:CO increases from 1.8 at the start of the run to 6.5 towards the end
- Tar concentration decreases with time
- CO content decreases with time as water gas shift conversion increases

Therminator Temperature Profile



- Therminator absorber bed temperature : 1100-1150 ºF
- Regenerator mixing zone temperature prior to catalyst circulation: ~1000 ºF
- Circulation of catalyst increased temperature of catalyst in regenerator mixing zone
- Coke combustion in regenerator leads to increase in regenerator bed temperature by ~120 ºF
- Reactor and regenerator bed temperature reach a maximum and starts to slowly decrease with time as less coke is being burned

Effectiveness of Tar Removal



- Tar concentration in raw syngas decreases from 40 to 6 g/Nm^3
- Tar concentration in cleaned, cooled syngas: 0.4 to 1.3 g/Nm^3
- Tar conversion in therminator unit: 90-97%
- Tar removal in gas cleanup absorber: 10 to 2 g/Nm^3
- Tar conversion in gas cleanup absorber: 50-75%
- TGA of regenerated catalyst samples indicated no coke accumulation
- No catalyst deactivate due to coke deposition

Project Relevance – Quality of Gaseous Intermediates

Methods for tar reduction

Primary methods

- Gasifier Operating Conditions [T, P, residence time, gasifying agent, stoichiometric ratio (O_2, H_2O content)]
- Bed material

Secondary methods

- Thermal cracking
- Catalytic cracking (tar reforming)
- Mechanical methods – filtering, scrubbing, separation

courtesy Alf Tunheim

- Cost-effective gas cleanup technology development to remove contaminants (tars, sulfur, and ammonia).
- Validate that syngas from biomass can meet the rigorous quality specifications for catalytic liquid fuel synthesis.
- Supports the development of biomass gasification technology
    - Syngas quality
    - Catalytic fuel synthesis
    - Integrated process optimization

Critical Success Factors and Challenges

Biomass Gasification

- Long-term, steady-state operation
- Tar sampling
- Effect of biomass torrefaction on syngas quality and tar formation

Tar Cracking Reactor Sub-system

- Successful commissioning with biomass-derived syngas
- Complete 300 hours of integrated biomass gasification/gas cleanup
- Achieve gas cleanup targets for tar and sulfur removal
- Catalyst lifetime
- Methane utilization or down stream reforming
- Continued funding for future development

Integration Gasification/Gas Cleanup

- Validate techno-economics for scale-up
- Biofuels yield

Summary

Overall Summary

- Integrated testing for 63 hours with runs as long as 12 hours
  - 59 hours on untreated biomass and 4 hours on mildly torrefied biomass

Gasifier performance

- Average feed rate: 43 lb/hr
- Average syngas yield: 75%
- Average tar concentration: 12 g/Nm^3

Gas Cleanup performance

- Average temperature: 1120 ºF
- Catalyst circulation rate: 750 lb/hr
- Average tar removal efficiency: 90%
- Representative tar removal efficiency: 94.4%
- High coke combustion conversion with minimal coke accumulation on catalyst

Stage Gate Result – Project will not proceed to Phase 2 (300 hours of integrated testing not achieved in Phase 1)

- Gas cleanup unit decommissioned and returned to RTI
- Project closeout underway and Final Report being prepared.

