Direct Production of Gasoline and Diesel from Biomass using Integrated Hydropyrolysis and Hydroconversion (IH^2)

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U.S. DOE Award DE-EE-0002873

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Challenges for Pyrolysis or Pyrolysis Plus Upgrading

>Undesirable Pyrolysis Oil Properties

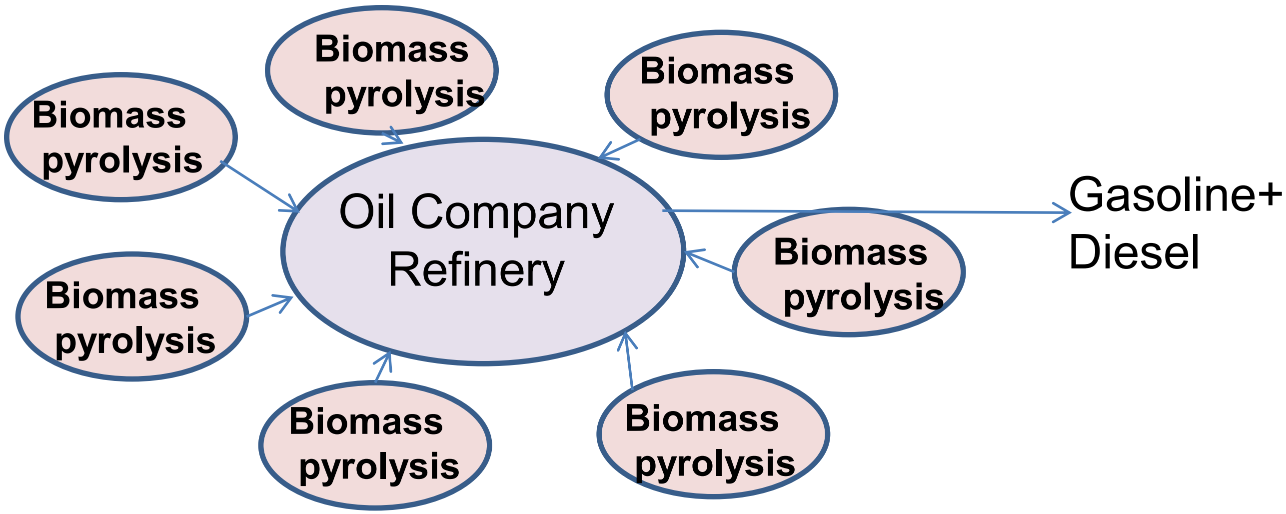
- > Limited demand
- > Expensive to transport
- > Incompatible with oil refinery metallurgy

>Expensive Upgrading to Make Fungible Fuels

- > High H_2 requirements
- > Severe conditions (low LHSV, high pressures)
- > Rapid catalyst bed fouling-plugging

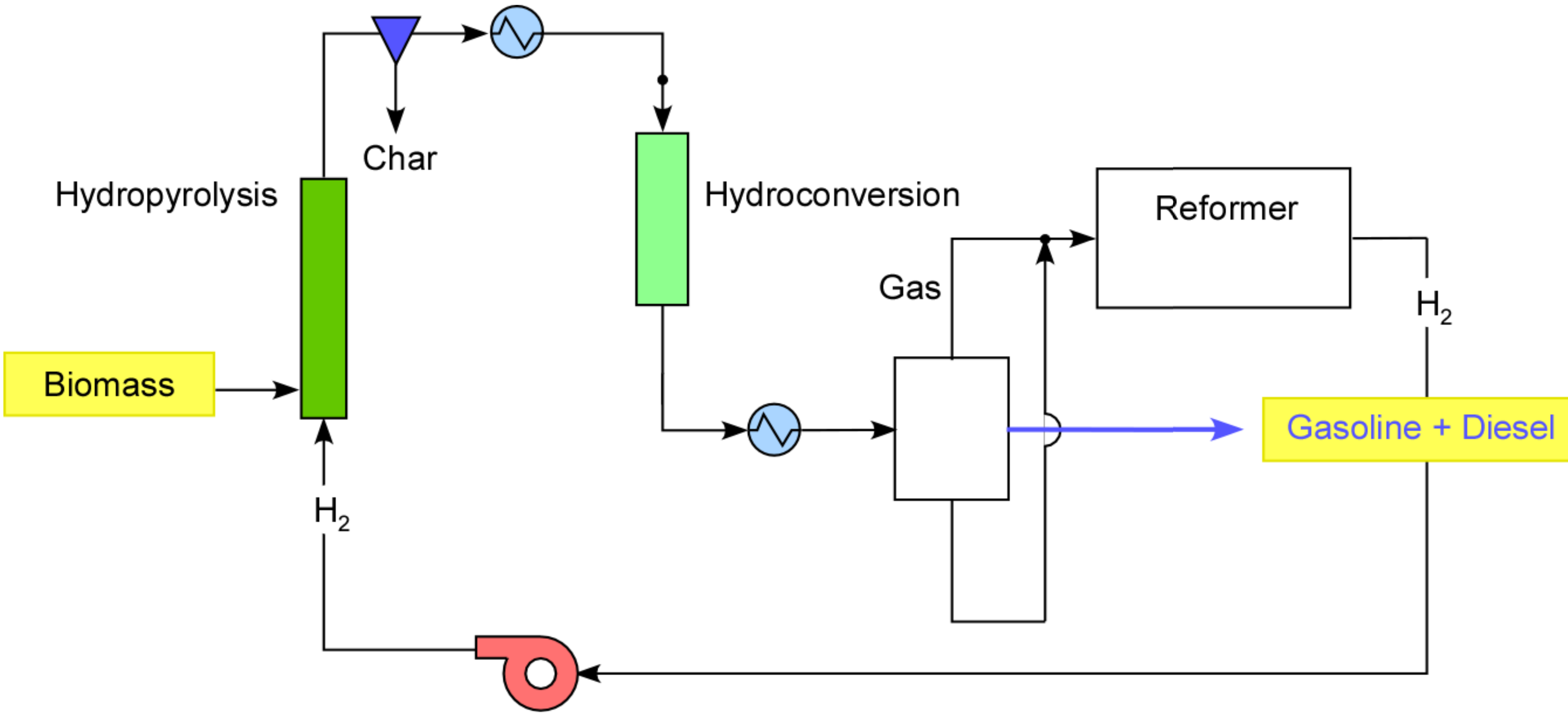
Overcoming Pyrolysis Problems has proved to be very tough

Challenges with Distributed Pyrolysis Business Model



1. Business Challenges
   - Requires long term off-take agreements between **many** biomass producers doing pyrolysis and an oil company refinery
   - Requires specialized capital investment by petroleum refineries
   - *Allows Oil Companies to control the flow of biooil to the market*
   - *Requires Oil Companies to displace crude oil in favor of biooil, when Oil Companies make their money from crude production not refining*

