

AQUEOUS PHASE BASE-FACILITATED REFORMING (BFR) OF RENEWABLE FUELS

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2010 DOE Hydrogen Program Annual Merit
Review
7 June 2010

Project ID #
PD063

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PROJECT OVERVIEW

Timeline

- ❑ Start:
 - June 2008 (Phase I)
 - Sept 2009 (Phase II)
- ❑ End: Aug 2011
- ❑ Percent Complete:
 - Phase 1– Completed
 - Phase 2 – 20%

Budget

- ❑ Total project: \$850k
- ❑ Phase 1- \$100k
- ❑ Phase 2 - \$750k
 - Period 1: \$375k
 - Period 2: \$375k
- ❑ No Contractor Share

Barriers

- ❑ A. Reformer Capital Costs
- ❑ B. Reformer Manufacturing
- ❑ D. Feedstock Issues
- ❑ E. Greenhouse Gas Emissions

Partners

- ❑ ECD (Ovonics)
- ❑ SenTech, Inc.
- ❑ Western Michigan University
- ❑ Sierra Marine Technologies, Inc.

OBJECTIVES & RELEVANCE

- ❑ The project focus is to advance the BFR technology with experiments and define a market segment where commercialization of this technology is economically attractive.

- ❑ **Phase 2 Objectives**

- Demonstrate a continuous BFR reactor
- Identify optimum operating parameters
- Determine optimum BFR facility size, markets, and impacts

DOE Metric	Target	BFR Projected
Total Hydrogen Cost (delivered), \$/gge	\$3.80	\$2.27 - \$3.26 ^a
Production Unit Capital Cost (1500kgH ₂ /day)	\$1.0M	\$0.664M – 1.59M ^b
Production Unit Energy Efficiency	72%	79%

^a In 2005\$USD, includes only H₂ production costs, using H2A standard economic assumptions.

^b Linearly scaled down from a 2TPD modular production system.

ADDRESSING BARRIERS

Relevance

DOE Barriers	BFR Project Responses
A. Reformer Capital Costs	Process eliminates need for WGS & PSA
B. Reformer Manufacturing	Modular designed unit
D. Feedstock Issues	Process allows for renewable fuels, fuel flexibility, and co-location market synergies
E. Greenhouse Gas Emissions	CO ₂ is sequestered in carbonate

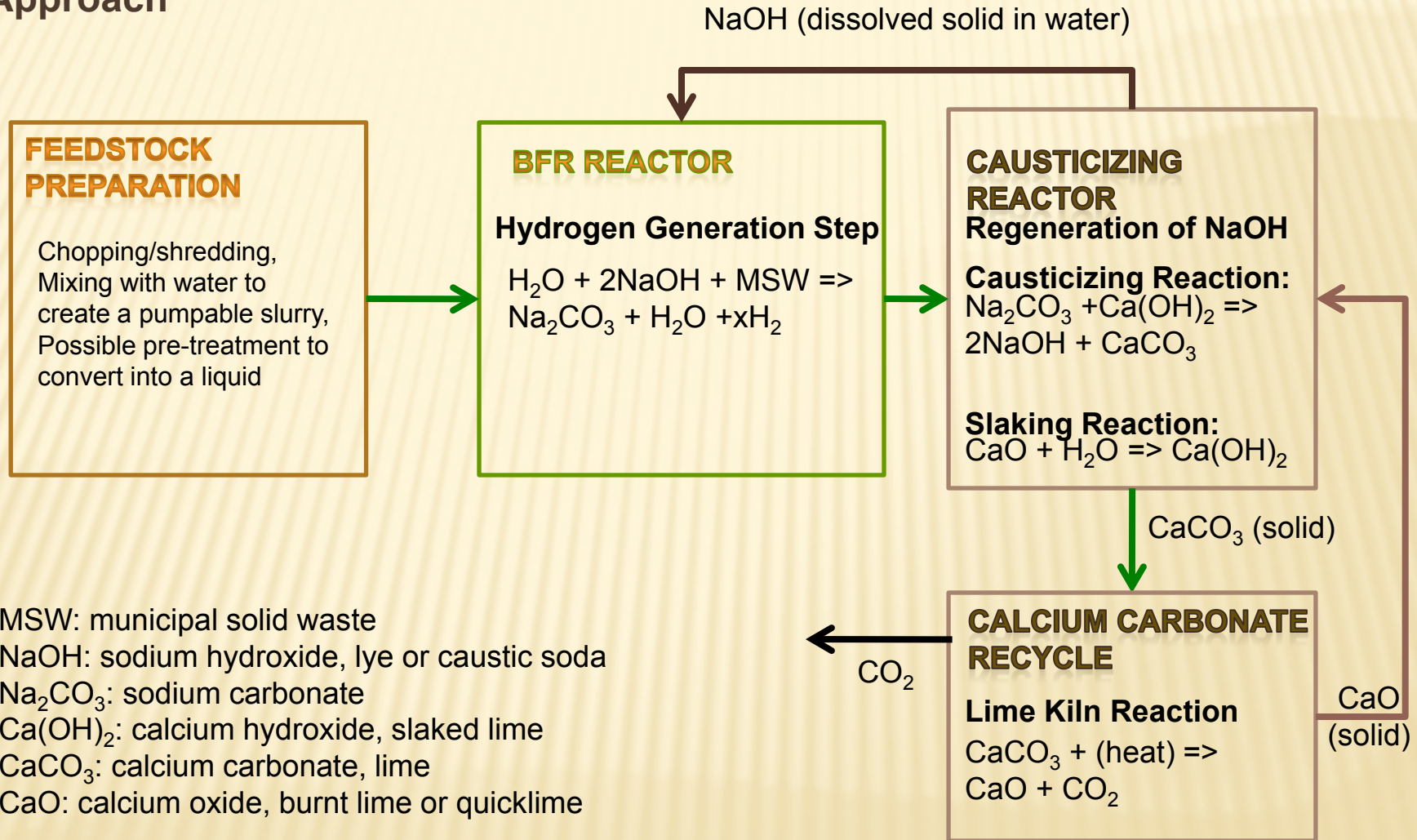
BFR PROCESS MAIN FEATURES

Approach

- ❑ **Converts Renewable Fuels:** Variety of liquid and solid renewable fuels into hydrogen. Main focus: MSW components (i.e. paper, grass, wood, & food waste)
- ❑ **Reforms in Liquid Phase:** Efficient compression of feedstock and water
- ❑ **Operates at Low Temperatures:** Reaction temperatures are 250-350°C thereby reducing energy requirements and allowing use of low cost metal components
- ❑ **Produces Excess Heat:** The BFR reaction is exothermic eliminating intra-reactor heat exchange
- ❑ **Creates High Purity Hydrogen Gas:** Typically produces 98%+ H₂ output gas with only ~1% methane (plus H₂O vapor)
- ❑ **Eliminates Water Gas Shift:** No CO, therefore no WGS

BASIC REACTIONS

Approach



UNIQUENESS & CHALLENGES

Approach

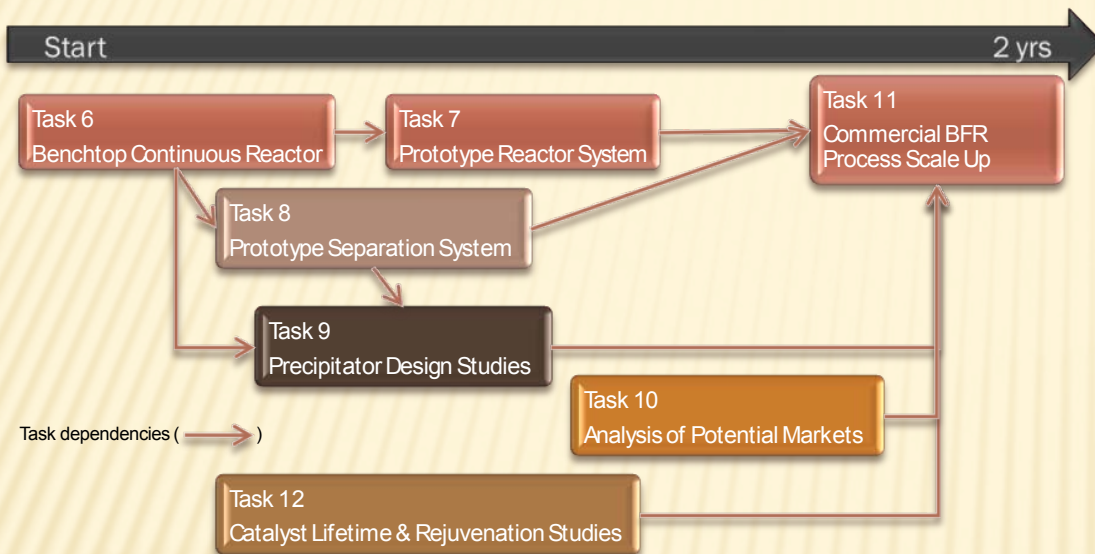
UNIQUE ATTRIBUTES

- ❑ Aqueous phase reaction
- ❑ Moderate temperature: 250° - 360°C
- ❑ Moderate pressure: <500psi
- ❑ Flexible feedstock: but focused on MSW
- ❑ Non-precious metal catalysts
- ❑ Produces nearly pure H₂ gas (98+% purity)
- ❑ Capture feedstock carbon in solid carbonate form
- ❑ Pathway to ~\$3/kg hydrogen

