Ramgen Supersonic Shock Wave Compression and Engine Technology

2012 NETL CO_2 Capture Technology Meeting
Sheraton Station Square, Pittsburgh, PA

July 11, 2012

Kirk Lupkes
Ramgen Power Systems

Company

- **Privately-held R&D company founded in 1992**
- **Focused on unique applications of proven supersonic aircraft technology**
- **Primary technology innovations**
  - Supersonic air & gas compressors
  - High velocity vortex combustor
  - Supersonic expander
- **Product embodiments**
  - Two-stage 100:1 Pr CO_2 Compressor
  - 20:1 High Efficiency ISC Engine

US Army Corps of Engineers

Project Overview

Funding and Objectives

- **Funding**
  - $ 50M Total Compressor and Engine DOE Funding
  - $ 29.7M Private funding including Dresser-Rand contribution

- **Overall Project Performance Dates**
  - Start: August 1, 2009
  - End: June 30, 2014

- **Project Participants**
  - Dresser-Rand: Engineering support and host to Olean CO2 test facility

- **Overall Project Objectives:**
  - Compressor Project: High-efficiency, low-cost CO2 compression using supersonic shock wave technology to significantly reduce capital and operating costs associated with carbon capture and storage
  - Engine Project: High power density engine with lower capital and operating costs and cogen efficiencies to 80+%. The heat:power ratio would approach 1:1

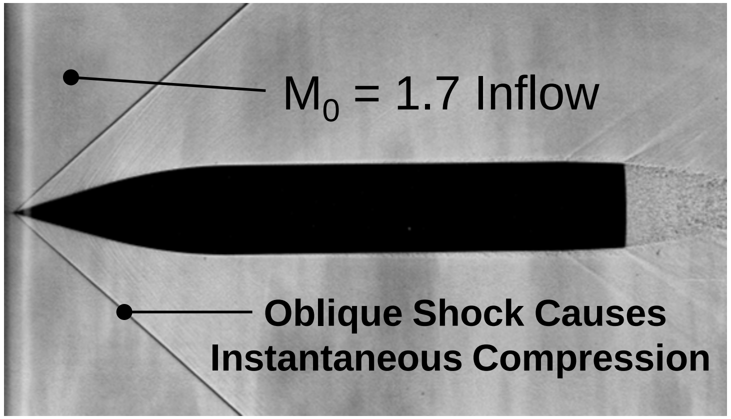
Dresser-Rand Investment in Ramgen

- **Dresser-Rand invests in Ramgen's "game-changing technology"**
  - Support on-going CO_2 compressor development
  - Satisfy DOE matching funds requirement
  - Consistent with strategy to be technology leader
  - Extend served market into Electric Utility industry
  - Investment to:
    - Fund development & demonstration
    - Obtain an option to purchase assets
- **Dresser-Rand is consistently ranked among top three manufacturers in its served markets**
  - Turbomachinery
  - Reciprocating compressors
  - Steam turbines
- **Leading supplier of CO2 compressors**
- **Global sales & service presence**

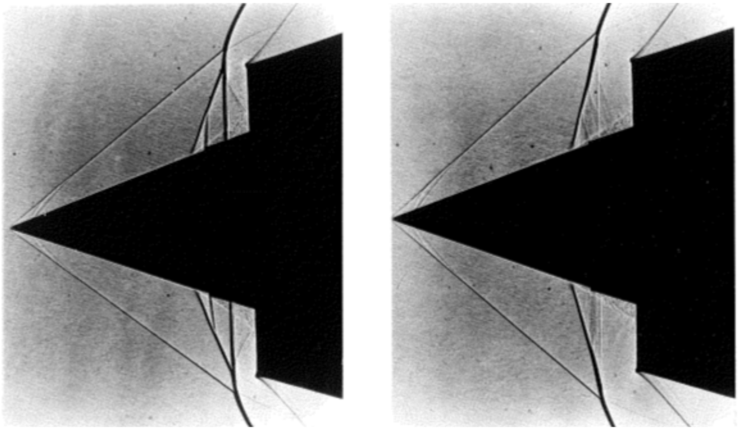
Ramgen Technology Fundamentals

Compressor

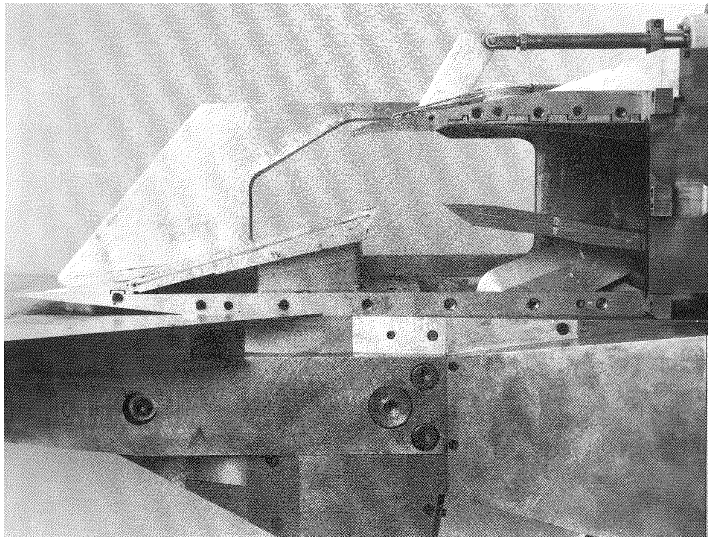
Shock Waves and Supersonic Inlets



Schlieren Photo of Projectile with Shocks



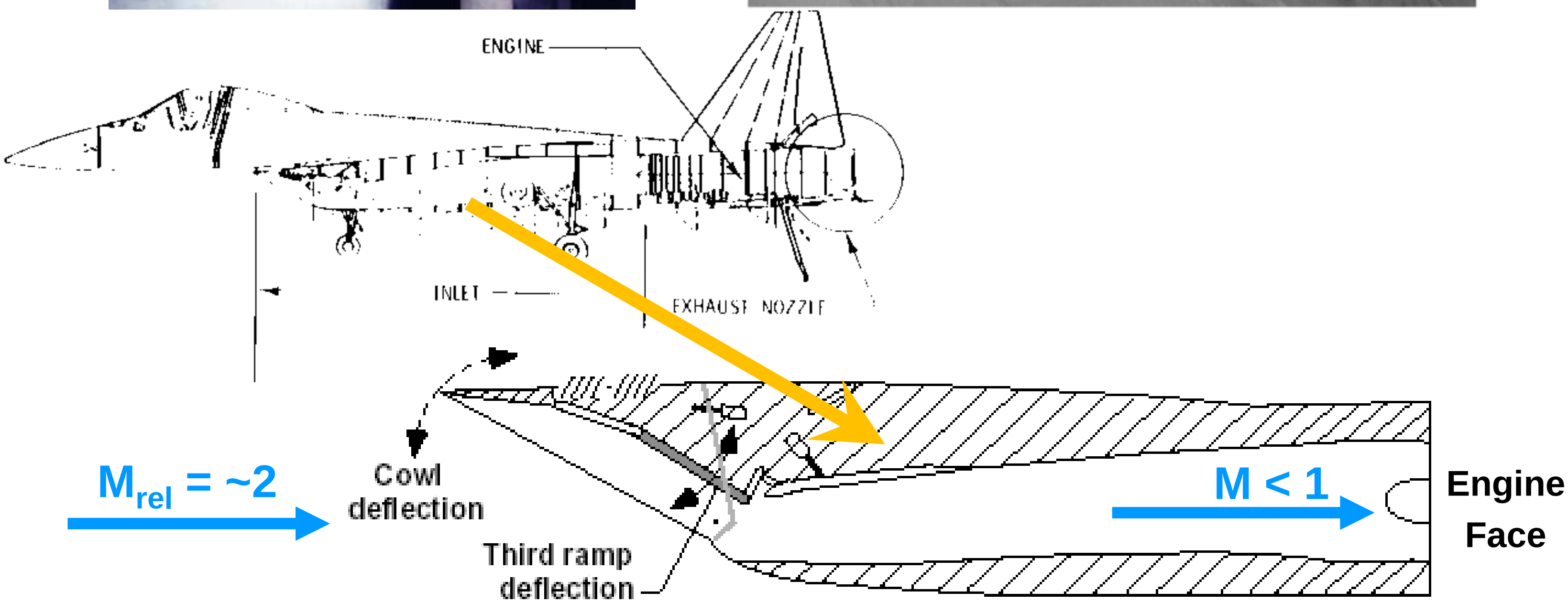
Schlieren Photo of Inlet Center-body and Cowl with Shocks