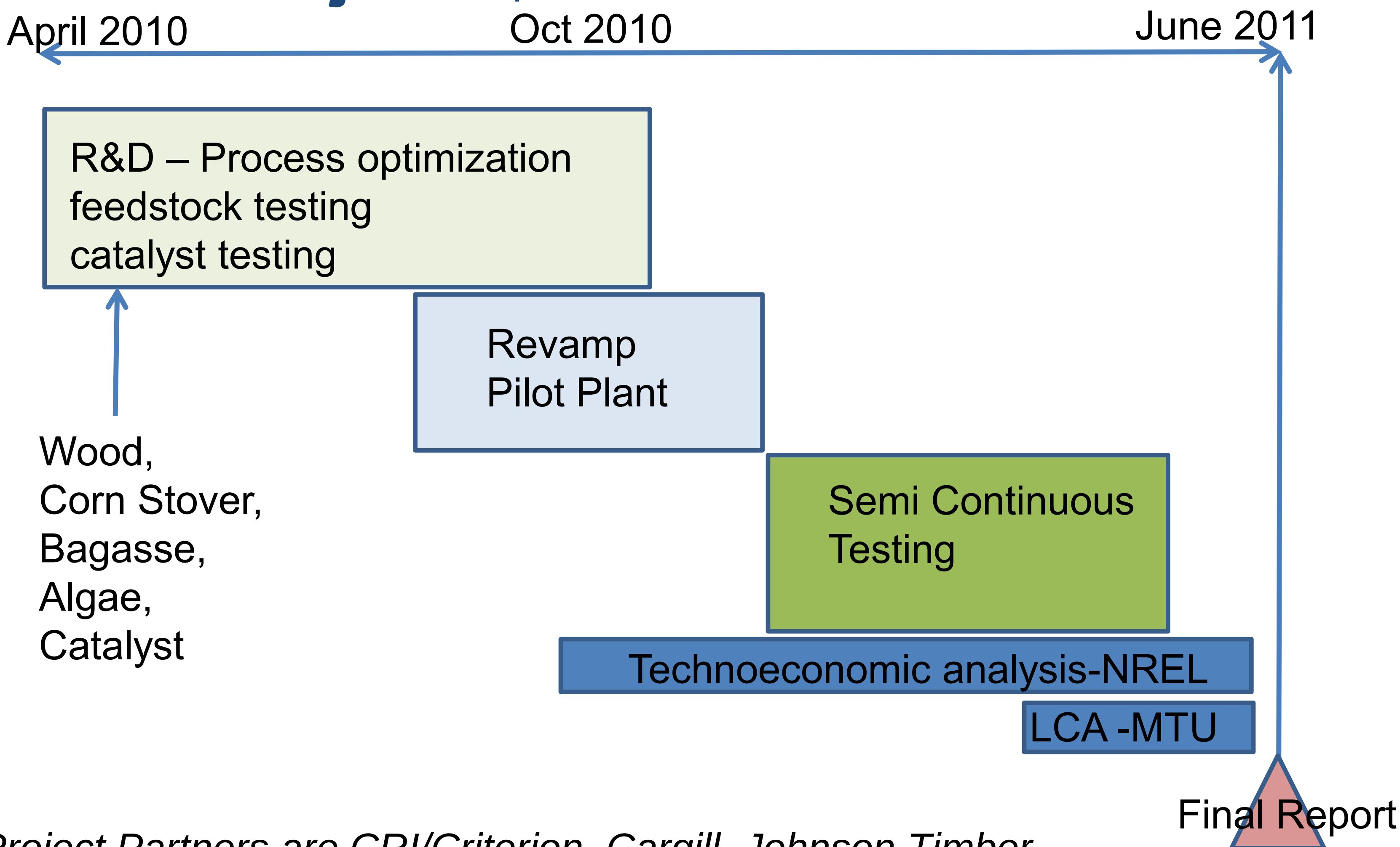
Integrated Hydropyrolysis and Hydroconversion



- Directly make desired products
- Run all steps at moderate hydrogen pressure (100-500 psi)
- Utilize C_1-C_3 gas to make all hydrogen required
- Avoid making "bad stuff" made in pyrolysis – PNA, free radicals

