Oxy-Combustion Pressurized Fluidized Bed with Carbon Dioxide purification

Principal Investigator:

Mark Fitzsimmons

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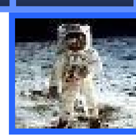
50+ Years of Space Propulsion

852 Humans Launched Into Space and **2112** Total Launches to Date

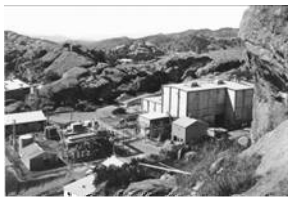
										ACTIVE				
Redstone 85	Navaho 11	Jupiter 46	Thor 380	Atlas I/II 568	Saturn I/1B 19	Saturn V 13	Titan I,II,III,&,IV 370	PK 51	Space Shuttle 135	THAAD 22	Delta I/II/III 341	Atlas III/V 48	Delta IV 22	Antares 1



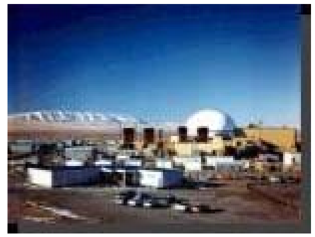
60+ years of energy experience

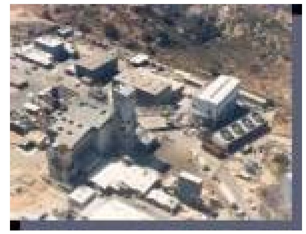
1950 1960 1970 1980 1990 2000 2010

Nuclear


SRE: 1st Nuclear Power on US Grid

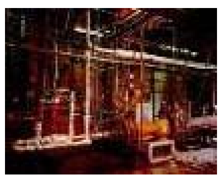

SNAP 10A: 1st Space Reactor


FFTF: Fast Flux Test Facility


SCTI: Test Facility & Cogeneration Plant

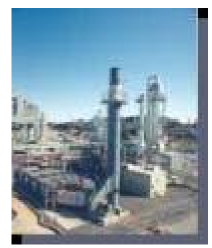

Mars Curiosity Rover Power Radioisotope Power Source

Fossil


Coal Combustion Technologies


Downhole Steam Generator


Fluidized Combustion


Kalina Waste Heat Plant

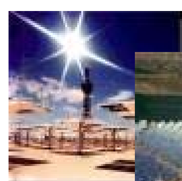

Gasification System

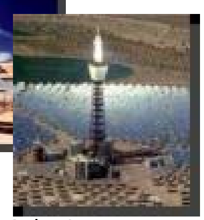

Hydrogen Generator


Zero Emission Power & Steam (ZEPS)

