Compact Absorber Retrofit Equipment (CARE)

July 10, 2012

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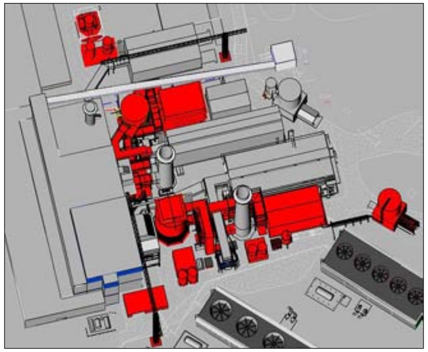
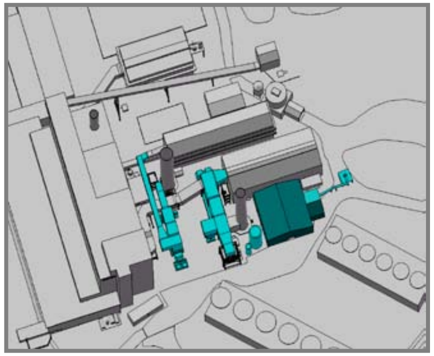
The *NeuStream*™ Advantage

NeuStream™ Enables Significantly Lower Cost of Ownership

Desulfurization System Comparison

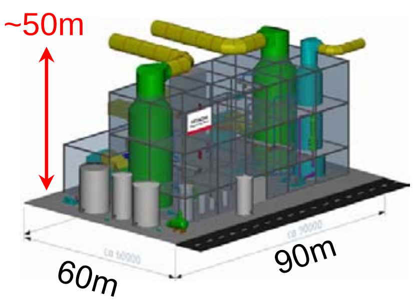


Conventional Dry Scrubber

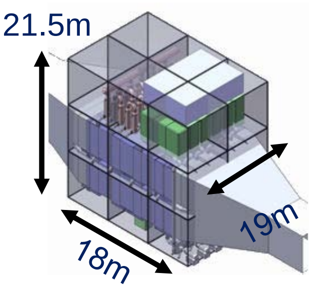


NeuStream™-S

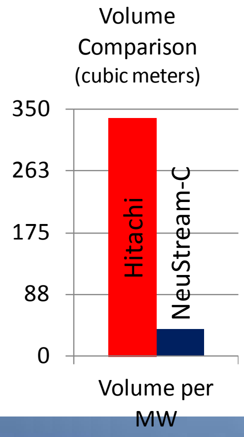
CO_2 System Comparison



Hitachi 800MW CO_2 System



NeuStream™-C 800MW CO_2 System



Modular

- Reduce order to commission time
- Maximize plant availability

Compact

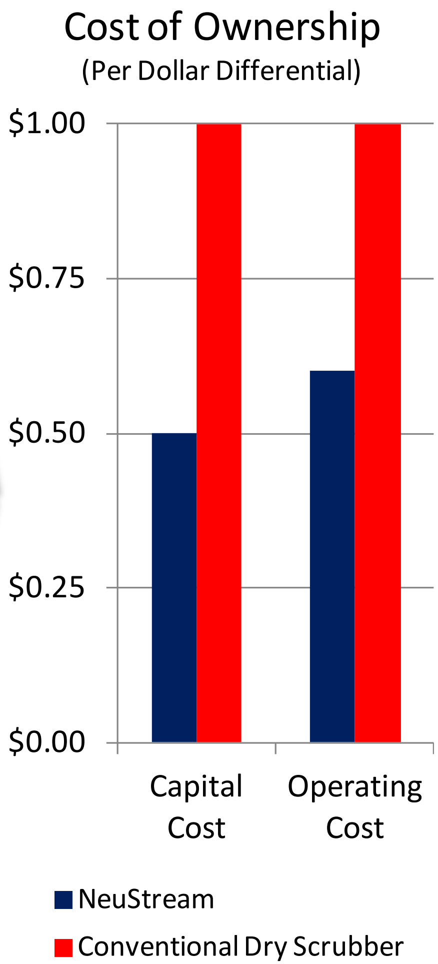
- Consume less plant real estate
- Minimize plant reconfiguration

Efficient

- Lower parasitic power
- Much lower water usage

Adaptable

- Site-specific conditions
- Variety of saleable by-products



CARE Schedule

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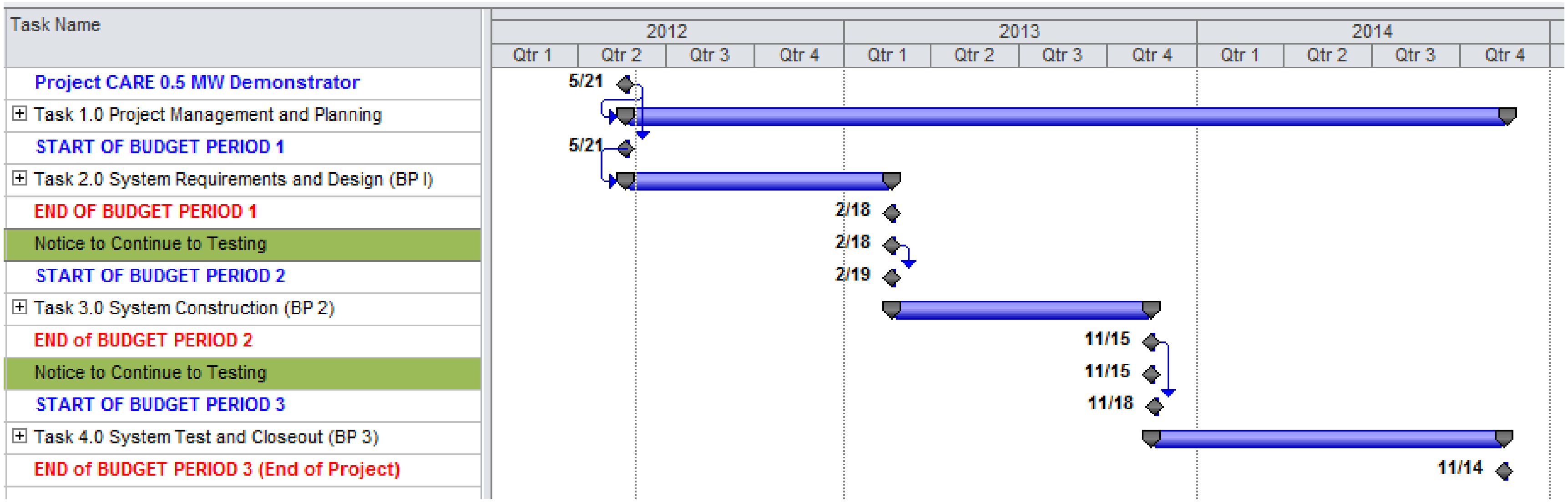

Key Milestones	
Project Start	5/21/2012
Kickoff Meeting: Final Requirements Review/Concept Design Review	6/14/2012
Preliminary Design Review	8/20/2012
Detailed (Critical) Design Review	2/18/2013
Test Readiness Review	11/15/2013
Final Project Briefing	11/17/2014

CARE Project Objectives

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- Design and fabricate 0.5 MW system
- Minimize parasitic power through efficient design
- Demonstrate
  - Steady 2 month state operation with 3-Stage Absorber and Multi-stage Stripper
  - 90% CO_2 capture efficiency utilizing best available solvent
- Show unit traceability to commercial scale

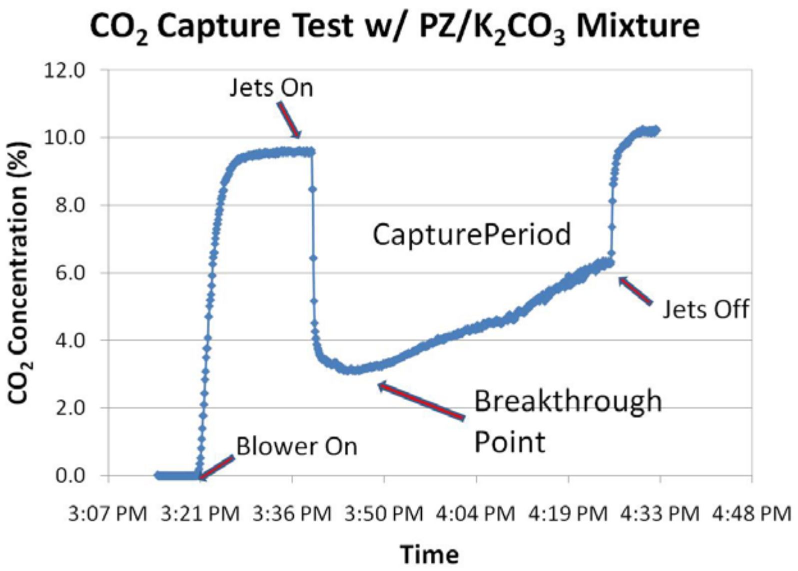
CARE Partners

- Energy and Environmental Research Center (EERC)
  - Techno-Economic Feasibility Study
  - EH&S risk assessment for carbon capture and storage
  - Brandon Pavlish (Lead and Consultant)
- URS – Bob Keeth
  - Consultant
- Colorado Springs Utilities
  - Host Site (Martin Drake Power Plant)
  - Significant Cost Share
- Service Partners
  - Althouse Electric
  - Vision Mechanical
  - ICM Construction
  - Palmer Holland (Chemical Provider)