PROCESS CHALLENGES AT PROJECT START

- ❑ Residence time is minutes (not seconds)
- ❑ Phase 1 catalyst is in powder/pellet form therefore it needs to be captured and recycled, adding complexity
- ❑ Fouling and separation of catalyst from unreacted feedstock is a concern
- ❑ Economics seem to favor a Full Recycle Configuration: unfortunately this is the non-CO₂ sequestration pathway

APPROACH



Period 1 Milestones	
A	Demonstrate steady-state conditions and 0.2kg H ₂ /day
B	Develop Prototype BFR Reactor Design
C	Proof of Concept Tests at Pressure
D	Develop Catalyst Separation System Design
E	Precipitate CaCO ₃ at pressure & temperature
F	BFR Market Research Analysis
G	Quantify catalyst performance over time

Period 2 Milestones	
H	Demonstrate steady-state conditions and 10kg H ₂ /day
I	Achieve > 99% catalyst recovery & < 5% Na ₂ CO ₃ loss

Task	Milestone	Accomplishments
Task 6 Benchtop Continuous Reactor	A	Reactor sized. Parts list created. Hardware sourced. Testing pre-treated feedstock to develop liquid fuel and simplified design.
Task 7 Prototype Reactor System	B, H	Design progressing based on work from Task 6.
Task 8 Prototype Separation System	C, D, I	Feedstock work in Task 6 has modified this task. Catalyst containment and monolithic catalysts under investigation.
Task 9 Precipitator Design Studies	E	Analysis of commercial re-burnt lime completed. Test equipment calibrated. Testing at 100°C underway. Higher temperatures will follow.
Task 10 Analysis of Potential Markets	F	Task start delayed.
Task 11 Commercial BFR Process Scale Up		On schedule to start in Month 13.
Task 12 Catalyst Lifetime & Rejuvenation Studies	G	Task start delayed.

SIMPLIFYING THE HARDWARE DESIGN

Technical Accomplishments & Progress

FACTORS COMPLICATING BFR DESIGN



Solid Feedstock

- Potential for unreacted waste in output stream from reactor
- Could cause catalyst fouling



Powdered Catalyst

- Mixed with solid fuel & water
- Requires catalyst separation and transport to front of reactor



NaOH Concentration Tradeoffs

- Tradeoff between three factors
- H₂ Yield: prefers high concentration
- Causticizer: prefers low concentration
- Oper. Press: prefers high concentration

PHASE 2 SIMPLIFIED DESIGN



Conversion to Liquid Feedstock

- Solid-to-liquid fuel dissolution in batch reactor
- Filtration required upstream of reactor



Monolithic Catalyst

- Made possible by liquid fuel
- Fixed catalyst allows for:
 - Liquid (not slurry) pumping into reactor
 - Elimination of catalyst separator



Solution Additives

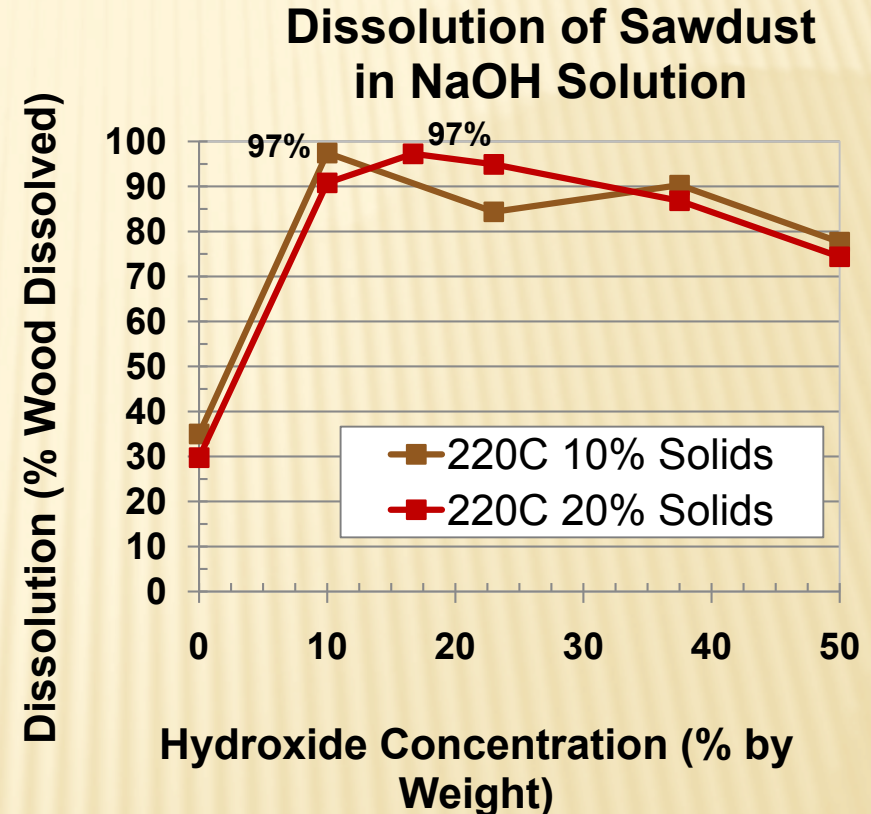
- Raises boiling point thereby lowering the operating pressure for reactor
- Inert to the BFR reaction

Recent innovations result in a significantly simplified Phase 2 design.

PHASE 2 DISSOLUTION TESTS

Technical Accomplishments & Progress

- ❑ Dissolving the solid fuel into a liquid fuel allows:
 - ❑ Use of liquid instead of slurry pumps
 - ❑ Monolithic catalyst
 - ❑ Elimination of catalyst separation
- ❑ **>40 tests on a variety of fuels & conditions**
- ❑ **Typical conditions:**
 - ❑ 200-240°C
 - ❑ 10-20% NaOH
 - ❑ 10-15 minutes
 - ❑ <200psi

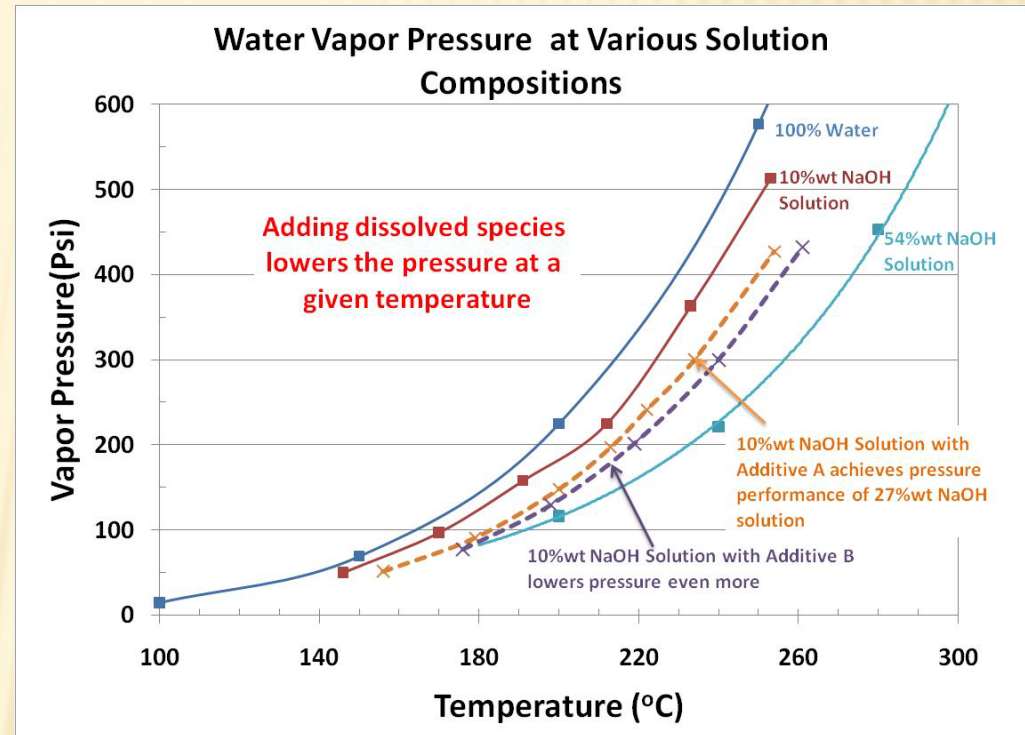


Greater than 90% dissolution is achieved at low temperature (~220°C) and low hydroxide concentration (~10%)