2-D Mixed Compression Inlet Model

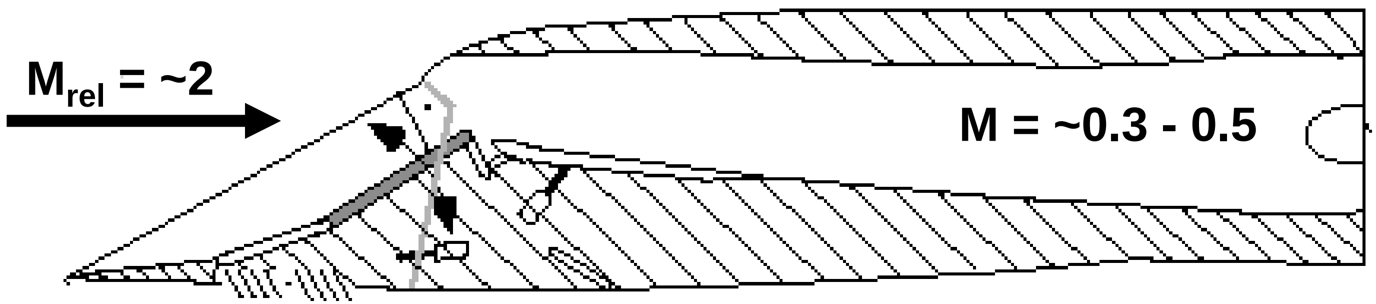
- Initial External Shock System Followed by Internal Shock System
- Throat Bleed Slot For Inlet Starting
- Side Window For Schlieren Photography

