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Driving Innovation ♦ Delivering Results

REMS Reactor Material Design, Construction, and Testing

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U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

Outline

- Goals – REMS design, construction, and testing
- REMS process considerations
- Material considerations
- AM technology being evaluated
- Structure limitations
- Ash considerations (coal and biomass)
- Current research
- Future material direction
- Conclusions

REMS Module Environment *(material exposure)*

Goal = use information from computational fluid dynamics REMS models as a basis to:

1) ***identify and evaluate potential material needs*** for building REMS prototype and full size REMS reactors for testing/evaluation

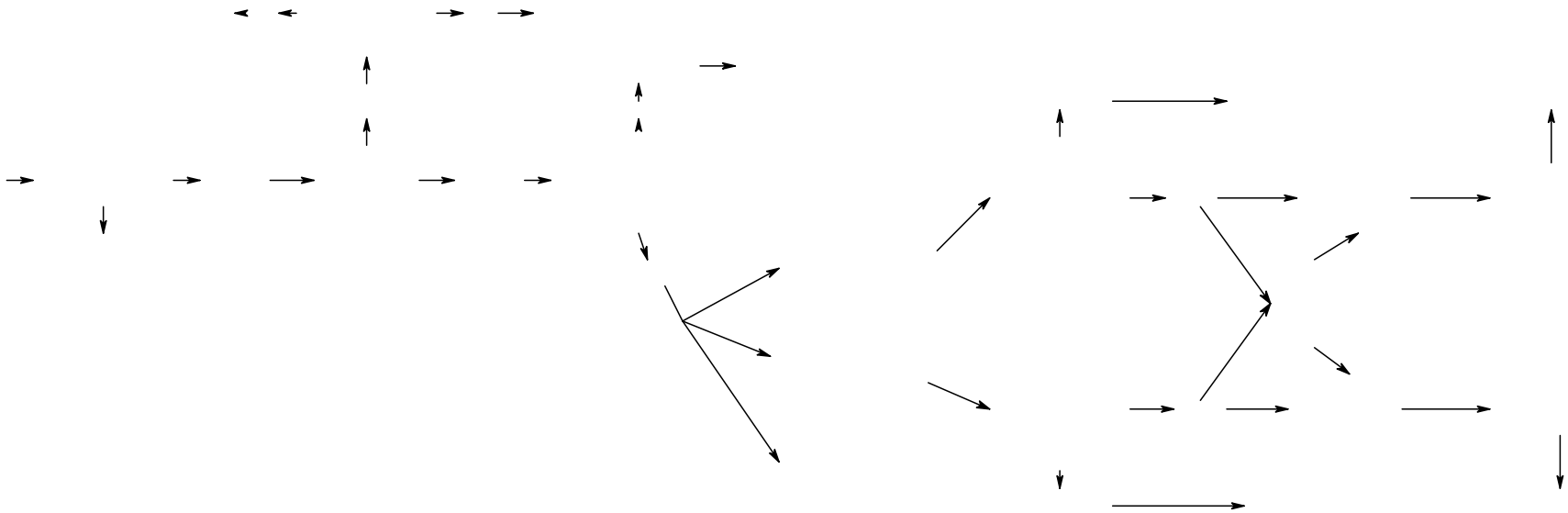
2) ***fabricate prototype gasification systems*** using appropriate advanced technologies (emphasis on additive manufacturing where advantageous)

3) ***evaluate the performance*** of the REMS modules against planned performance criterial, make design changes when necessary

As a part of the project, research will evaluate the tendency of REMS carbon feedstock materials to agglomerate. Targeted feedstock materials are coal and/or biomass, although other opportunistic fuels can be used.