PRESSURE REDUCING ADDITIVES

Technical Accomplishments & Progress

- Dissolved NaOH in the BFR reactor significantly raises the boiling point, thereby allowing a high temperature liquid reaction at a lower pressure.
- By dissolving an additive in the reactants' solution, the pressure can be reduced further.
- This allows decoupling of the NaOH concentration and the operating pressure.
- Additive composition is proprietary.
- Work underway to verify that additives don't impede BFR or causticizing reactions.

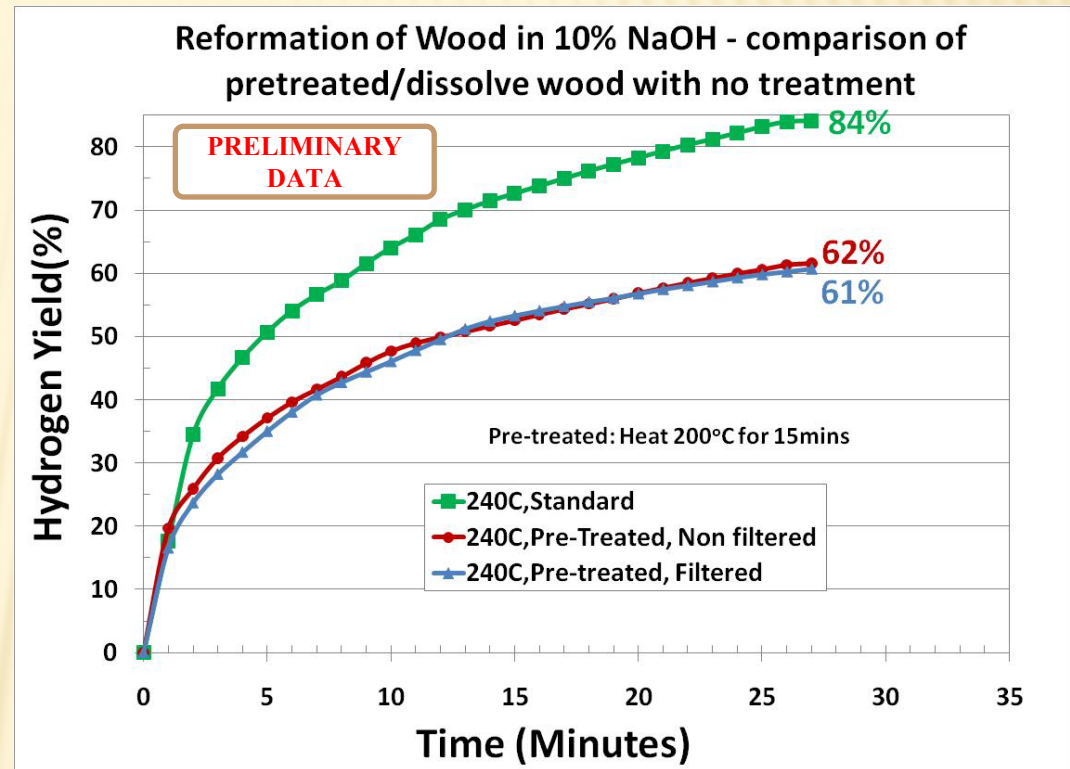


Additives can be used to lower pressure, thereby decoupling pressure & NaOH concentration.

BFR PERFORMANCE ON DISSOLVED LIQUIDS

Technical Accomplishments & Progress

- Wood (sawdust) was pre-treated to create a dissolved liquid fuel.
- H₂ Yield from dissolved liquid should be very similar to H₂ Yield of the solid-wood BFR because:
 - Mass fraction of wood converted to a liquid is >90%
 - Same reactions are occurring, in two separate reactors
- A lower H₂ Yield was observed from dissolved liquid
- Experiments will continue to optimize conditions and identify loss mechanism.



Unexpected drop-off in H₂ Yield when operating on dissolved liquid fuel. Investigation and condition optimization will continue.

DEFINING NaOH CONCENTRATION

Technical Accomplishments & Progress

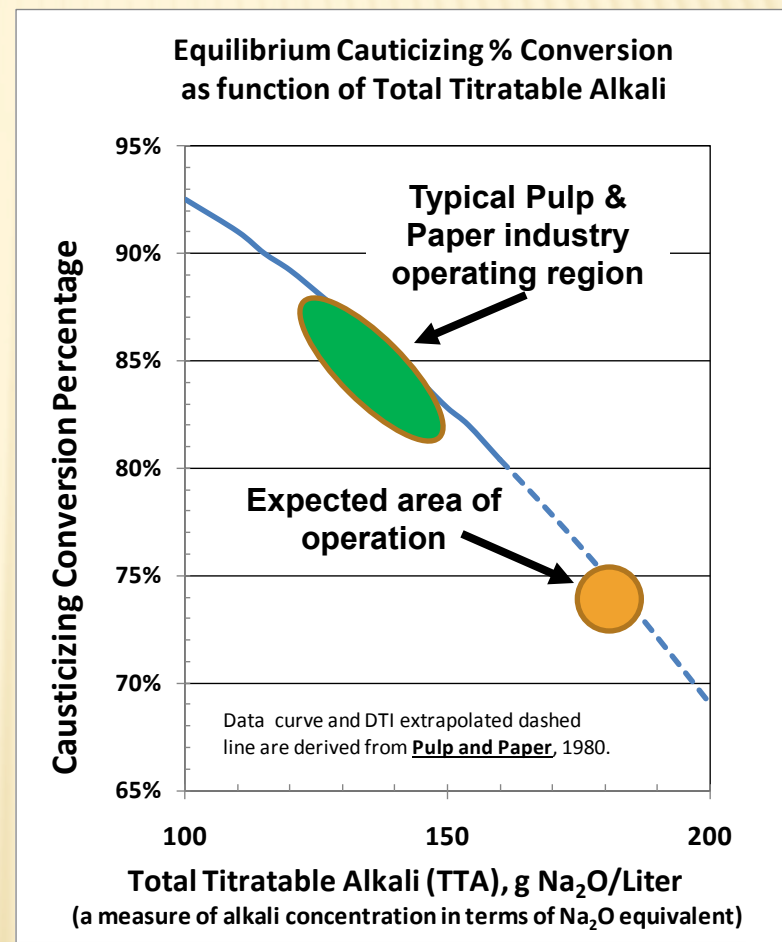
- Components modeled to examine composition changes throughout system
- High NaOH concentration leads to low conversion % of NaOH into Na_2CO_3
- Consequently, we are driven to a NaOH concentration of ~11%wt to achieve a stable balance within the recycle loop
- While causticizing is conducted commercially in the Pulp & Paper industry, conditions are slightly different for the BFR system
- Experiments at WMU are underway to verify:
 - basic causticizing kinetics & equilibrium relationships
 - kinetic rate at elevated temperature and pressure
 - exact performance at expected conditions (including the presence of pressure suppressing additives)

