Scale-up of Chemical Looping Reactors: Practical Considerations and Design of Industrial Systems

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Overview

Purpose

- Bench-scale and pilot-scale demonstrations have significantly advanced chemical looping technology
- Intermediate-scale demonstrations must bridge technology gap and incorporate features of commercial-scale units
- Active applications of chemical looping applications growing

Goal of Presentation

- Provide non-technology specific discussion of scale-up considerations and design issues.
- Focus on power as most complicated implementation

Objectives

- Particle manufacture
- Reactor scale-up
- Thermal integration
- Environmental
- Sparing philosophy
- Operation
- Safety

Particle Manufacture Scale-up

Particle formulation and performance demonstrated successfully at small scale

Raw material sourcing & specification

Material(s) processing issues:

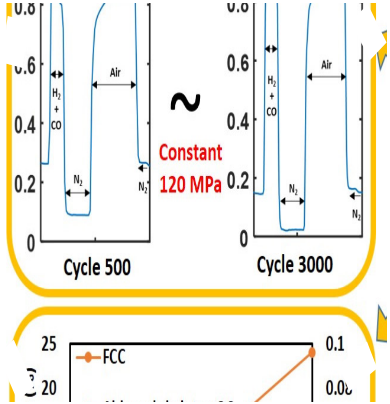
- Flowability and segregation
- Hygroscopicity and compactability
- Gel/emulsion/suspension stability

Equipment scale-up issues:

- Intermediate stages required
- Mixing and comminution effectiveness and energy demand
- Heating/cooling kinetics
- Temperature uniformity
- Safety risk assessments / hazard studies

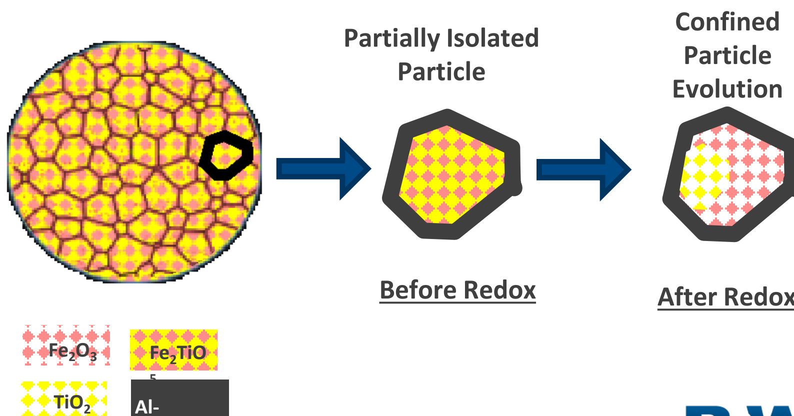
Control issues:

- Process monitoring and control
- Product specifications
- Process cost evaluation



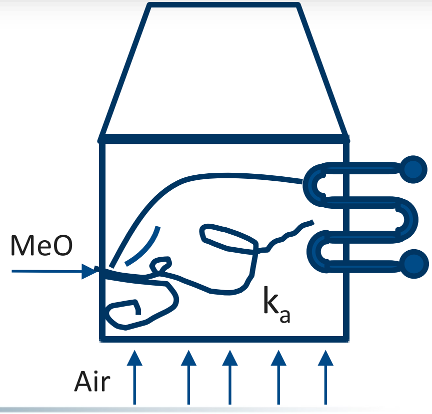
After 0 redox cycles

After 3,000 redox cycles



Reactor Scale-up

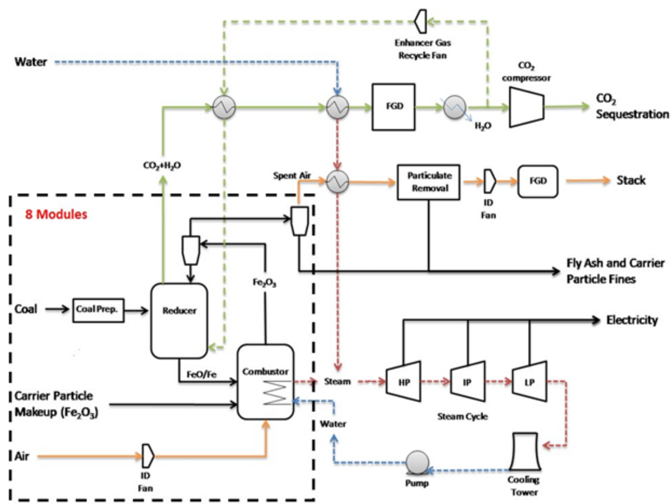
- **Surface-to-volume ratio**
  - Refractory-lined, electrically heated
  - Membrane wall
- **Feed point spacing – unit cell**
  - Fuel
  - Metal Oxide
- **Matching air/fuel distribution and kinetics to lateral and vertical mixing rates**
  - Multiphase computational fluid dynamic models (MFiX, Barracuda® and Fluent) provide effective design tool
  - Intrinsic kinetic and mixing data from laboratory and sub-pilot facilities