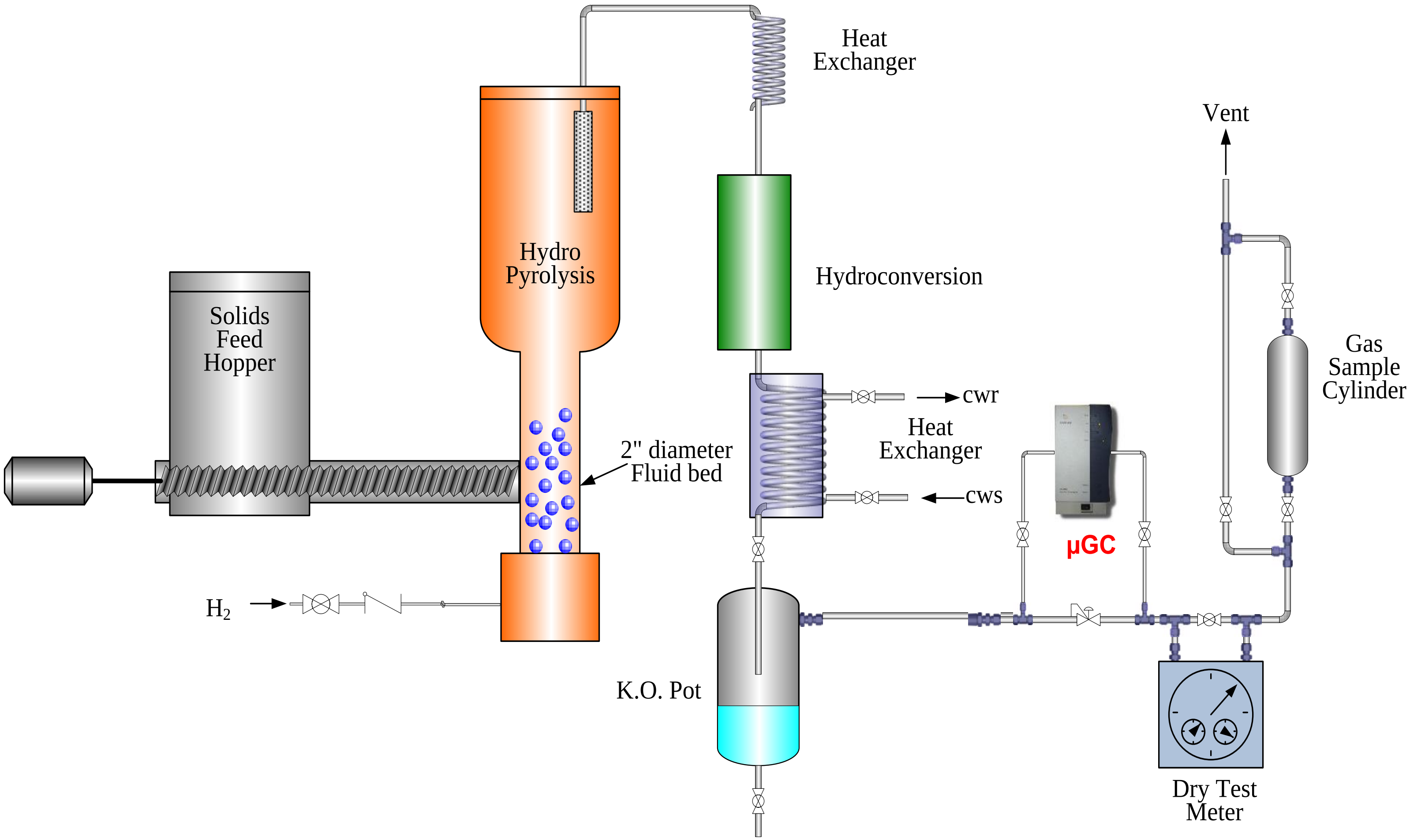
Initial IH2 DOE Project Plans

14 Month Project - $3.1 MM

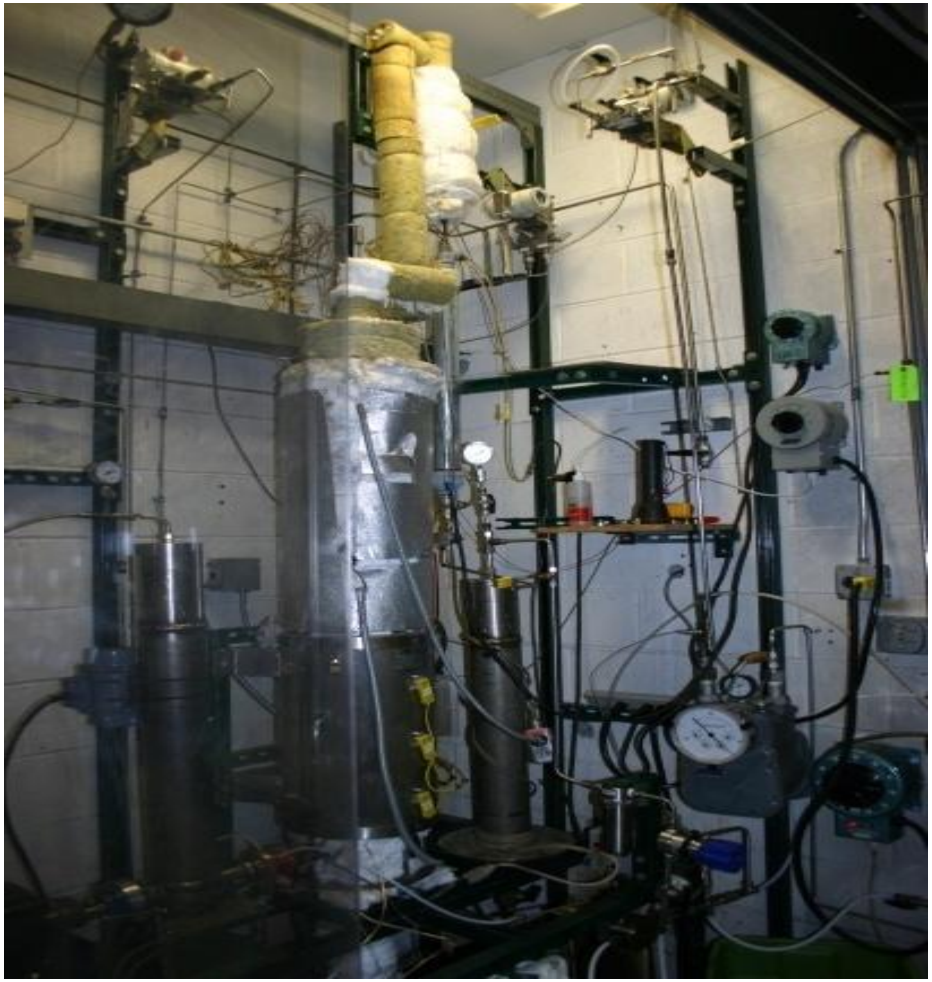


Project Partners are CRI/Criterion, Cargill, Johnson Timber, Blue Marble Energy, Aquaflow, NREL and MTU

IH2 Proof of Principle Unit



GTI IH2 Equipment



- Hydrogen pressures of 100-500 psi
- Fast heat up of continuously fed biomass
- Specially designed feeder
- Well fluidized bed of catalyst for hydropyrolysis
- No signs of coking or pressure buildup across hot internal filter
- Integrated fixed bed hydro-treating – using CRI/Criterion Inc. CoMo catalyst
- Hydrocarbon product floats on top of *separate* water phase

IH2 Feedstock Flexibility

	Wood	Lemna (Minor Duckweed)	Corn Stover
% C	49.7	46.3	45.6
%H	5.8	5.8	5.5
%O	43.9	35.7	40.7
%N	0.11	3.7	0.87
%S	0.03	0.3	0.08
% Ash	0.5	8.2	7.2
Cellulose	40		45
Hemicellulose	32		26
Lignin	28		15
Carbohydrate		52.2	
Protein		28.7	
Lipid		1.0	
Fiber		6.0	
% C_4 + Liquid Yield (MAF)	22-30	22-30	
% Oxygen	<1%	<1%	

IH2 works with a variety of feedstocks – very feed flexible

GTI IH2 Proof of Principle Experimental Results

Feedstock	Wood	Lemna
C_4 + Liquid yields (MAF) wt%	22-30%	22-30%
% Oxygen in liquid	<1%	<1%
% Gasoline boiling range in liquid product	54-75	55-72
% Diesel boiling range in liquid product	25-46	28-45
% Char (MAF)	7-15	3-15
% CO_X (MAF)	13-23	2-20
% C_1-C_3 (MAF)	10-14	4-16
% Water (MAF)	31-35	30-40

Adjustment of process conditions (temperature, pressure catalyst) – adjusts yield structure - further optimization likely

Product Property Comparisons

	Fast Pyrolysis Oil	IH2 product
% Oxygen	50	<1.0%
% Water	20	<0.2%
TAN	200	<1
Stability	poor	Good
Heating value (Btu/lb)	6560	18000
% Gasoline	Non-distillable	54-75
% Diesel	Non-distillable	23-46
Compatibility with crude oil or refinery products	No	Excellent
Relative transportation cost	1.0	0.3

It is easier to find a market for desirable products than undesirable ones.

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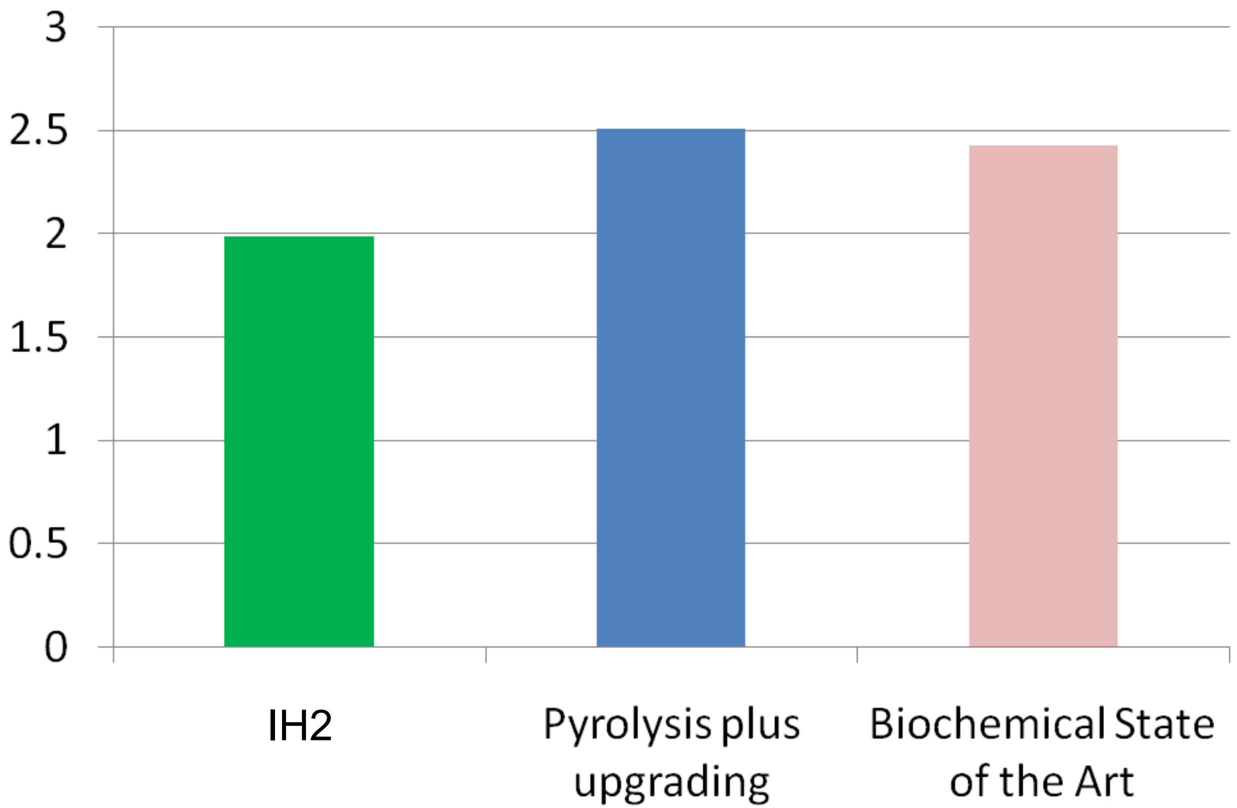
Technology Comparison

	Fast Pyrolysis	Distributed Pyrolysis + Upgrading	IH2
Product properties	Poor	Excellent	**Excellent**
External hydrogen required	None	3-4%	**None**
Capital costs	Medium	High	**Medium**
Hot filtering	Difficult	Difficult	**Straightforward**
Heat of reaction	Endothermic 300J/g	Pyrolysis = Endothermic Upgrading = Exothermic	**Both Stages Exothermic**
Integration with upgrading	None	No	**Yes**
Transportation costs	Medium	High	**Low**
Char production	No, typically char burned	No, typically char burned	**Yes**