REMS Module Process Flowsheet

Proposed General Flowsheet for REMS Modules



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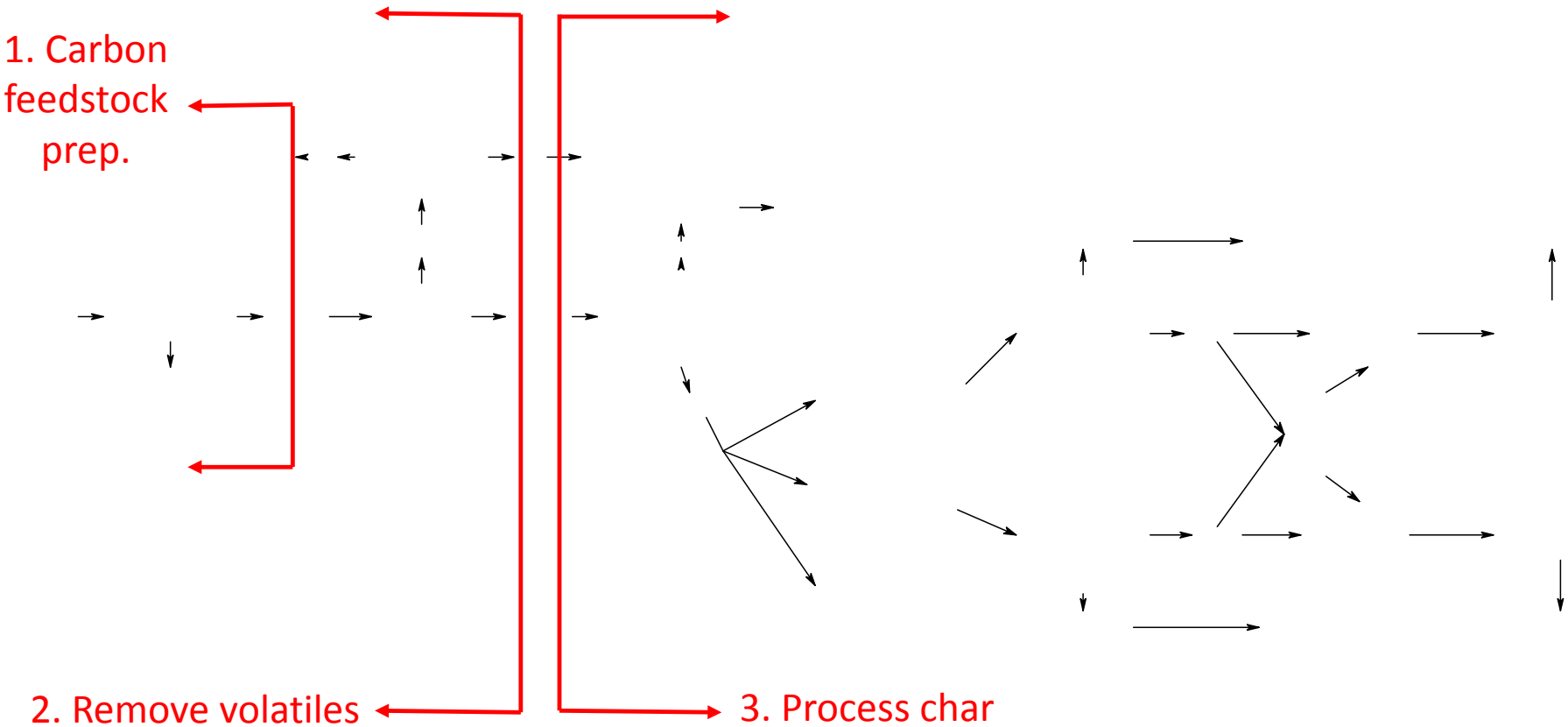