F-15 2-D Planar Supersonic Inlet

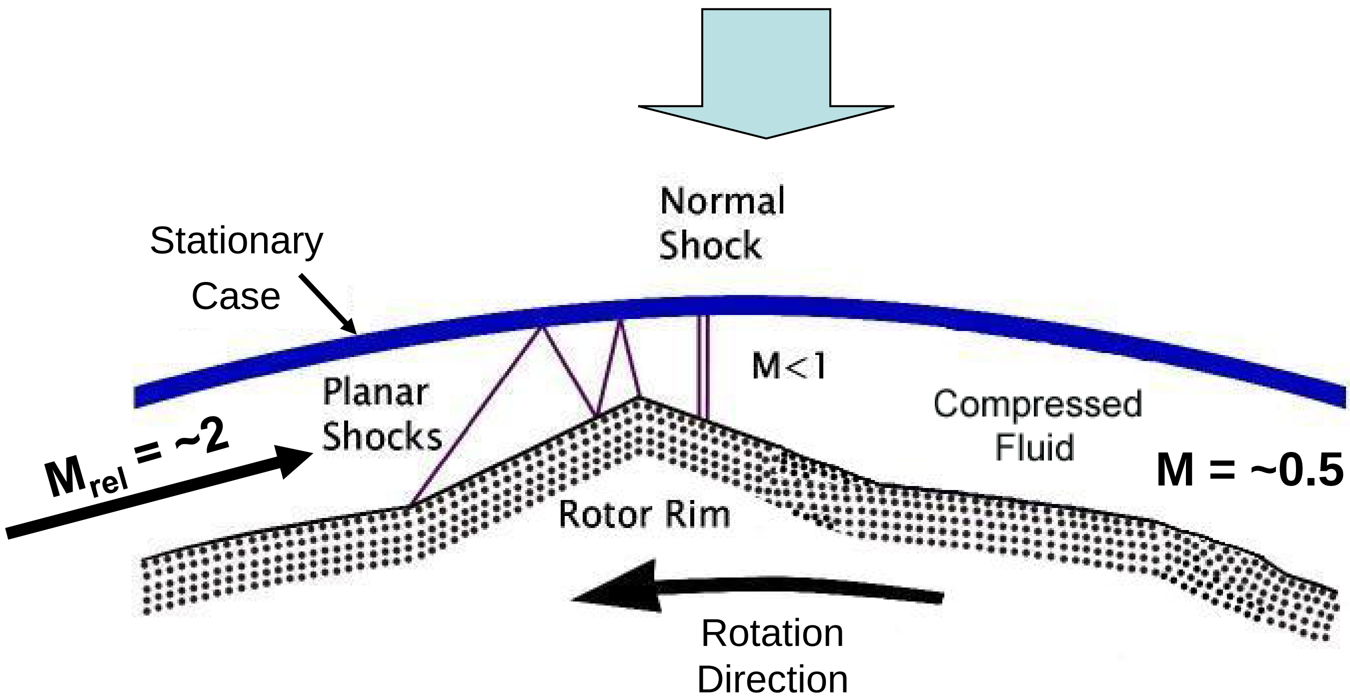


Inlet Cross Section

Rampressor Rotor Development

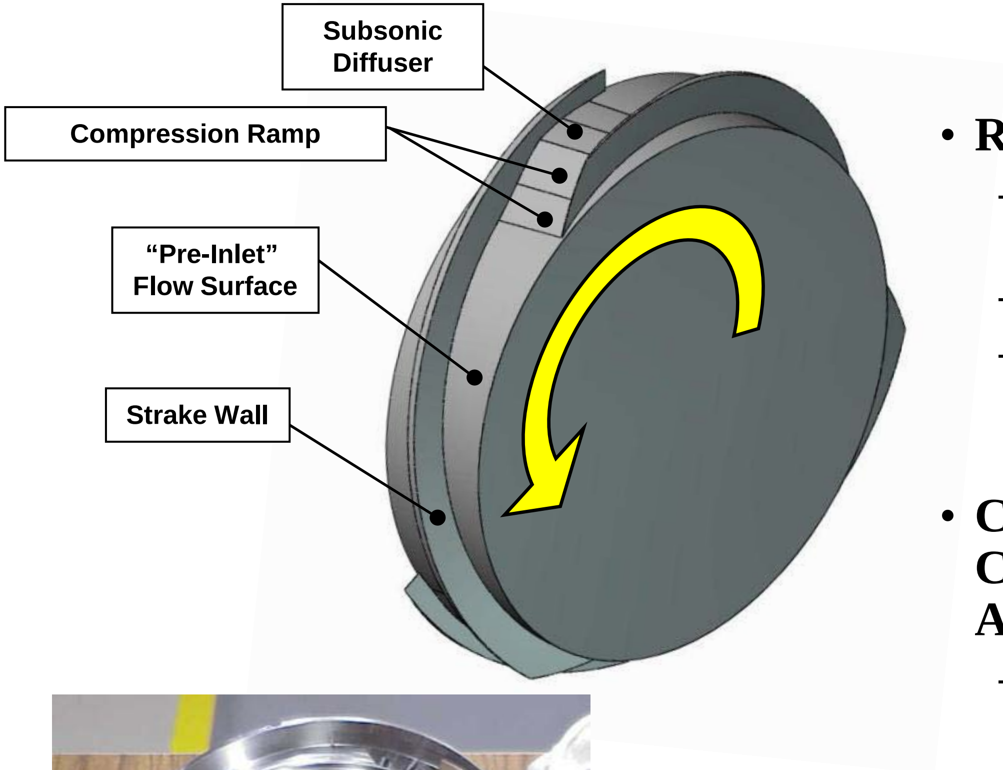


Supersonic F-15 Inlet



Rampressor Rotor

Typical Rotating Supersonic Flow Path



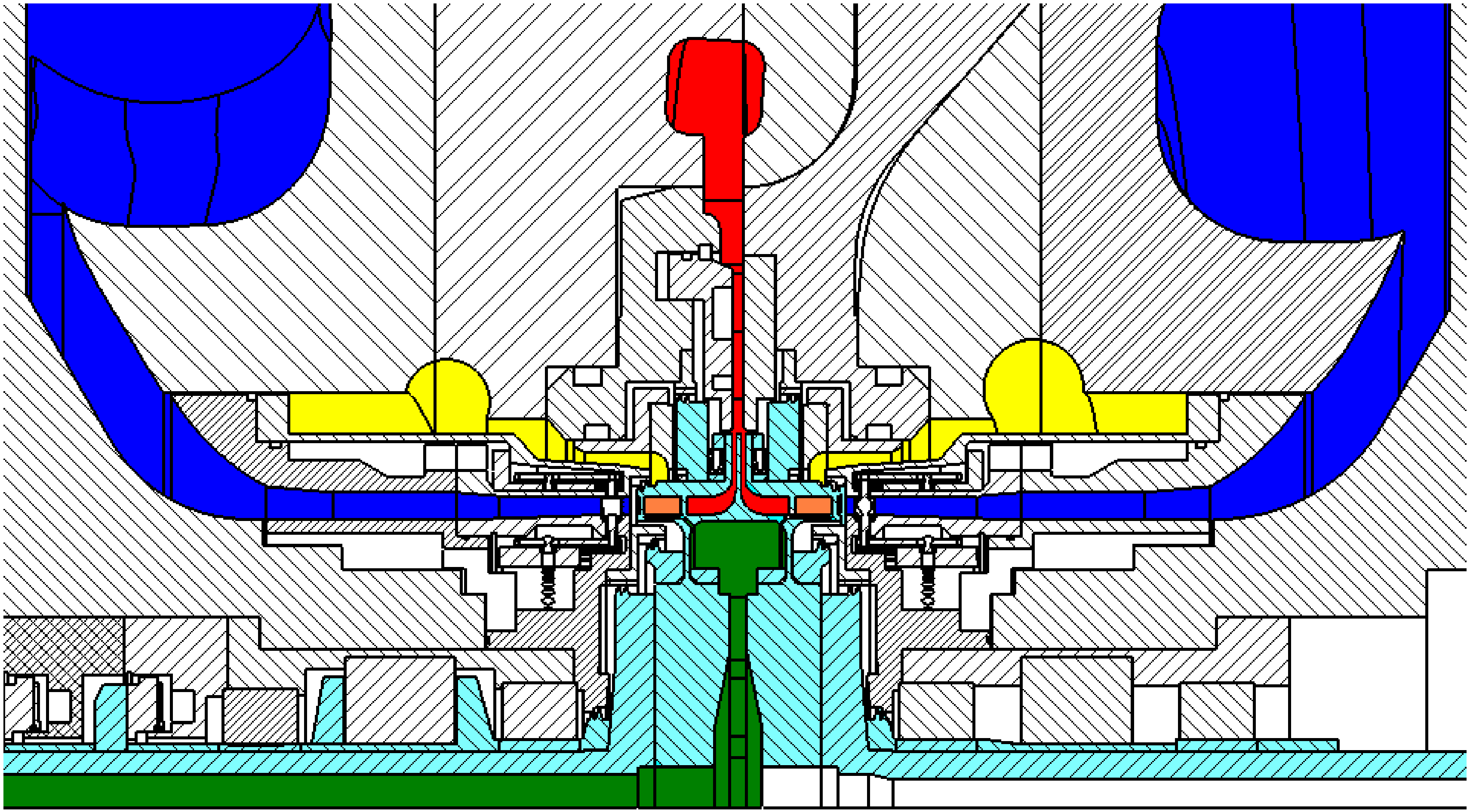
- **Rotor Flow Path:**
  - Three Supersonic Compression Inlet Flow Paths On Disk Rim
  - High Efficiency, Compact Compression
  - Flow Path Geometry Similar For Different Pressure Ratios

- **Combination of Supersonic Flight Inlet & Conventional Axial Flow Compressor Aerodynamics:**
  - Rotor Rim Radius Change Produces Compression
  - 3 "Blades" (Strakes) Do Minimal Flow Work
  - Axial Inflow/Outflow for the rotor shown

HP Stage Utilizes Back-to-Back Configuration

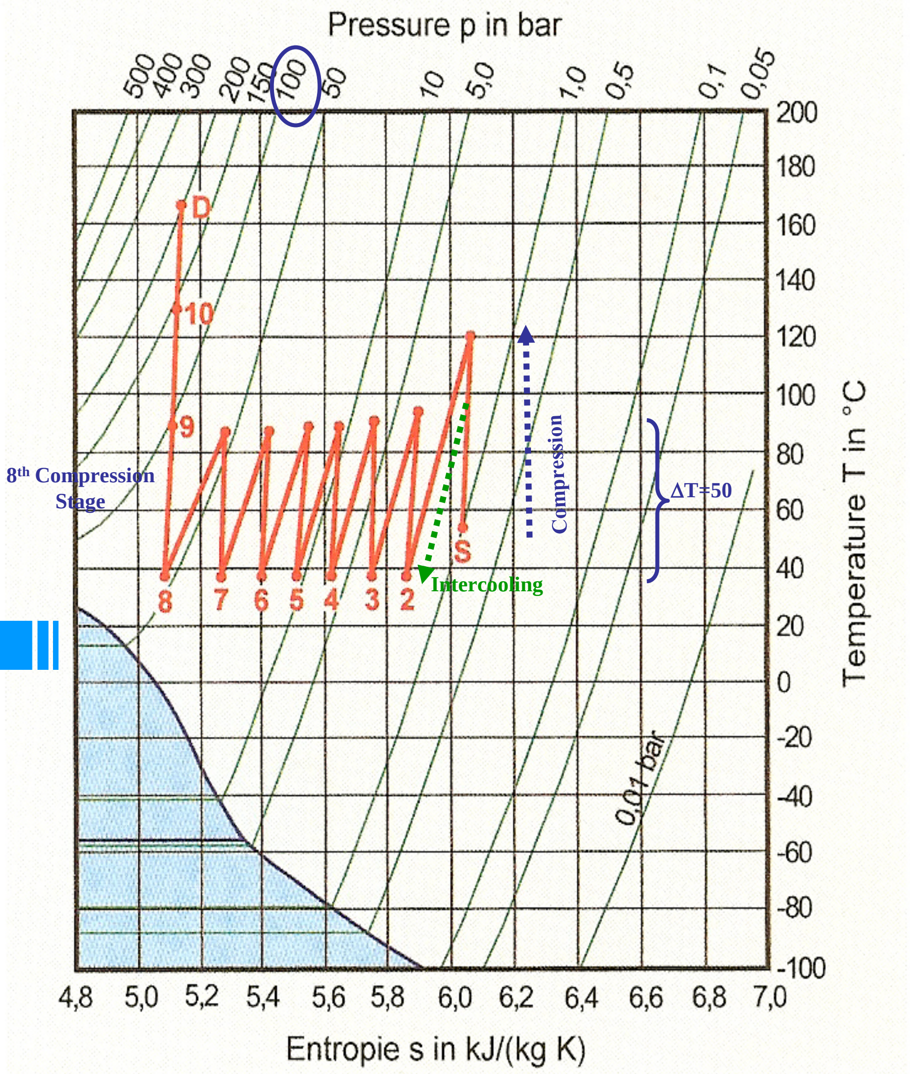
Key fluid flow features

- Suction (inflow)
- Discharge (outflow)
- Starting/bleed recycle
- Rotor



The "State-of-the-Art" is Expensive

- **10-stage 6000 hp**
  - **$8.0 million ⇨$1350/hp**
  - **Pr 200:1 ⇨1.70 per stage**