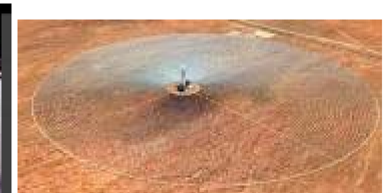
Solar


Dynamic Space Solar Receiver

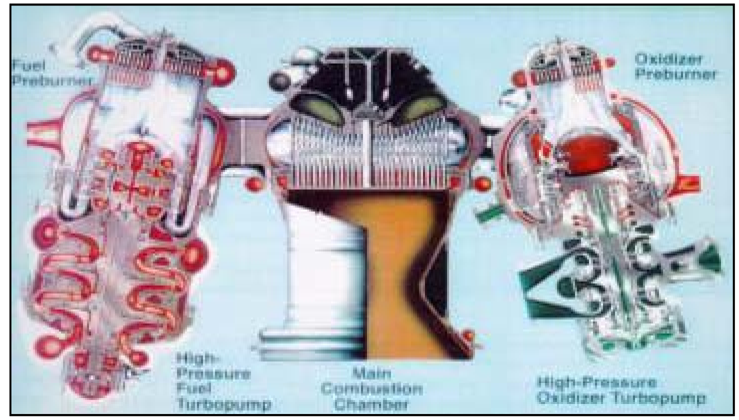

Solar 1 Steam


Solar 2 Molten Salt


Space Station Power System


Concentrated Solar Power

Applying aerospace capabilities to solve complex energy challenges



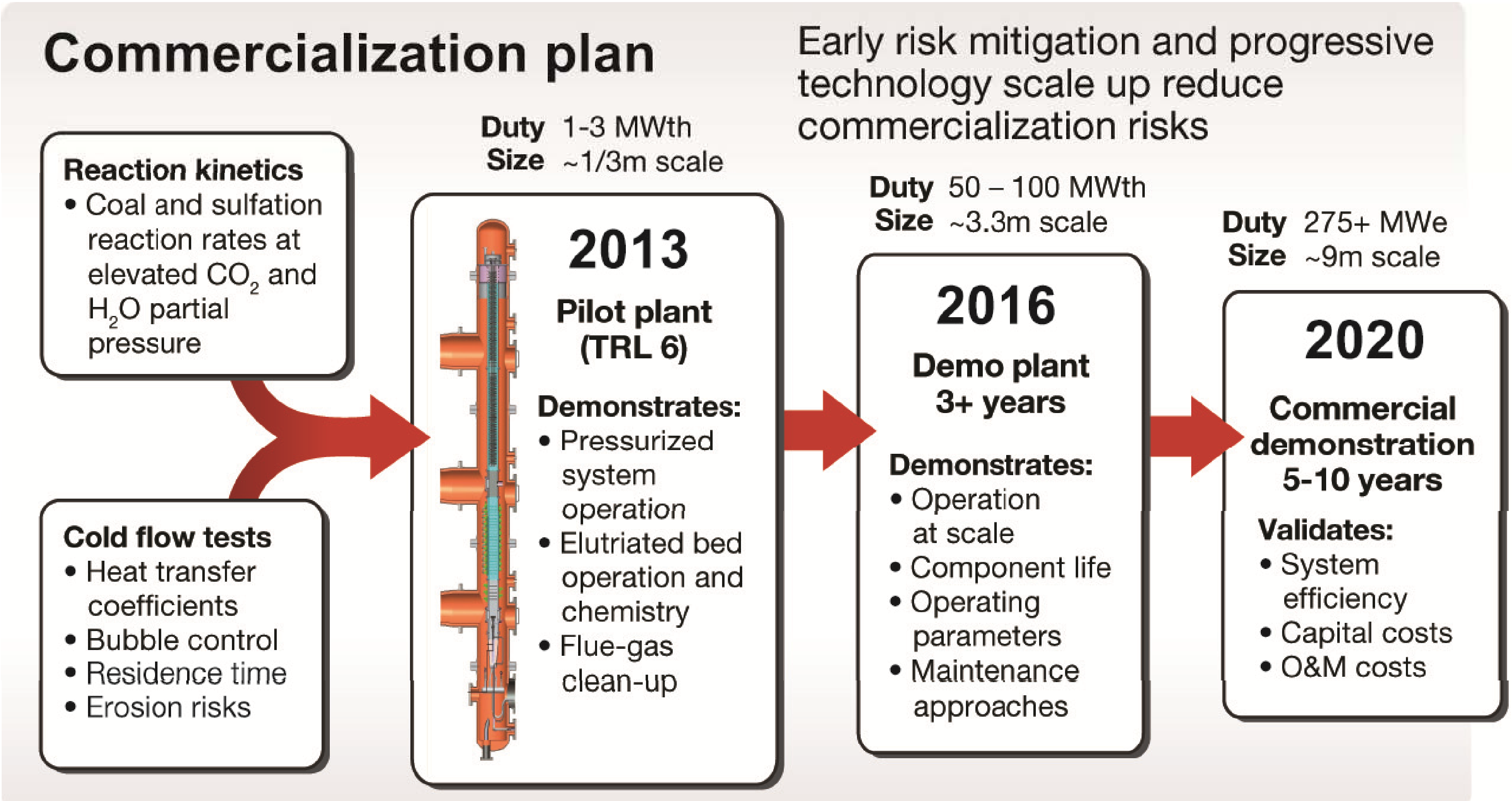
- High energy density combustion
  - ➢ 6000º F
  - ➢ 5000 psia
- Regenerative cooling
  - ➢ Low metal temperatures
  - ➢ High system efficiency
- Short Residence Time Reactions & Control
- High speed rotating equipment
  - 36,000 rpm