Array of Jets

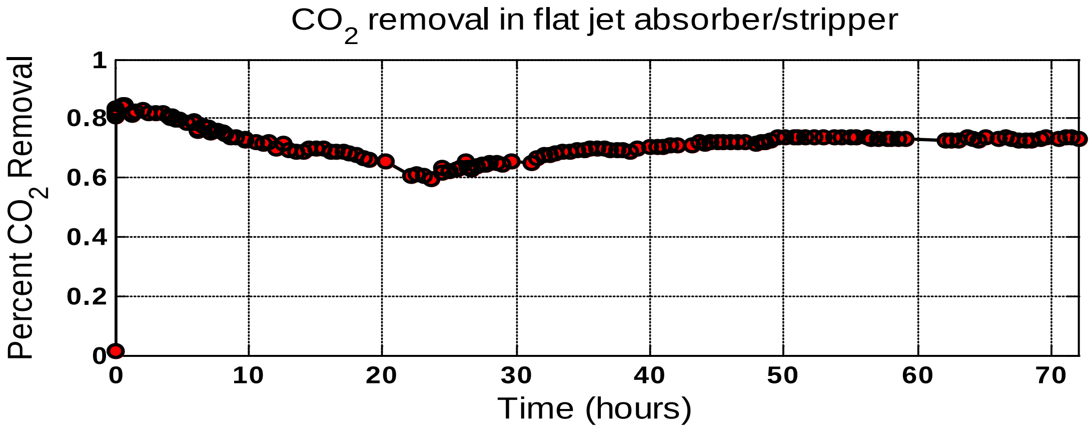
- Jets are 7 cm wide with a 4 PSI pressure drop across the nozzles
- Gas is contacted with jets via cross-flow at 3-15 m/s
- Jet velocity of 5-6 m/s
- The jet array for the CO_2 scrubber have jets spaced at 3 mm along the Jet Tube (4 mm shown on left)
- Jet Tubes are spaced at 3.5 cm, and are interlaced resulting in a theoretical specific surface area of 900 m^2/m^3

NeuStream – C Development



- De-rated our 2MW FGD scrubber for a 0.45 MW slipstream
- Capture only; using 3.2m K_2CO_3/1.6m PZ solvent
- Single stage capture with approximately 1000 SCFM Flow (~1600 ACFM - residence time of 0.4 sec)
- Capture efficiency ranged from 65% to 30% depending on solvent loading

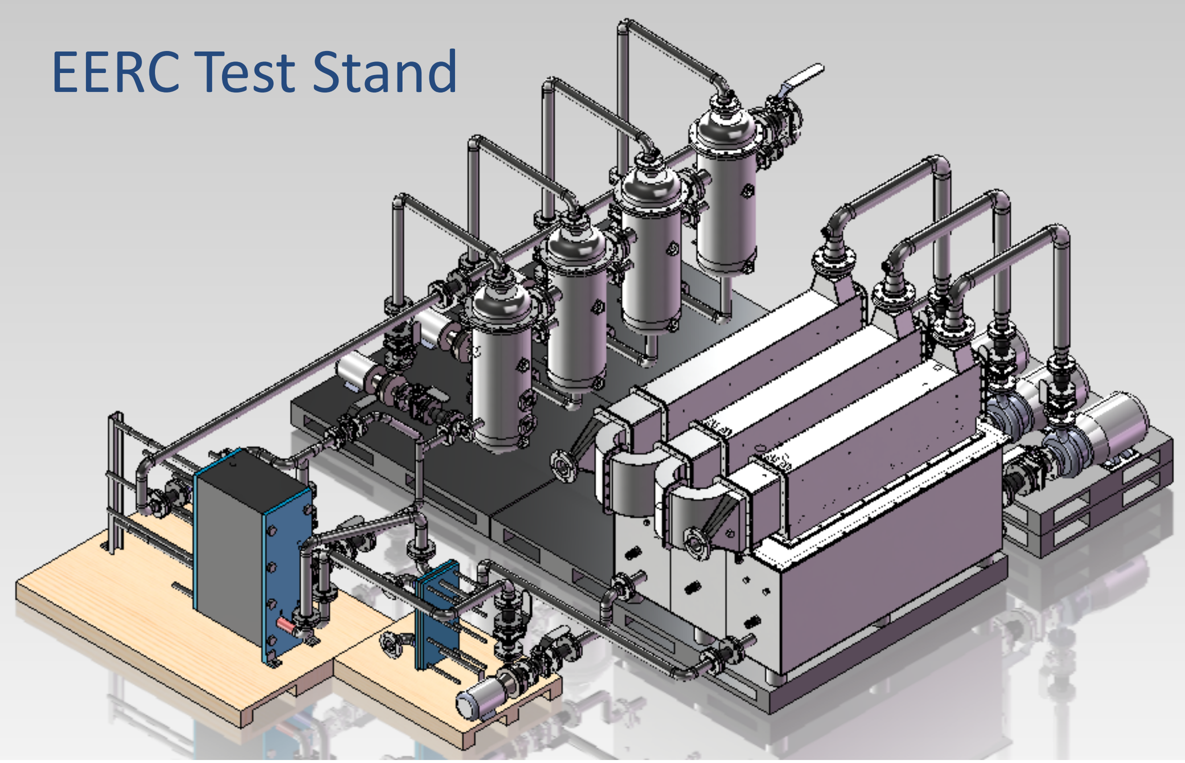
NeuStream – C Development



- Bench scale closed system with vacuum stripping
- ~1kW flow rate (65 slpm); simulated flue gas
- 3.2m K_2CO_3/1.6m PZ
- Single Stage
- >70 % Capture Efficiency

NeuStream – C Development

EERC Test Stand



- Contract is for 90% removal at 160 SCFM
- Design Points:
  - 3 stage absorber; 4 stage stripper
  - ½ Jet box channels to increase gas velocity through jets
  - ULFT Nozzles: 4 psi operating pressure, 7 cm wide jet
  - 27 Nozzles/Tube, staggered with 3.5 cm Tube/Tube spacing and 3 mm Nozzle/Nozzle spacing

- Post Design Alterations:
  - Reflux tank added post stripper
  - Reflux tank added post absorber
  - Increased pump size for rich pump

EERC Testing

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- System transport to UND-EERC and setup completed on Sept 12, 2011
- Scheduled Test Dates:
  - Sept 26-Oct 6, 2011 (EERC training and acceptance testing)
  - Nov 7-11, 2011
  - Dec 19-23, 2011
  - Jan 9-13, 2012
  - ~~Feb 6-12, 2012~~ (no alternative solvent, system modifications)
  - Feb 27-Mar 2, 2012
  - ~~Mar 19-23, 2012~~ (reschedule to allow for system modifications – TBD)

EERC Test Results

- System Performance
  - Capture Subsystem is performing on the same level as baseline testing
  - Stripper Subsystem is also consistent with baseline testing
  - Comparison of Stripper subsystem to EERC traditional packed tower stripper indicates that the NSG stripper is undersized
    - Working capacity of NSG stripper:
      0.06 – 0.07 mol CO_2/mol Alk
    - Typical working capacity of a packed tower stripper:
      0.12 – 0.15 mol CO_2/mol Alk
    - The under-performing stripper is reducing the performance of the system, resulting in lower than expected capture efficiencies

EERC Modifications

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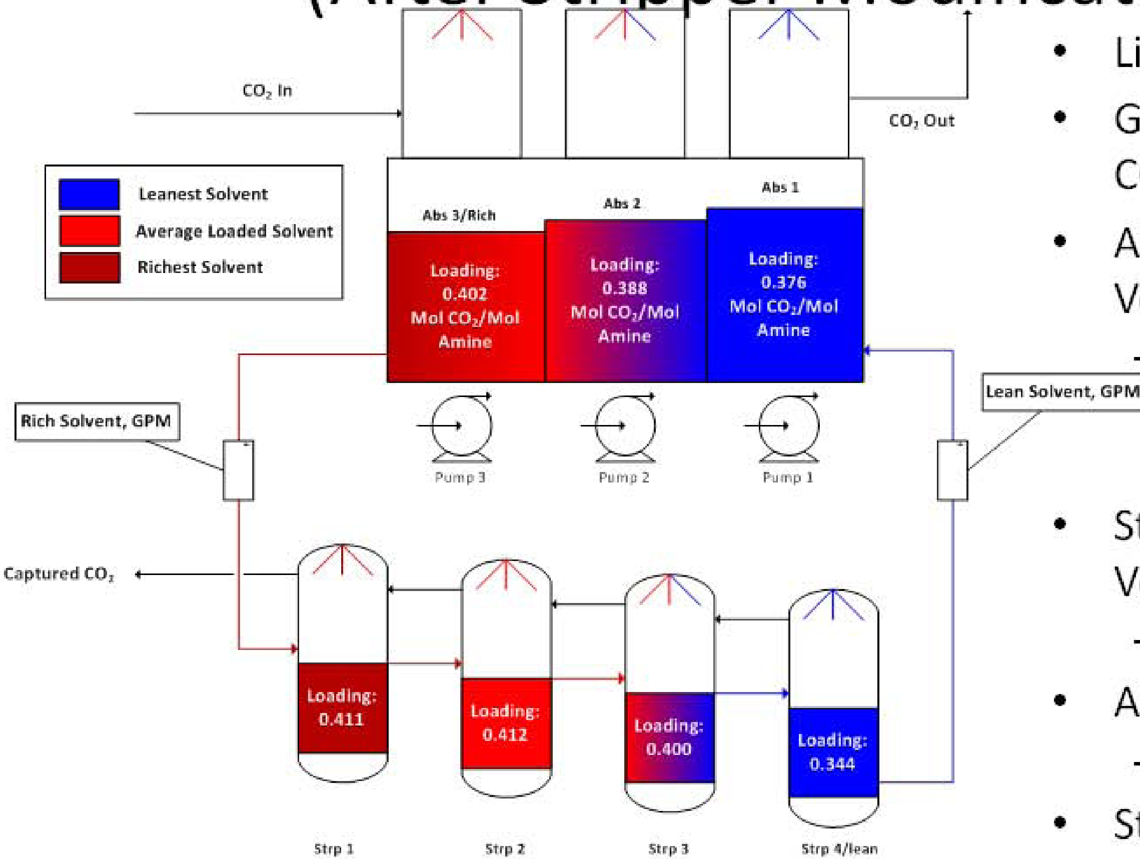
- **Stripper Subsystem Modification #1:**
  - Carryover flooding in gas path due to high liquid levels
  - Liquid flows limited to 12 GPM max
  - Added 12” section to vessels to allow for required liquid head to maintain higher flows.
  - Have since operated up to 18 GPM with no flooding or increased carryover