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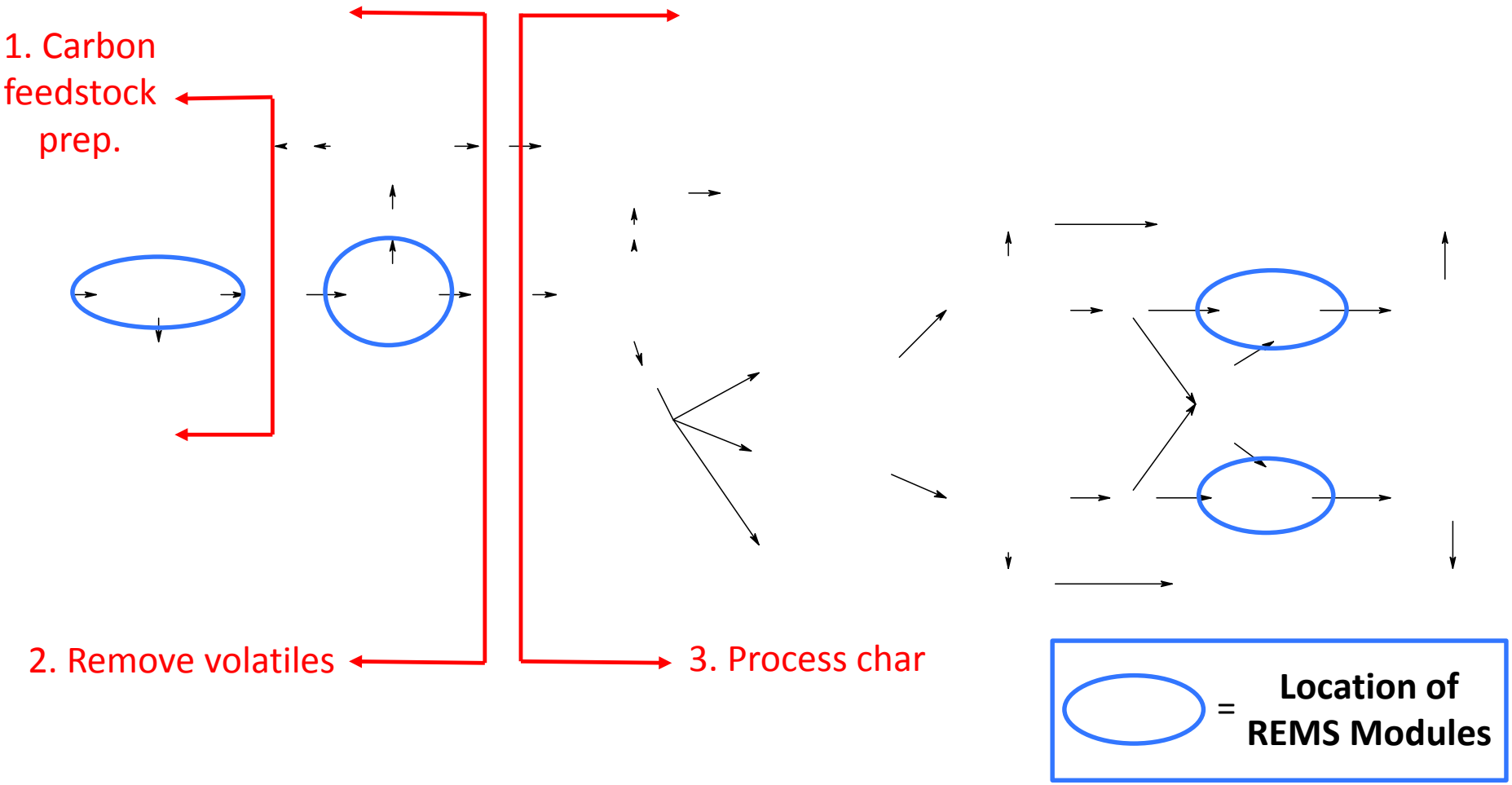


Process Considerations

- **Processing occurring in REMS module**
  - Thermal gasification of carbon feedstock
  - Chemical looping combustion
  - Carbon feedstock chemical extraction/catalytic reactions
  - Microwave heating/processing of materials
- **Process environment** (temperature, gas flow and environment, type carbon feedstock, feedstock throughput) and ash chemistry
- **Material compatibility** (REMS liner and carbon feedstock)
- **Phases present - solid/liquid/gas**
- **Fouling -** agglomeration, gas phase condensation, or molten slag (ash chemistry)

NOTE: Each module must have materials and structure optimized for its process environment - current focus

Material Considerations – *Each Module Different*

- **Temperature** (materials need to have minimal interactions with carbon feedstock, products, and process by-products)
- **Thermal management** (exterior REMS module must be at an acceptable temperature) – air or water cooling
- **Resist process/material and wear/abrasion**
- **Withstand process cycling**
- **Provide long service life and materials fail predictability**
- **Affordable in cost**
- **Ease and speed of repair**
- **Portable**

Issues with Biomass Carbon Feedstock

- **Feedstock quantity, consistency, and availability**
- **Feedstock chemistry** (pct carbon, ash, and moisture)
- **Ash softening/fusion temperature**
- **Hazardous material nature of by-products**, including ash and tars (flash point, volatility, health)
- **Ability to process as a gasifier feed**
- **Shipping distances** (feedstock to gasifier) – *50 km max.*
- **Feedstock energy density**
- **Ease of gasification**

Prefer low gasifier operational temperatures (650-900°C) because of low ash melting temperatures and the aggressive nature of the liquid slag formed. When operating at low temperatures, tar formation and condensation must be monitored.