Conversion Efficiency = $\text{NaOH}/(\text{Na}_2\text{CO}_3 + \text{NaOH})$

Total Tritratable Alkali (TTA) = $\text{NaOH} + \text{Na}_2\text{S} + \text{Na}_2\text{CO}_3$

where all concentrations are expressed in Na_2O equivalents

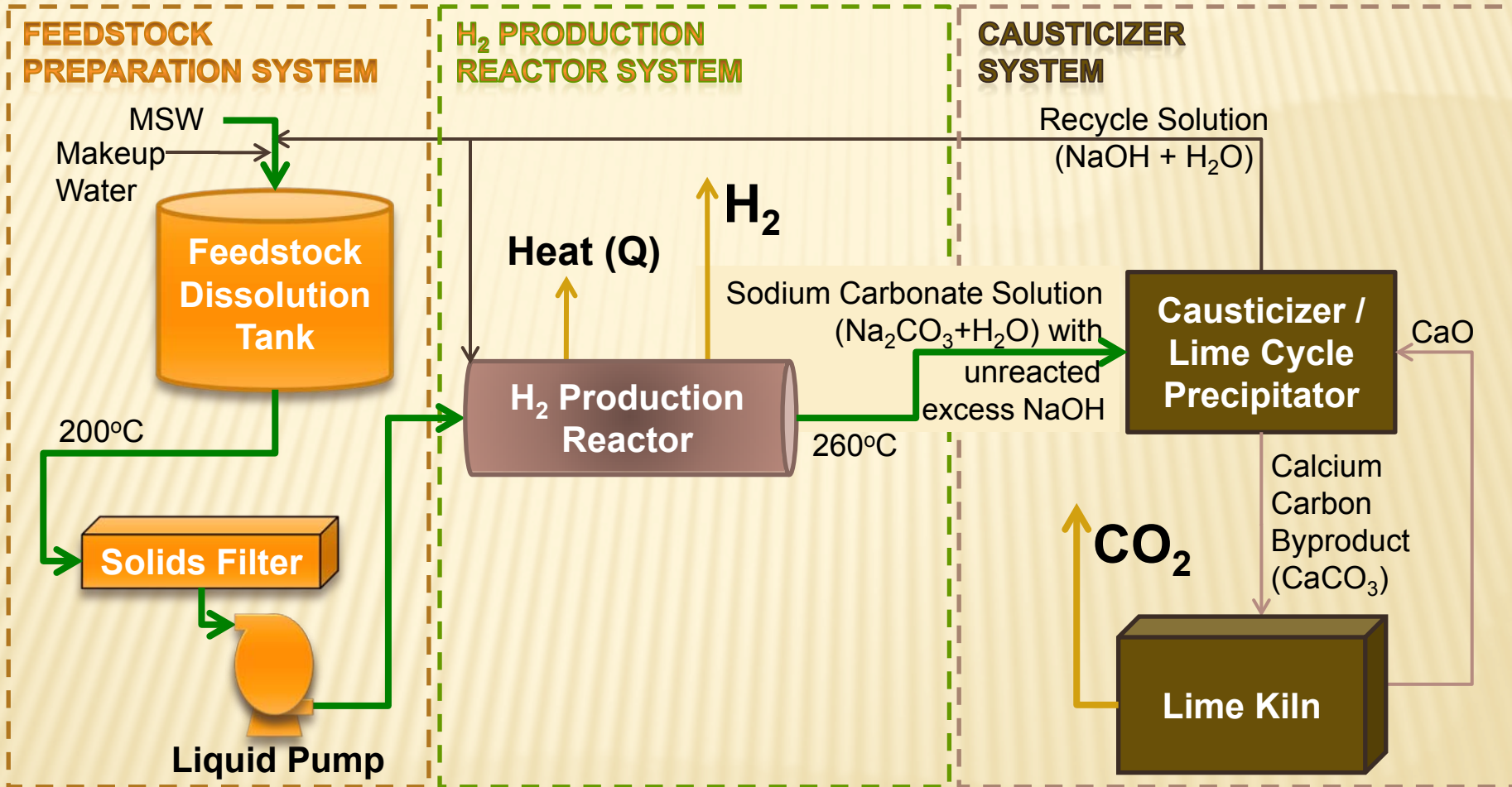
- 1 kg NaOH = 0.775 kg Na_2O
- 1 kg Na_2CO_3 = 0.585 kg Na_2O



Causticizer modeling indicates a required 11%wt NaOH concentration.
Experiments underway to verify this value.

FUTURE SYSTEM EMBODIMENT

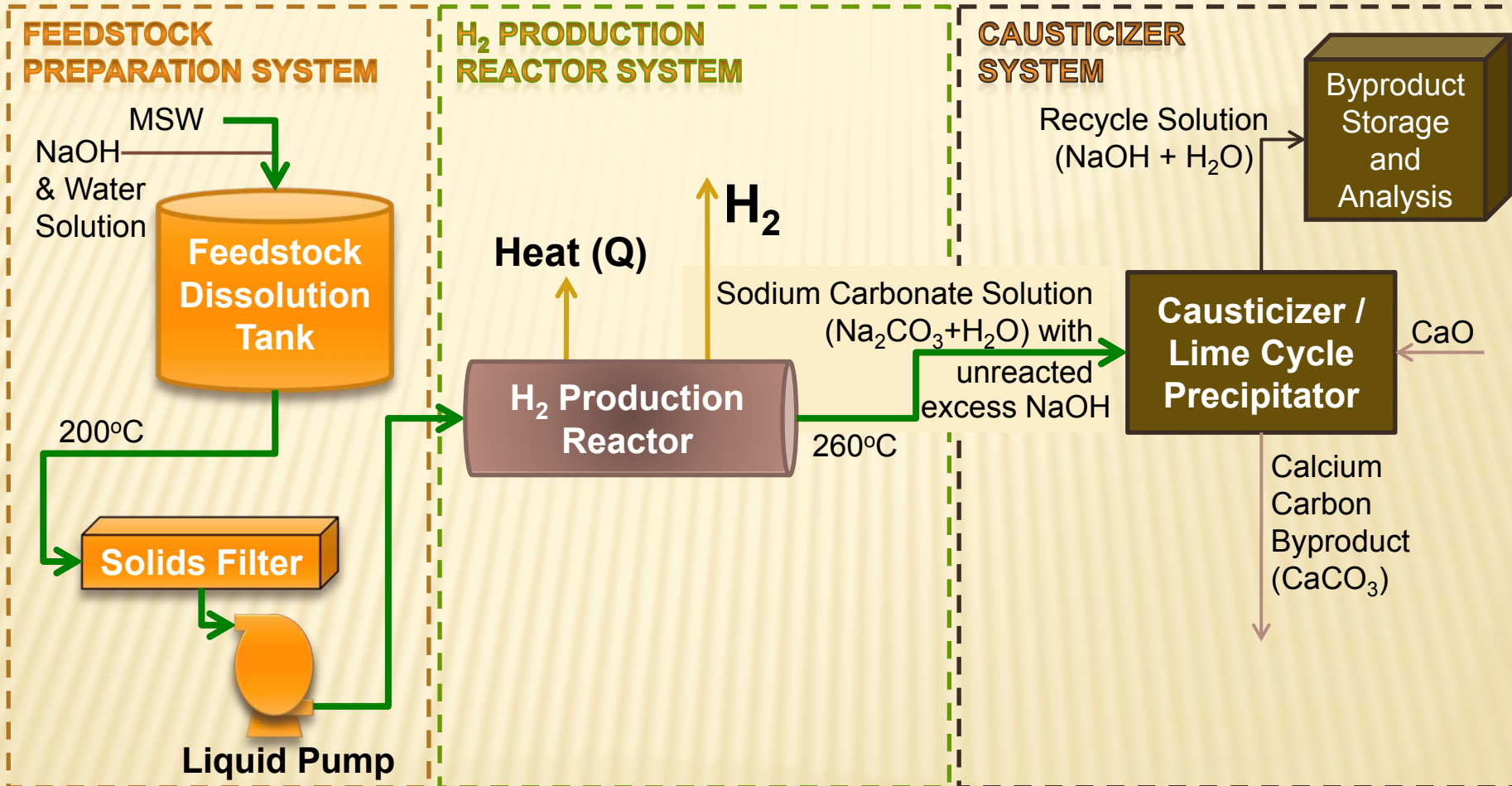
Technical Accomplishments & Progress



System design geared towards lower manufacturing and operating costs.