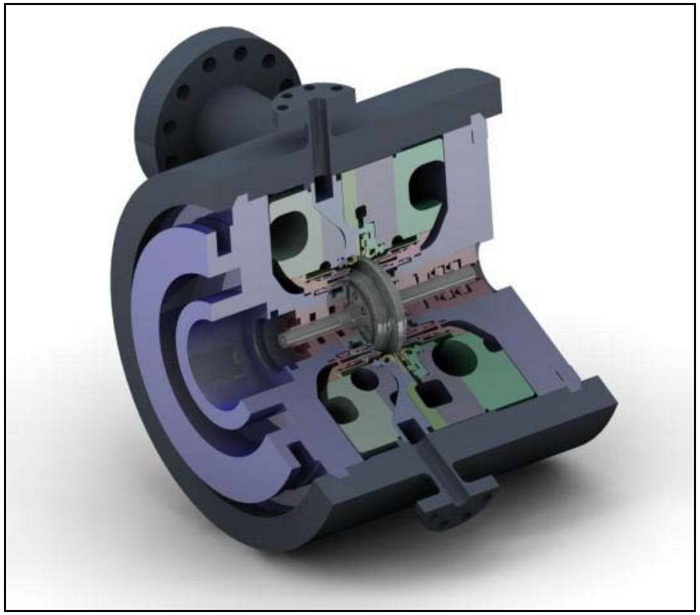
- **8-stage 20,000 hp**
  - **$15.0 million ⇨$750/hp**
  - **$23.0 million installed ⇨$1150/hp**
  - **Pr 143:1 ⇨1.86 per stage**

Reduce CC(C)&S COE Penalty

MAN Turbo CO_2 Compressor

- **10-stage 6000 hp**
  - $8.0 million ⇨$1350/hp
  - Pr 200:1 ⇨1.70 per stage
- **8-stage 20,000 hp**
  - $15.0 million ⇨$750/hp
  - $23.0 million installed⇨$1150/hp
  - Pr 143:1 ⇨1.86 per stage

Ramgen CO_2 Compressor

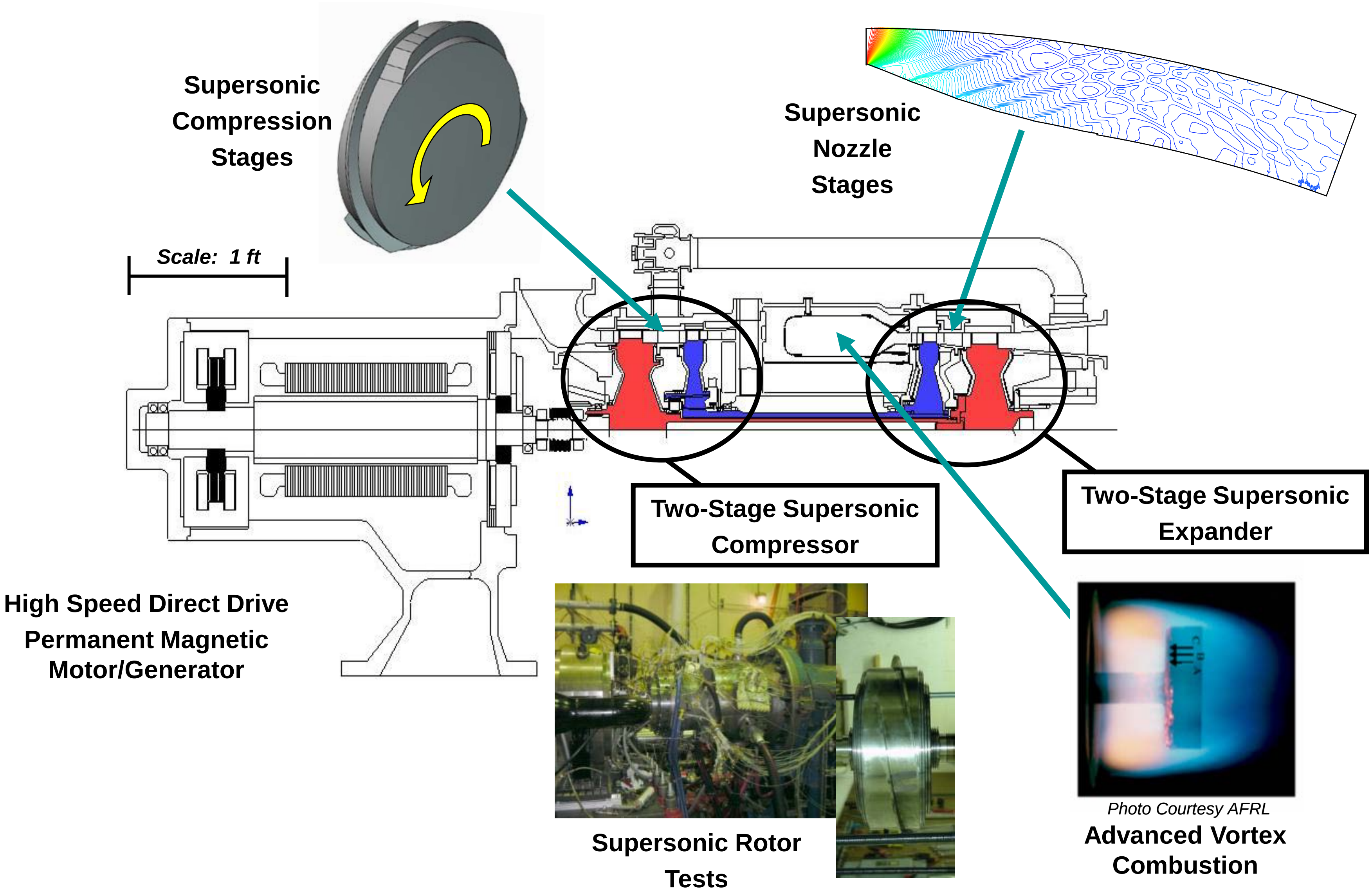


- **Pr 10+:1 per stage**
- **1/10th the physical size**
- **40-50% of the installed capital cost**
- **~Same shaft input power requirements**
- **Recover of ~80% of the input Btu at 500°F**
  - Improve CCS efficiency
  - Reduce power plant de-rate