Carbon Feedstock Ash *(U.S. Coal Ash Chemistry)*

Chemistry (wt pct oxide)	Coal Type								
	Eastern			Western			Powder River Basin		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Al_2O_3	25.2	45.1	2.2	19.4	40.7	1.7	15.2	28.2	5.9
CaO	2.4	25.1	0.1	8.8	43.7	0.1	15.5	36.2	1.0
Fe_2O_3	20.1	77.4	0.3	10.1	66.1	0.6	8.1	38.3	1.1
K_2O	2.0	6.9	0.1	0.9	6.7	Tr	0.8	3.5	0.1
MgO	0.9	11.8	Tr	2.2	13.9	Tr	4.2	13.9	Tr
MnO	Tr	1.4	Tr	0.1	1.5	Tr	0.1	0.3	Tr
Na_2O	0.4	4.7	Tr	1.6	14.2	Tr	3.4	13.9	Tr
SiO_2	44.6	83.7	8.0	46.2	87.9	7.9	35.5	70.2	7.9
TiO_2	1.3	5.2	Tr	1.0	6.1	Tr	1.0	2.2	0.2
P_2O_5	0.4	5.2	Tr	0.8	10.3	Tr	0.9	4.3	Tr
SO_3	2.7	26.0	Tr	8.9	37.6	Tr	15.4	37.6	Tr

Source: W.A. Selvig and F.H. Gibson; Analysis of Ash from United States Coals; USBM Bulletin 5670

Biomass Ash Chemistry

Property (Wt %)	Material					
	Rice Straw	Wheat Straw	Switch Grass	Sugar Cane Trash	Sugar Cane Bagasse	Douglas Fir (wood)
% Cl (dry wt biomass)	0.7	2.0	0.1	0.2	0.03	0.01
% Ash (dry wt biomass)	19.5	13.0	9.0	5.0	2.4	0.5
Oxides (in Ash) - Al_2O_3	1.4	2.5	4.5	NL	17.7	2.8
CaO	1.6	4.7	5.6	13.1	4.5	37.1
Fe_2O_3	0.7	1.0	2.0	1.7	14.1	4.2
K_2O	11.3	18.3	11.6	13.4	4.2	17.0
MgO	1.9	2.5	3.0	4.3	33	5.9
Na_2O	1.9	10.5	0.6	0.3	0.8	3.2
SiO_2	74.3	35.8	65.2	57.4	46.6	12.3
P_2O_5	2.7	1.5	4.5	2.3	2.7	1.9
TiO_2	0.02	0.2	0.2	NL	2.6	0.1
SO_3	0.8	5.5	0.4	7.3	2.1	11.2
Unknown	3.4	17.6	2.3	0.3	1.4	4.4

NL = Not Listed

Other carbon sources include municipal solid waste and industrial by-products

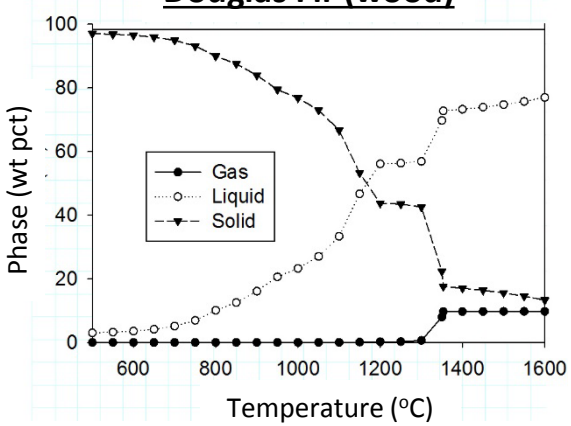
Source: B. Jenkins, R. Bakker, and J. Wei; On the Properties of Washed Straw; Biomass and Bioenergy; vol. 10 (1996), no. 4, pp 177-200.