LABORATORY SYSTEM

Technical Accomplishments & Progress



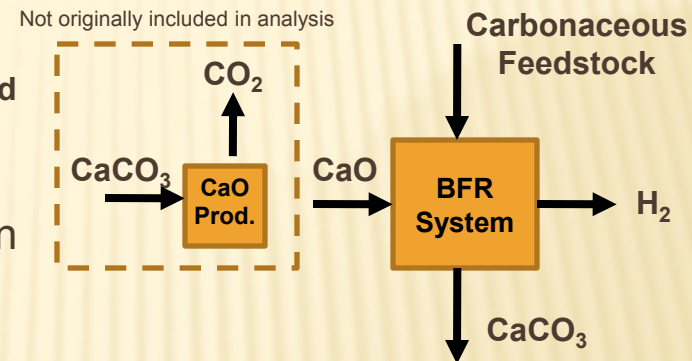
Liquefying feedstock complicates preparation but simplifies reactor system.

CO₂ EMISSIONS & NET IMPACT

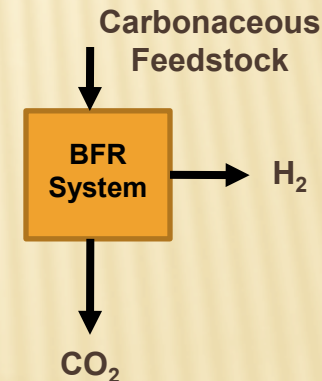
Technical Accomplishments & Progress

- Two configurations proposed in Phase I:
 - “Sequestration” which captures carbon in solid CaCO₃ form but requires CaO input
 - “Full Recycle” which recycles all intermediaries and releases CO₂.
- Initial Logic: BFR system could lead to net sequestration of carbon by capturing carbon in solid calcium carbonate form
 - $\text{Feedstock} + \text{CaO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CaCO}_3$
- Current Logic: Because production of CaO releases CO₂, the “sequestration” configuration is not a net sequester of carbon.
- The “Full-Recycle” configuration is:
 - Favorable in economic terms
 - Can result in zero net CO₂ release if renewable feedstock (wood, paper, MSW, etc.) is used

“Sequestration” Configuration



“Full-Recycle” Configuration



No alternative non-CO₂ releasing source of CaO found.

COLLABORATIONS

FOR BOTH PHASE I AND PHASE II:

- **ECD/Ovonics**
 - Subcontractor
 - ECD is technology originator/patent-holder
 - Ben Reichman/Willy Mays
 - BFR concept development
 - BFR experiments
 - Fabrication
- **Sentech, Inc.**
 - Subcontractor
 - Elvin Yuzugullu lead
 - Marketplace analysis
 - Macroeconomic analysis

NEW FOR PHASE II:

- **Western Michigan University**
 - Subcontractor
 - Prof. John Cameron
 - Pulp & Paper expertise
 - Causticizer configuration design
 - Causticizer operating conditions
- **Sierra Marine Technologies**
 - Subcontractor
 - Prototyping
 - Custom fabrication

PROPOSED FUTURE WORK

FY10

- ❑ H₂ generation experiments in a continuous flow-through reactor
 - Produce 0.2kg H₂/day
- ❑ Design fixed catalyst bed
- ❑ Study other causticizer options
- ❑ Begin evaluation of catalyst lifetime
- ❑ Investigate design option where NaOH concentration can be changed between reactor and causticizer

FY11

- ❑ Increase scale of continuous reactor
 - Produce 10kg H₂/day
- ❑ Study commercial and market options
- ❑ Optimize causticizer design
- ❑ Develop commercial integrated system design

SUMMARY

□ Relevance

- Project aims at reducing petroleum use by developing and validating a hydrogen production method using renewable feedstock (e.g. MSW)

□ Approach

- Design and test a continuous aqueous reactor based on Base Facilitated Reforming (BFR) and determine optimum operating conditions

□ Technical Accomplishments & Progress

- Developed conceptual process designs
- Conducted feedstock dissolution experiments (pre-treatment to dissolve solid fuel into a liquid fuel)
- Improved/Simplify system to reflect feedstock dissolution to liquid fuel
- Overall process and operating conditions optimization
- Modeling of causticizer system and initiation of bench-top experiments

□ Collaborations

- Active partnership with ECD, SenTech, WMU, and Sierra Marine Technologies

□ Proposed Future Research (2nd year of Phase 2 SBIR grant)

- Fabricate and assemble continuous-flow BFR reactor and test at various operating parameters (10kg H₂/day)

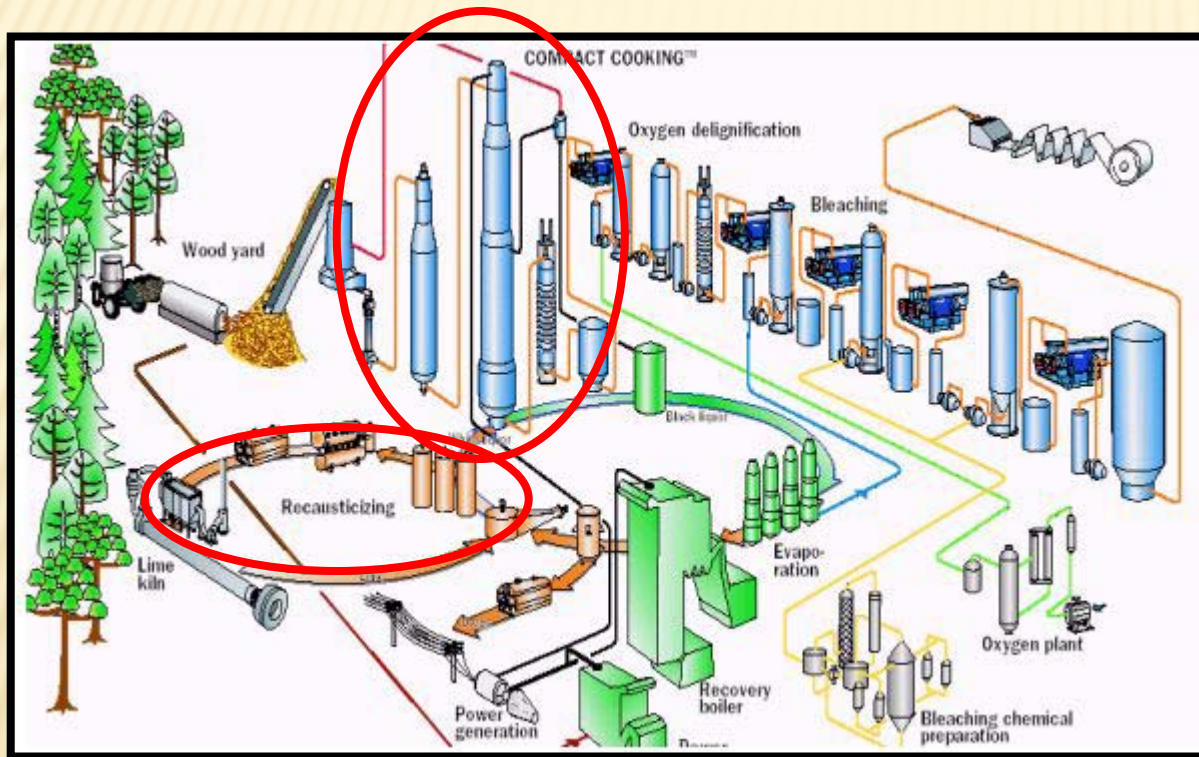
SUPPLEMENTAL SLIDES (AND PHASE 1 RESULTS)

MYPP MILESTONES

Task 2: Distributed Reforming of Renewable Liquid Feedstocks

- 4 Down-select research for distributed production from distributed renewable liquids. (4Q, 2010)
- 5 Verify feasibility of achieving \$3.80/gge (delivered) from distributed renewable liquids. (4Q, 2012)
- 6 Verify feasibility of achieving less than \$3.00/gge (delivered) from bio-derived renewable liquid fuels (4Q, 2017)

BFR AND KRAFT PROCESS SIMILARITIES



The Kraft Process for Making Paper


- Our process shares many similarities with the Kraft Process but target process conditions are not identical.
- Prof. John Cameron, Western Michigan, is key participant/consultant.

PHASE 2 FEEDSTOCK PREPARATION EXPERIMENTS

Status:	<ul style="list-style-type: none"> • >40 tests conducted to date • Conducting literature review • Conducting batch tests (using Phase 1 setup)
Approach:	NaOH hydrolysis to achieve peeling and glycosidic cleavage of cellulose. High rate, high conversion to liquids is possible due to elevated NaOH concentration and temperature.