- Hydrogen technology
- Low cost < $10 per kW thermal
  - ➢ Unique design capabilities
  - ➢ Advanced manufacturing processes
- Manufacturing and test
  - ➢ Capacity > 200 GW thermal per year
  - ➢ Rapid prototyping
  - ➢ Extensive test capability

Providing competitive, step-change technologies in large-growth global markets

Multi-Phase Project Objective:

Commercialize clean coal technology by 2020



Phase I	Phase II	Phase III	Phase IV
(TRL 3-4)	**(TRL 5-6)**	**(TRL 6-8)**	

Phase II costs: DOE $12.9M   Partner cost share $7.4M Total $20.3M

Roles are aligned to team member capabilities

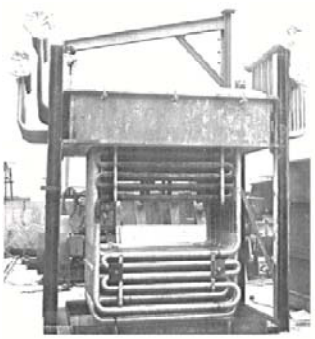
AEROJET ROCKETDYNE

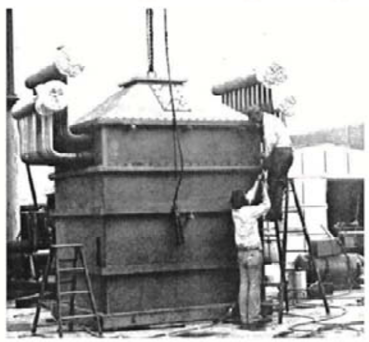
Organization	Role/Responsibility
AEROJET ROCKETDYNE	• Project lead & PFBC technology • Process & system engineering • Risk mitigation & pilot test planning
Linde	• Gas supply and clean-up systems • PFBC Heat exchanger design support
CanmetENERGY	• Fluidized bed pilot test facility • Procure and construct pilot test facility • Operate PFBC pilot test facility
ALSTOM	• PFBC Design support • Commercialization partner
PENNSTATE 1855	• Fuel and limestone testing • MFIX physics model development
JAMESTOWN bpu BOARD OF PUBLIC UTILITIES	• Field demonstration unit site • Support demo plant design & cost estimates
EPRI ELECTRIC POWER RESEARCH INSTITUTE	• Voice of the end-user • Review of process and cost modeling

Oxy-PFBC Project Heritage

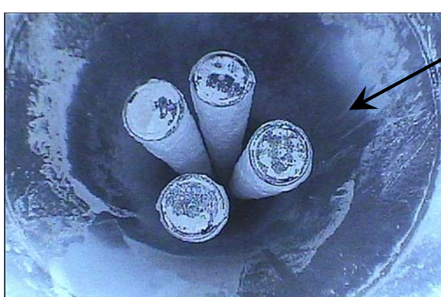
Combustor design and test heritage

- 2m x 2m atmospheric unit
- Air-fired fluidized bed
- Coal and limestone
- Mature injector design
- Elutriated fly ash removal
- In-bed heat exchanger
- Convective heat exchangers
- Manifolding and hanger designs

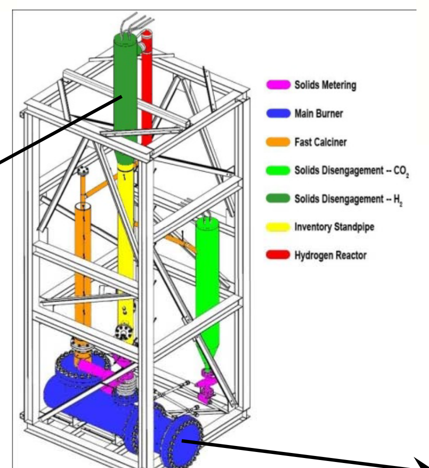




1980-1985 Air Heater Experiment at Rocketdyne for Sandia National Lab



Gas filtration and solids removal



Fluidized bed system

2004-2012 Bubbling fluidized bed reactor and gas filtration solids looping tests for hydrogen production, Rocketdyne facility at EERC