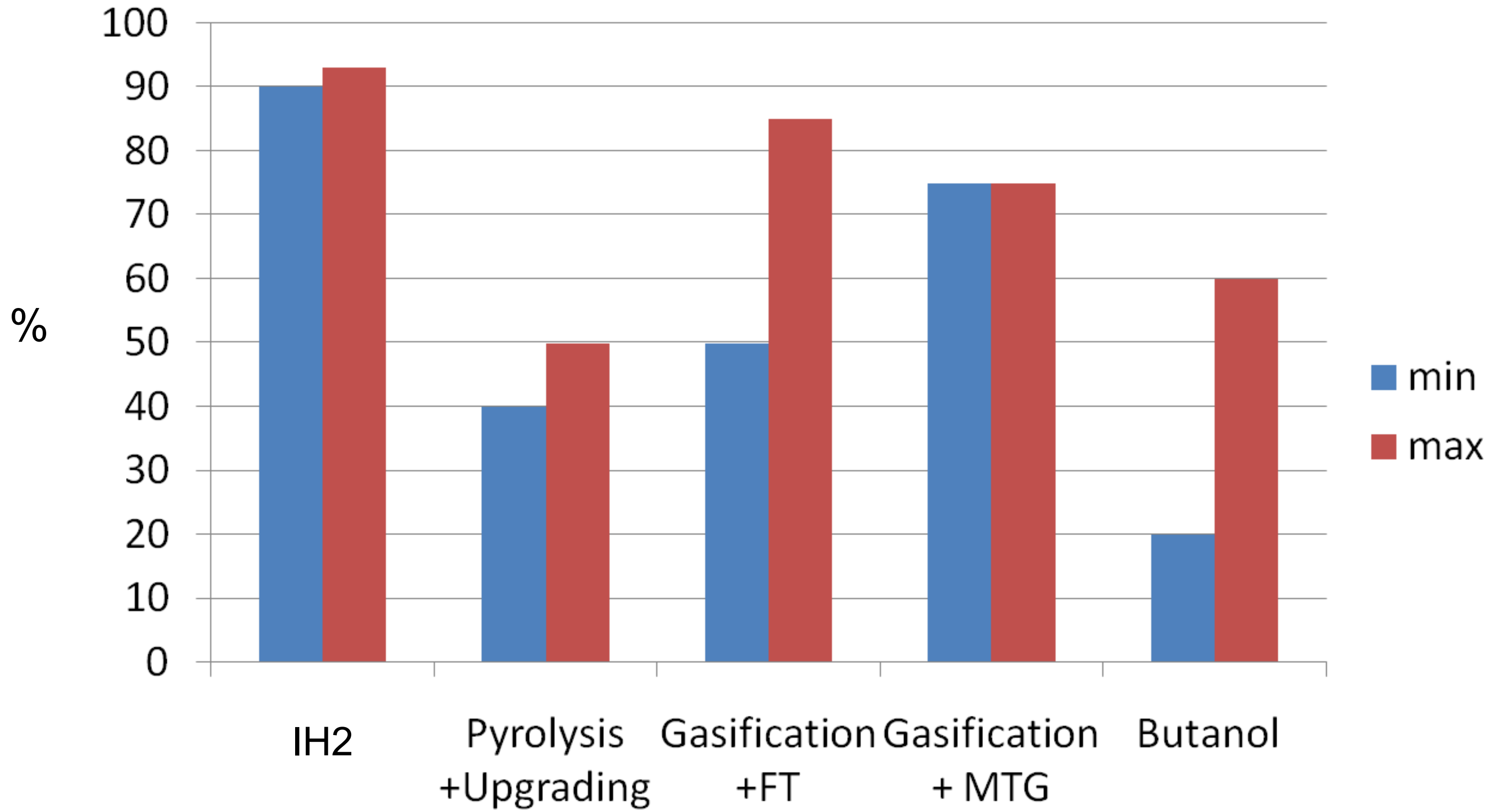
Economic Comparison

FCOP +ROI - $/gal



Based on 2000 t/d of biomass feed

Preliminary Estimate of Greenhouse Gas Reduction



Other technologies LCA from David Hsu "Biofuels Beyond Ethanol" Sept 9, 2008

Hydropyrolysis vs Pyrolysis 1st Stage Product Comparison from wood

	Hydropyrolysis Step of IH2	Pyrolysis
Catalyst	A	None
H2 Partial pressure,psi	325	No
% Oxygen in C4+ Product	1.53	50 (40 water free basis)
% TAN in C4+ product	.35	200
% water in C4+ product	<.2	20
density	.85	1.2

•There is a big difference between Hydropyrolysis products and pyrolysis products
•Much easier to upgrade hydropyrolysis product than pyrolysis product

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C7+ Liquids from Hydropyrolysis of Wood Catalyst A vs Inert -1st Stage only

	Inert	Catalyst A
%C	70.69	88.32
%H	9.09	8.81
%N	.28	.06
%S	.15	.18
%O(by difference)	19.82	2.63
TAN	50	.60

Catalyst Choice in the hydropyrolysis stage has big impact on 1st stage Product quality

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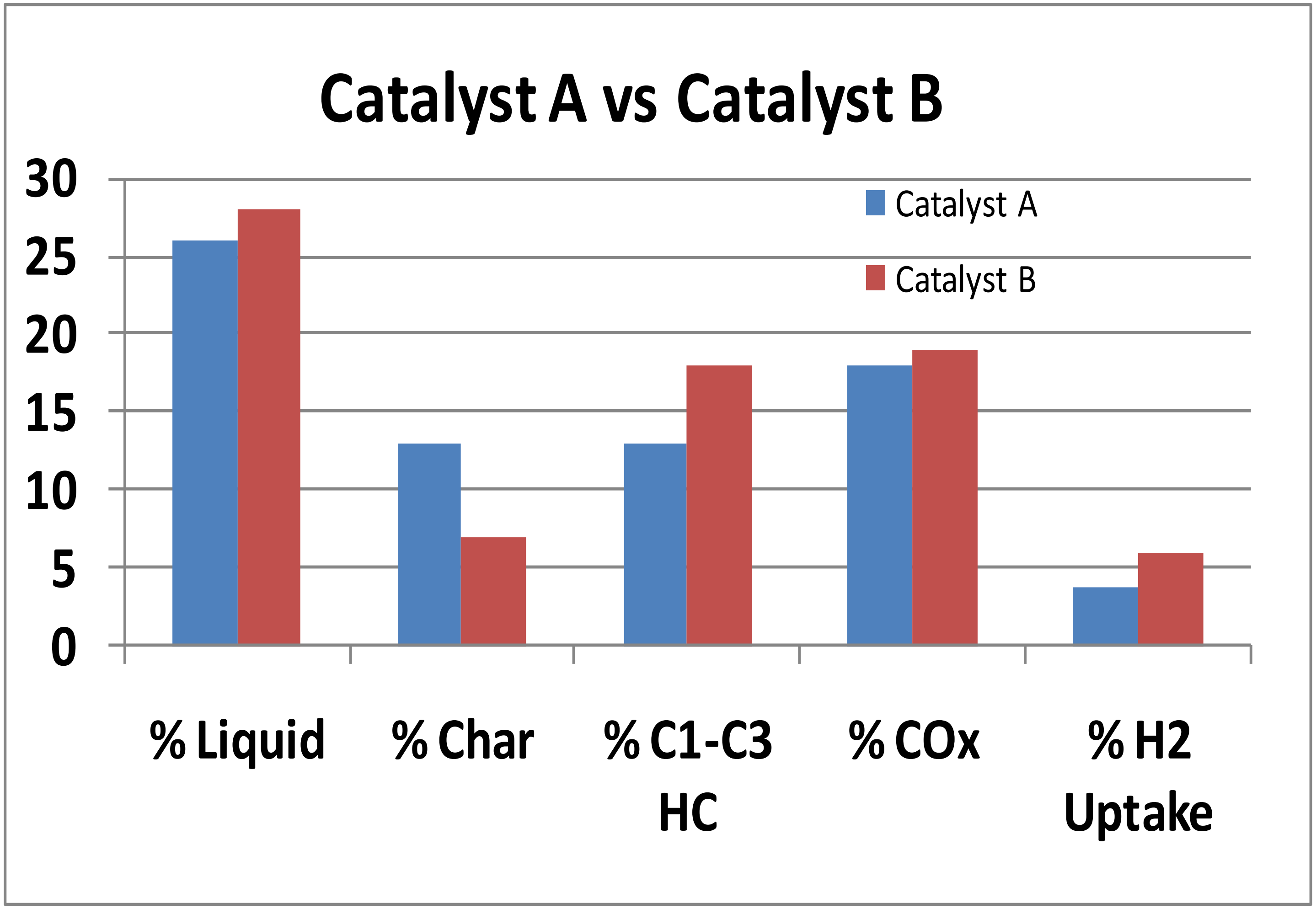
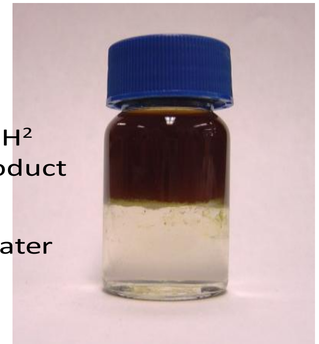
Effect of Hydropyrolysis Catalyst on IH2 Yields – Wood Feed