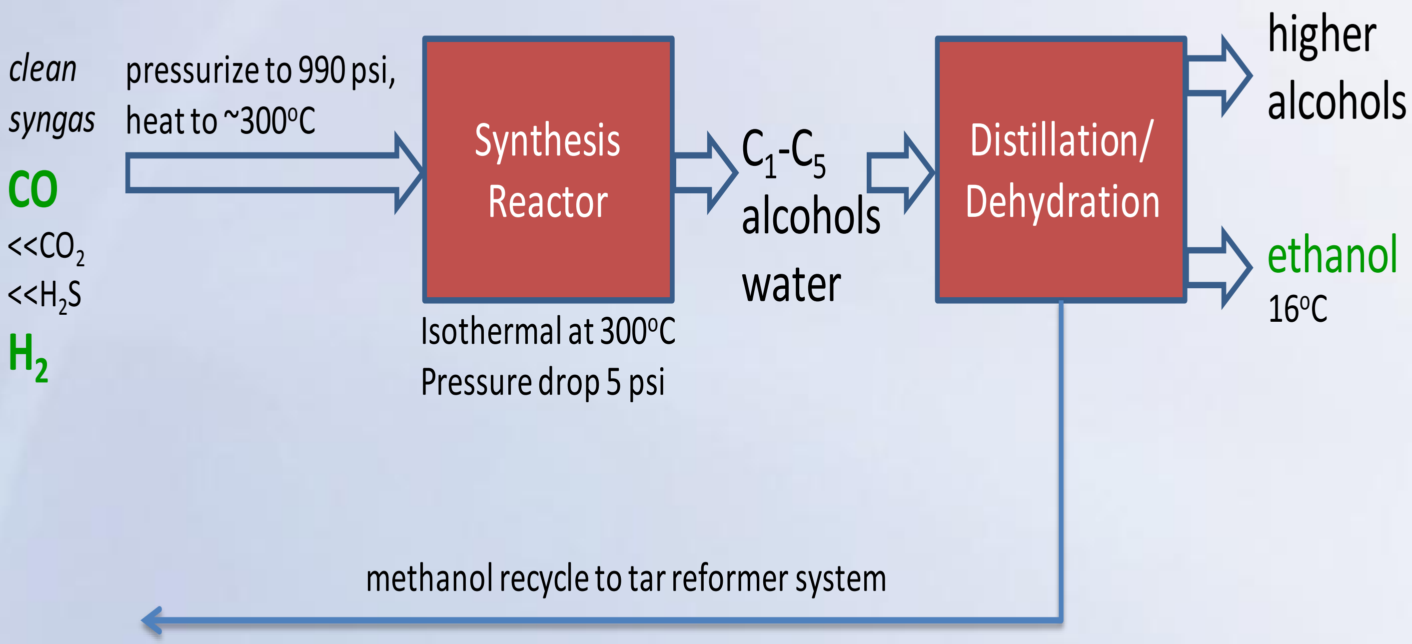
Acknowledgments

- RTI Team
  - Atish Kataria
  - Pradeepkumar Sharma
  - Matt von Holle
  - Ranjeeth Kalluri
  - Brian Turk
  - Wesley Yellin
  - Unitel Technologies
  - Service and Technology Corporation
- University of Utah
  - Professor Kevin Whitty
  - Dan Sweeney
- North Carolina State University
  - Professor Steve Kelley
  - Mike Jett

Additional Information

Cleanup technology effects on fuel synthesis

NREL mixed alcohols model block diagram



- Non-kinetic stoichiometric based synthesis
- Standard distillation and mole sieve dehydration

2000 tpd Biomass Gasification Process - Tar Cracking versus Tar Reforming

(lb/hr)	Syngas Feed	NREL Output	RTI Gas Cleanup Output
Total Flow	232,771	131,314	147,702
H_2	3465	11050	3641
H_2O	82790	477	845
CO	80309	91783	80210
CO_2	37488	24095	36998
H_2S	161	27	0
NH_3	355	31	1
CH_4	16577	2861	16530
Ethane	474	4	464
Ethylene	7971	688	7868
Acetylene	753	65	740
Benzene	607	5	114
Tar ($C_{10}H_8$)	1821	2	18

- NREL model combines H_2S removal with acid gas (CO_2) removal
- RTI Gas Cleanup unit has no CO_2 removal section
- Methane reforming generates more H_2
- More biofuel yield with reforming but revenue from fuel plus electricity is comparable for both cleanup options