Carbon Feedstock Agglomeration

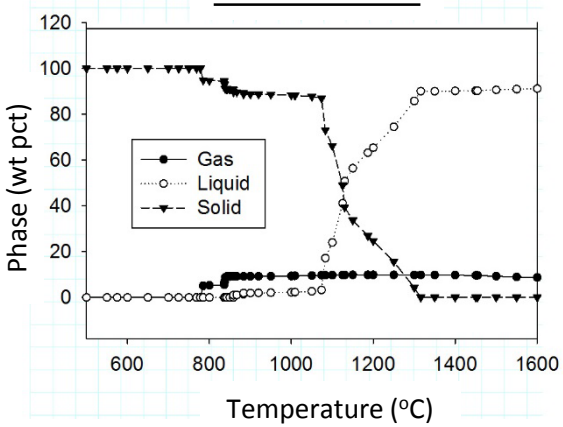
- **Studying tendencies for carbon feedstock to volatilize/agglomerate**
  - High temperature controlled atmosphere TGA (1600°C max)
  - High temperature CONFOCAL laser scanning microscope (1900°C max)
  - Ash agglomeration furnace (air, CO/CO_2 – 1500°C max)
  - Viscosity (air, CO/CO_2 – 1600°C max)

Ash Phases vs Temp

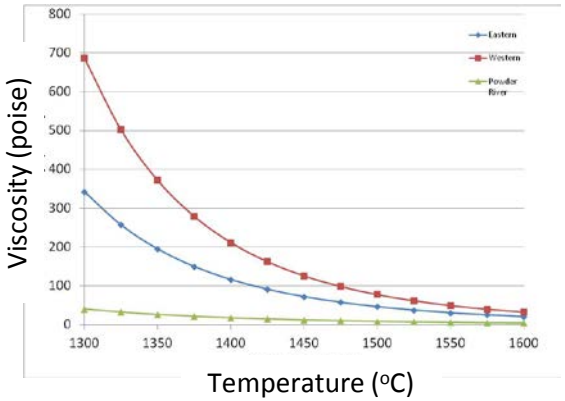
Douglas Fir (wood)