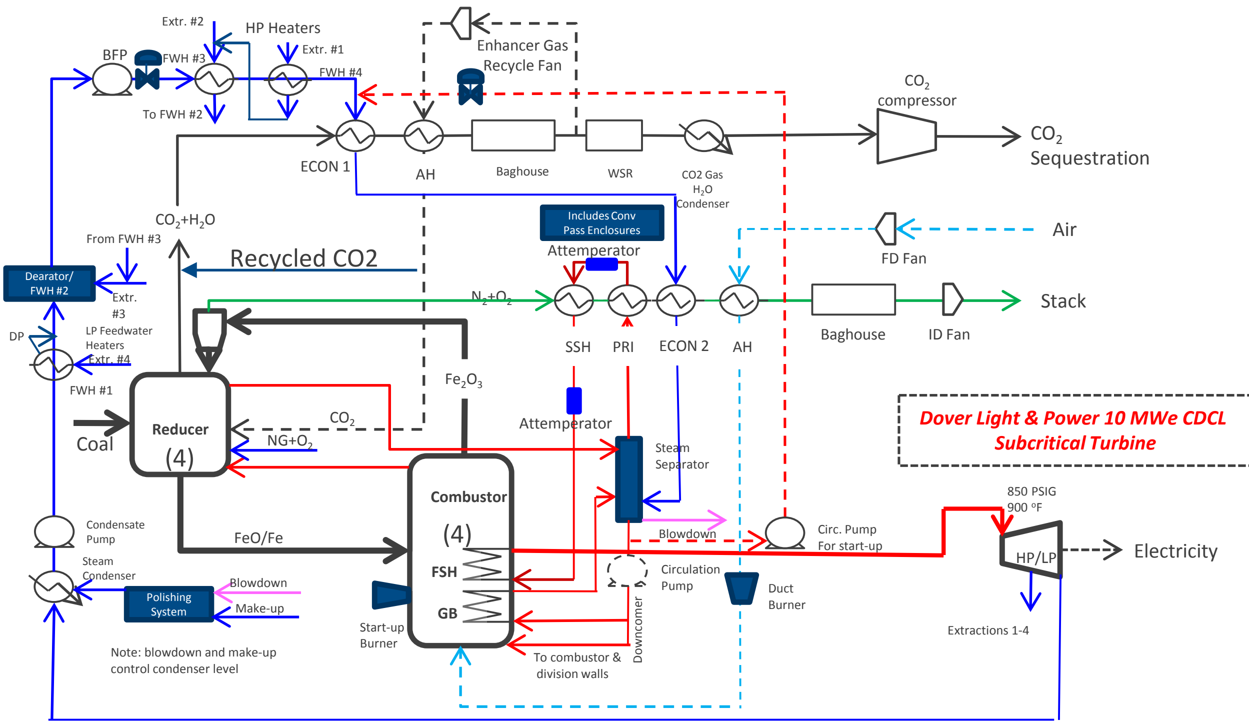
Thermal Integration – High-Grade Heat Recovery

Steam Cycle

- Heat recovery schemes
  - Pinch analysis - ASPEN Energy Analyzer module
- Metal temperatures
  - Sufficient cooling during start-up or part-load
  - Gas tempering with recycle
  - Attemperator sprays
- Steam separation (subcritical) or once-through design (supercritical
- High temperature valves