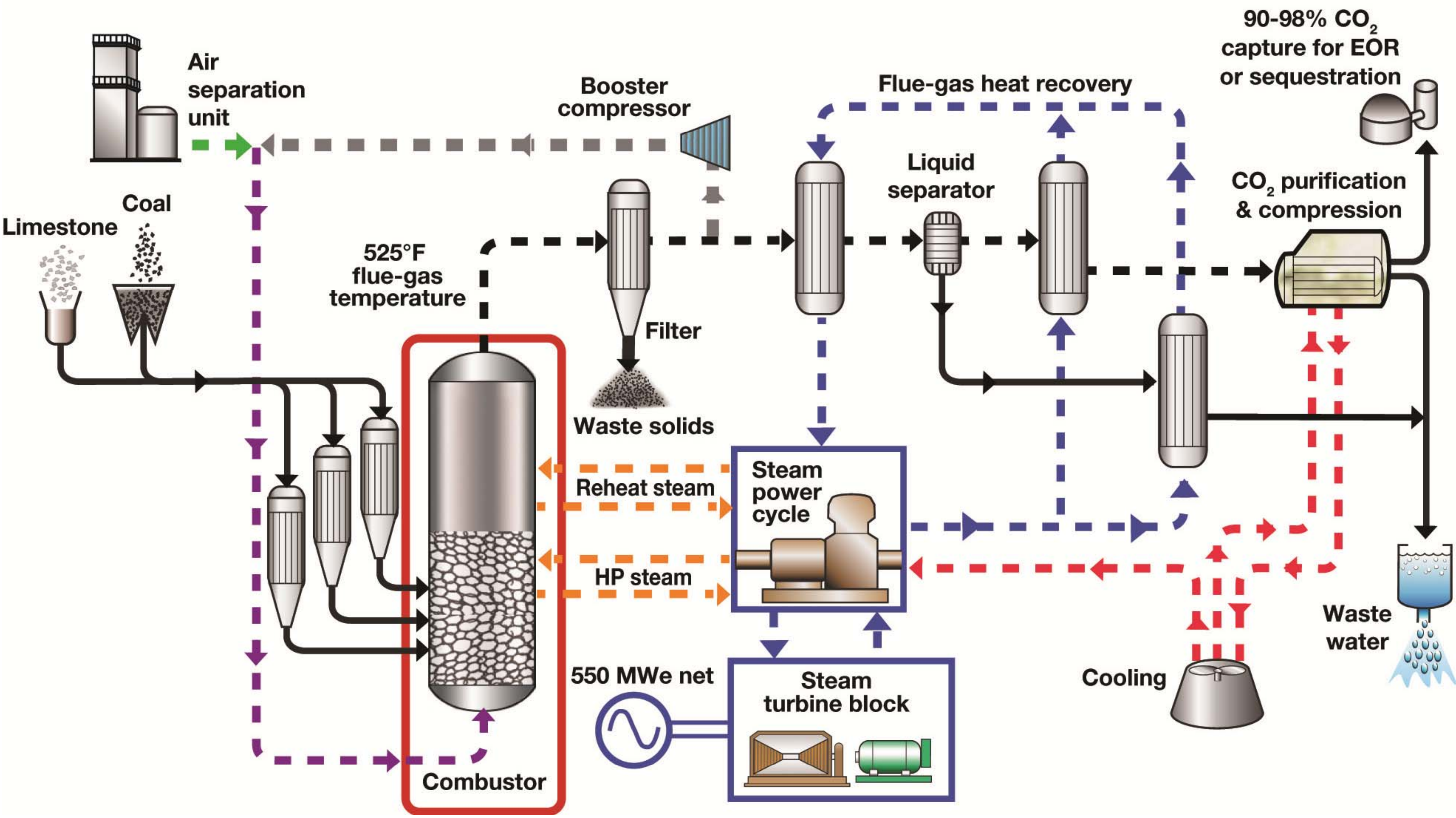
Leveraging demonstrated technologies

Linde's units in Vattenfall's 30 MWth oxyfuel pilot plant at Schwarze Pumpe, Germany

CO_2 purification unit

Solids injection

System Description



Equipment List (Omitting items from Case 5A)