Western Coal

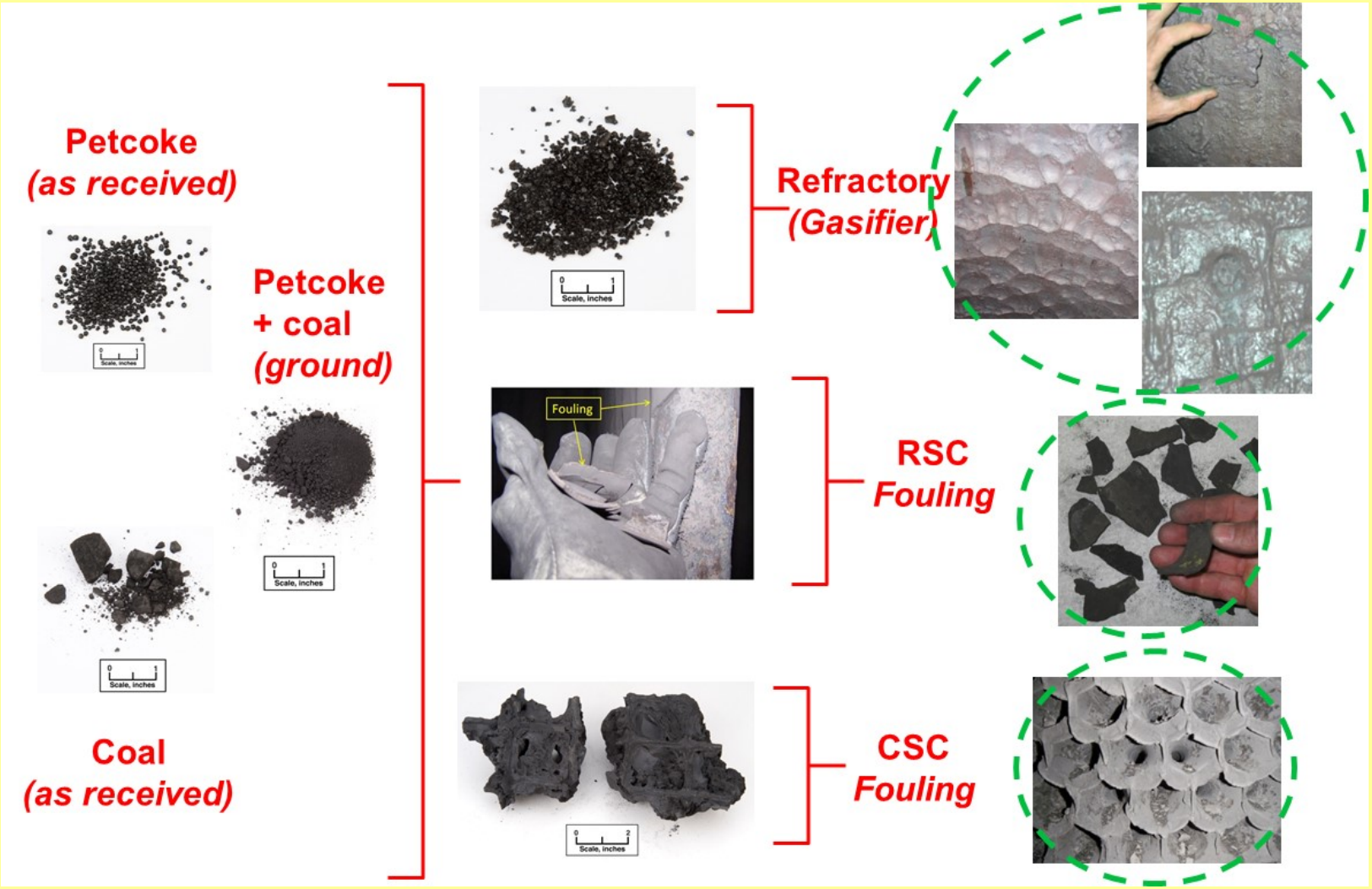


Coal Ash Viscosity



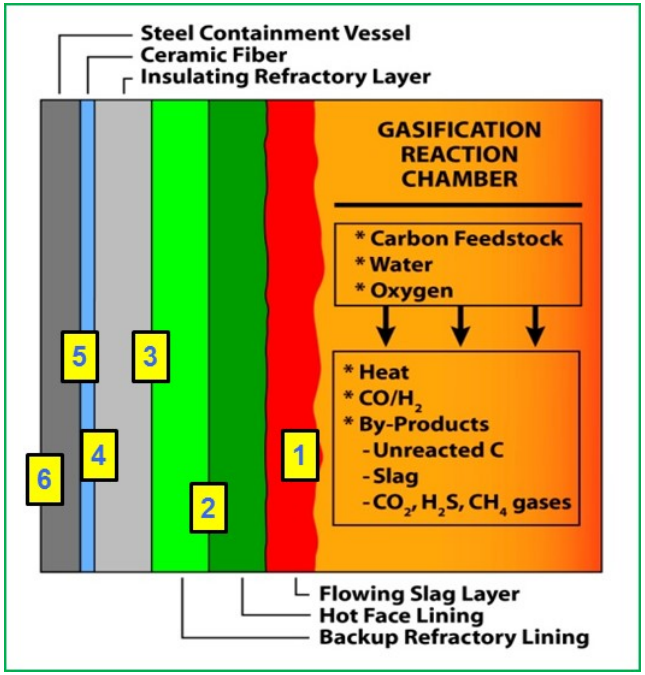
Phases present and viscosity curves based on thermodynamic calculations using FactSage™ 7.0 (databases Ftoxide and FactPS).

Ash Impact in Entrained Flow Slagging Gasifiers



Structure Limitations

Process temperature and system cooling needs will impacts system size



Air cooled slagging gasifier = Refractory temperatures for a given carbon feedstock flow rate and HF brick thickness (9 or 0 in).

In of HF Brick	Temperature (°C) at Location In Gasifier					
	1	2	3	4	5	6
9	1450	929	671	429	257	90
0		1000	718	450	269	90

Key System Variables for Designing a REMS Gasifier

Maximum sizes that can be made by AM, internal gasifier temperature, carbon feedstock flow rates.

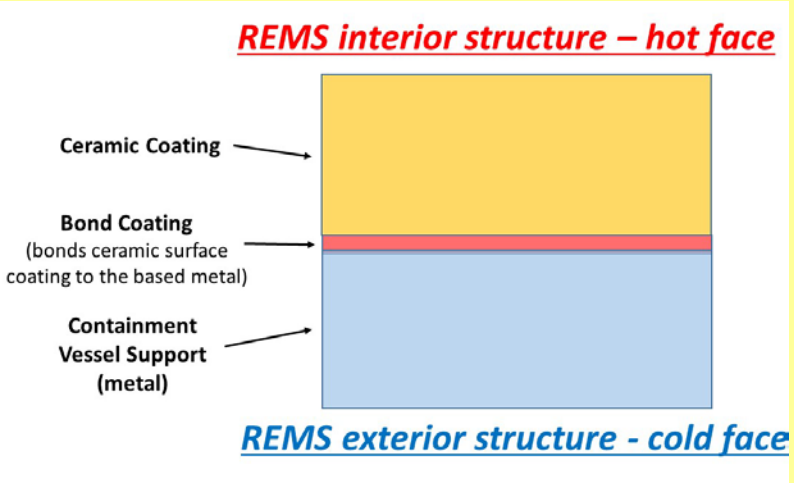
- **Factors deciding vessel size are how to cool a structure (air vs water [water needs more infrastructure]), material thicknesses/thermal conductivity, and surface shell temperature.**
- **FHA weight limits for trucks on highways = non permit, 36 tons.**