Hydrocarbon Reforming in NREL process

Contaminant Removal

CO_2 removal

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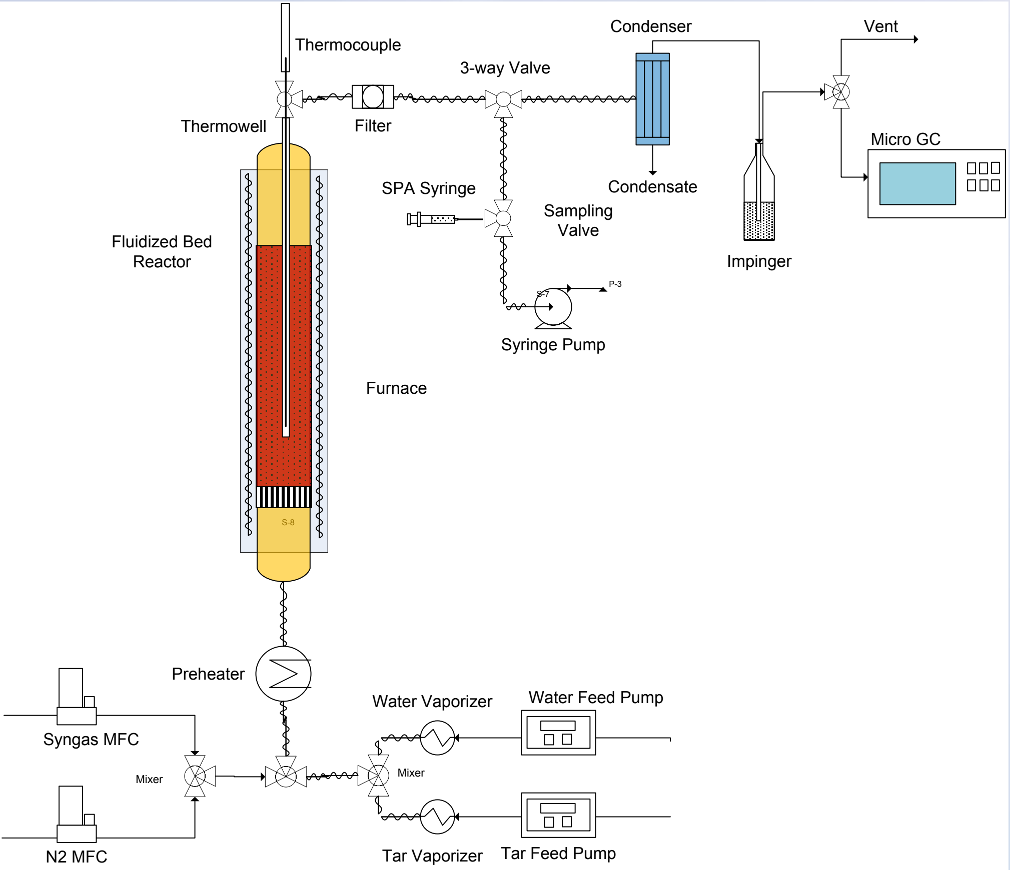
Tar Cracking Catalyst Development
RTI Catalyst Testing



Objectives

- Measure tar cracking rates and activity
- Determine carbon deposition rates
- Develop operating conditions for pilot-scale system

Reaction conditions: 1 atm, 600-700 ° C

Feed composition: 30% H_2,15% CO, 5% CO_2, 40% H_2O, 10% N_2, 35 g/Nm^3 Tar, 100 ppm H_2S