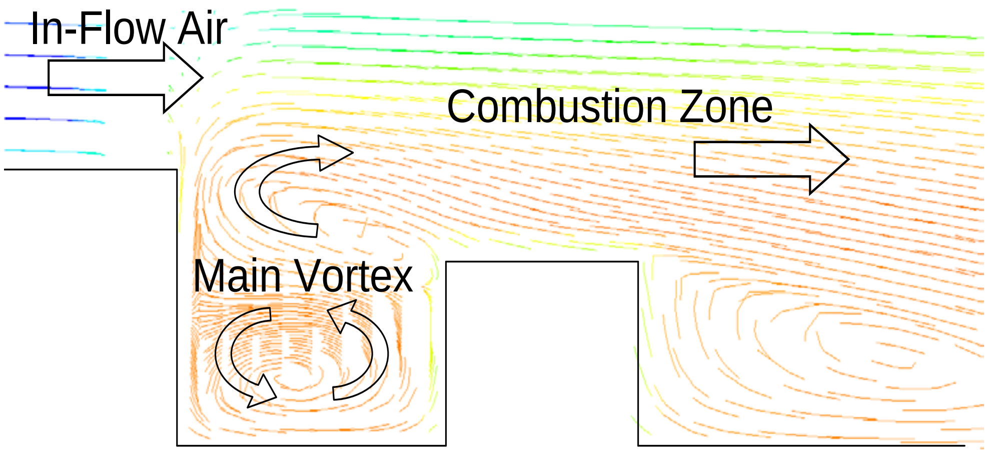
Ramgen Technology Fundamentals

ISC Engine

ISC Engine Technologies

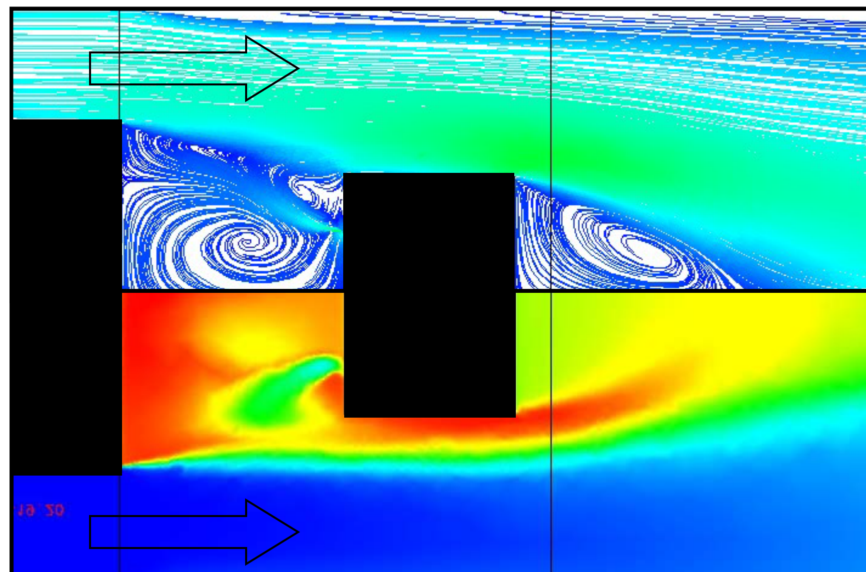


Advanced Vortex Combustion (AVC)



Conceptual Rendering

Flame is Independent of Main Airflow Velocity



- **Geometric features control fluid mechanics**
- **Vortex shielded inside cavity providing excellent flame stability**

Ramgen ISC Engine

Improves Distributed Generation efficiency

- High net electric efficiency
- 80% cogeneration efficiency
- ~1:1 heat:power ratio

Extracts power from Opportunity Fuels

- Ventilation Air Methane
- Landfill gas
- Eliminates methane emissions
- Improves mine safety
- Compelling return on investment

Enable intermittent renewable resource as a Fuel-fired Flywheel

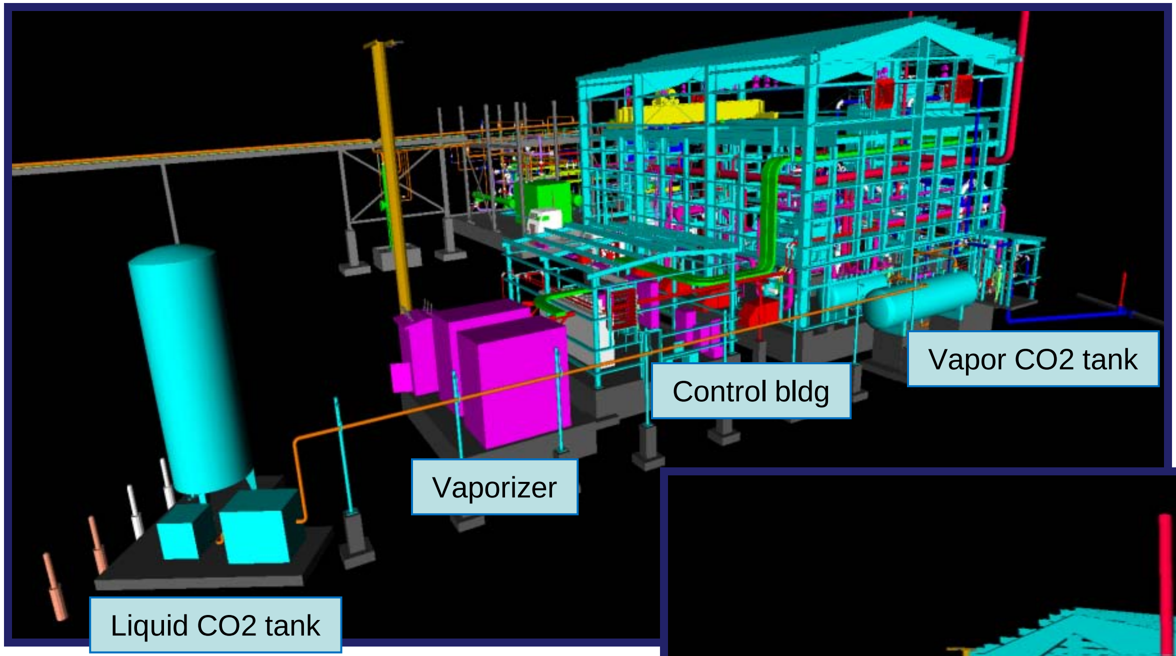
- "Instant-on" capability supports intermittent/unpredictable renewable resources
- Supports a variety of dual use applications

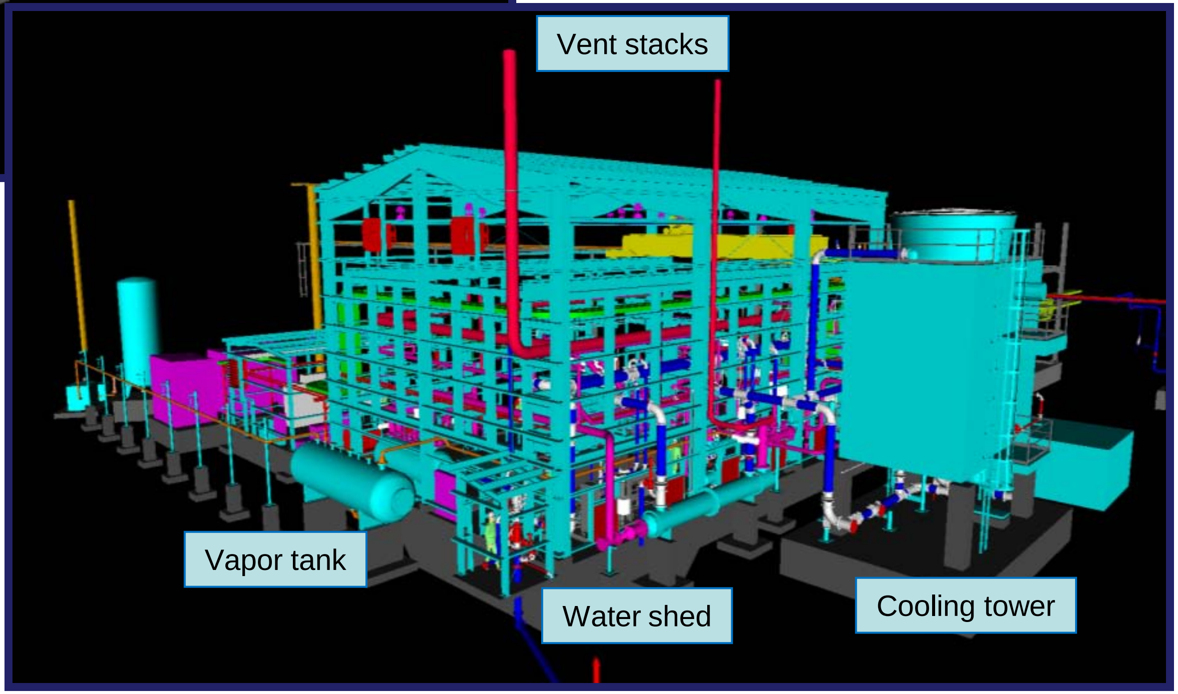
Project Status

Project Schedule – CO2 Compressor

- **10 MW Test Facility Complete - *Fall 2011***
- **Full Speed Test Rotor Runs Complete - *Winter/Spring 2012***
  - 10 MW VFD, Motor, Gearbox, Couplings and Bearing Systems validated
- **Compressor "Inner Bundle" Assembly currently underway**
- **Build 1 compressor test scheduled to begin - *September 2012***
- **Build 1 compressor test completion - *December 2012***
- **Build 2 compressor design currently underway**
  - Oakridge National Laboratory Supercomputer utilized for CFD optimization studies
  - 18 hour / 200,000 core CFD simulation recently completed in which 800 flowpath configurations were modeled
  - This capability has a tremendous impact on the rate of technology development we are able to achieve
- **Build 2 test - *Spring/Summer 2013***