Air cooled 1450°C slagging gasifier 6 ft dia., outer shell temp. 90°C , 2.5 in steel shell - 1000 psi, 20 ft long, wt is 61.0 tons

Air cooled 1000°C non-slagging gasifier 6 ft dia., shell temp. 90°C, 0.75 in steel shell - 1 atm, 20 ft long,, wt is 39.1 tons.

Current Research

- **Identified appropriate materials structure** *for system evaluation and candidate materials*
- **Evaluating powder feed AM as primary manufacturing means;** *considering conventional and hybrid fabrication technologies*
- **Evaluating ceramic/metal adherence –** *Materials dictate temperature of application, can be a metal/ceramic mismatch of thermal expansion*



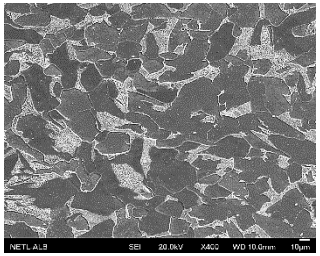
AM Deposited Ceramic Coatings on Metal

Scale = 5 cm

Current Research

- **AM processing parameters – depositing ceramic-based refractory materials on metal support structure** *(need to understand how to apply thick ceramic coatings over metal sub-straight)*
- **Began evaluation of coating microstructure (ceramics) used as hot face laminate on metals.** *Using powder feed – all materials are sprayed on surface molten (high melting temperatures may create issues)*
- **Began modeling temperature and stress profiles for simplified REMS geometries and materials**
- **Began modeling anticipated damage mechanisms of materials in a range of potential operating conditions**

a)



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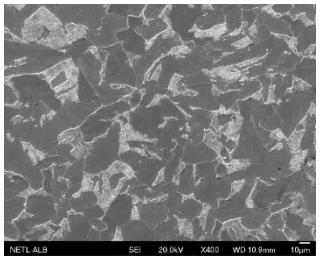

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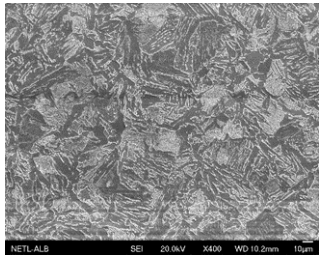
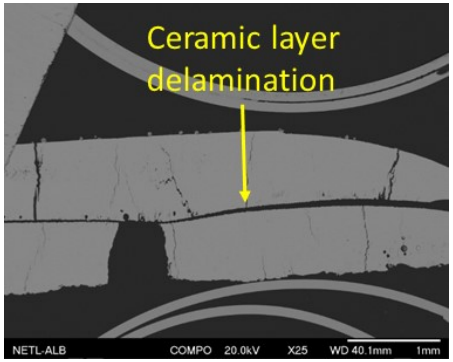


Base metal alloy with:

a) No treatment – metal only
b) With MCrAlY base coat
c) With YSZr ceramic coating

Base alloy

$C_{2.7}Si_{0.3}Mn_{0.8}Fe_{95.8}Co_{0.4}$ (wt.% by EDS)