4.10 ASU	4.2 PFBC Injectors Assy	5A.3 Pressure Vessels, Filters, Pulse Cleaning System, Ash Removal
2.1-2.5 Pulverizing system	4.3 PFBC Pressure Vessel	5A.5 Warm Gas Recycle compressor
2.15 Bag House	4.4 PFBC FB Container & Cooling system	5B.1 Condensing Heat Exchanger
2.12, 2.13, 2.14 Lock Hoppers	4.5 Inerts Injection Lock Hopper	5B.1 SOx/NOx Removal
4.1 Fluidized Bed	4.6 CO_2 Accumulator Tank	5B.1 Catalytic Deoxo reactor
4.1 PFBC Convective HEX & manifolding	4.7 Burners for Startup	5B.1 Cryo-compression
4.1 PFBC In-Bed Heat Exchanger	4.8 Trace Heat System	7.1 Boiler Feedwater Bypass Heat Exchangers
4.1 PFBC Reheat HEX	4.9 Tuyere System CO2 / O2 Injection System	7.2 Gas Cooler for Recycle stream

A few options examined in Phase I Study

Option	%COE increase relative to Case 11	% CO_2 capture	Cost of CO_2 captured (2011$/ tonne)	Case description
Option 1C	34.8	90	33	Highest TRL, 90% capture, ASU producing 97% O2, cryogenic CPU
Option 2	32.4	98.3	27.9	Baseline AR case ASU with 99.2% O2, non-cryogenic CPU
Option 2C	31.8	90	30	Baseline AR case with 90% CO_2 capture
Option 3	30.0	98.3	26.3	Advanced ASU (future technology with improved efficiency based on Linde patent)
Option 3C	29.5	90	27.5	Case 3 with 90% CO_2 capture
Option 4 (SCOT)	19.2	98.3	18.4	Case 2 with supercritical CO_2 Brayton cycle
Retrofit 2R	34.3	96.5	30	Same as baseline case, for retrofit application
Retrofit 3R	31.9	96.5	27.9	Same as Case 3, for retrofit application
Retrofit 3RC	30.6	90	28.7	Same as Case 3R, with 90% CO_2 capture

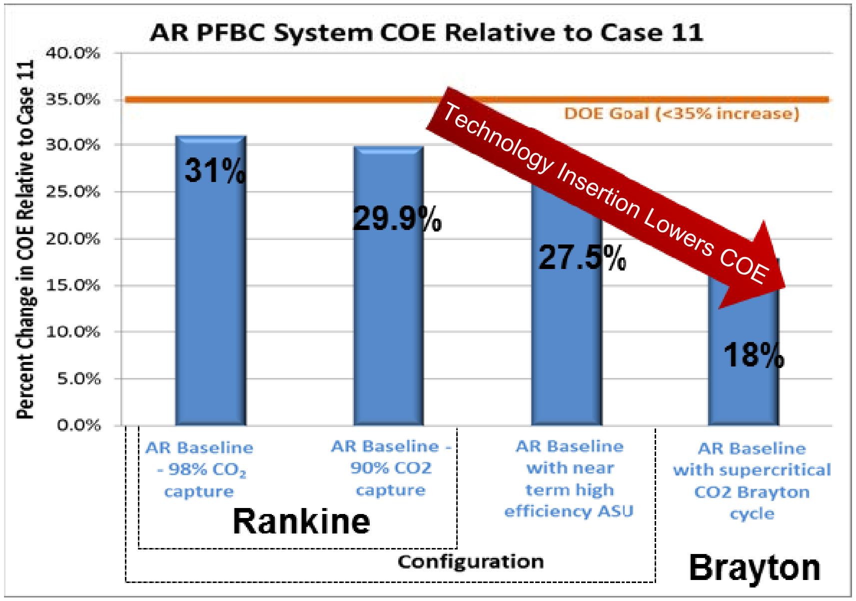
Table 1: AR/Linde Plant Options Presented in Techno-Economic Analysis