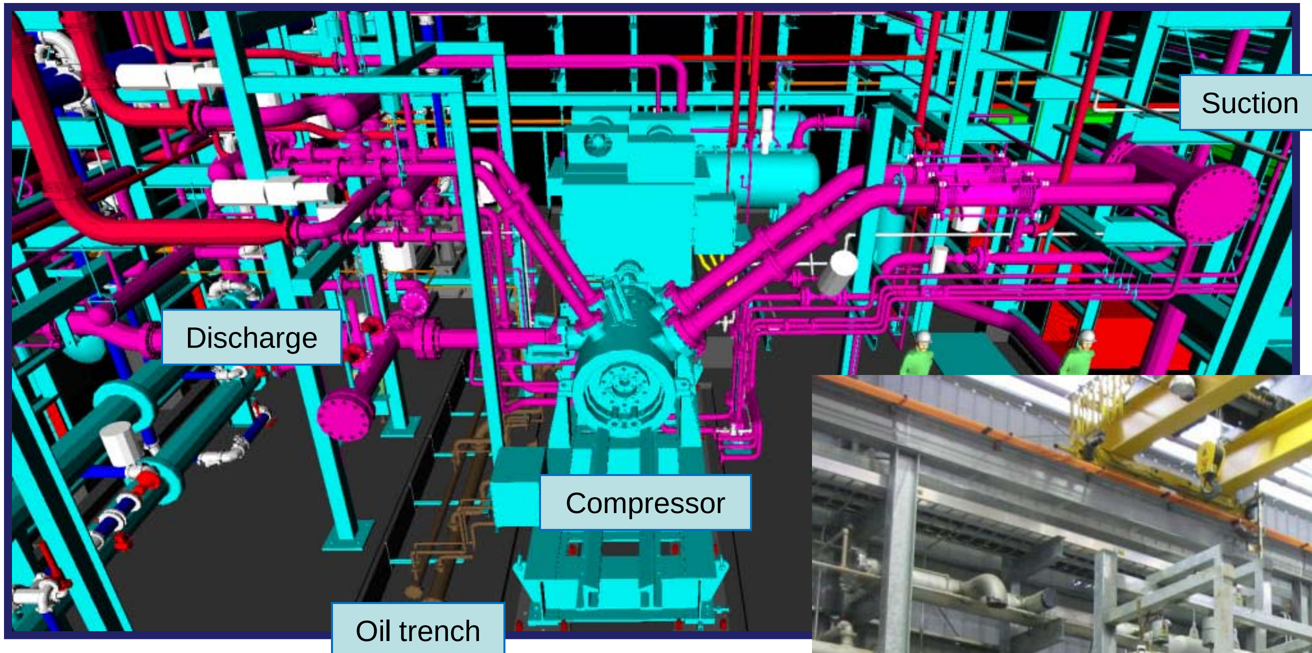
High Pressure CO2 Compressor Facility





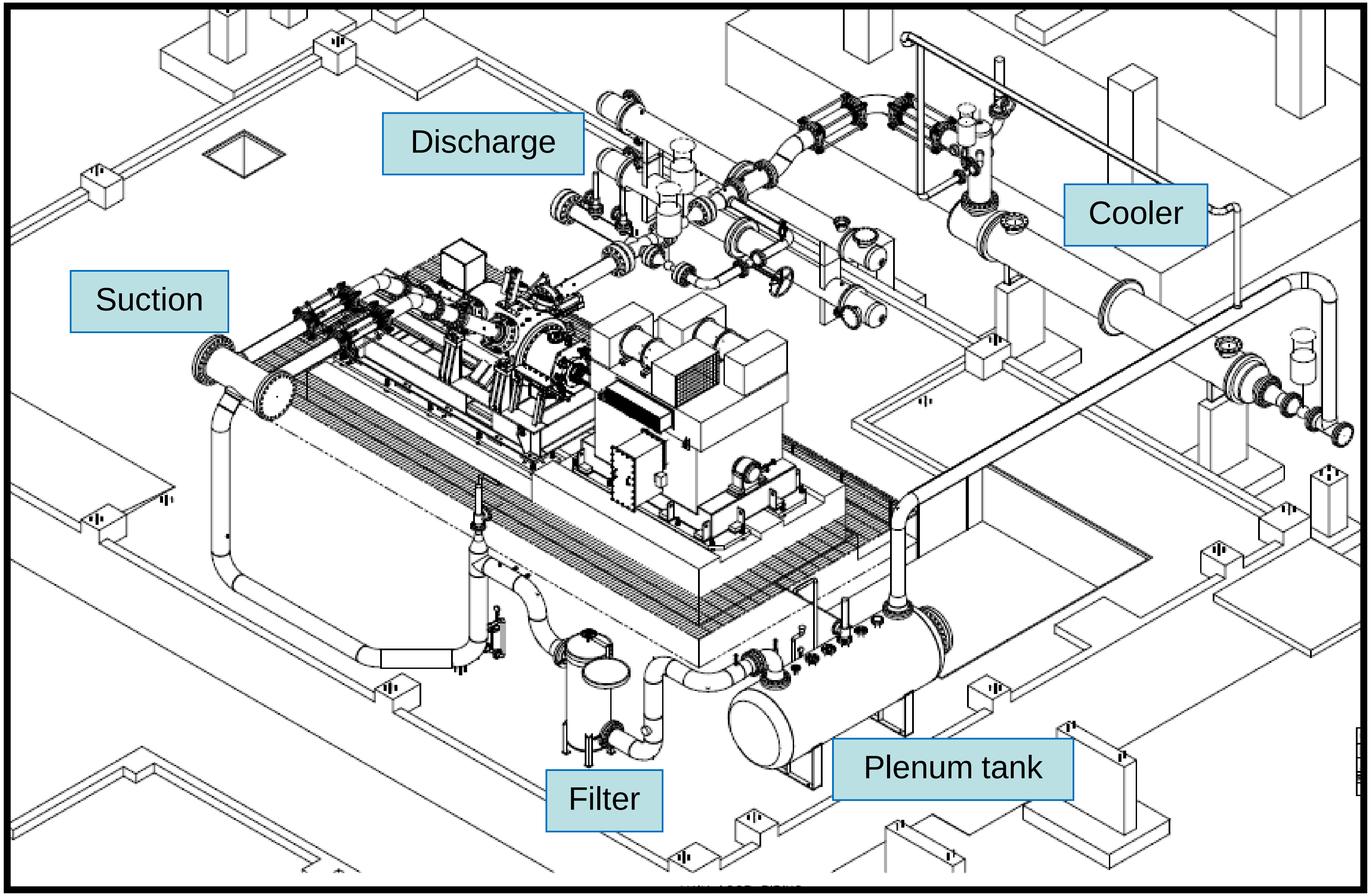
High Pressure CO2 Compressor Facility

10MW HP CO_2 Compressor Test Stand

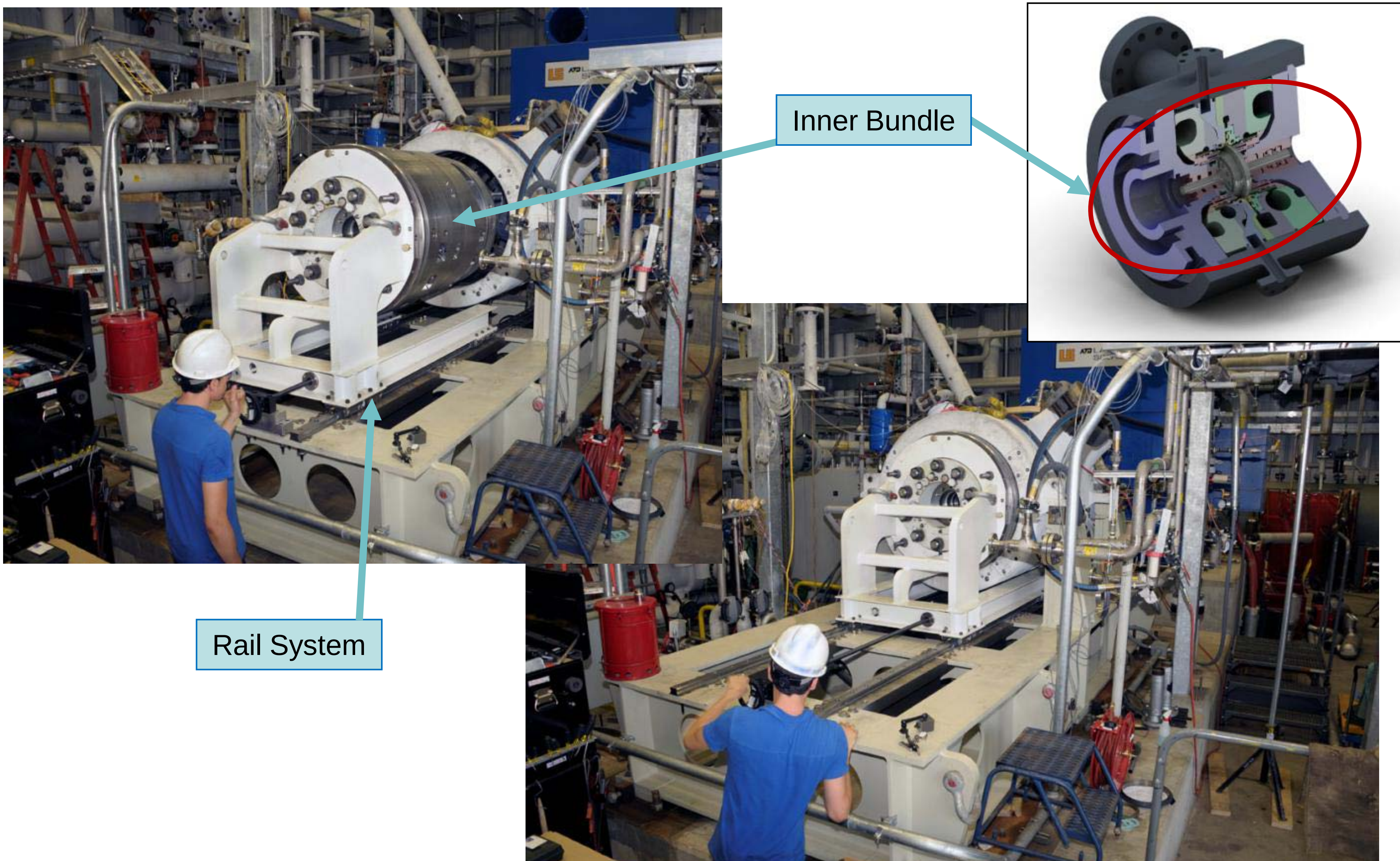


– Dresser-Rand Facility, Olean, NY
– 10MW Electric Variable Speed Drive
– Closed loop CO2
– P1 = 210 psia
– P2 = 2100 psia

High Pressure CO_2 Compressor Facility

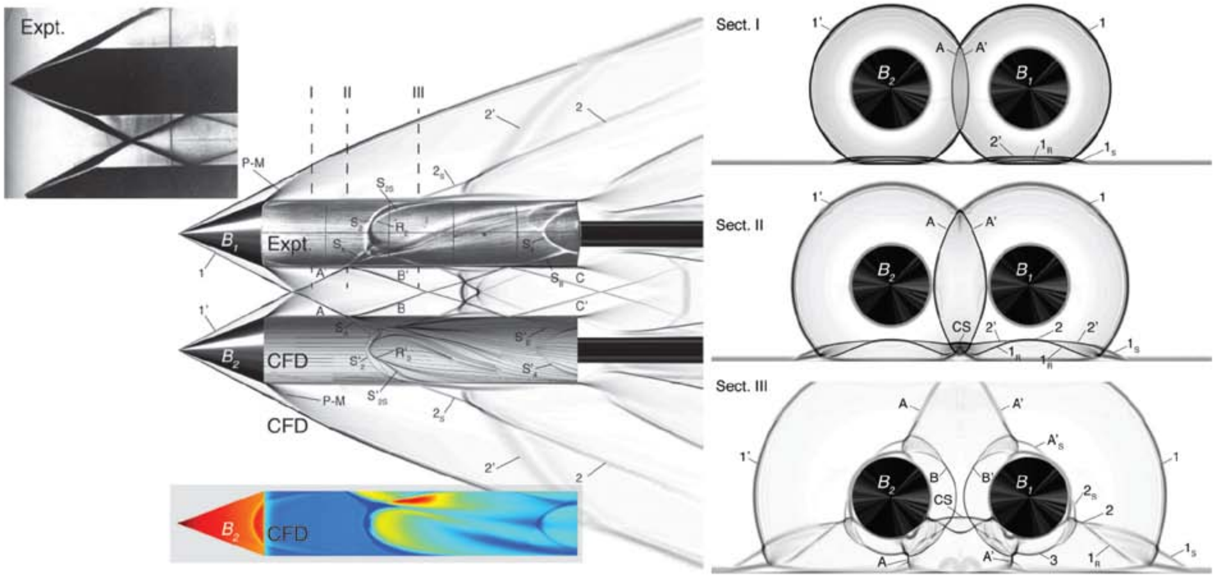


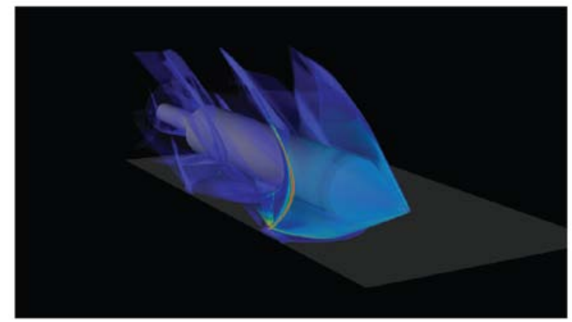
Test Insertion of Inner Bundle Assembly