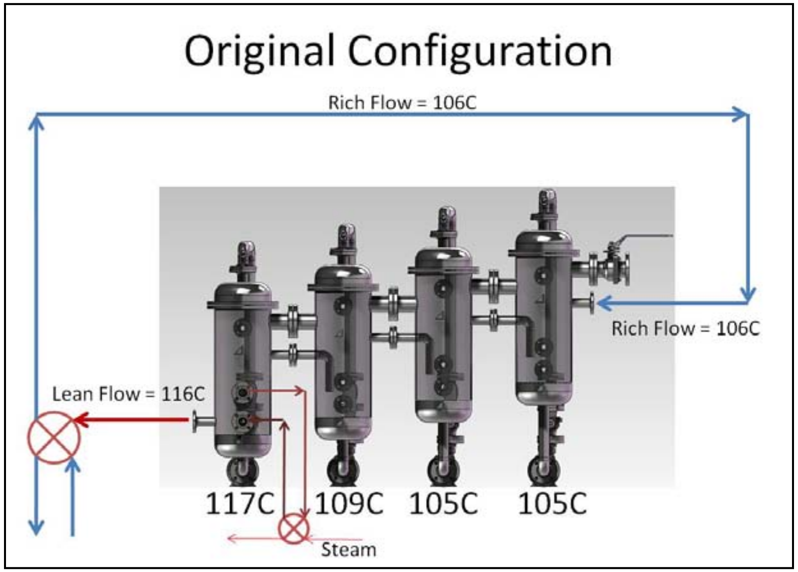
EERC Testing: Loading (After Stripper Modification 1)

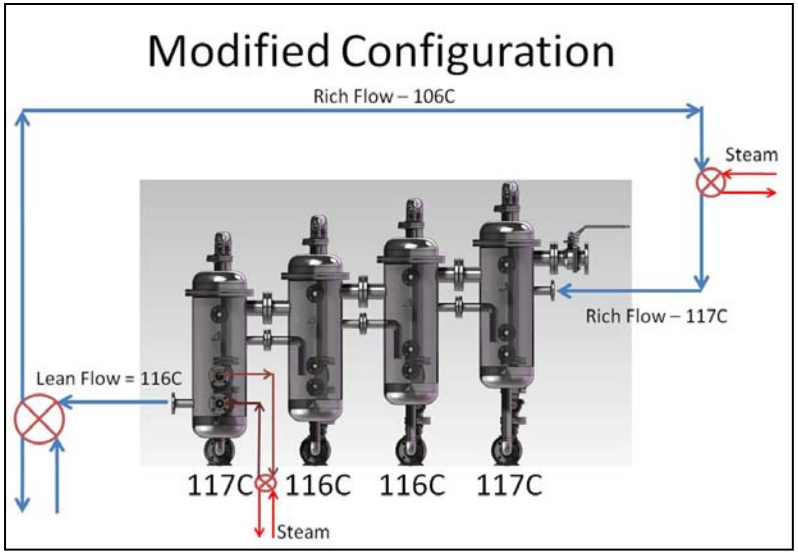


Working Capacity ~ 0.06 mol CO_2/mol Alk

- Liquid Flow: 16 GPM
- Gas Flow: 160 SCFM (14.4% CO_2)
- Absorber (1,2 and 3) Volumes:
  - 115, 110, 101 Gal
- Stripper Volume (Each Vessel):
  - 11 Gal
- Absorber Residence Times:
  - 7.2 min, 6.8 min, 6.3 min
- Stripper Residence Times:
  - 41.2 seconds per vessel
  - 2 min 45 sec for stripper subsystem

EERC Modifications





- **Stripper Subsystem Modification #2**
  - Original configuration
    - Mimicked a traditional packed tower with 4 stages (trays)
    - Heat added via reboiler stage only
    - First two stages were for heat transfer (heat of condensation)
    - Last two stages primarily where stripping CO_2 occurred.
  - Modified Configuration
    - Heat added to rich stream to bring to target stripper temperature
    - Reboiler used to maintain heat throughout the stripper and reduce re-absorption of CO_2

EERC Testing: Loading (After Stripper Modification 2)

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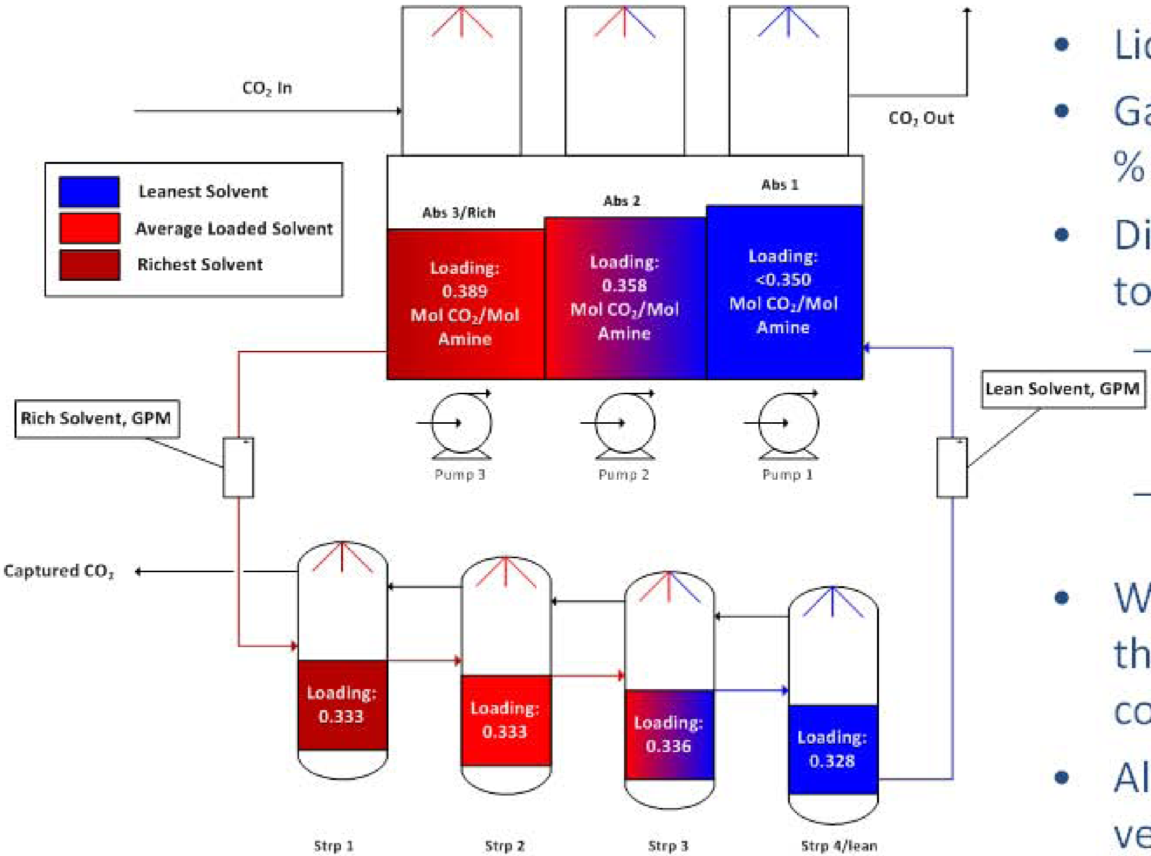
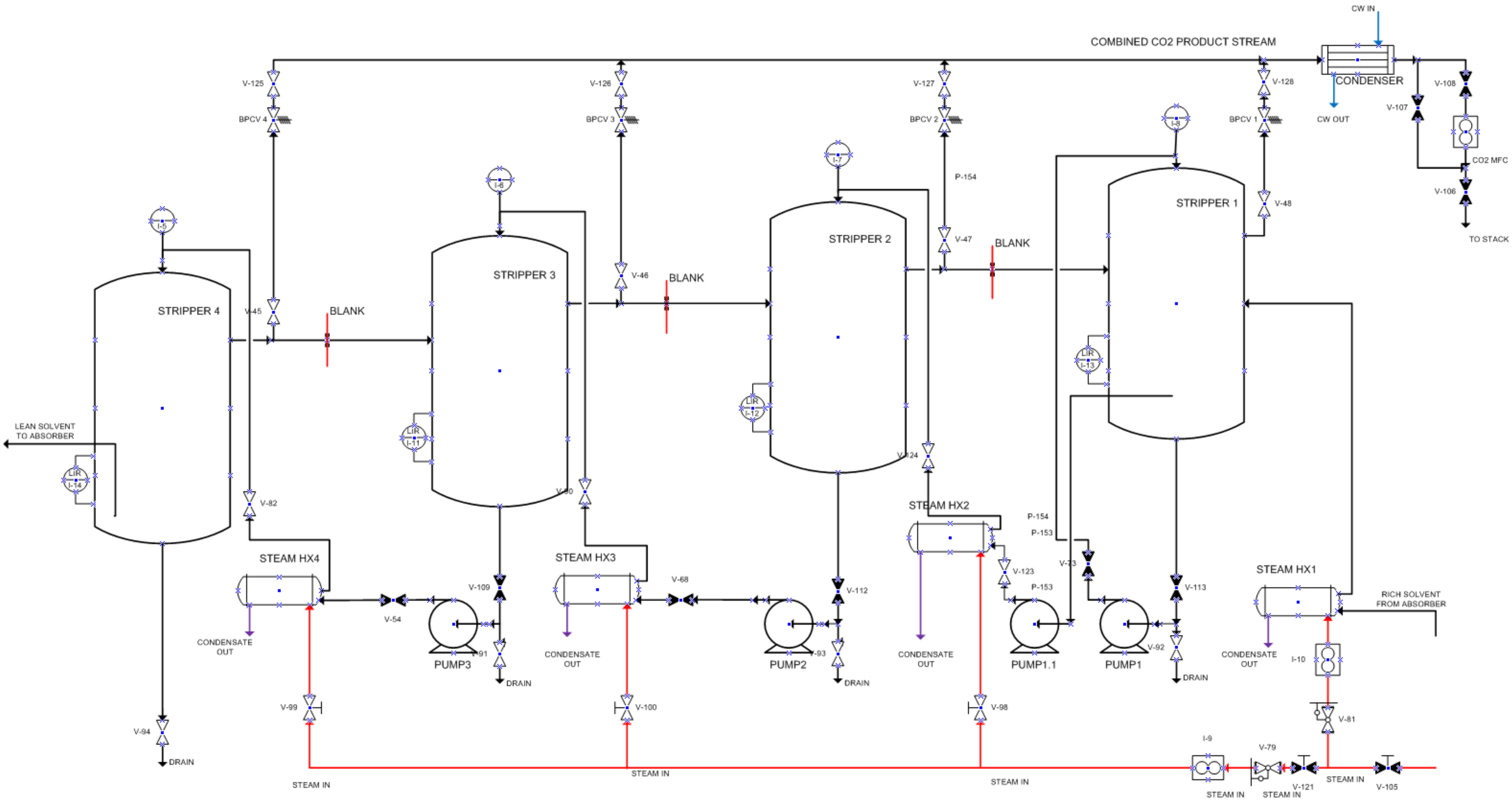