Metrics	Preliminary Goals	Independent Variables
Temperature/Pressure	$\leq 220^{\circ}\text{C}$ at $< 200\text{psi}$	Temperature
Time to dissolution	< 10 minute residence time (to match H_2 prod. cycle time)	Caustic concentration
% H_2 capture (i.e. theoretical H_2 prod. capacity of dissolution liquids)	80+% H_2 Capture	Dissolution Catalysts
Liquid composition		

Primary factors in dissolution kinetics



PHASE 2 FEEDSTOCK DISSOLUTION

Main MSW Constituents	Description	Approx. Mass %	Form	Dissolution Products
Cellulose	Glucose polymer	40-50%	60-90% Crystalline	Sugars, acids, 100+ different organic compounds
Hemicellulose	Polymers of other sugars	20-30%	Amorphous	
Lignin	Complex polymers built from propane phenyl units	20-30%		
Extractives	Everything else, fatty & resin acids, etc.	2-10%		
Normal Kraft Pulping			BFR	
<=175°C: higher temp. leads to cellulose breakdown		~200°C: want to breakdown cellulose		
~1-3M Base solution		High Molarity: converts cellulose structures from crystalline to amorphous, easier to break down		
Rate: 1-2 hours		Rate: Expect 8+ times faster, ~10 minutes		

PHASE 2 CAUSTICIZER EXPERIMENTS

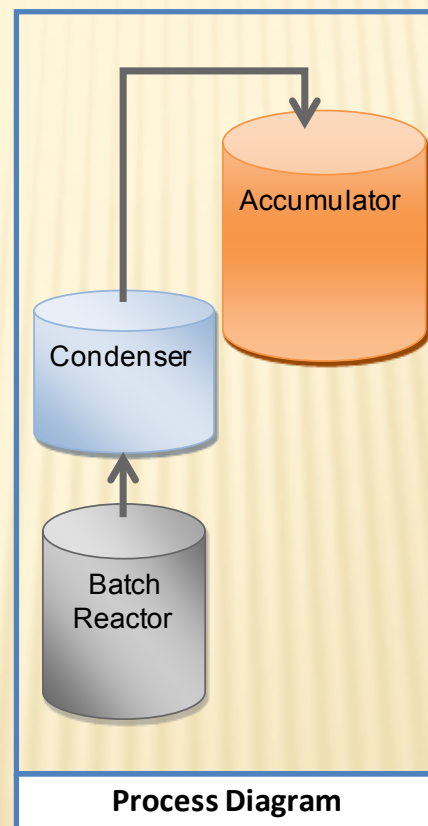
Status:	<ul style="list-style-type: none">• Computations & literature search conducted• Hardware specification• Preliminary testing at 100°C• Tests conducted at Western Michigan University (WMU)
Approach:	Experimental determination of kinetic rates at expected temperatures and concentrations

Causticizer in Kraft Process	Causticizer in BFR Process
~70-100°C	240-350°C
~1-2 atm	300-500 psi
White Liquor	Similar but slightly different composition and molarity

PHASE 1 PROOF OF CONCEPT

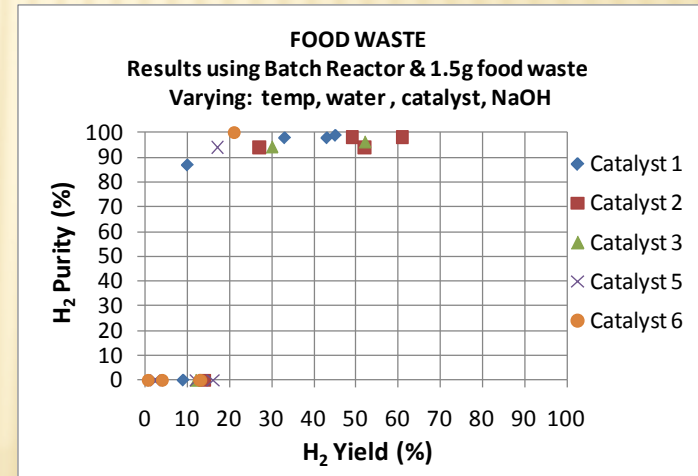
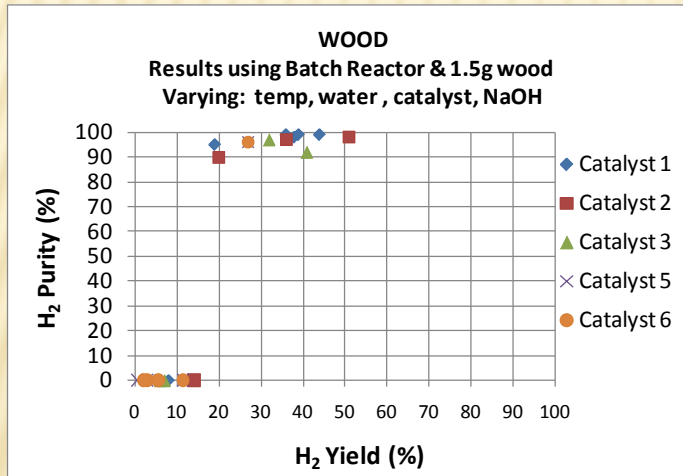
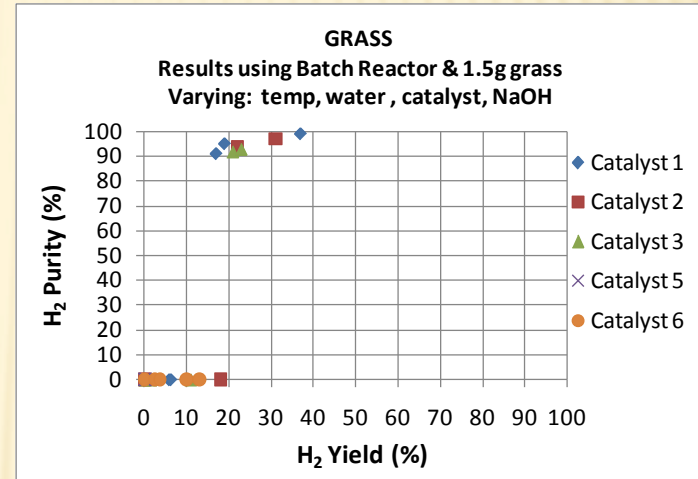
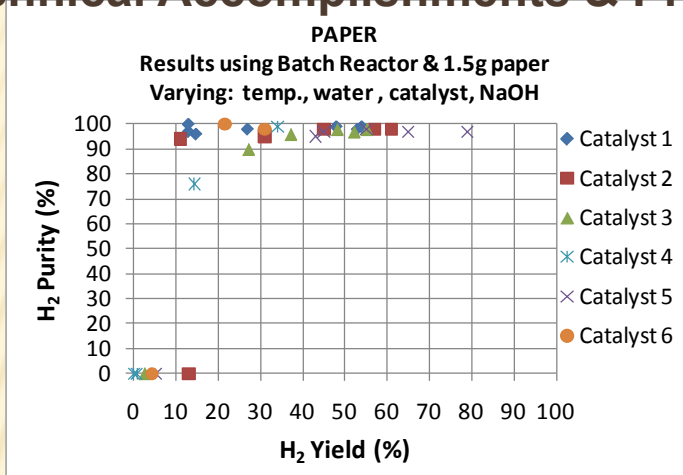
Technical Accomplishments & Progress

- Input variables:
 - type of feedstock
 - type of catalyst
 - catalyst amount
 - water amount
 - NaOH amount
 - Temperature
- Output measurements:
 - H₂ yield (as a % of stoichiometric H₂ production)
 - H₂ purity (% H₂ of dry product gas)
 - total liters of product gas
 - product gas composition
 - H₂ yield vs. time