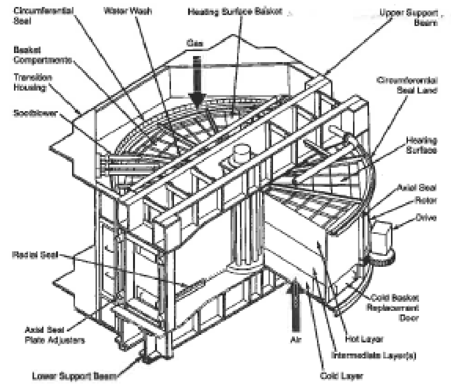


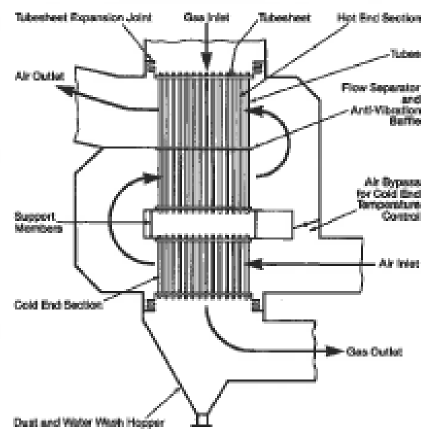
Thermal Integration



Thermal Integration – Low-Grade Heat Recovery

- **Mismatch between reducer and combustor exhaust gas**
- **Air Heaters**
  - Coal dryer
  - Pulverizer
- **Air heater for combustion air – regenerative design**
- **Gas heater for recycle CO_2 – tubular design???**





Steam: its generation and use edition 41, The Babcock & Wilcox Company, 2005.

Environmental

- **Split backpass issues**
  - CO_2 for baghouse cleaning – pulse jet or reverse flow – not chemical looping specific
  - Strict emission limits for pipeline quality CO_2
  - Wet scrubber performance with CO_2-rich flue gas
  - SO_2 and H_2S removal
- **Permitting**
  - Pilot facility demonstrated emissions for permit application
  - Waste disposal of metal oxide
  - CO_2 credits???
    - Sequestration
    - Beneficial use

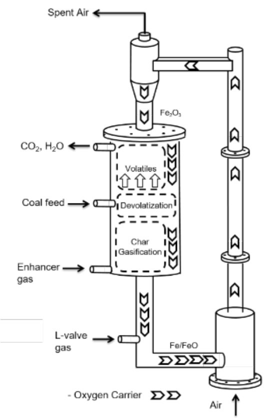
Exhibit 2-1 CO_2 Stream Compositions Recommended Limits

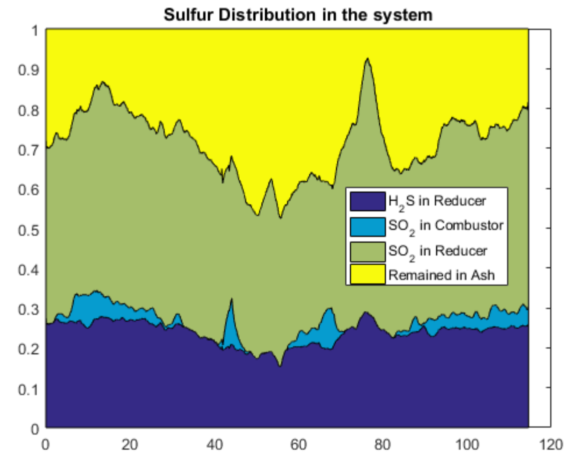
Component	Unit (Max unless Otherwise noted)	Carbon Steel Pipeline		Enhanced Oil Recovery		Saline Reservoir Sequestration		Saline Reservoir CO_2 & H_2S Co-sequestration		Venting Concerns (See Section 3.0)
		Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	Conceptual Design	Range in Literature	
CO_2	vol% (Min)	95	90-99.8	95	90-99.8	95	90-99.8	95	20 – 99.8	Yes-IDLH 40,000 ppmv
H_2O	ppm_{wt}	300	20 - 650	300	20 - 650	300	20 - 650	300	20 - 650	
N_2	vol%	4	0.01 - 7	1	0.01 - 2	4	0.01 - 7	4	0.01 – 7	
O_2	vol%	4	0.01 – 4	0.01	0.001 – 1.3	4	0.01 – 4	4	0.01 – 4	
Ar	vol%	4	0.01 – 4	1	0.01 – 1	4	0.01 – 4	4	0.01 – 4	
CH_4	vol%	4	0.01 – 4	1	0.01 – 2	4	0.01 – 4	4	0.01 – 4	Yes-Asphyxiate, Explosive
H_2	vol%	4	0.01 - 4	1	0.01 – 1	4	0.01 – 4	4	0.02 – 4	Yes-Asphyxiate, Explosive
CO	ppm_v	35	10 - 5000	35	10 - 5000	35	10 - 5000	35	10 - 5000	Yes-IDLH 1,200 ppmv
H_2S	vol%	0.01	0.002 – 1.3	0.01	0.002 – 1.3	0.01	0.002 – 1.3	75	10 - 77	Yes-IDLH 100 ppmv
SO_2	ppm_v	100	10 - 50000	100	10 - 50000	100	10 - 50000	100	10 - 50000	Yes-IDLH 100 ppmv
NO_X	ppm_v	100	20 - 2500	100	20 - 2500	100	20 - 2500	100	20 - 2500	Yes-IDLH NO-100 ppmv, NO_2 - 200 ppmv