IH2 Product Quality

IH² Product

Water



GTI IH² Composite Sample Distilled Fractions From wood

Cold trap liquids	Gasoline	Light Jet	Heavy Jet	Diesel	Vacuum Gas Oil
< 72 F at 100 torr	IBP - 350 F	350-410 F	410-570 F	570-680 F	680+ F
3.8 wt%	34.7 wt%	12.9 wt%	25.5 wt%	15.6 wt%	7.6 wt%

38.5 wt% total gasoline

38.4 wt% total jet

51.4 wt% extended gasoline (IBP-410 F)

41.1 wt% remaining distillate

IH² Product Properties - Composite Sample Fractions

Component	Gasoline from Lemna (IBP-220°C)	Gasoline from Wood (IBP-220°C)	Diesel from Lemna (220-360°C)	Diesel from Wood (220-360°C)
% Oxygen	<1	<1	<1	<1
TAN	< 0.05	< 0.6	< 0.05	< 0.6
RON	86	89		
Cetane Index			40	
H/C	1.76		1.64	
% Aromatics	30		23	
ppm sulfur	170	16	142	92

Gasoline from wood – excellent quality
Further improvement of properties likely as we optimize process
NiMo second stage likely better choice to improve properties

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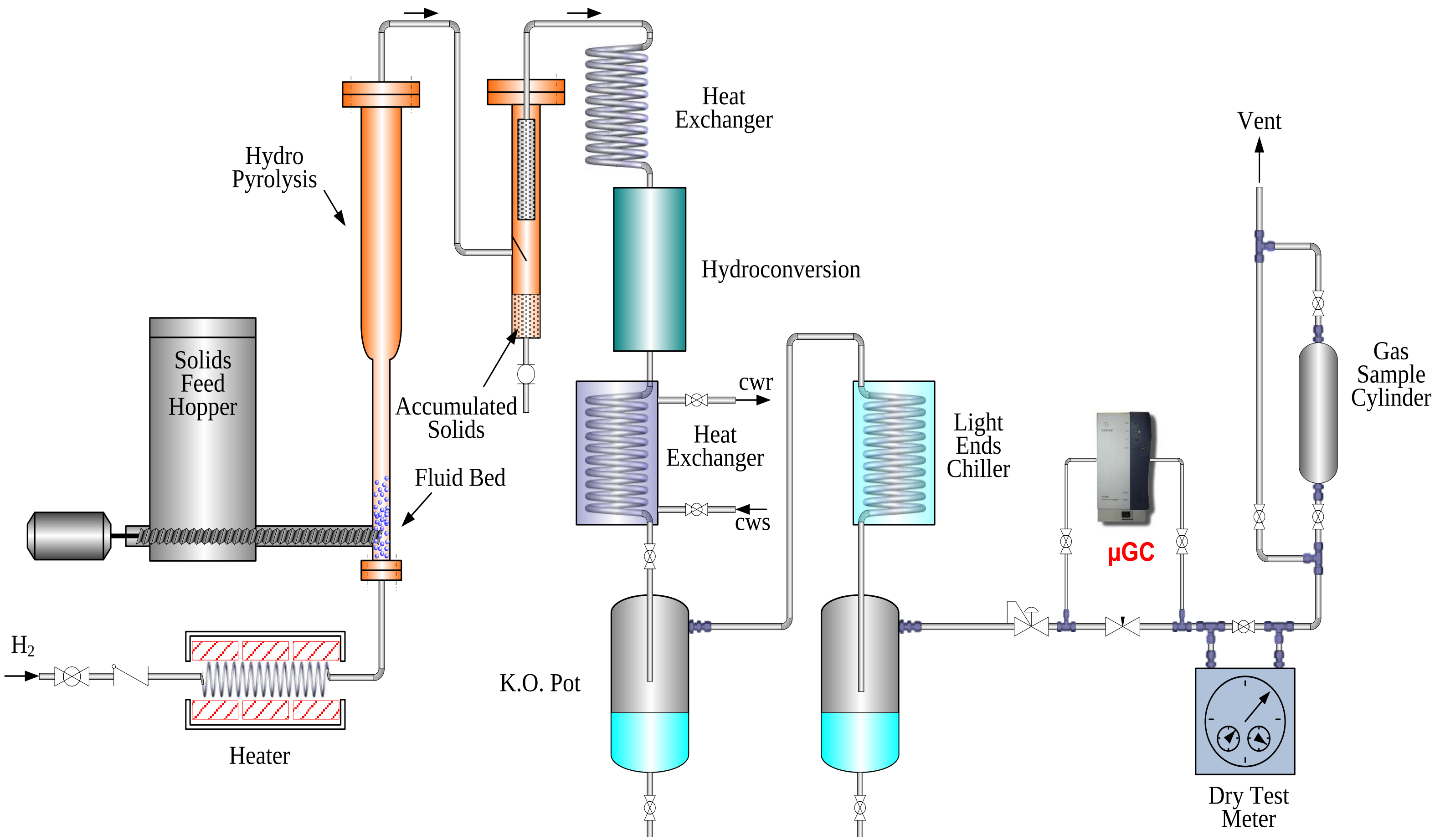
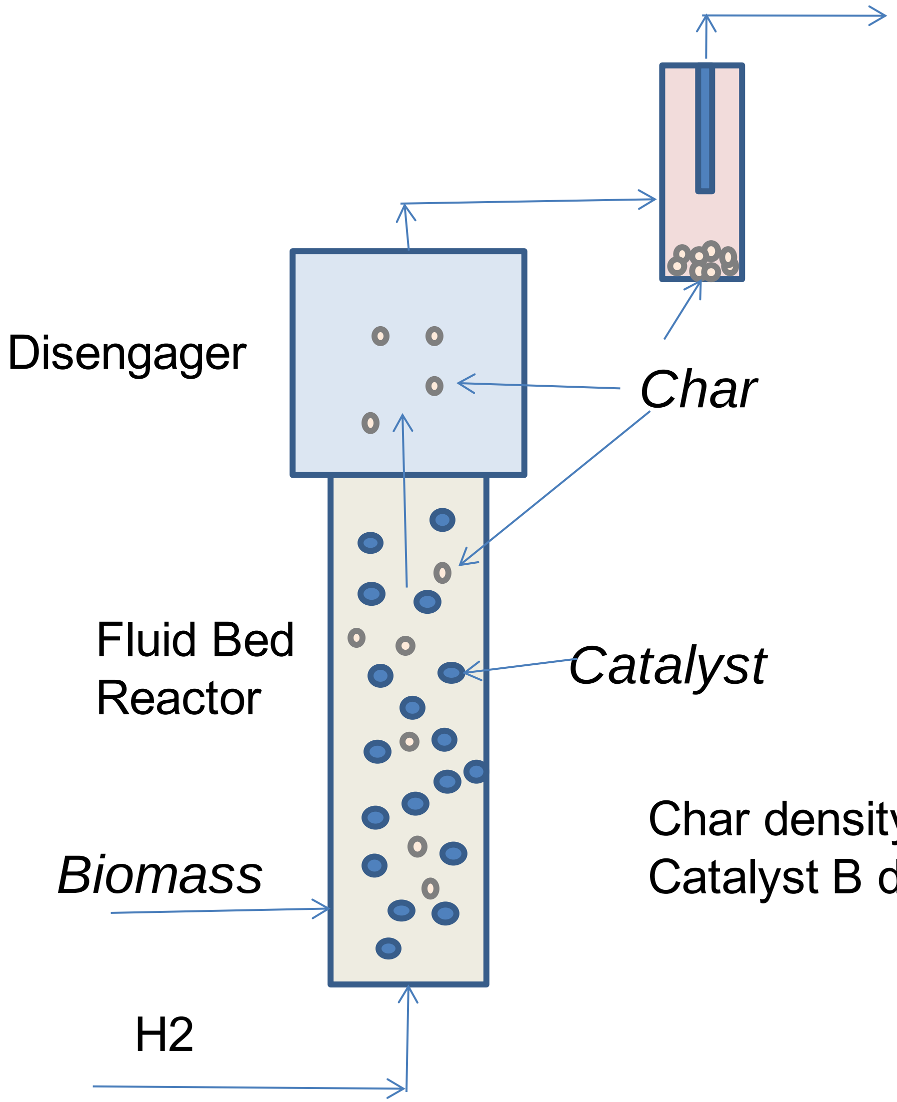
Improved IH2 Pilot Plant