PHASE 1 EXPERIMENTAL RESULTS

Technical Accomplishments & Progress

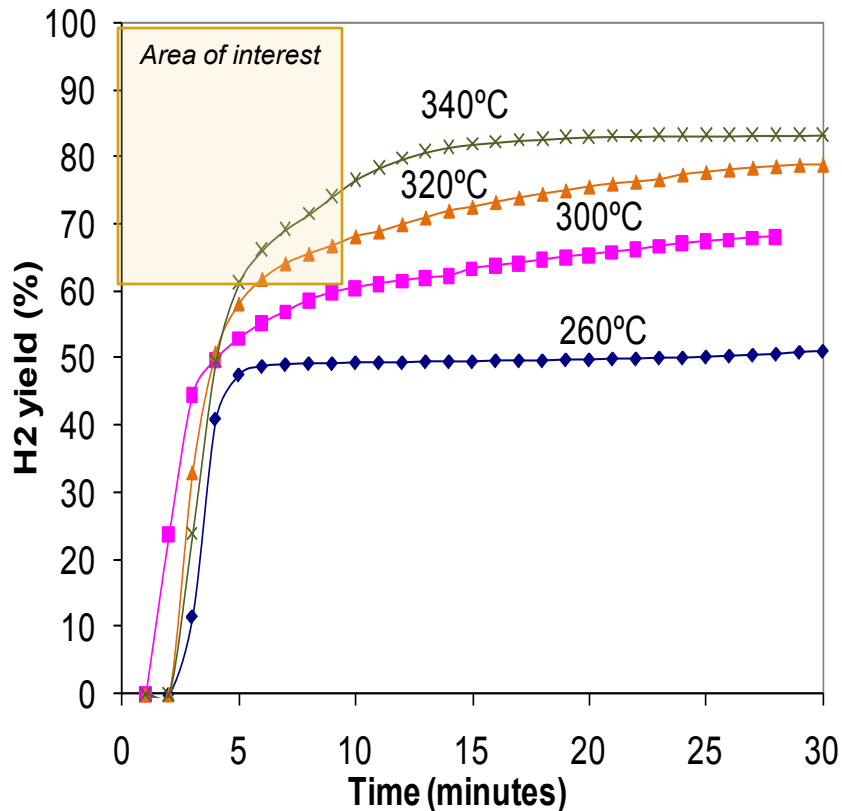


High H₂ purity achieved under many different catalysts/conditions.

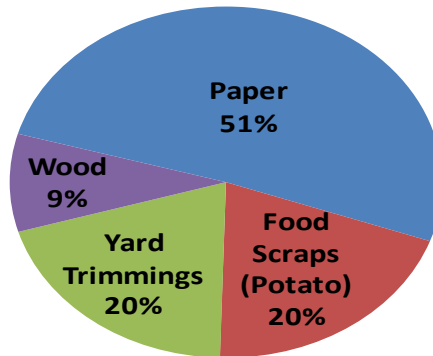
PHASE 1 MSW RESULTS

Technical Accomplishments & Progress

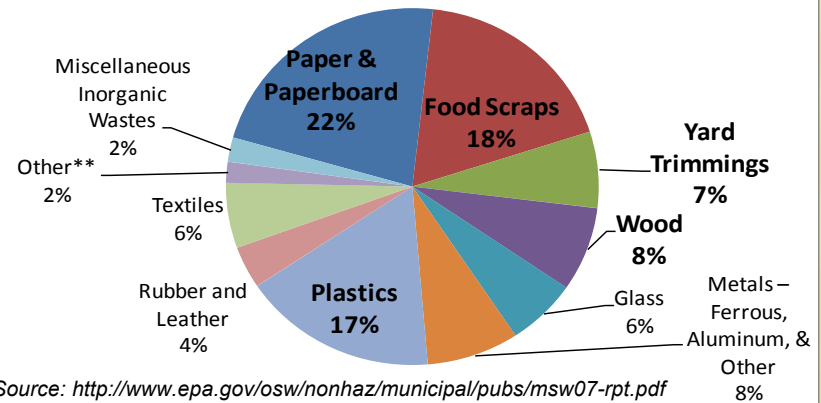
Base Facilitated Reformation of MSW at Different Temperatures



Simulated MSW Composition



Discarded MSW Composition



Source: <http://www.epa.gov/osw/nonhaz/municipal/pubs/msw07-rpt.pdf>

With < 7 minutes residence time and only 300°C, BFR can achieve H₂ yields >50%.

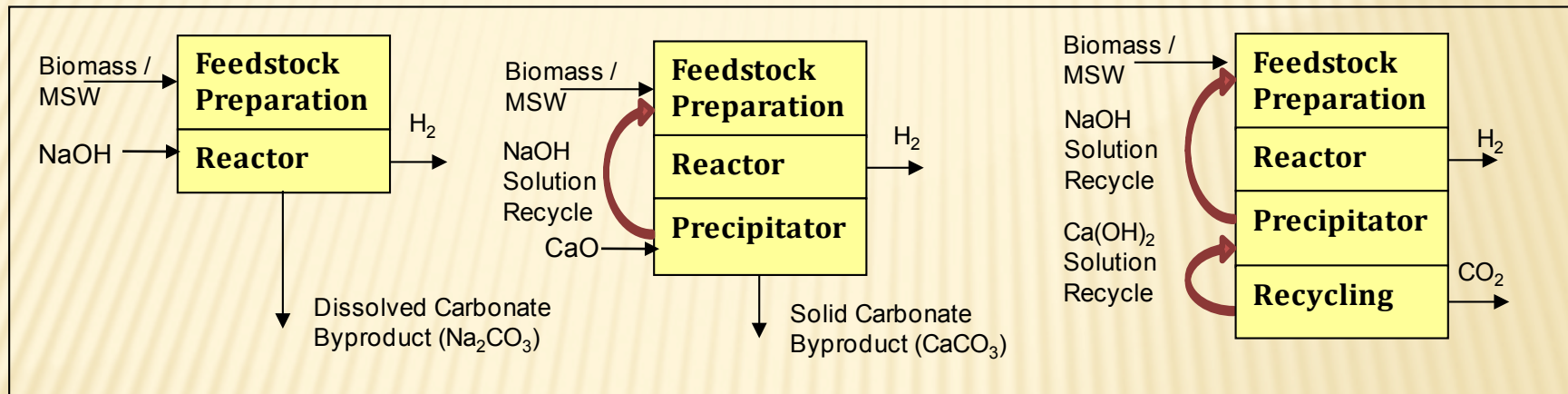
BASE-FACILITATED REFORMING (BFR)

Three potential basic configurations:

Configuration #1
(Basic)

Configuration #2 and #3
(Basic + NaOH Recycle)

Configuration #4
(Full Recycle)



- ❑ Uses base materials, such as NaOH, and $\text{Ca}(\text{OH})_2$ as a reactant in the reforming reaction with the organic fuels or biomass
- ❑ Nickel based catalysts incite the reaction of biomass with hydroxide materials (NaOH, KOH, etc).
- ❑ Liberates the same amount of H_2 as in steam reforming, however, a solid salt - Na_2CO_3 – is produced instead of CO_2 gas.
- ❑ Reaction is often exothermic
- ❑ Simple reactor design and low operating temperature allows the BFR reactor to be significantly less expensive

PHASE 1 CO₂ EMISSIONS ANALYSIS

BFR CARBON DIOXIDE EMISSIONS (TONNE/DAY)	CASE 1				CASE 2		CASE 3		CASE 4	
	Case 1a: Zero CO ₂ emissions from NaOH production		Case 1b: Full CO ₂ emissions from NaOH production							
For a 10 tonne H₂ / Day Production Capacity										
From production of upstream input materials	0		395		104		104		1.4	
From transporting input materials to BFR production facility	0.04		0.04		0.22		0.22		0	
Directly created in actual BFR reaction	0		0		0		0		109	
From heating lime kiln during recycle process	0		0		0		0		9.0219	
From displacing MSW [if otherwise landfilled (left) or combusted (right)]	-4	1	-4	1	-4	1	-4	-1	-4	-1
NET Carbon Dioxide Emissions (Metric Ton/day)	-4	1	391	396	101	106	101	104	115	118
NET Carbon Emissions (Metric Ton/day) of a 10tonneH ₂ /day MSW Steam Reforming Plant at 70% LHV efficiency					156					
NET Carbon Emissions (Metric Ton/day) of a 10tonneH ₂ /day Natural Gas Steam Reforming Plant at 70% LHV efficiency					78					

- ❑ Analysis uses EPA's Waste Reduction Model (WARM) Version 9
- ❑ For this analysis, MSW is not considered a renewable fuel (If considered renewable, Case 4 emissions go to near zero).
- ❑ Significant CO₂ emissions are from the electricity of NaOH production (via chloralkali process)
- ❑ That the net CO₂ emissions from Cases 2, 3, and 4, all of which sequester carbon in carbonate form, were not dramatically lower was a surprising result from Phase 1.
- ❑ A search for a non-CO₂ releasing source of CaO was unsuccessful.