Working Capacity ~ 0.06 mol CO_2/mol Alk

- Liquid Flow: 16 GPM
- Gas Flow: 160 SCFM (13.3 % CO_2
- Difficult to compare results to previous testing:
  - Lower CO2 concentration in flue gas leads to lower loadings
  - Lower loadings results in better capture efficiency
- Working capacity is about the same as previous configuration
- All stripping occurs in first vessel… no benefit from remaining vessels or reboiler.

EERC Modifications



- Separate gas flow between vessels
- Single Pass through vessels 2-4
- Recirculation on vessel 1
- Vary pressures per stage (decreasing)

EERC Solvent Testing

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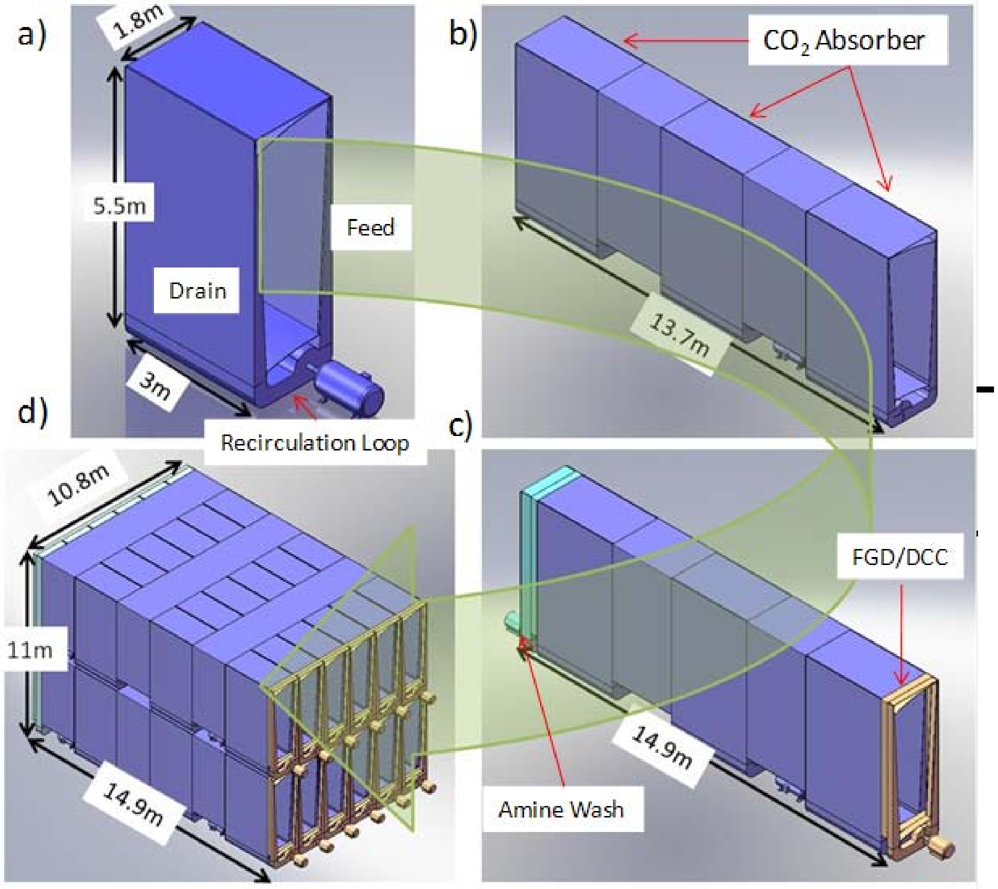
	Conditions		Capture Efficiency - O_2 Corrected				Stg 3 Loading	
Date	Gas Flow Rate	Liquid Flow rate	Overall	Stage 3	Stage 2	Stage 1	mol CO2/ mol Alk	Expected CE*
2/28/2012	190.1	15.9	68.3%	29.9%	22.5%	41.7%	0.405	72.0%
2/28/2012	159.3	16.1	72.9%	34.9%	23.9%	45.2%	0.392	77.1%
2/29/2012	130.1	16.1	79.6%	41.7%	25.1%	53.2%	0.377	84.5%
3/1/2012	130.6	17.2	88.1%	54.4%	29.4%	63.0%	0.301	92.1%
2/29/2012	158.8	17.1	85.5%	48.7%	33.8%	57.2%	0.275	88.4%
3/1/2012	189.2	17.5	83.9%	44.3%	32.0%	57.5%	0.308	87.0%
3/1/2012	218.0	17.8	79.9%	41.4%	28.8%	51.9%	0.301	83.3%

- MEA (4.3M) and Piperazine (4.0M) Testing
  - Tested at 16 gpm liquid transfer rate with various gas flow rates
  - Investigated capture efficiency per stage
  - Working capacity of stripper is less than typical; indicating that we are operating at higher loadings and reduced capture efficiencies.
  - Stage 2 absorber CE data indicated a problem in the system; gasket on stage 2 absorber had slipped resulting in up to 50% gas bypassing this stage
  - "Expected CE*" column is the expected CE when stage two is fixed
  - Piperazine (Pz) solvent had drastically improved performance

NSG Absorber (Flat Jet)



Project CARE Modular Design (Conceptual)

- Currently achieving (experimental) **400 m^2/m^3** surface area at **4+ m/s flow**
- Results in a **2x reduction** in reaction volume of absorber compared to packed tower
- Has approximately a **15 m/s gas velocity limit**, where the absorber can be operated with any gas velocity below 15 m/s
- Measured pressure drop due to jets with a 4 m/s gas velocity: **5 inH_2O** through 6 m of jets

Implementation to Plant

- Advantages:
  - 90% capture: greater than 2-4x reduction in absorber volume, resulting in less capital cost and footprint
  - Variable gas velocity (up to 15 m/s) through jets due to low pressure drop and no flooding, where increased gas flow moves to a more efficient capture regime and increases the total carbon capture (EOR)
  - Solvent agnostic
    - tested with: 7m MEA (CO_2), 7m PZ (CO_2), FGD dual alkali solvent, BHP (chemical laser); scheduled to test with a Huntsman Solvent (CO_2) and a potassium carbonate with CA enzyme (CO_2)
- Challenges:
  - No data on a full scale system (perceived risk)

CARE Schedule – Task 2.0

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- Task 2.0 – System Requirements and Design (BP 1)
  - 2.1 – System Requirements (FOA, EERC results, ASPEN, DVT)
  - 2.2 – Preliminary Design
  - 2.3 – Detailed Design
  - 2.4 – Absorber Modeling and Analysis (EERC results, ASPEN, DVT and COMSOL)
  - 2.5 – Stripper Modeling and Analysis (EERC results and ASPEN)
  - 2.6 – Process Modeling and Analysis (ASPEN)
  - 2.7 – Absorber Verification Testing (Feeds design efforts)
  - 2.8 – Process Verification Testing (Reclaimer and Amine Wash)
  - 2.9 – Preliminary Assessment of EH&S Risks (HCCL)
  - 2.10 – Preliminary Technical and Economic Assessment (EERC)