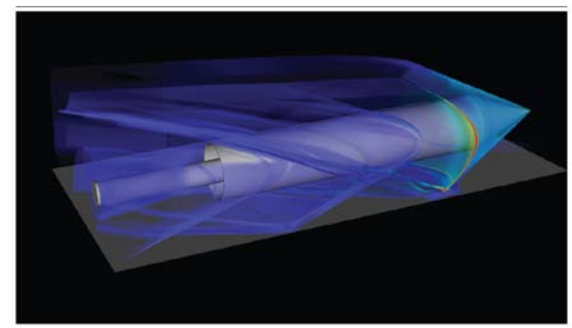


CFD Development at Oak Ridge National Labs

Aero CFD Tool development has benefitted greatly from utilizing the Oak Ridge National Laboratory Jaguar Supercomputer to optimize Ramgen designs. Models of Shock Wave Structures and Interactions Anchored to Experimental Test Cases to Validate Codes.







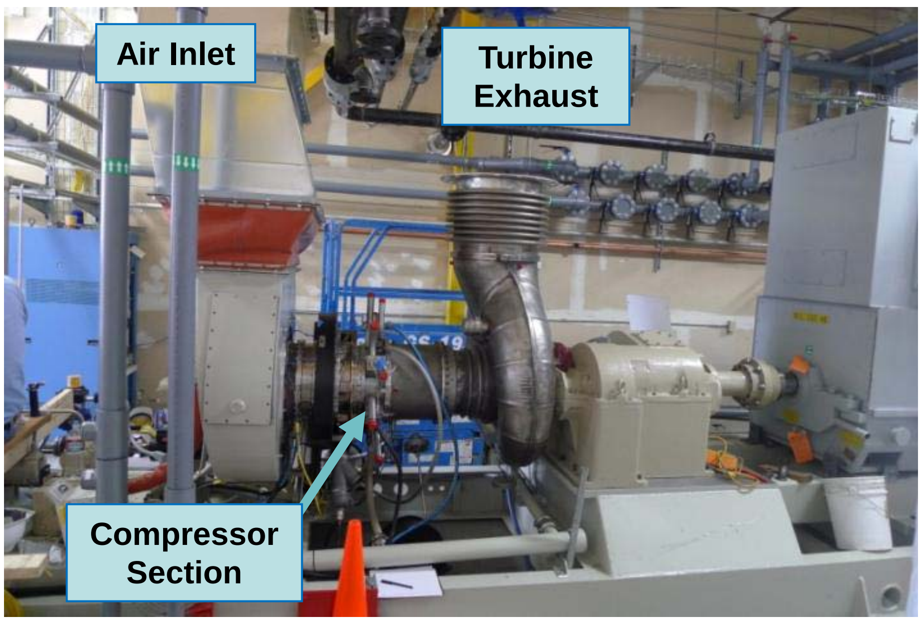
Ramgen recently executed a 200,000 core simulation employing intelligently driven optimization algorithms to analyze 800 compressor configurations in 18 hours.