PHASE 1 CAPITAL COST ESTIMATES

- ❑ Estimated costs: not based on detailed DFMA
- ❑ 2 tonne H₂/day BFR modules: multiple modules can be arrayed in parallel
- ❑ 20 inch reactor tube diameter for 2 tonne module: not expected to grow
- ❑ Subsystem are also module: don't require specialization between cases
 - Case 2 is the exception due to shared facilities

Subsystem	Element Cost	Subsystem Cost Summary			
		Case 1	Case 2	Case 3	Case 4
Handling System					
Raw Materials Handling Subsystem	\$102,300	\$102,300	\$102,300	\$102,300	\$102,300
BFR Reactor System		\$262,420	\$262,420	\$262,420	\$262,420
Reactor Subsystem	\$20,570				
Gas Collection Subsystem	\$3,850				
Catalyst Separation (Pressurized)	\$150,000				
Solids Separation	\$88,000				
Precipitation System		\$0	\$144,910	\$289,820	\$289,820
Slaker	\$50,000				
Causitizer	\$100,600				
Clarifier	\$139,220				
Lime Kiln System		\$0	\$0	\$0	\$220,000
Calcium Carbonate Recycle System	\$220,000				
Assembly	--	\$37,534	\$52,447	\$67,360	\$90,000
Miscellaneous	--	\$40,225	\$56,208	\$72,190	\$96,454
Total Material Cost	--	\$442,479	\$618,284	\$794,089	\$1,060,994
Markup (set for 50% gross margin)	--	\$442,479	\$618,284	\$794,089	\$1,060,994
Total Capital Cost	--	\$884,958	\$1,236,569	\$1,588,179	\$2,121,988

Total Capital cost between ~\$1-2M for 2 TPD Module

PHASE 1 STANDARD H2A ASSUMPTIONS USED

90% operating capacity factor
10% real rate of return
20 year plant lifetime
2010 start-up
All costs reported in 2005 dollars
20 year analysis period
20 years MACRS depreciation schedule
100% equity financing
6 month start-up
100% of fixed costs during start-up
75% of variable operating costs during start-up
75% of revenues during start-up
38.9% total tax rate (federal and state)
15% working capital
1% of direct capital for site preparation
13% of direct capital for eng. & design
20% of direct capital for process contingency
\$5000/acre land cost
2% property tax and insurance rate
0.5%/year of direct cost for production maintenance and repairs
2%/year of total direct depreciable costs for unplanned replacement capital
\$50/hour burdened labor rate
20% G&A rate (applied to labor)

PHASE 1 HYDROGEN COST PROJECTION

- **Case 1 – Chloro Alkali:**
 - High NaOH consumable cost
 - Low selling price of the Na₂CO₃ byproduct
- **Case 2 – Pulp Mill**
 - Low / Med / High byproduct revenues
 - If possible to sell carbonate at the premium price, the hydrogen could be given away for free as the carbonate revenue more than pays for production process
- **Case 3 – Low Cost Feedstock**
 - Low / Med /High byproduct revenues
 - Plant uses its own optimized precipitator
- **Case 4 – Full Recycle:**
 - Most complicated and capital intensive
 - Releases CO₂ into the atmosphere at the plant site.

\$2.27- \$3.26/kgH₂ Most Likely

		Case 1	Case 2				Case 3			Case 4
		BFR Reactor	BFR Reactor With Precipitator (shared with a Pulp Mill)				BFR Reactor With Precipitator (high pressure, high temperature)			BFR Reactor With Precipitator (high pressure, high temperature) plus Lime Kiln
Plant Size	kgH ₂ /day	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	
Feedstock										
Type		MSW	MSW	MSW	MSW	MSW	MSW	MSW	MSW	
Efficiency (LHV)	%	44%	44%	44%	44%	44%	44%	44%	44%	
% Yield	%	50%	50%	50%	50%	50%	50%	50%	50%	
Price	\$/tonne	0	0	0	0	0	0	0	0	
Usage	kg/kgH ₂	13.56	13.56	13.56	13.56	13.56	13.56	13.56	13.56	
C Factor	kgC/kgFeedstock	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
C Production	kgC/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H ₂ Cost Impact	\$/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
NaOH										
Price	\$/tonne	380.19	380.19	380.19	380.19	380.19	380.19	380.19	380.19	
Loss Factor	%	0%	5%	5%	5%	5%	5%	5%	5%	
Excess Factor	%	10%	0%	0%	0%	0%	0%	0%	0%	
Usage	kg/kgH ₂	21.82	0.99	0.99	0.99	0.99	0.99	0.99	0.99	
C Factor	kgC/kgNaOH	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	
C Production	kgC/kgH ₂	39.28	1.79	1.79	1.79	1.79	1.79	1.79	1.79	
H ₂ Cost Impact	\$/kgH ₂	8.30	0.38	0.38	0.38	0.38	0.38	0.38	0.38	
Na₂CO₃										
Selling Price	\$/tonne	-165.30	-165.30	-165.30	-165.30	-165.30	-165.30	-165.30	-165.30	
Production	kg/kgH ₂	26.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
H ₂ Cost Impact	\$/kgH ₂	-4.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CaO										
Price	\$/tonne	110.20	110.20	110.20	110.20	110.20	110.20	110.20	110.20	
Loss Factor	%	0%	0%	0%	0%	0%	0%	0%	5%	
Usage	kg/kgH ₂	0.00	13.91	13.91	13.91	13.91	13.91	13.91	0.70	
CO ₂ Factor	kgC/kgCaO	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	
C Production	kgC/kgH ₂	0.00	10.43	10.43	10.43	10.43	10.43	10.43	0.52	
H ₂ Cost Impact	\$/kgH ₂	0.00	1.53	1.53	1.53	1.53	1.53	1.53	0.08	
CaCO₃										
Type of Sale			No sale	Ag. Lime	Prem. Lime	No sale	Ag. Lime	Prem. Lime		
Selling Price	\$/tonne	0.00	10.00	-15.00	-300.00	0.00	-15.00	-300.00	0.00	
Production	kg/kgH ₂	0.00	24.82	24.82	24.82	24.82	24.82	24.82	0.00	
H ₂ Cost Impact	\$/kgH ₂	0.00	0.25	-0.37	-7.45	0.00	-0.37	-7.45	0.00	
Lime Kiln										
C Factor for Crelease	kgC/kgCaCO ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	
C Factor for NG usage	kgC/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	
C Production	kgC/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.92	
Capital Cost										
Total Cap. Cost (uninstalled)	\$	4,355,980	6,086,691	6,086,691	6,086,691	7,817,402	7,817,402	7,817,402	10,444,940	
H ₂ Cost Impact	\$/kgH ₂	0.47	0.68	0.68	0.68	0.84	0.84	0.84	1.06	
Energy	\$/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	
Utilities										
H ₂ Cost Impact	\$/kgH ₂	0.10	0.16	0.16	0.16	0.16	0.16	0.16	0.45	
Fixed O&M										
H ₂ Cost Impact	\$/kgH ₂	0.38	0.41	0.41	0.41	0.43	0.43	0.43	0.46	
H₂ Cost Summary										
Feedstock	\$/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
NaOH	\$/kgH ₂	8.30	0.38	0.38	0.38	0.38	0.38	0.38	0.38	
Na ₂ CO ₃	\$/kgH ₂	-4.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CaO	\$/kgH ₂	0.00	1.53	1.53	1.53	1.53	1.53	1.53	0.08	
CaCO ₃	\$/kgH ₂	0.00	0.25	-0.37	-7.45	0.00	-0.37	-7.45	0.00	
Energy	\$/kgH ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	
Capital	\$/kgH ₂	0.47	0.68	0.68	0.68	0.84	0.84	0.84	1.06	
Decommissioning	\$/kgH ₂	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Fixed O&M	\$/kgH ₂	0.38	0.41	0.41	0.41	0.43	0.43	0.43	0.46	
Total H₂ Cost	\$/kgH₂	4.80	3.26	2.64	-4.44	3.19	2.82	-4.26	2.27	