Tar Composition: Phenol, cresol, naphthalene and methyl naphthalene in toluene

Flow rate: ~20 slpm

Solid loading: ~500 g

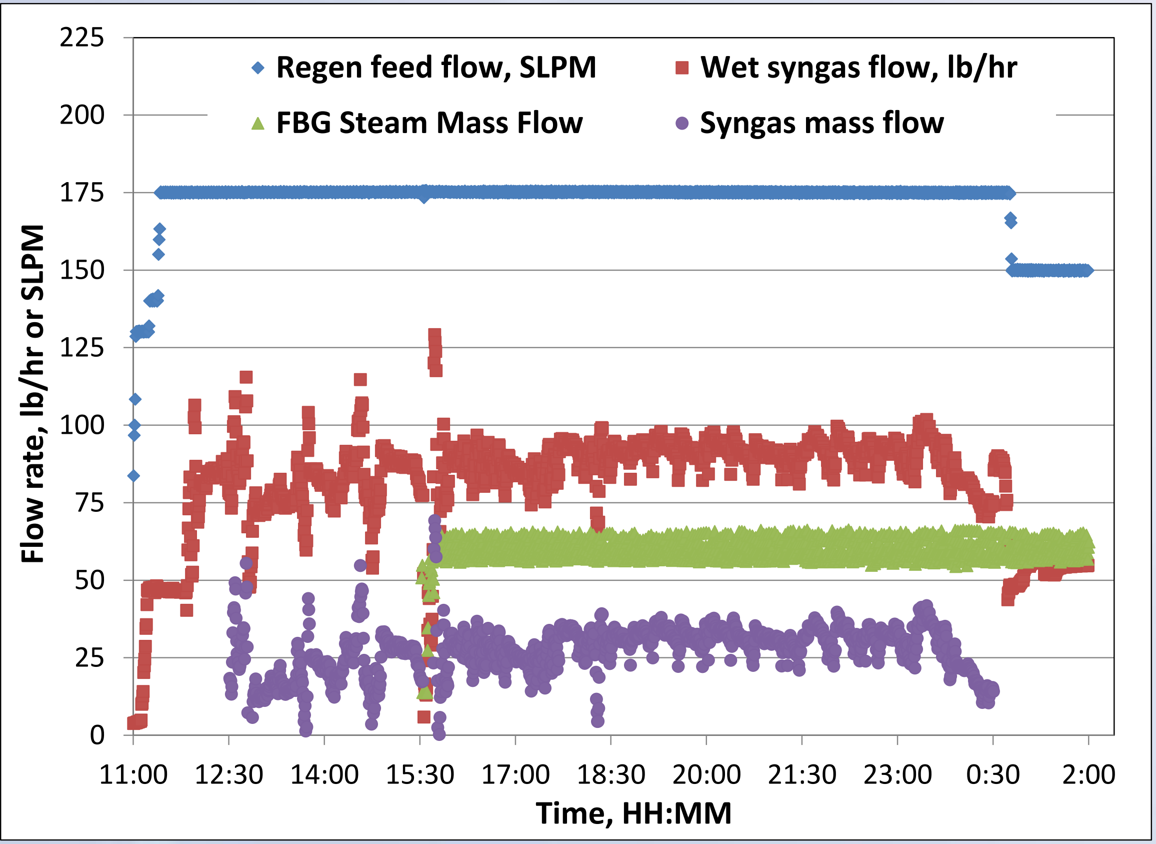
Tar Cracking Catalyst

Property	Value
Average particle size, µm	72
Average bulk density, g/cc	0.85
Surface area, m^2/g	170
Pore volume, cc/g	0.3
Fines content, wt%	8

Commercial FCC Catalyst supplied by Inprocat Inc.