Continuous char-catalyst separation,
Improved light gasoline recovery

Mechanics of Char - Catalyst Separation In IH^2 Pilot Plant



Char density = .3 g/cm3
Catalyst B density =1.0g/cm3

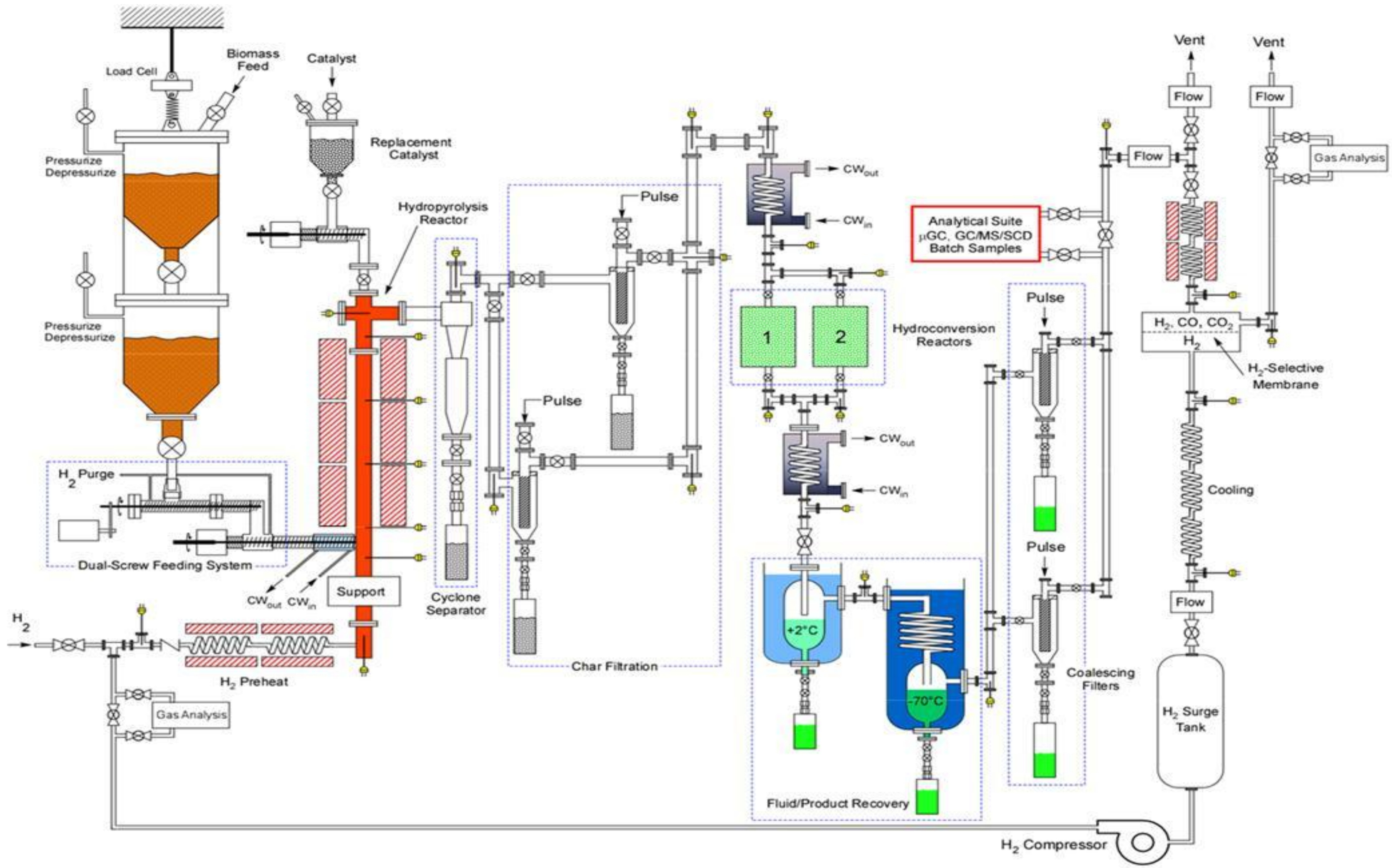
IH² JDA Agreement with CRI/Criterion Inc. Sept, 2010

>Goal

- > Rapidly Develop the IH2 Technology
- > Build Continuous Pilot Plant
- > Freely License the Technology
- > Enable QUICK Commercialization and deployment
- > Have a Significant Impact QUICKLY
  - > Create New Jobs
  - > Reduce Dependence on Foreign Crude
  - > Reduce CO2 Emissions
  - > Reduce Trade deficit

Seize the Moment !