Effect of >90% Capture and EOR Assumption

COE ($/MWhr)	Option 1	Option 2	Option 3
1. Max. CO_2 Recovery	107.6	106.1	104.0
2. 90% CO_2 Recovery, EOR Assumption	106.8	105.2	103.2
3. 90% CO_2 Rec + Reduced CO_2 Purity	102.8	104.1	102.1
COE vs Case 11 (%)	Option 1	Option 2	Option 3
1. Max. CO_2 Recovery	32.9%	31.0%	28.5%
2. 90% CO_2 Recovery, EOR Assumption	**32.0%**	**29.9%**	**27.5%**
3. 90% CO_2 Rec + Reduced CO_2 Purity	**27.0%**	**28.6%**	**26.2%**
CO_2 Cost ($/MT) w/o TS&M	Option 1	Option 2	Option 3
1. Max. CO_2 Recovery	29.4	26.7	25.2
2. 90% CO_2 Recovery, EOR Assumption	30.2	28.1	26.3
3. 90% CO_2 Rec + Reduced CO_2 Purity	25.5	26.9	25.0

Phase I Study Results

- **Exceeds DOE goal of >90% CO2 reduction with COE increase of 35% or less**
  - 98% capture
  - 31% COE increase



- **Oxy-PFBC technology enables future adoption of supercritical CO2 Brayton cycle for significant additional performance improvement**

- **Focus on clear path to commercialization**
  - Current approach utilizes a suite of demonstrated technologies with high TRL components to minimize system development risk
  - Team is in place to commercialize the technology (Linde, Alstom, Jamestown BPU, CANMET)

Project Background:
Oxy-Pressurized Fluidized Bed Combustor (PFBC)

PRODUCT

- Oxy-fired, pressurized fluidized bed combustor equipment for coal-fired power plants
- Elutriated flow removes ash and sulfur prior to recycle

BENEFITS

- Produces electric power with near zero emissions
- Produces steam for heavy oil recovery using low value feedstock (petcoke, coal, biomass)
- Produces pure CO_2 for Enhanced Oil Recovery (EOR)

MARKETS

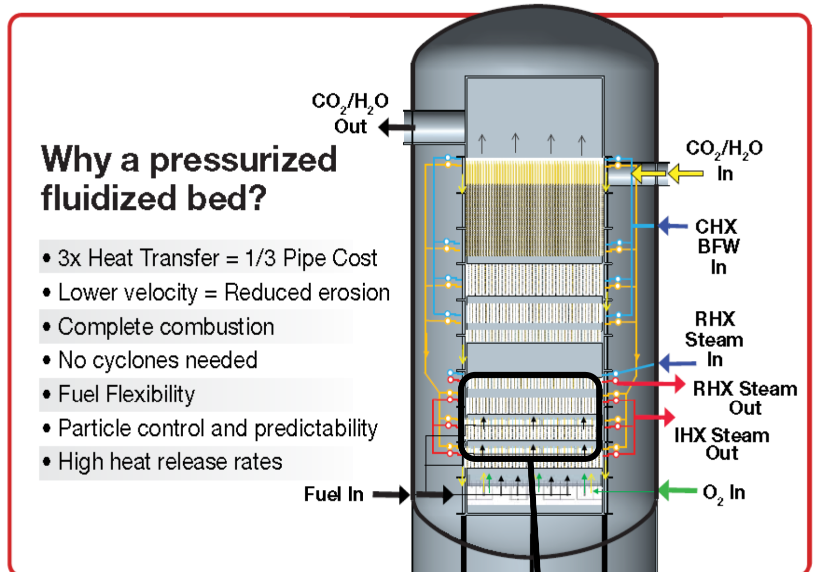
- Electric power generation with CO_2 capture
- Heavy oil production (once-through steam)
- Light oil production (CO_2 floods)

STATUS

- Long-life, in-bed heat exchangers demonstrated in 1980s
- Concept modified for oxygen-firing rather than air
- Technology development contracts w/DOE