Source: "QGESS: CO2 Impurity Design Parameters", NETL August 2013, DOE/NETL-341/011212

Fate of Sulfur: Injection of high sulfur coal

25 kW_{th} Sub-Pilot Test Unit





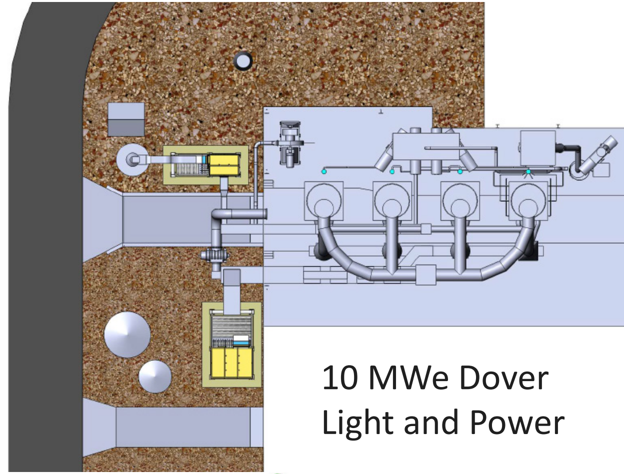
- >95% sulfur capture efficiency
- 1.2 lb SO_2/MW_{gross} from spent air
- Meet EPA's sulfur regulation for new power plants
- Cost saving in desulfurization unit on the combustor

C	H	N	S	O	Ash
71.80	4.22	1.24	1.27	14.02	7.45

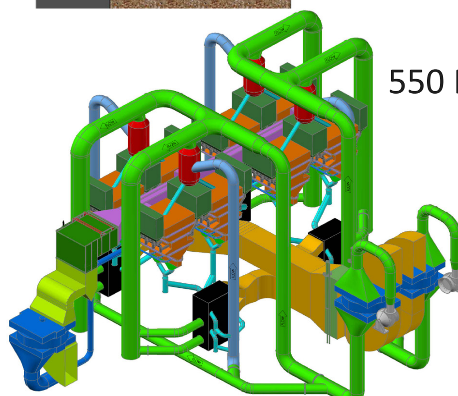
Chung, C., Pottimurthy, Y., Tong, A. Applied Energy Journal, 2017

Sparing Philosophy

- **Single vs. multiple module capacity**
  - Standalone plant
  - Coupled capacity
- **Fuel preparation system capacity**
- **Redundant feedwater and recirculation pumps**
- **Instrumentation**
- **Environmental equipment**
  - No redundancy in wet scrubber
  - Spare baghouse modules