New Automated, Continuous IH2 Pilot Plant in Construction
50 kg/day biomass feed

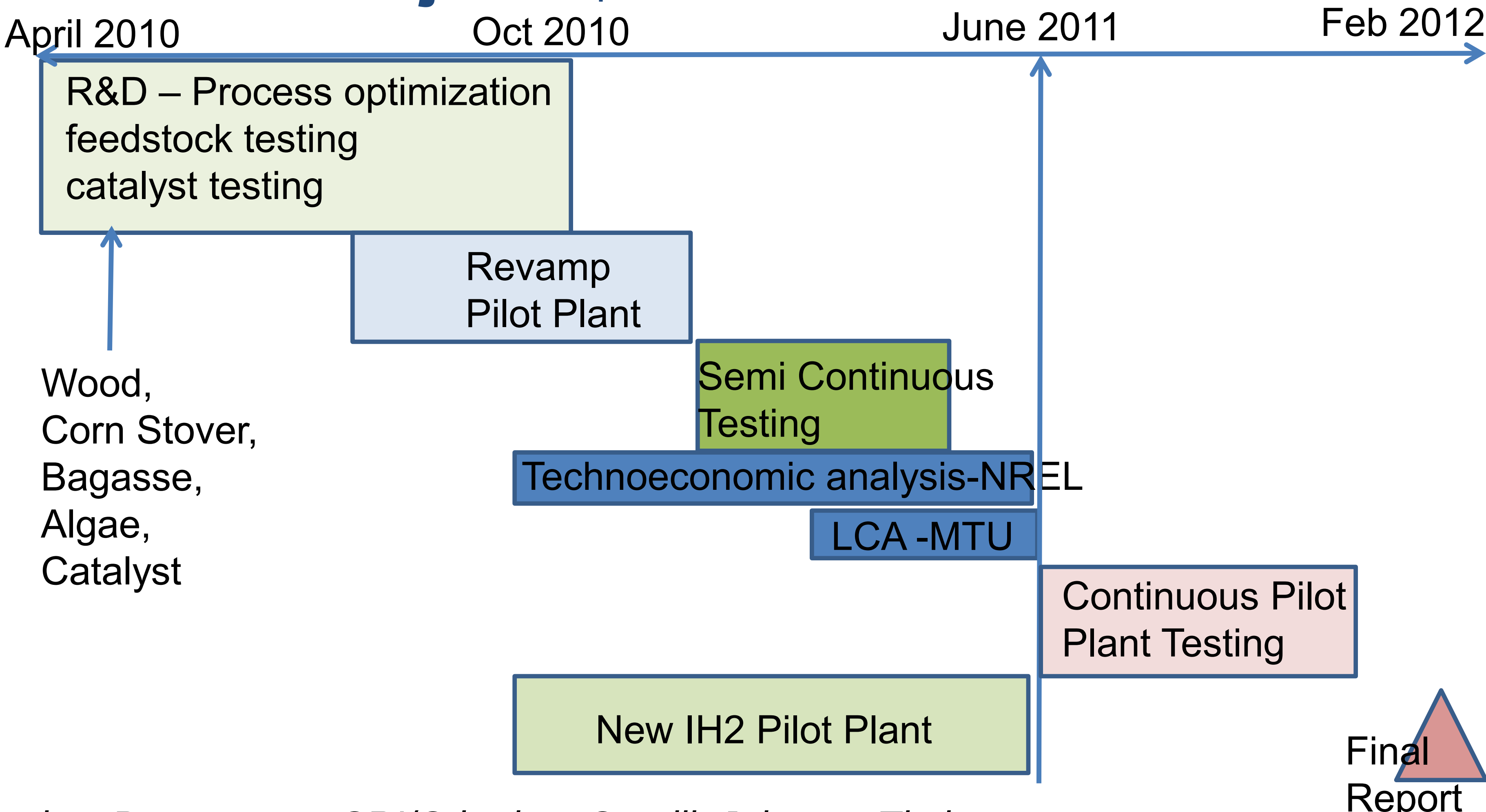


Targeted for Start-up June 2011

U.S. DOE Award DE-EE-0002873

Expanded IH2 DOE Project Plans

22 Month Project - $4.3 MM



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U.S. DOE Award DE-EE-0002873

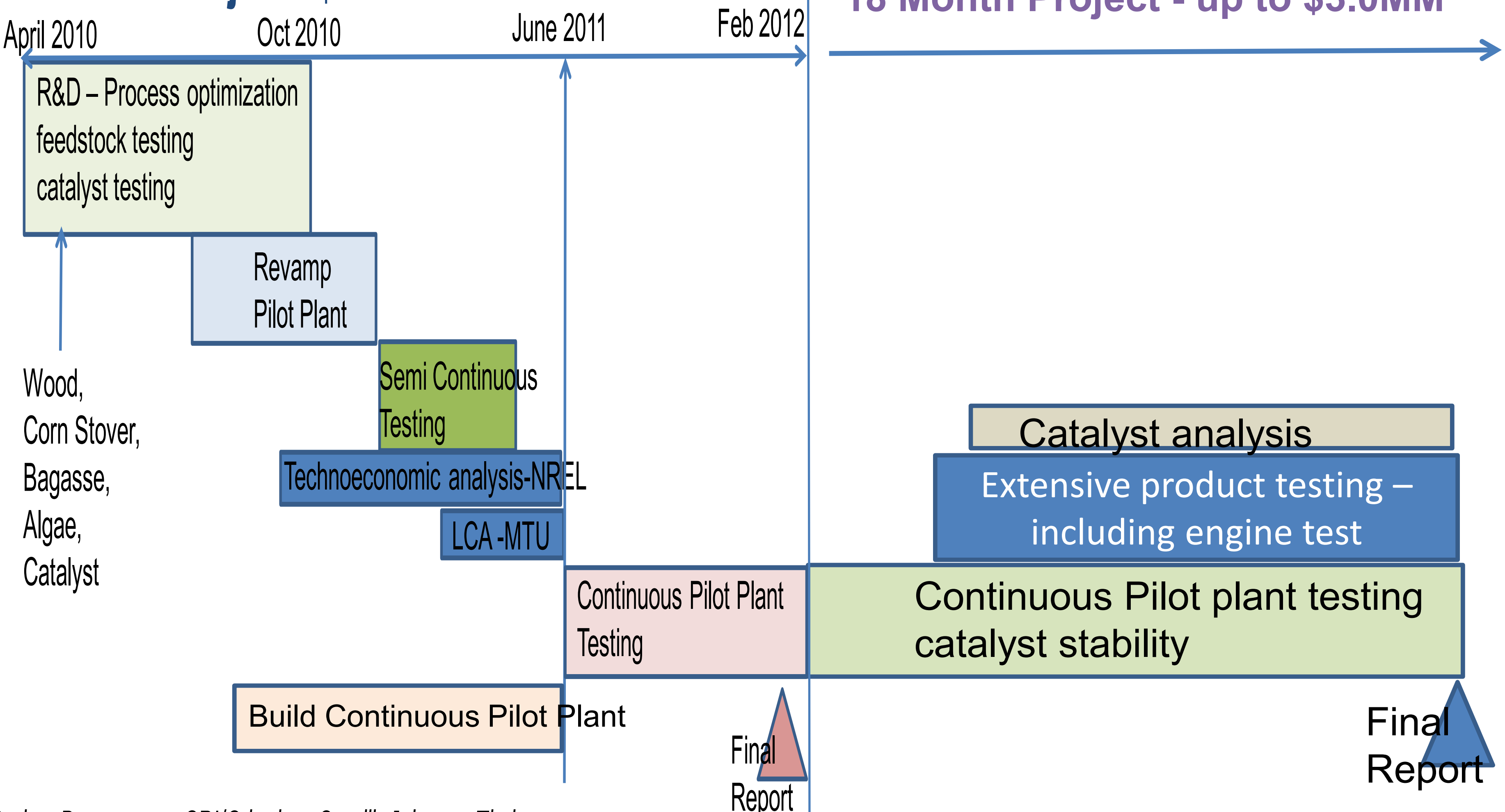
Expanded IH2 DOE Project Plans

22 Month Project - $4.3 MM

U.S. DOE Award DE-EE-0000342

New Continuous IH2 testing program

18 Month Project - up to $3.0MM



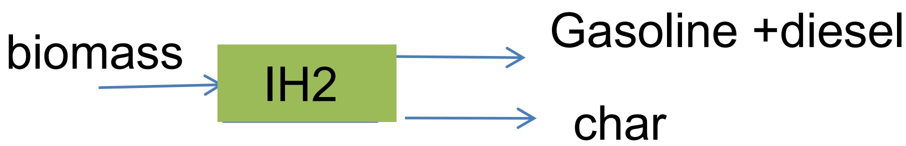
Project Partners are CRI/Criterion, Cargill, Johnson Timber, Blue Marble Energy, Aquaflow, NREL and MTU

Project Partners are CRI/Criterion, Shell Global Solutions,Cargill, Johnson Timber, PetroAlgae

Long Term Continuous Testing Plans

- Run for more than 4000 hours
- Test several Catalyst combinations
- Test a variety of biomass types
- Establish Catalyst Stability and Attrition/Replacement rates
- Produce lots of product (enough for engine testing) and get more test data

IH2 Business Model



- Simple is better
- Directly make high quality products with high demand
- Use Shutdown or underutilized pulp and paper mills - infrastructure for wood collection already there
- Use 75 existing corn ethanol producer locations (they have infrastructure for shipping corn already- straightforward to add stover)
- New PetroAlgae locations
- Gives Biomass Producers Control of Products