CARE Schedule – Task 2.0

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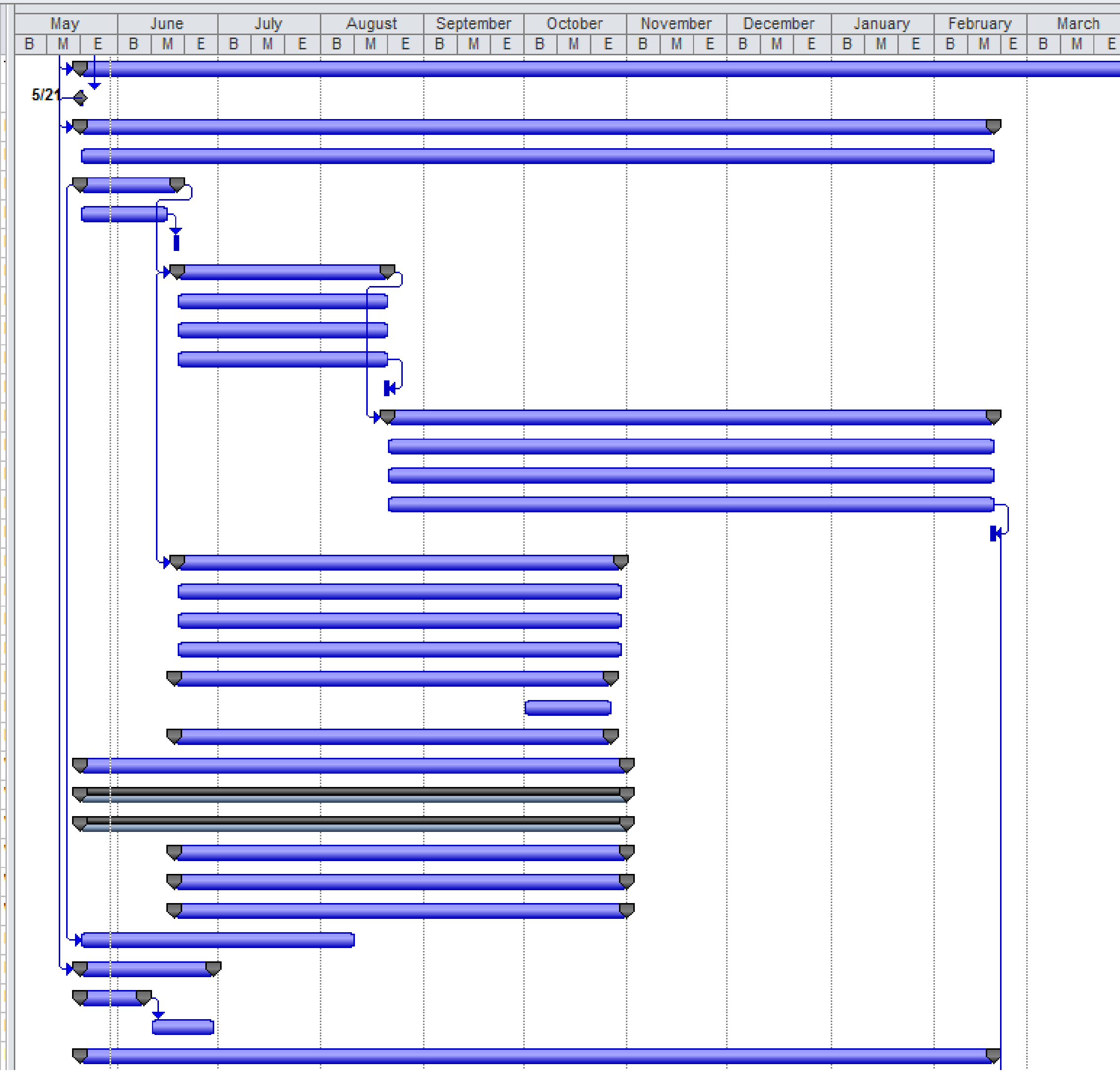
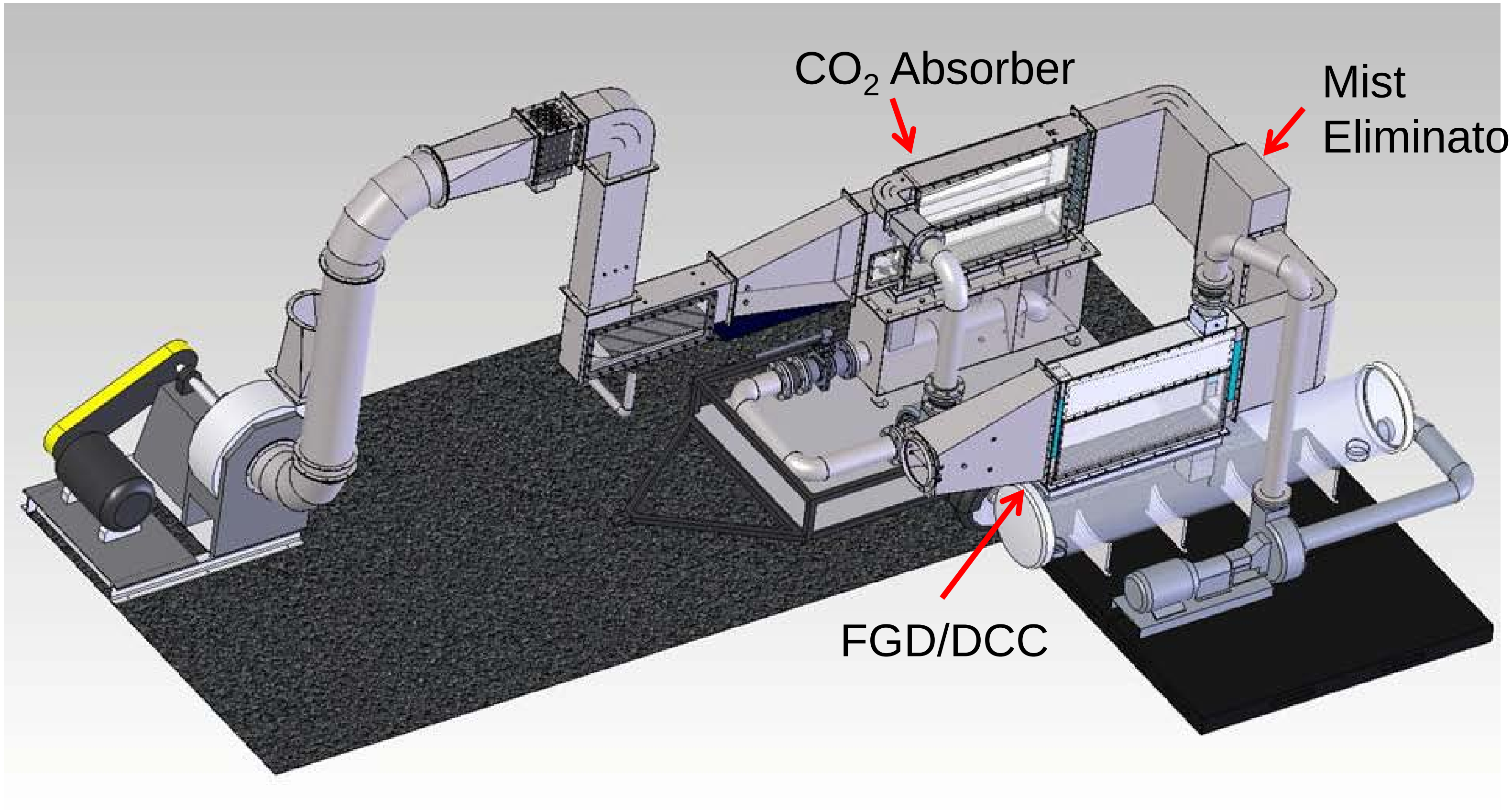
Task Name	Start
⊞ Task 1.0 Project Management and Planning	Mon 5/21/12
START OF BUDGET PERIOD 1	**Mon 5/21/12**
⊟ **Task 2.0 System Requirements and Design (BP 1)**	**Mon 5/21/12**
Cost Share (BP 1)	Mon 5/21/12
⊟ **2.1 System Requirements**	**Mon 5/21/12**
2.1.1 System Requirements Compilation	Mon 5/21/12
2.1.2 System Requirements Review	Mon 6/18/12
⊟ **2.2 Preliminary Design**	**Tue 6/19/12**
2.2.1 Absorber Preliminary Design	Tue 6/19/12
2.2.2 Recirculation Loop Preliminary Design	Tue 6/19/12
2.2.3 Auxiliary Equipment Preliminary Design	Tue 6/19/12
2.2.4 Preliminary Design Review (PDR)	Mon 8/20/12
⊟ **2.3 Detailed Design**	**Tue 8/21/12**
2.3.1 Absorber Detailed Design	Tue 8/21/12
2.3.2 Recirculation Loop Detailed Design	Tue 8/21/12
2.3.3 Auxiliary Equipment Detailed Design	Tue 8/21/12
2.3.4 Critical Design Review (CDR)	Mon 2/18/13
⊟ **2.4 Absorber Modeling and Analysis**	**Tue 6/19/12**
2.4.1 COMSOL Models on Gas flow through Preliminary Abs	Tue 6/19/12
2.4.2 COMSOL Models on Liquid Flow through Sump-Recirc	Tue 6/19/12
2.4.3 DVT Results Evaluation	Tue 6/19/12
⊟ **2.5 Process Modeling and Analysis**	**Mon 6/18/12**
2.5.1 Evaluation of EERC Data (Flash vs Reboiler)	Mon 10/1/12
⊞ 2.5.2 ASPEN Model of System	Mon 6/18/12
⊟ **2.6 Absorber Design Verification Testing**	**Mon 5/21/12**
⊞ 2.6.1 Absorber Configuration Design Testing	Mon 5/21/12
⊞ 2.6.2 Recirculation Loop Design Testing	Mon 5/21/12
⊟ **2.7 Process Design Verification Testing**	**Mon 6/18/12**
⊞ 2.7.1 Reclamation Testing	Mon 6/18/12
⊞ 2.7.2 Amine Wash Testing	Mon 6/18/12
2.8 Preliminary Environmental, Health, and Safety Risk An	**Mon 5/21/12**
⊟ **2.9 Preliminary Technical and Economic Analysis**	**Mon 5/21/12**
⊞ 2.9.1 Preliminary Commercial System Model Update	Mon 5/21/12
2.9.2 Preliminary Technical and Economic Analysis Update	Mon 6/11/12
⊞ **2.10 Subcontracts**	**Mon 5/21/12**



Tasks Required to Meet CARE Objectives

- Develop Systems Requirements
- Develop Preliminary then Detailed Design
  - Design Verification Testing (Task 2.7; Feeds Tasks 2.1-2.4)
    - Build stand with stainless sump and piping for CO2 capture
    - Modify existing test stand for FGD/DCC use
    - Build transition ducting between FGD and CO2 absorber
    - Test Stand will need "simple" stripping subsystem so that steady state can be reached
    - Develop Performance Optimization Plan:
      - » Vary packing densities
      - » Vary jet lengths
      - » Vary gas flows
    - Results feed directly to 0.5MW demonstrator design