NEXT STEP

- Build & operate Pilot plant(s) with DOE funding



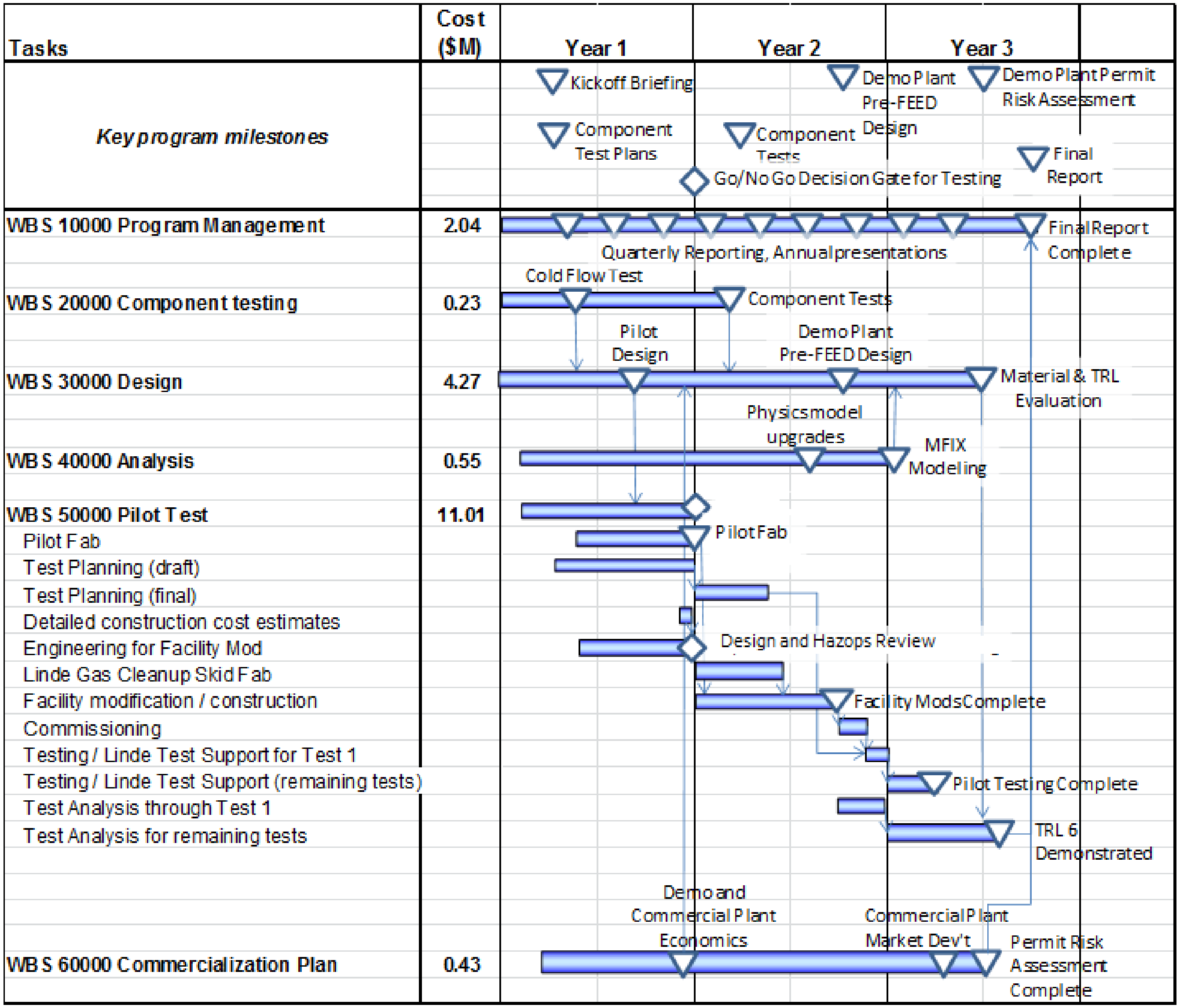
Commercial Scale PFBC Concept

Heritage Rocketdyne Test Facility that Demonstrated Long Life In-bed Heat Exchanger

Project Objectives for Phase II

- Assess the components of the system designed in Phase I to confirm scalability, performance, and cost.
- Test the system at subscale pilot facility to evaluate system performance and operability.
- Develop algorithms to model the components and system for scale-up.
- Use the validated models to predict commercial scale cost of electricity.
- Develop Phase III (Demonstration at 20-100 MW) project plan, risk mitigation status and TRL advancement, and identify partners and sites.