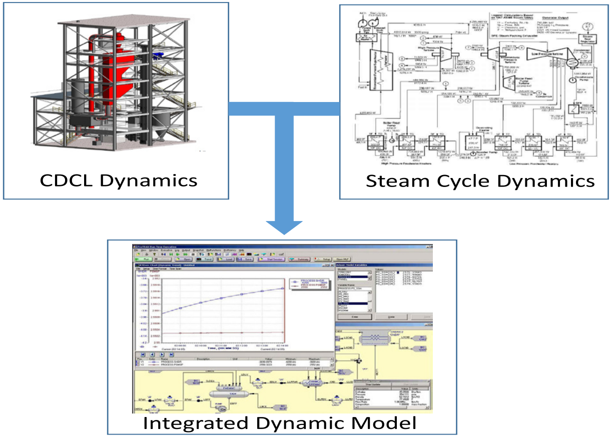
10 MWe Dover Light and Power



550 MWe Concept

Operation

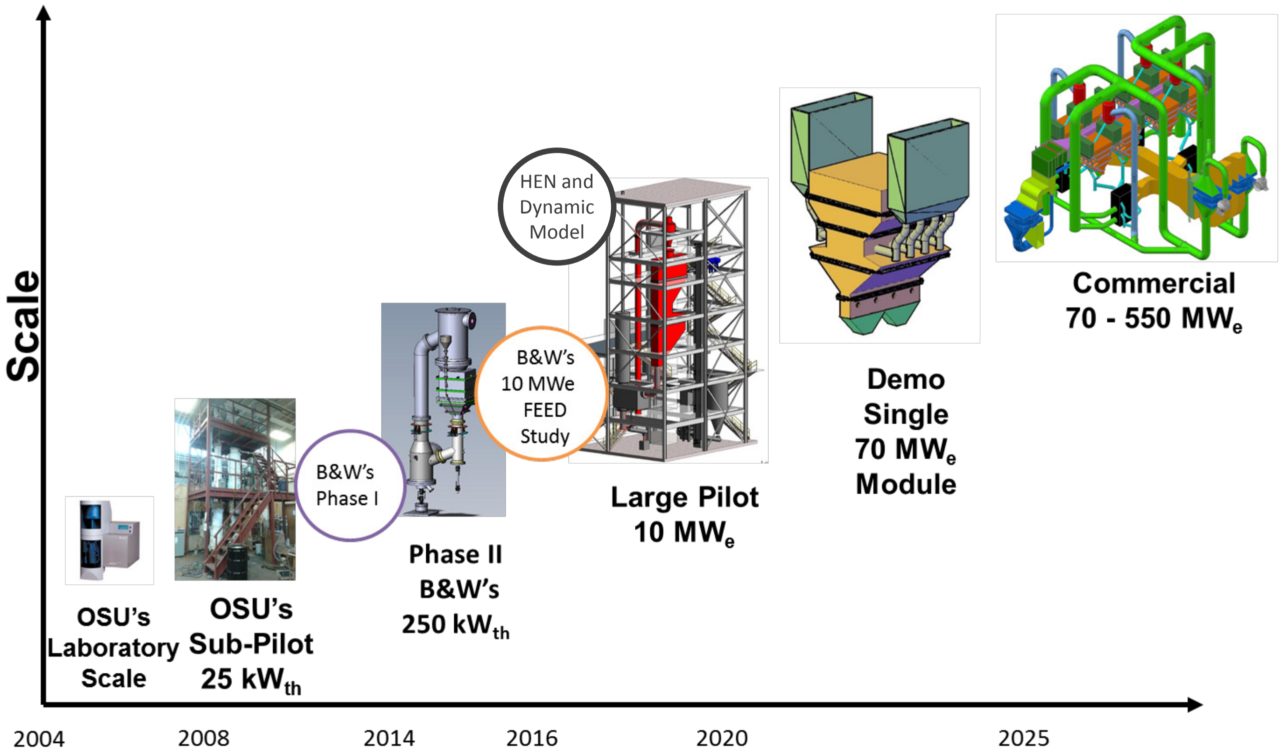
- **Start-up of Modular Reactors**
  - Start-up burner capacity
  - Auxiliary circulation pumps
  - Rapid start-up vs baseload
- **Transient response**
  - Long transient response due to inventory of metal oxide (time constants)
  - Impact of fuel variability on steam quality
  - Shutdown, trip, black plant trip
  - ASPEN or ProTRAX dynamic modeling
  - Rules-based optimizer or neural net



Safety

- **Hazard Design Analysis and Hazardous Operation Analysis (HAZOP)**
- **Area Classification**
  - Combustible mixtures (Class I Div II Classification)
  - Hydrogen
  - Hydrogen sulfide
- **Pressurized operation for gasification and reforming applications**
- **Metal oxide components**
- **Hazardous waste – exothermic reaction of metal oxide in air**

Commercialization Pathway



Conclusions

- Timing is right to consider scale-up issues.
- Need to consider scale-up in the design of sub-pilot facilities and test conditions – design test matrices that span operating space and provide intrinsic design data.
- Current pilot-scale facilities have many hours of operation but lack thermal integration and heat recovery.
- Start-up, transient operation (e.g., load following), shutdown and black plant trip scenarios introduce additional complexity in the design.
- As a community, success for one is success for all!!!!

B&W

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