Absorber Verification Stand



HEXs, Condenser and Stripper Flash not shown

Tasks Required to Meet CARE Objectives (cont)

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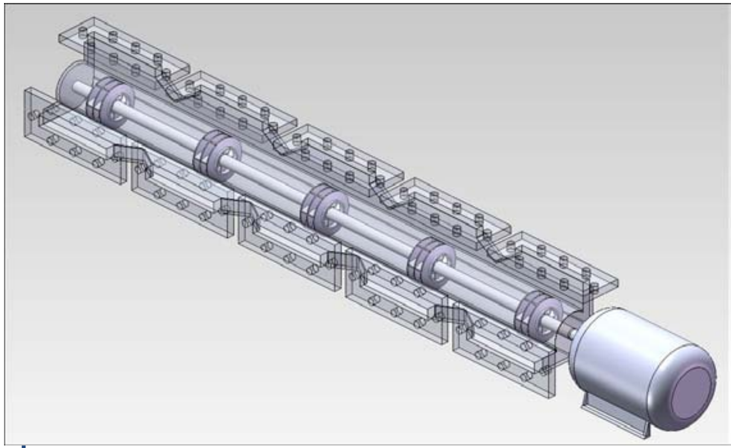
– Develop Preliminary then Detailed Design (cont)

- Design "sumpless" pump
  - Communicate with pump manufacturer to drive design
  - Fabricate prototypes:
    - » Develop Stand to utilize prototype pumps
      - » Metrics for test stand:
        - » Flow Requirements
        - » Plenum pressure
        - » **Pump Efficiency** comparable to traditional centrifugal pumps

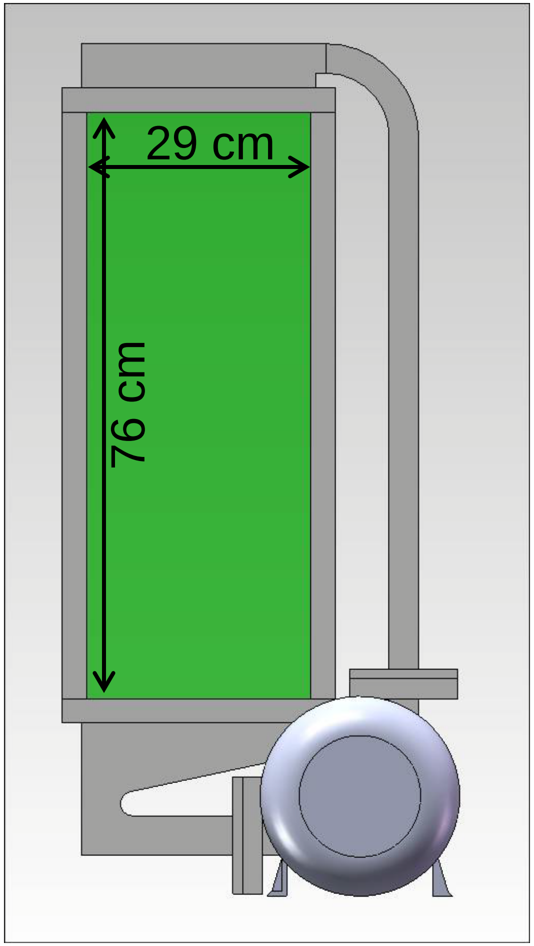


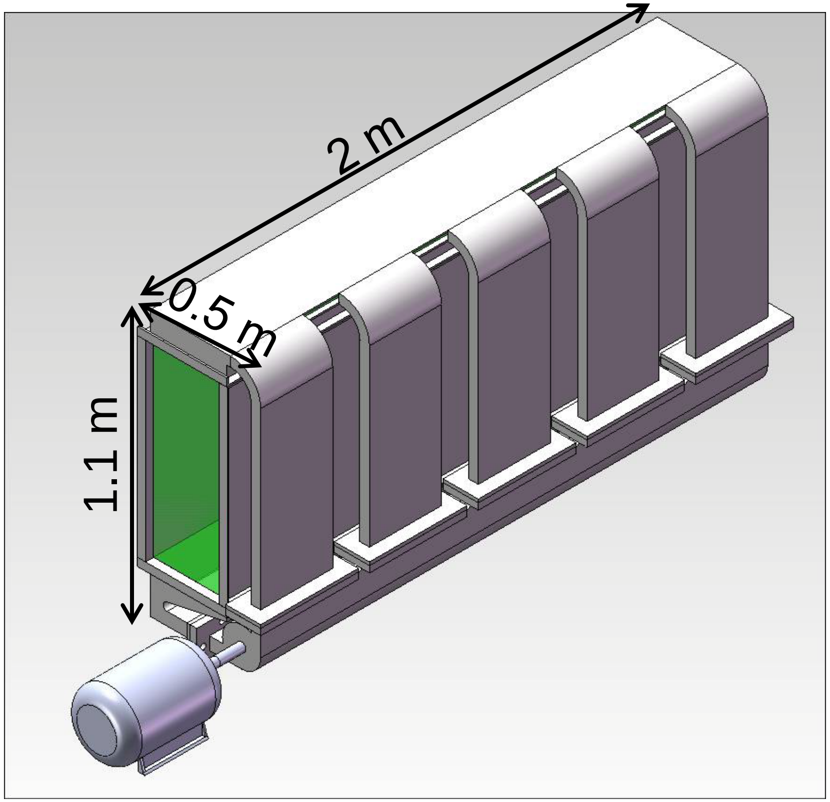
- Flow Modeling – Gas and Liquid Flow
  - Modeling Liquid Flow through drain – pump – plenum
  - Modeling Gas Flow through jets and transition pieces
- Process Modeling
  - ASPEN modeling of System components and interactions
  - Sizing of HEXs, Amine Wash, etc.

Tasks Required to Meet CARE Objectives (cont)

- Process Verification Testing
  - Reclaimer and Amine Wash – bench scale testing
- Develop Assessment of Environmental, Health and Safety (EH&S) Risks
  - To be completed by EERC
  - Preliminary EH&S assessment to be completed in Budget Period 1
  - Final EH&S assessment to be completed at project closeout
- Develop Technical and Economic Assessment (TEA)
  - To be completed by EERC (Brandon Pavlish)
  - Preliminary TEA to be completed within 8-weeks of contract start
  - Final TEA to be completed at project closeout