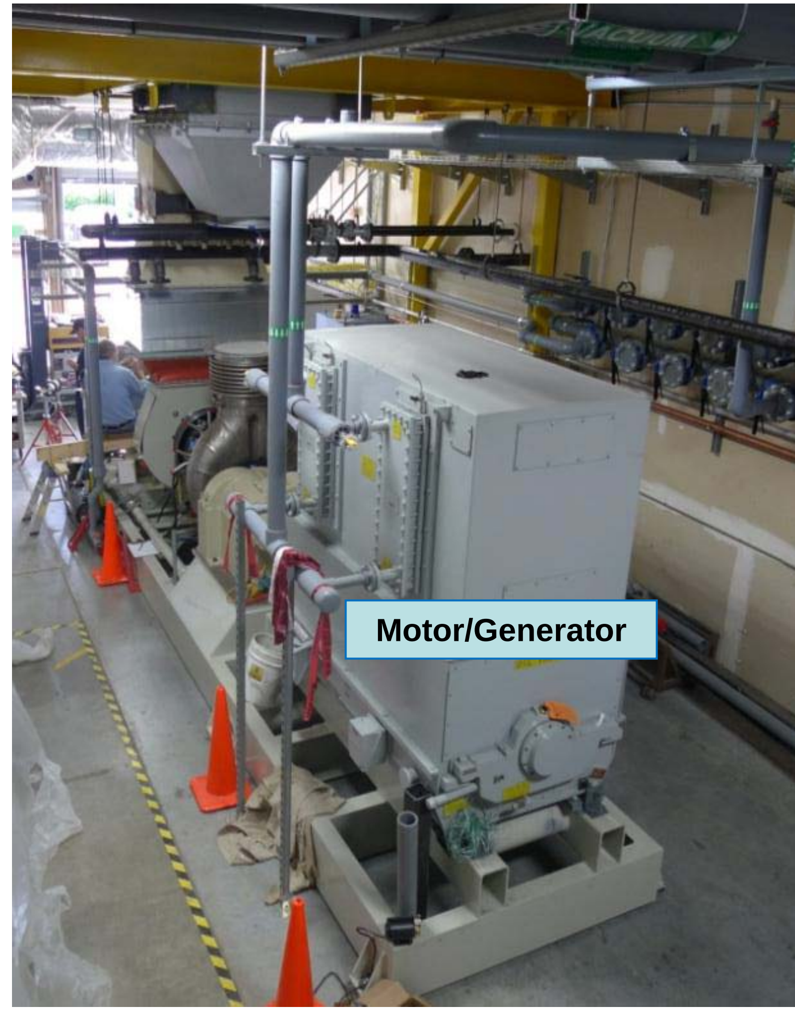
Project Milestone – ISC Engine

- **Build 1 - 1.5MW engine design complete (Ramgen compressor retrofit to existing gas turbine engine) – *September 2011***
- **Build 1 - 1.5MW engine assembly – *May 2012***
- **Build 1 facility installation complete – *July 2012***
- **Build 1 engine test start - *August 2012***
- **Build 2 design start (1.5MW compressor/combustor/turbine) - *January 2012***
- **Build 2 design complete – *January 2013***
- **Build 2 testing start - *April 2013***

ISC Engine Build 1 Installation

1.5MW Build 1 ISC engine installation currently underway in Ramgen's newly upgraded Redmond, WA test facility





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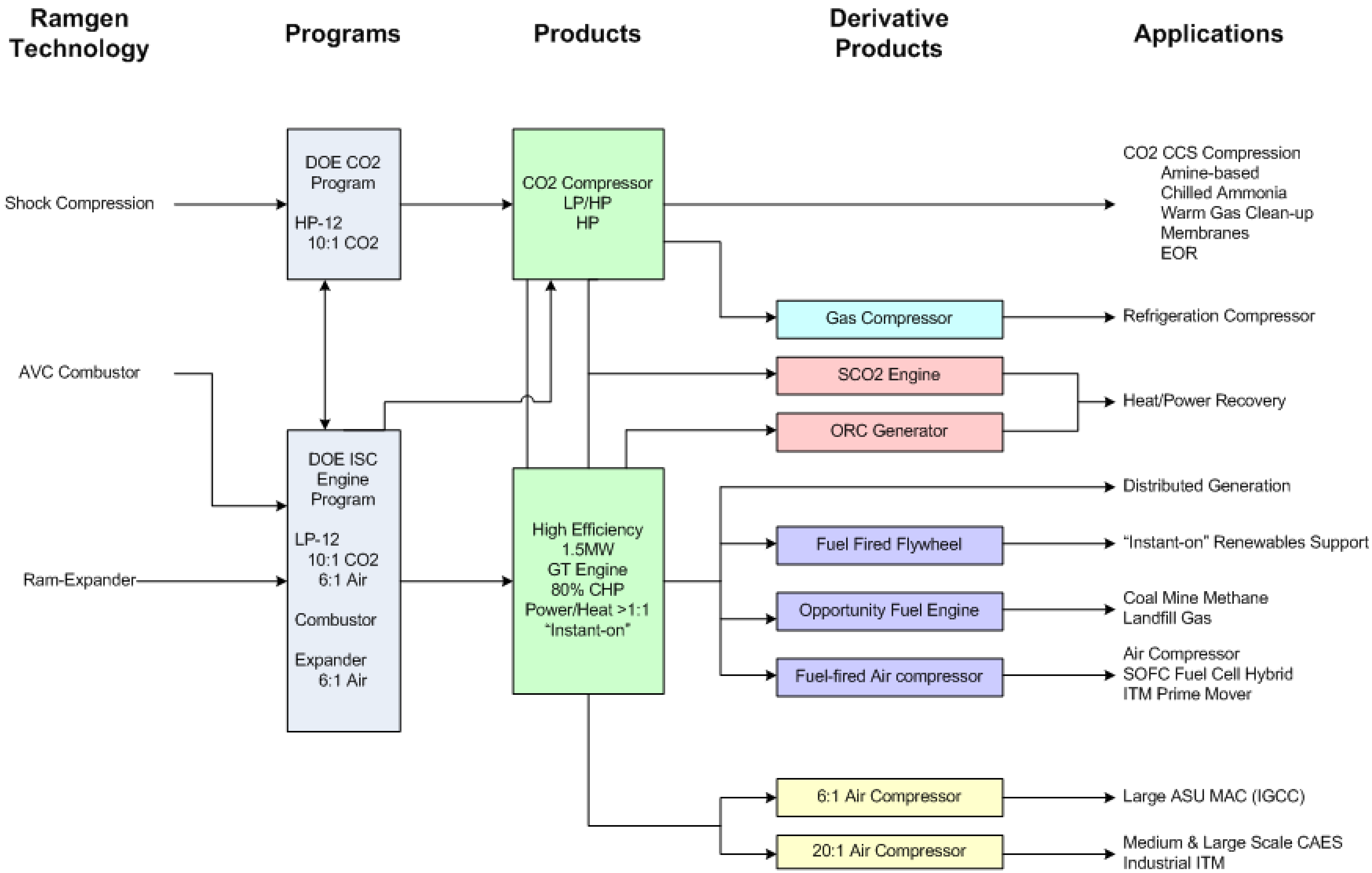
Future Testing and Commercialization

Technology Development Roadmap



Acknowledgements

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