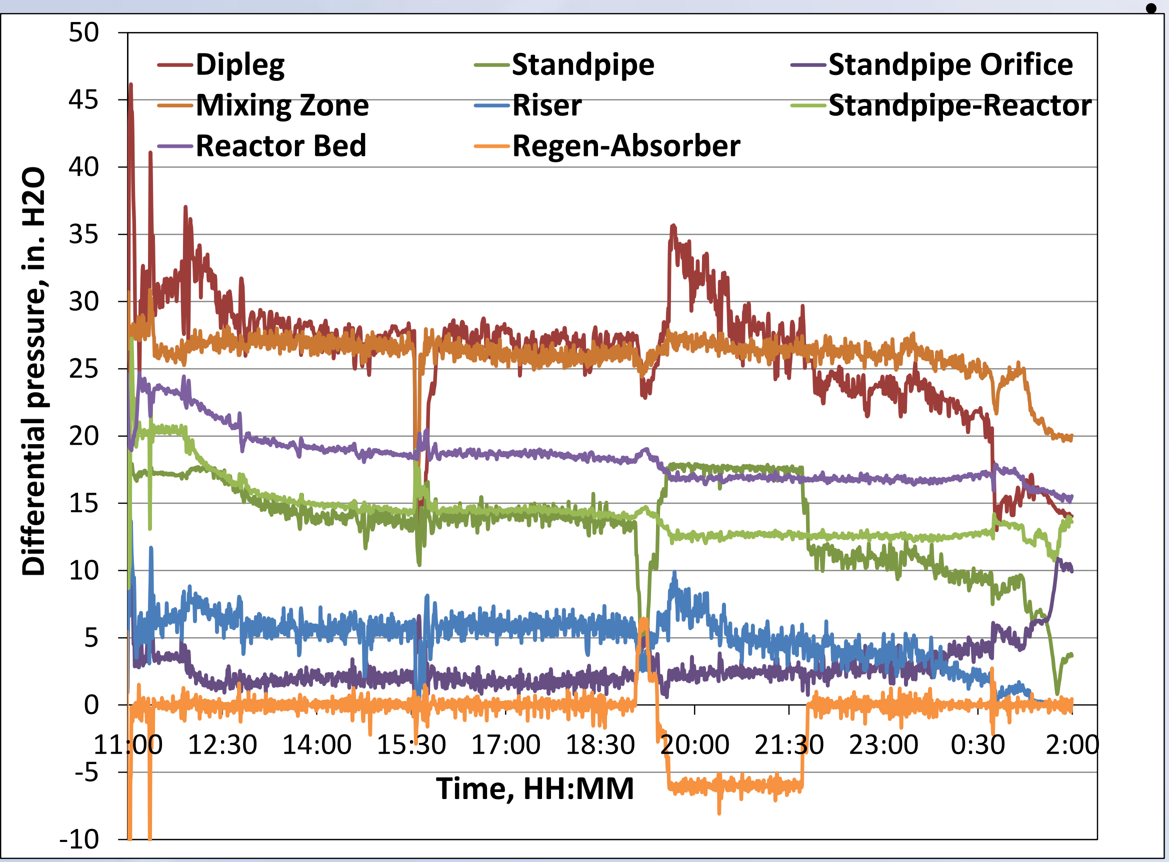
- EnlightenMax®
- Zeolite content: 15 wt%
- Completely rare earth exchanged
- Desired physical properties
- Good fluidization characteristics
- Good attrition resistance

Feed and Product Flow Rates



- Superheated steam used as fluidization gas in gasifier
- Flow rate maintained at 60-70 lb/hr
- Wet syngas flow rate calculated using calibrated orifice meter
- Syngas flow represents product flow rate from biomass addition
- Average yield of syngas throughout the experiment was ~70.5 wt%
- Although most of the oxygen in regenerator air feed was unreacted, air feed flow as maintained constant to sustain catalyst circulation

Catalyst Circulation Rate



- Rate of catalyst circulation through regenerator estimated using pressure drop across riser
- Able to maintain high catalyst circulation rate for over 12 hours
- Catalyst circulation rate of ~900 lb/hr
- High rate of regenerated catalyst return (based on dP across standpipe orifice)
- Reactor bed pressure drop decreased with time due to continuous loss of catalyst
- Loss of catalyst through reactor and regenerator cyclone
- Regenerator cyclone >99% efficiency