Conceptual Design





Design results in a 5 m/s gas velocity under nominal testing conditions

Conceptual Design

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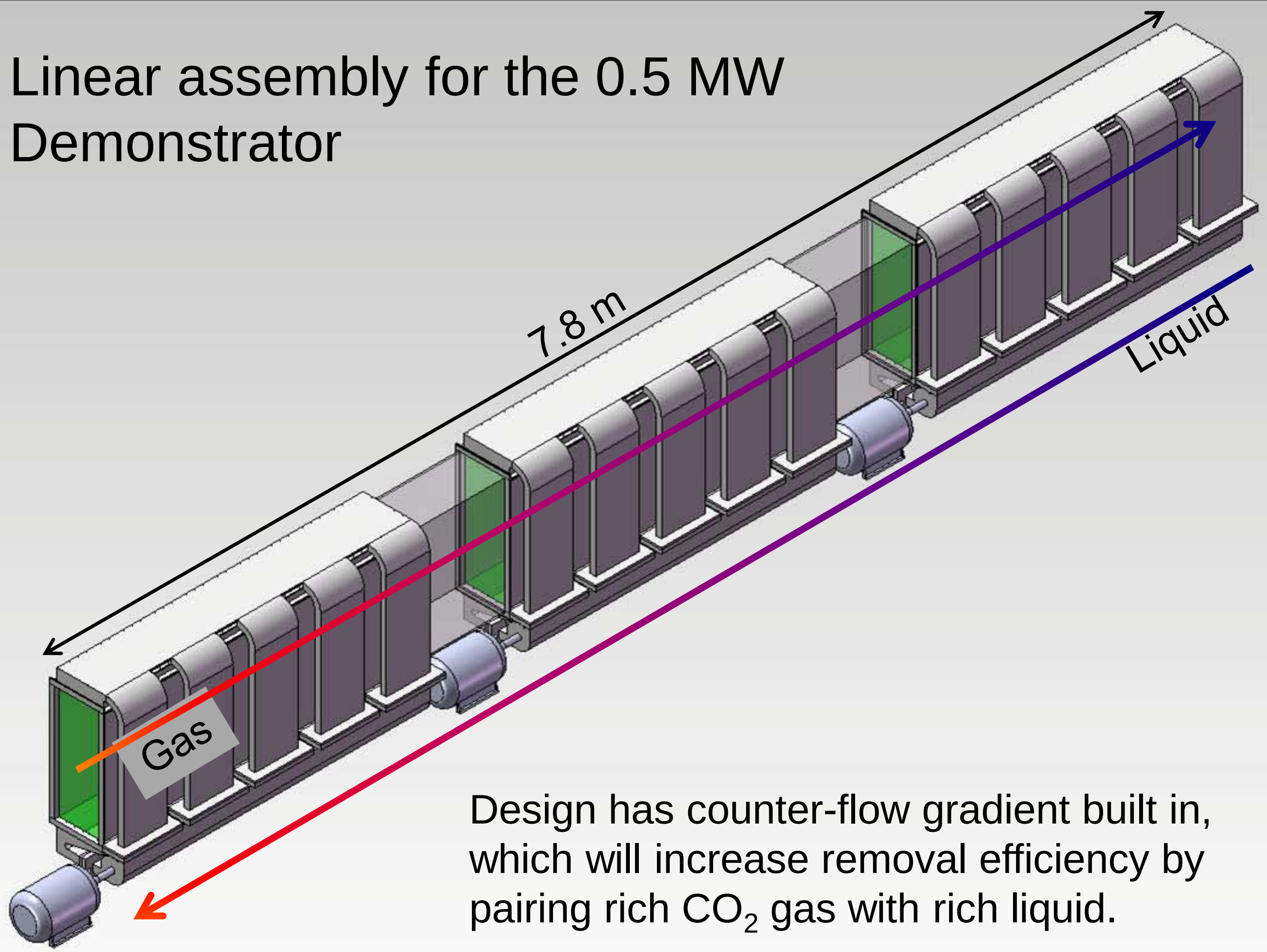
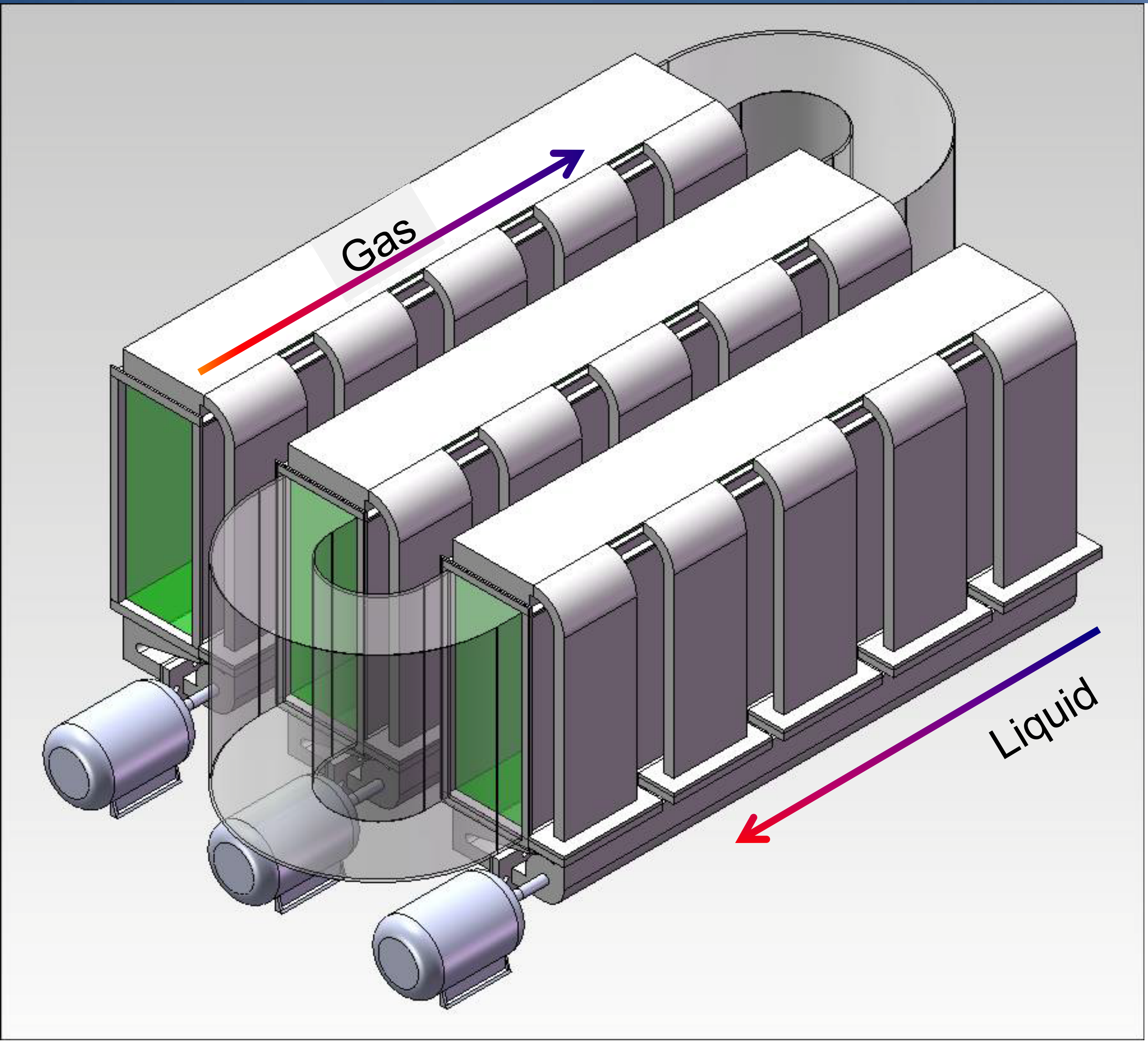
Linear assembly for the 0.5 MW Demonstrator



Design has counter-flow gradient built in, which will increase removal efficiency by pairing rich CO_2 gas with rich liquid.