Potential IH2 Market is Huge

Conclusions and Future Work

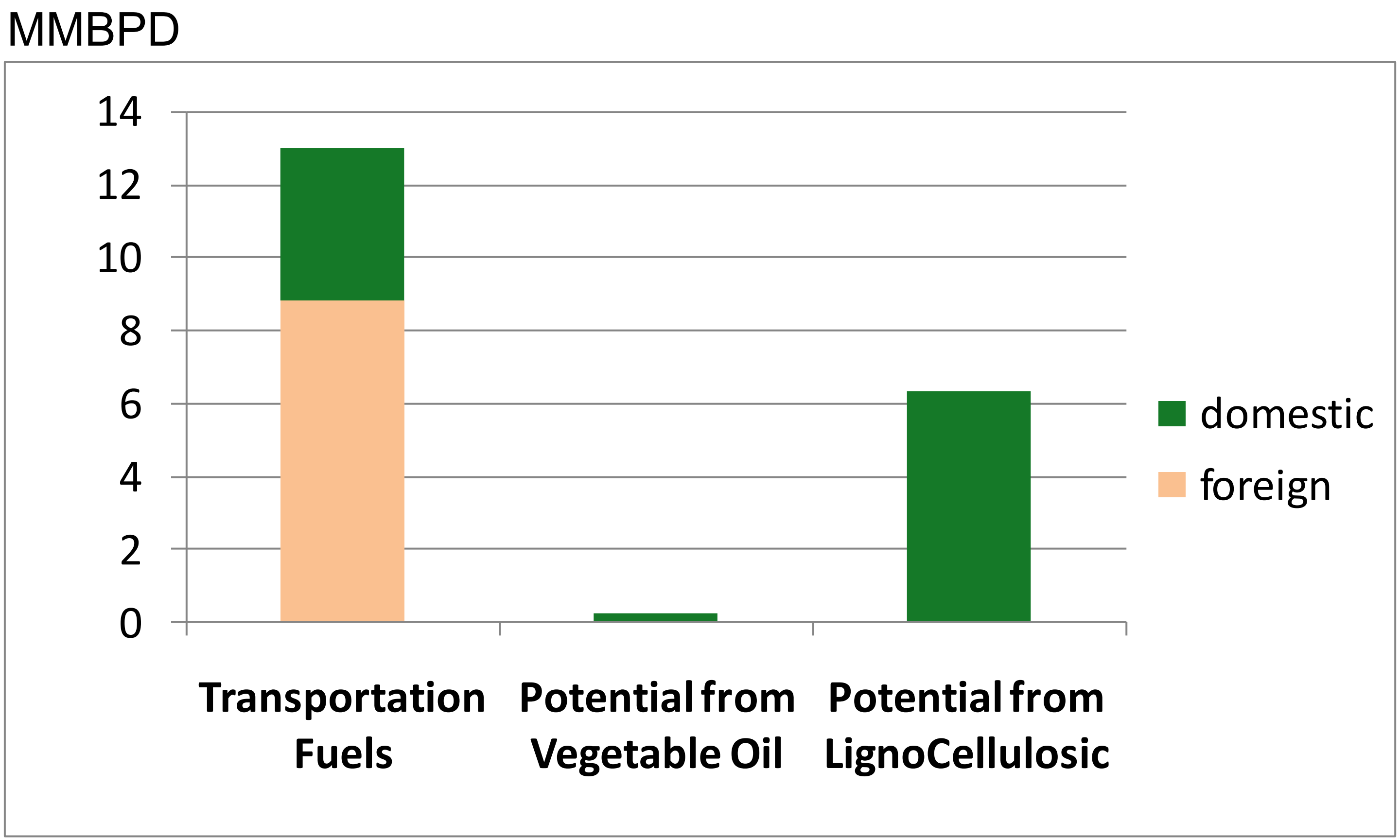
- IH2 is a promising new technology approach with excellent LCA, economics, potential
- **2-3 Years** to commercialization !
  - Will allow feedstock providers to produce valuable fuel products *directly*
  - Will produce products which can be easily used by refiners
- **If successfully developed, could quickly result in significant shift in source of U.S. transportation fuel**
- *Lots of work left to be done!*
  - *Optimal conditions and catalyst*
  - *Catalyst stability- separation*

Acknowledgements

- > CRI/Criterion Inc.
  - > Catalyst is key to project success
  - > Continuous Pilot Plant is key to commercialization
- > Prof David Shonnard of MTU
  - > LCA analysis
- > DOE Funding and Support

IH2 Background

Potential for U.S. Liquid Fuels from Lignocellulosic Feed



Based on billion ton per year of biomass and 28wt% conversion to liquid

Typical Water Analysis from IH2 – Wood feeds

	Catalyst A	Catalyst B
%C	.64	.52
PH	9	9
%N	.31	.31
%ammonia	.35	NA
% S	.03	.07

Low Carbon in water, High PH because of dissolved ammonia

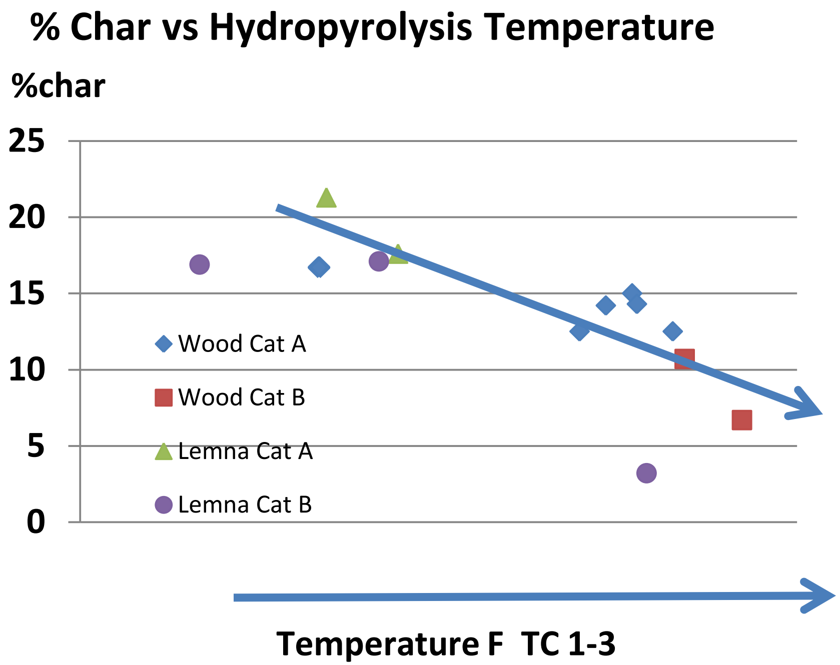
IH2 Char Composition – Compared to Starting Wood

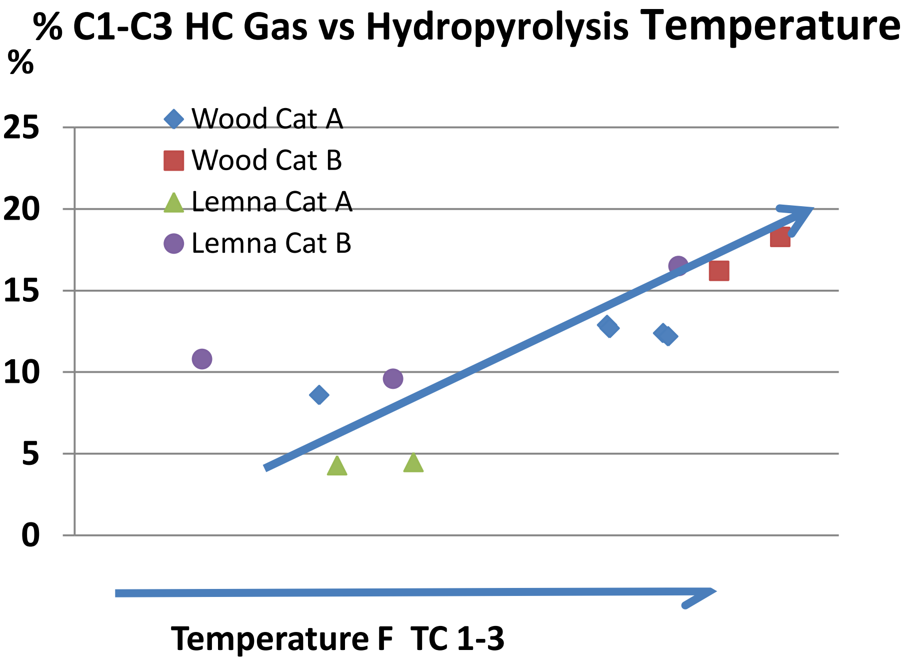
	Wood	CHAR Catalyst A
%C	49.66	93.47
%H	5.96	5.72
%S	.07	.24
%N	.22	.56
%O	42.97	-
H/C	1.44	.73

Char has high levels of nitrogen and sulfur and depleted hydrogen

Char recovery- reuse as fertilizer offers a way to return nutrients to soil – Sets IH2 apart from standard pyrolysis
Char also sequesters carbon – source of carbon credits

Effect of Hydropyrolysis Temperature on % Char, %Gas





As Hydropyrolysis temperature goes up, Char goes down, Gas goes up

IH2 - Liquid Product TAN Numbers vs Run Number