Summary of Integrated Tests

Test #	Duration	Biomass Feedrate (lb/hr)	Steam Mass flow (lb/hr)	Bed Temp. (deg F)	Reactor Pressure (psig)	Filter dP (in H2O)	Syngas Flowrate (lb/hr)	Syngas yield, %	Syngas HHV, Btu/lb	Tar conc., g/Nm^3 Gasifier	Tar conc. g/Nm^3 Absorber	Tar conc. g/Nm^3 Therminator
1	2.00	34.7	70.0	1453	18.3	5.2	31.4	89.7	6152	9-8	4-2	-
2	4.65	31.4	67.4	1476	19.3	6.6	32.7	40.7	6177	9	3.3	-
3	4.03	47.7	60.0	1460	21.5	9.6	39.7	83.2	6112	15-4	12-3	-
4	4.67	48.1	60.0	1434	21.8	10.3	37.4	78.0	6160	21-8	11-8	-
5	5.45	43.8	60.0	1433	24.5	OR	37.4	85.3	6083	34-1	11-3	0.8-0.3
6	4.77	40.0	62.4	1384	26.0	OR	32.9	82.1	5924	20-13	15-6	-
7	4.63	45.5	63.9	1368	21.7	8.9	-	4.63	-	20.5	13.0	0.6
8	2.50	40.6	70.0	1361	25.3	OR	32.8	2.50	5941	4.4	4.1	0.7
9	4.85	45.6	68.1	1281	24.0	OR	33.2	72.3	5946	6.5	4.9	0.6
10	7.00	-	-	-	-	-	27.5	7.00	5551	11-4	6-3	1.3-0.5
11	12.50	42.9	60.0	1367	20.4	OR	30.3	70.6	6086	40-6	9.8-2.4	1.3-0.4

- Maintained desired biomass feed rate of 44 lb/hr and treated entire raw syngas stream
- Achieved high catalyst circulation rates
- Able to demonstrate the therminator process of continuous reaction and regeneration
- Conducted integrated gasification and syngas cleanup tests for 63 hours
- Achieved syngas yields in excess of 70%
- Average tar concentration in therminator syngas outlet: 0.7 g/Nm^3 (>95% conversion)
- Catalyst does not change syngas composition

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Response to Previous Review – Project Approach

Reviewer Comments

- Criteria Score: 7 The approach is methodical and well planned leading to a pilot demonstration of significant size (20 kg/hr) and run time (100s of hours). It would be helpful to see more information on the project management plan such as the schedule and milestones. The work is broken down into two phases with a go/no-go between them.
- Criteria Score: 8 1/2 ton/day circulating/regeneration loop for one-step catalytic gas cleanup (tar cracking, ammonia decomposition, sulfur absorbent) to oxidize sulfur to SO2 initial catalyst - zinc titanium oxide Partners: Univ. of Utah (fluidized-bed indirect gasification pilot plant) North Carolina State (pine wood chips feedstock)
- Criteria Score: 8 Well defined goals. 300 operation hours for the integrated gasification/ gas cleanup is not a lot.
- Criteria Score: 7 The overall approach looks reasonable. It was good to see technical, economic and efficiency goals listed. However, a project management plan was not really discussed.
- Criteria Score: 9 Project divided into two phases with intermediate Go/NoGo decision point before adding syngas conversion. Nice marriage of existing gasifier facility and capability at UoU with RTI capabilities and technology. RTI technology has potential for process intensification, combining tar cracking, NH3 and S capture, but requires separate methane reforming and CO2/acid gas removal necessary for fuels synthesis (not required for biopower applications). Use of NREL model will allow "apples to apples" TEA comparison with tar reforming approach. Solid technology development approach outlined, however did not provide milestone plan or PMP approach.

Presenter Response

General response about Project Management Plan: A Project Management Plan has been developed for the project and yearly updates to this plan are submitted to DOE. The presentation templates requested a description of Management Approach but not specifically a summary of the Project Management Plan, hence this was not included. The information is available, reviewed, and updated yearly so perhaps this information can be explicitly requested for the next review. Keep in mind that some organizations may consider the details of the PMP confidential so high level overviews may be considered. While 300 hours of integrated gasification/gas cleanup is not a lot of time, it is what was required in the original RFP and is all that can be achieved within the project budget.