Conceptual Design



Wrapped assembly for the 0.5 MW Demonstrator

-More compact packaging

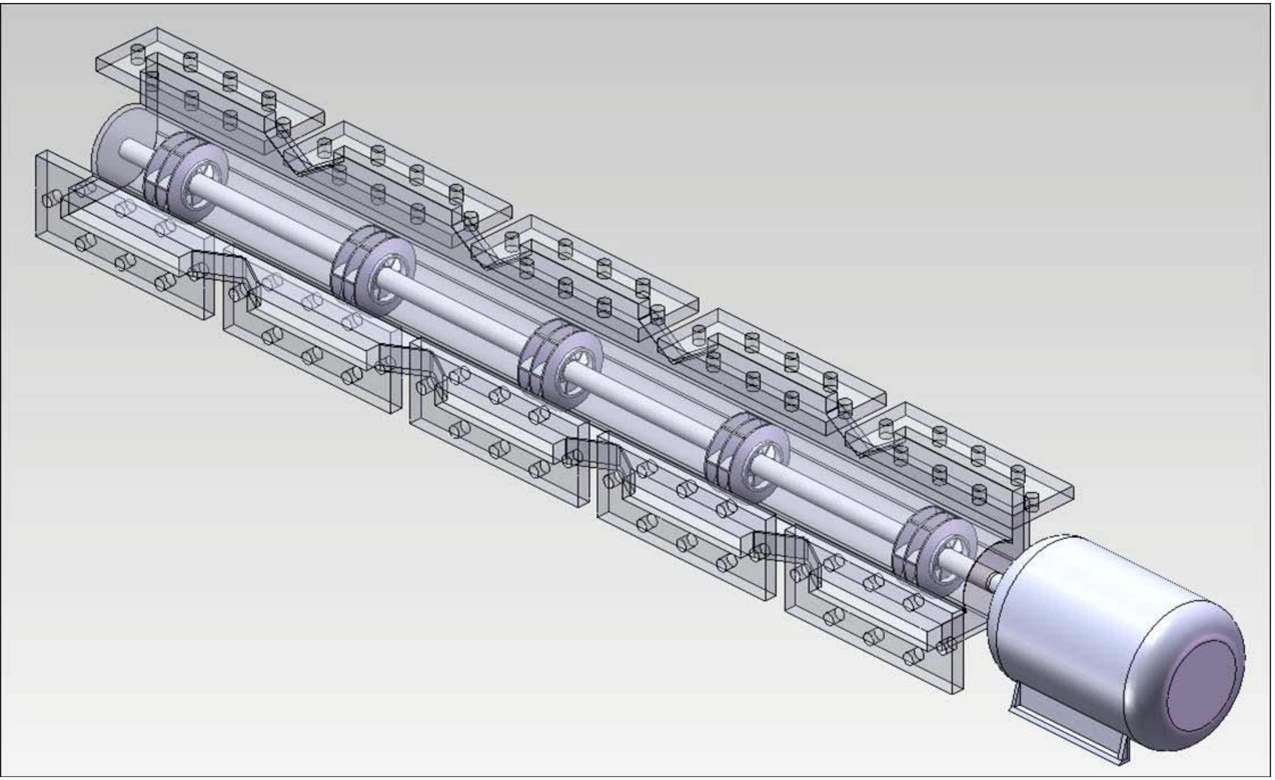
-Flow concerns introduced by turns

-Design still has counter-flow gradient built in

-Dimensions:
  Width = 1.8 m
  Length = 3.2 m
  Height = 1.1 m

Conceptual Design

Pump Design



-Working with pump manufacturer to develop

-5x impellers

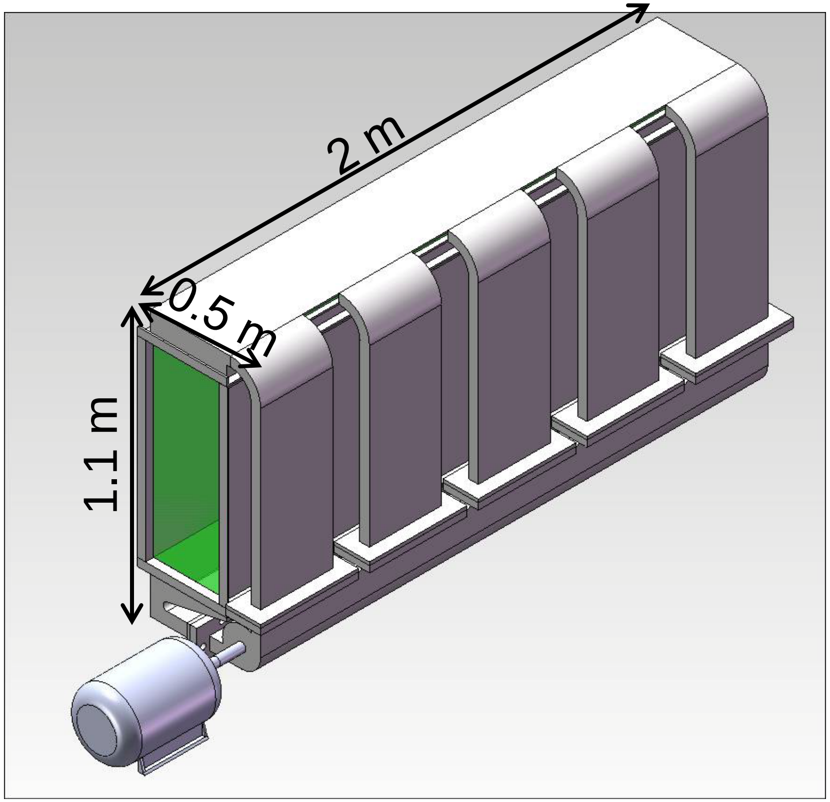
-Design will maintain separate channels

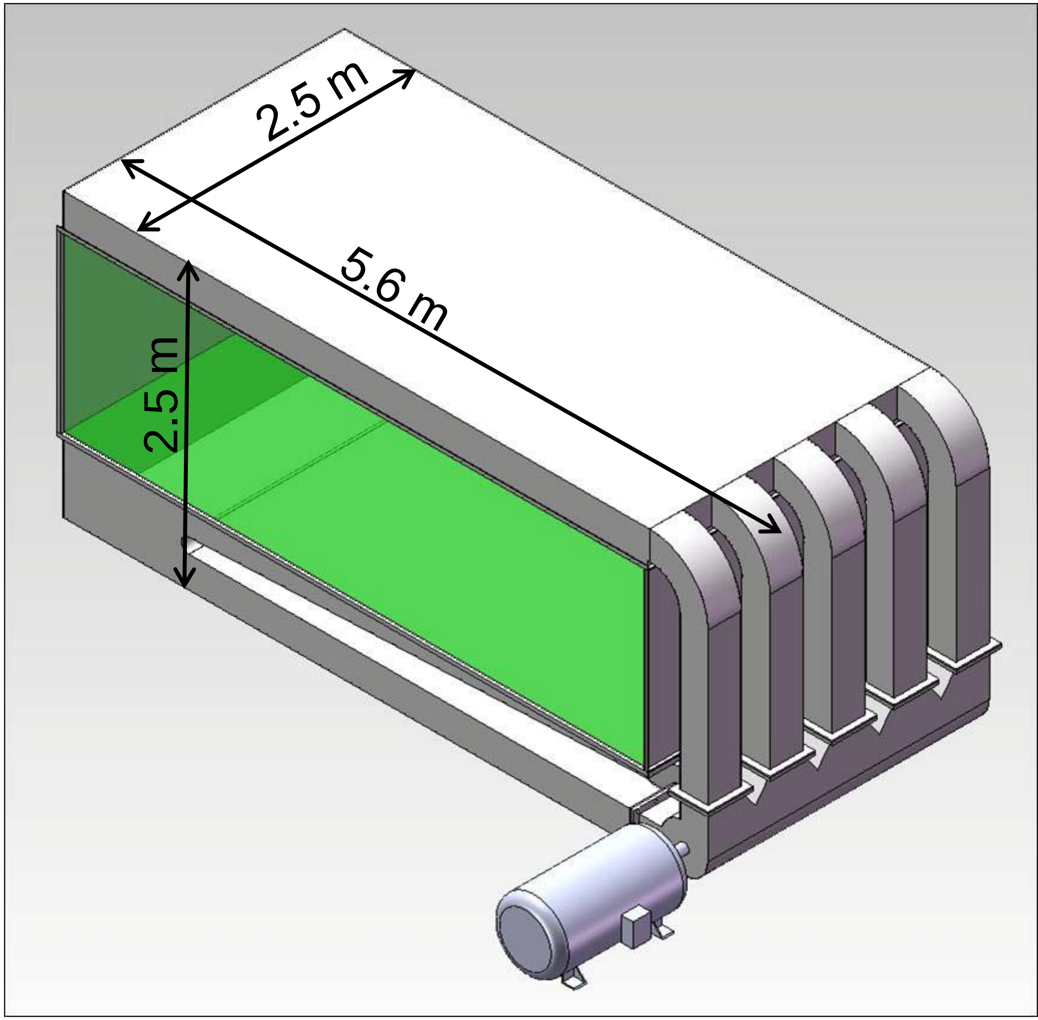
-Metric for pump is operating efficiency

-Expected efficiency about 70% (resulting in parasitic power of 0.5% per stage – 3 stages has 1.5%

Conceptual Design

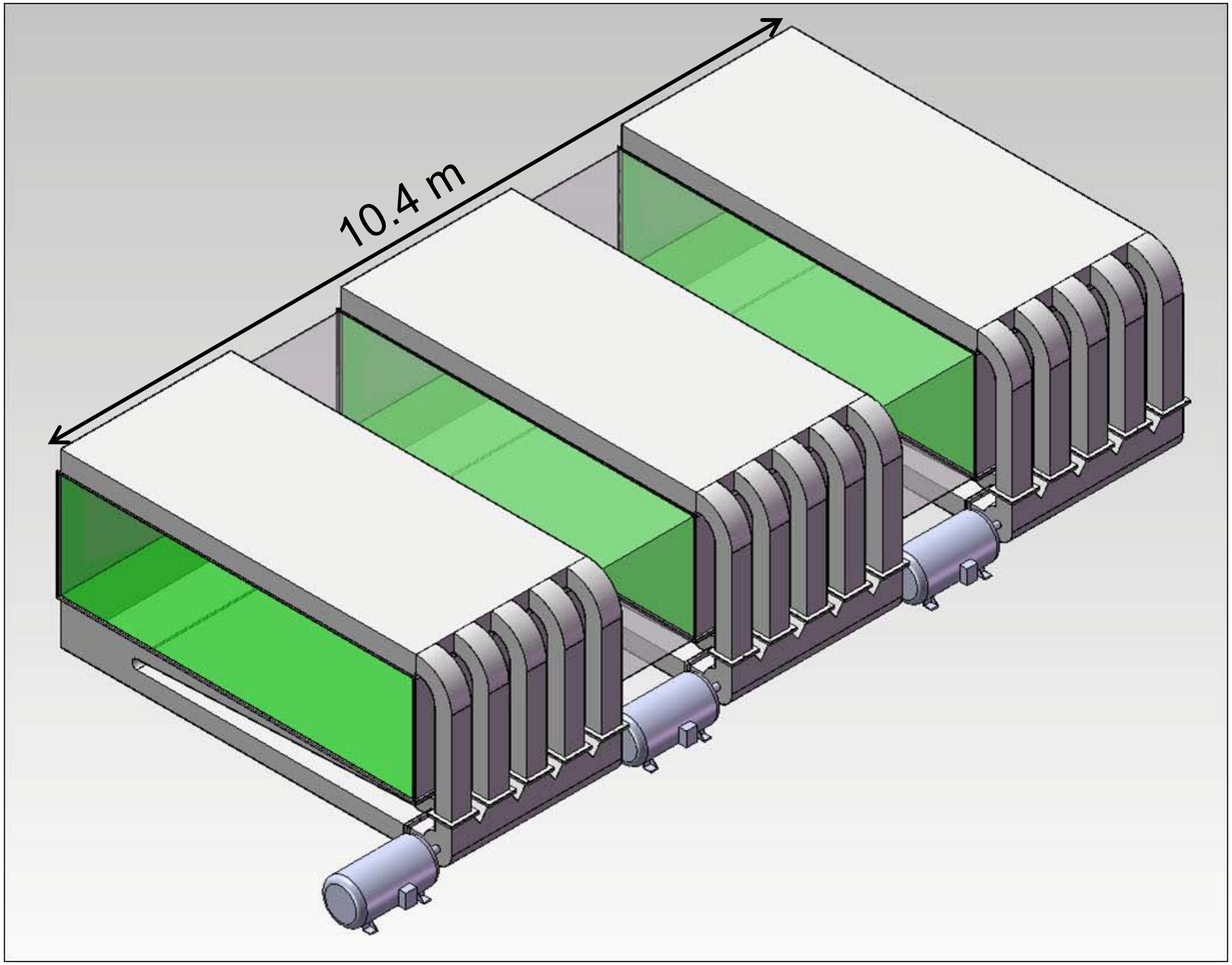
Traceability to a Commercial Scale Reactor



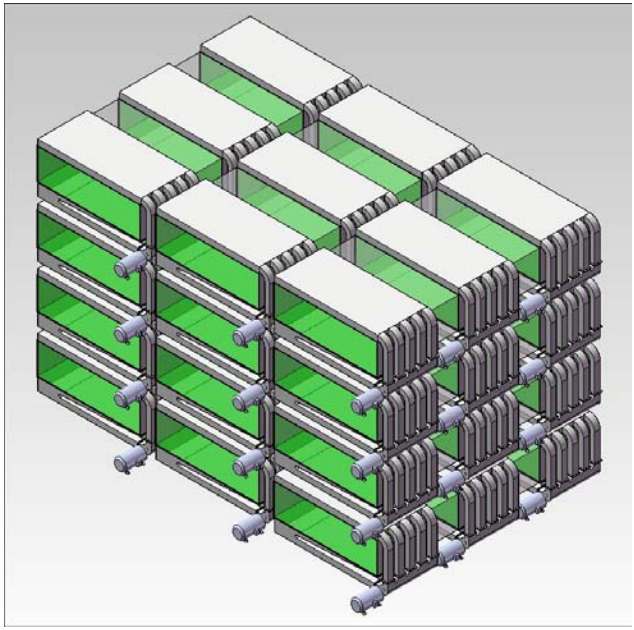


Conceptual Design

3-stage, 45-MW CO_2 Module to achieve 90% capture



550 MW system Model



System Dimensions
(W x H x L):
17.1m x 10.7m x 10.4m

Scale up potential

- Modular approach to the Flat Jet Absorber
  - Reduces risk for scaling up scope of absorber
  - Rapid deployment of modular parts due to in-house fabrication
  - Commercial design will utilize same configuration

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End