Phase II Schedule

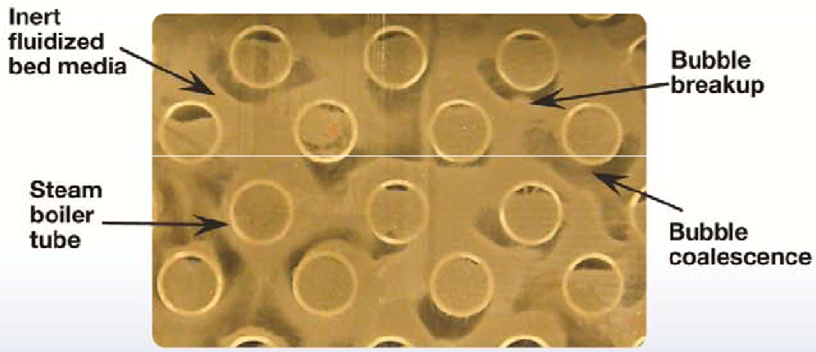


Phase II Tool Development

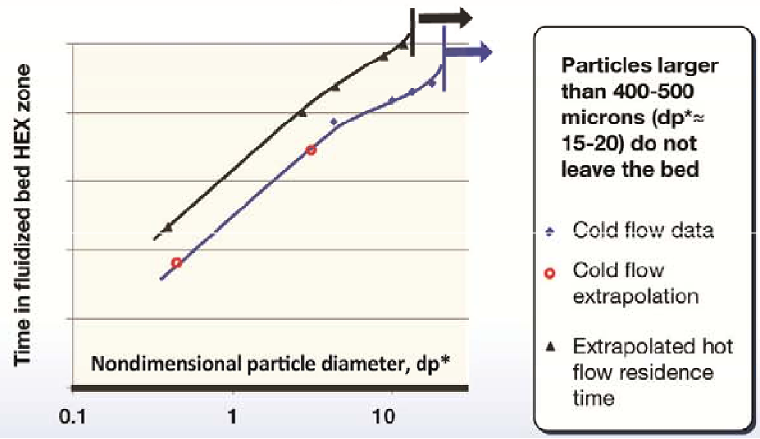
Cold Flow testing

Design relationships for bubble control and heat transfer validated

Heat transfer and residence times measured for fullscale in-bed heat exchanger elements

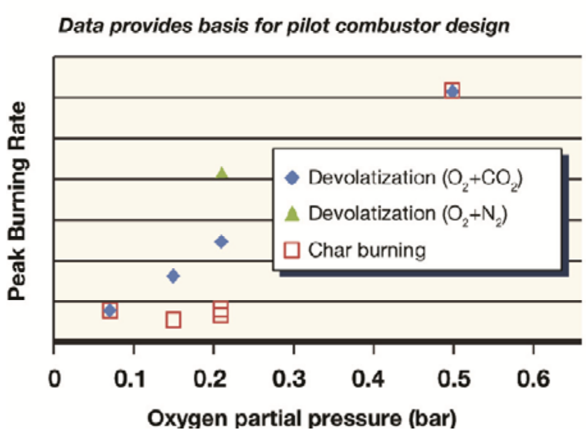


Particle residence time exceeds reaction time requirements



Kinetics testing

A range of particle sizes and oxygen pressures tested to develop a complete picture of heat release



Goal:
Develop analytical tools to allow scaled-up design of Phase III and IV Projects

Pilot Plant Progress

- Preliminary test matrix
- Pilot plant PFD and Aspen model
- Pilot plant P&ID
- Pilot scale conceptual design and CAD model
- Equipment list for long lead purchases
- Defined existing equipment which can be reused
- Priced new equipment to procure
- Preliminary site plan

Commercialization Plan (BP 2 & 3)

- **Demonstration Plant:**
  - Economics of plant (profit/loss analysis, gap funding sources)
  - Permitting risks and mitigation development
  - Pre-FEED engineering
  - Develop Pitch Package
- **Commercial Plant:**
  - COE analysis refinement

  (Pilot Test → Anchored models → Partial capture plant options)
  - Commercial Market study (Plants slated for retirement and upgrade)
  - Commercialization partners identified

Partial Capture Concepts being developed for potential customers to generate clean electricity and steam cogeneration.