Lamination in YSZ ceramic coating

Current Research

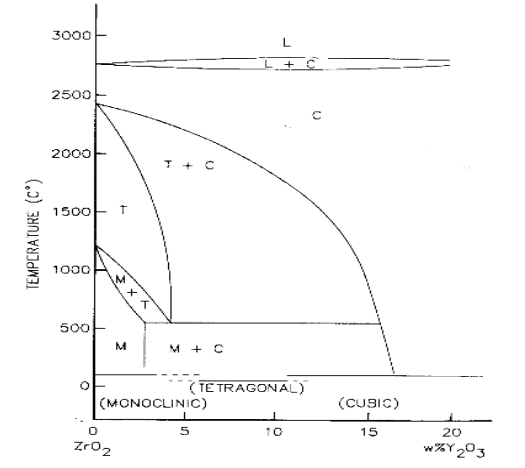
AM Deposited Ceramic Coatings on Metal

Scale = 5 cm

Evaluating

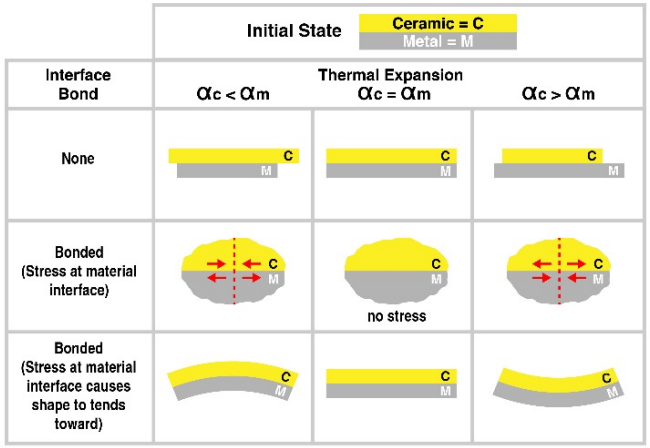
- Base and coating materials
- Application rate
- Scan speed
- Laser energy

Phase stability, melting temp



Thermal expansion differences

Material	Coefficient of Linear Thermal Expansion (10^{-6}/°C) (to 400°C)	Melting Temperature or Upper Use Limit (°C)	Thermal Conductivity (W/mK)
304 Stainless	17.3	870	12-45
316 Stainless	10.1	870	16
Mild Carbon Steel	12	700	41
Mullite	5.0	1810	17
ZrO_2	10.5	2700	3
SiC	4.4	2600 (sublimes)	200
Al_2O_3	7.2	2015*	32
Si_3N_4	2.6	1900 (sublimes)	27
AlN	4.6	>2200	150



Future Research

- **Continue study of ceramic layers on a metal surface (ceramic/bond coat/metal adherence)**
- **Evaluate bond coat materials, layering, metal foam, and/or lower melting temperature ceramic materials**
- **Consider cermet coating on metals**
- **Study hybrid processed structures and conventional fabrication technologies**
  - gunned, cast, or plastic ram refractory materials
  - use of anchors or “hex” mesh to apply refractory monolithics

NOTE = Figures on this page are taken from the internet – location available on request

Conclusions

- REMS will consist of a number of customized modules to process different carbon feedstock materials and to products
- Modules will be exposed to a variety of different material demands
- System cost, easy of repair, durability will drive module design
- Carbon feedstock/module material interactions must be minimized and predictable
- Agglomeration or fouling must be minimized and controlled
- Materials must have a long service life, with repairs being quick to minimize system downtime
- Use of AM technology is necessary to speed laboratory testing. It may be necessary to use prototyping that is a mixture of AM and conventional technology

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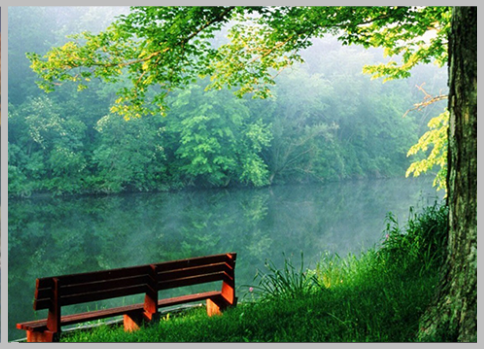

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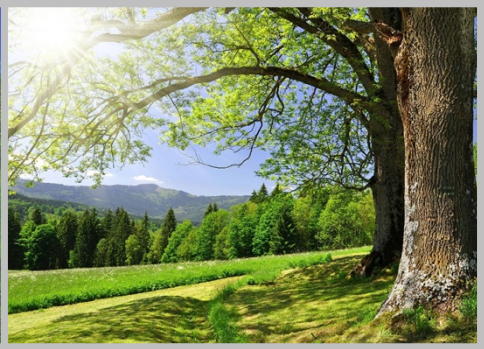
the ENERGY lab

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