Response to Previous Review – Technical Progress and Accomplishments

Reviewer Comments

- Criteria Score: 5 The project has made significant mechanical progress towards building out the pilot. There have been several catalysts tested. However, the results are far from MYPP targets (methane mol%, methane conversion, and benzene conversion).
- Criteria Score: 8 75-80% tar removal with FCC catalyst
- Criteria Score: 8 Fundamental research on catalyst development for tar cracking has been done beforehand which gives a good basis for the implementation in the pilot plant (reactor design). Inter-comparison of tar cracking versus tar reforming with the use of a process model has been performed which gives a "calibration" of the two approaches.
- Criteria Score: 8 The presentation did not show specific milestones but nevertheless, the project looks to be achieving its overall objectives. The PI indicated that the pilot scale skid is designed, fabricated & being commissioned at the University of Utah.
- Criteria Score: 9 Completed screening of commercial cracking catalysts. Therminator design completed, fabricated, and delivered on schedule & budget. Modifications to UoU gasifier completed and commissioned on schedule & budget. Overall project appears to be progressing as planned.

Presenter Response

Agree that with thermal cracking it will be difficult to reach methane and benzene conversion targets but this will not affect process operation, only final syngas yield. We have tried to quantify the impact of improved thermal integration with reduced syngas yield to higher methane and benzene conversion with a reforming step that operates at a higher temperature (850C). We have quantified that the potential revenue from an integrated thermochemical conversion process that includes our tar cracking concept could be economically feasible if excess electricity (produced from the higher heating value tail gas) is sold as a co-product. Therefore, the co-product value of excess electricity could offset the revenue for the lower biofuel yields. This will continue to be evaluated and quantified as more technical information becomes available for the models.

Response to Previous Review – Project Relevance

Reviewer Comments

- Criteria Score: 7 The project is aimed at a key challenge in the Thermochem Platform. Additionally, it will be targeting at a larger scale/pilot.
- Criteria Score: 9 pilot testing of gas cleanup catalysts
- Criteria Score: 9 Relevance to the MYPP is given.
- Criteria Score: 8 The project relevance was clearly articulated in the presentation. Hopefully, it will provide a good point of comparison to the NREL pilot plant activities. There was no explicit consideration of application of the expected results, but project goals are clear. It is interesting that they are also looking at adding some torrefied wood. I appreciate the interest in torrefied wood, but this work should include an assessment of the net energy and cost implications, to see if the use of torrefaction is justified. However, since the project is not trying to maximize biofuel yield, this may make comparisons more difficult.
- Criteria Score: 8 Project is well aligned with DOE MYPP goals for syngas cleaning and condition, validation of syngas quality.

Presenter Response

Agree that the overall energy efficiency and cost implications of utilizing torrefied wood need to be evaluated. The objective is to determine if using torrefied wood for gasification produces less tars and therefore correlates with lower gas cleanup costs that offset the higher feedstock costs. This is to be determined from the pilot-plant testing and inputting the technical results into the process models.

Response to Previous Review – Critical Success Factors

Reviewer Comments

- Criteria Score: 5 The project has identified several key success factors including the one which may be the most challenging for this project, achieving the cleanup targets for tar and sulfur removal. The project has not identified the methane conversion as a success factor.
- Criteria Score: 8 fully met this criteria
- Criteria Score: 7 Challenges are not clearly addressed. What is the hypothesis related to the use of torrefied biomass in relation to syngas quality and tar formation?
- Criteria Score: 8 CSFs and challenges were covered in the presentation. The project appears to have identified the right areas for focus.
- Criteria Score: 9 Using NREL TEA model as basis to evaluate process economics. TEA will show how this cracking approach compares with reforming approach. Separate methane reforming step with be required for syngas to fuels - case is more easily made for biopower application where downstream CH4 reformer is not necessary. Success factors related to achieving 300 hours continuous operation

Presenter Response

No response

Response to Previous Review – Technology Transfer and Collaborations

Reviewer Comments

- The project is making good use of its partners by leveraging the gasification facility at the University of Utah. The project could benefit from a more effective catalyst for methane reforming and should consider adding a partner for this. The gasification pathway to ethanol will have a significantly lower yield and uneconomical production of transportation fuel without meeting the MYPP methane reforming target.
- See answers above
- Partners providing expertise in the different fields related to the project.
- It was good to see that they are developing an economic model of their gas cleanup step as a "drop in" for the NREL economic model. However, the ability to do this was impacted by the high degree of integration in the existing model. Thus, they ended up creating a simpler version. Also, since the goal is to crack tars, but not methane, the overall biofuels yields may be low, further complicating economic comparisons (they could end up making more power instead). The PI indicated that they have done some economic analysis looking at revenues from power plus fuels. Regarding catalyst development, in the Q&A, the PI indicated they had discussions with GTI as well as some other catalyst manufacturers, but they were not currently looking at catalysts being developed at NREL. Given the number of projects looking at catalysts, there seems to be an opportunity here to share information more formally between projects.
- Well-coordinated collaboration between RTI and university partners (NCSU, UoU). Project might benefit from engagement of commercial catalyst supplier/developer.

Presenter Response

The tar cracking reactor system is flexible enough to entertain the use of a variety of catalysts form a number of different sources in the future. As of now the scope and budget does not allow for testing multiple catalysts at the pilot scale but can be considered for future projects. Future development would benefit by the participation of a catalyst development/manufacture and can also be considered for future efforts.

Response to Previous Review – Overall Impressions

Reviewer Comments

- The project is making good use of the Utah gasifier and making mechanical progress. However, I do not see how the project will meet the MYPP goals without improving the methane reforming.
- See answers above
- Clear project structure with a go/ no-go decision point. Economic analysis has to be shown more clearly.
- This looks like a solid overall program that should give a good point of comparison to NREL's pilot activities. Efforts should be made to ensure the two projects can be compared. Along those lines, I would like to see more data exchange/collaboration before this project is completed.
- Overall solid project combining resources of very reputable research institutions

Presenter Response

The techno-economic analysis of the tar cracking process will continue to be developed and updated with experimental results as they become available.

Publications and Presentations

An overview of this project was presented at the DOE/OBP Thermochemical Platform Review April 14-17, 2009 in Denver, CO.

Dayton, D.C., & Gupta, R. (2009, September). *Biomass gasification tar cracking technology development*. Presented at 2009 International Conference on Thermochemical Conversion Science (tcbiomass2009), Chicago, IL.

Dayton, D.C. (2009, October). *Biomass gasification and catalytic tar cracking process development*. Presented at Gasification 2009 – Gas Clean-up and Gas Treatment, Stockholm, Sweden.

D. Sweeney, B. Christensen and K. Whitty. "Primary methods for reducing tar content in syngas produced from pilot scale fluidized bed biomass gasification." Third Symposium on Energy from Biomass and Waste, November 10, 2010, Venice, Italy

D.C. Dayton, A. Kataria, and R. Gupta. "Biomass Gasification Tar Cracking Catalyst Development", 2010 Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, September 21-21, 2010, Iowa State University, Ames, IA.

D. Sweeny and K. Whitty, "Characterization of a 200 kW Fluidized Bed Biomass Gasifier", 2010 Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, September 21-21, 2010, Iowa State University, Ames, IA.

Dayton, D.C., Kataria, A.S., Yellin, W.J., Turk, B.S., & Gupta, R. (2010, July). *Biomass Gasification Tar Cracking Technology Development*. Presented at Biomass 2010, Grand Forks, ND.

An overview of this project was presented at the DOE/OBP Thermochemical Platform Review February 16-18, 2011 in Denver, CO.

Dayton, D.C., Turk, B., Gupta, R. (2011). Chapter 4. Syngas, Cleanup, Conditioning, and Utilization in *Thermochemical Processing of Biomass*. R.C. Brown., ed., John Wiley and Sons.

D.C. Dayton, A. Kataria, and R.G. Gupta. "Integrated Biomass Gasification and Syngas Cleanup Using RTI's Therminator Process", 2011 Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products, September 28-30, 2011, Chicago, IL.

Stage Gate Review presentation, December 14, 2011, in the Golden Field Office.