Ramgen Supersonic Shock Wave Compression Technology

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

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Aaron Koopman
Ramen Power Systems

Company Background

- **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**
  - High Pressure ratio, high efficiency CO_2 Compressor
  - High Efficiency ISC Engine

US Army Corps of Engineers

Project Overview

Objectives and Funding

- **Overall CCS Project Objectives:**
  - Compressor Project: Development and demonstration of analysis tools to design high-efficiency, low-cost CO2 compression using supersonic shock wave technology to significantly reduce capital and operating costs associated with carbon capture and storage

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

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

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

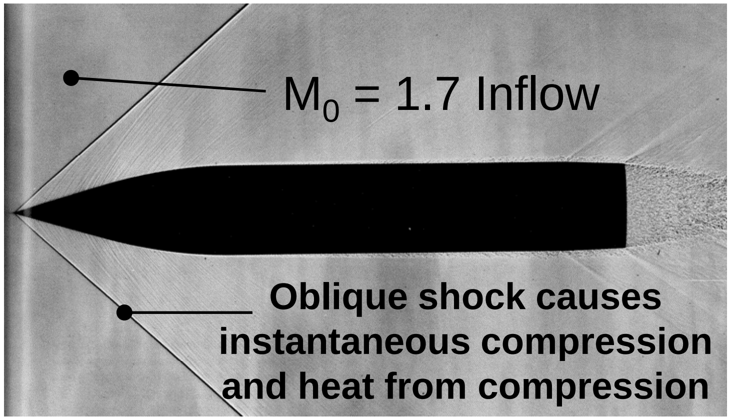
Dresser-Rand Investment in Ramgen

- **Dresser-Rand invests in Ramgen's "game-changing technology"**
  - Support on-going CO2 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**

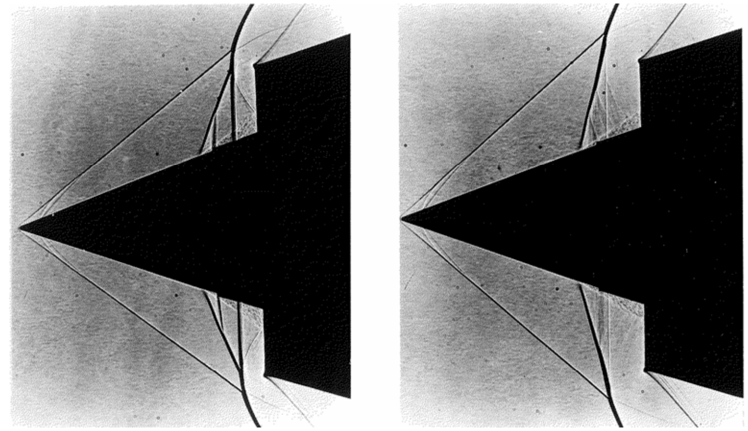
Ramgen Technology Fundamentals

Compressor

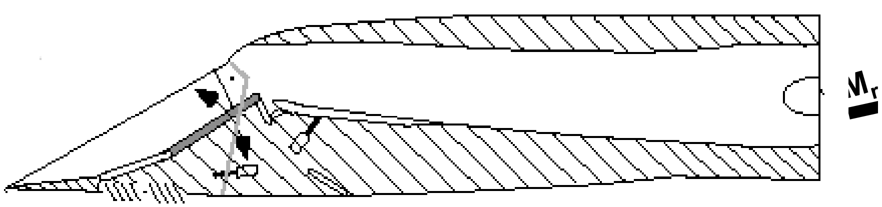
Shock Waves to Supersonic Inlets



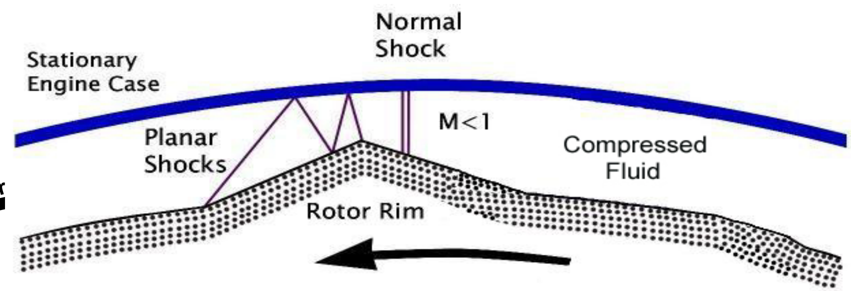
Schlieren Photo of Projectile with Shocks



Schlieren Photo of Inlet Center-body and Cowl with Shocks

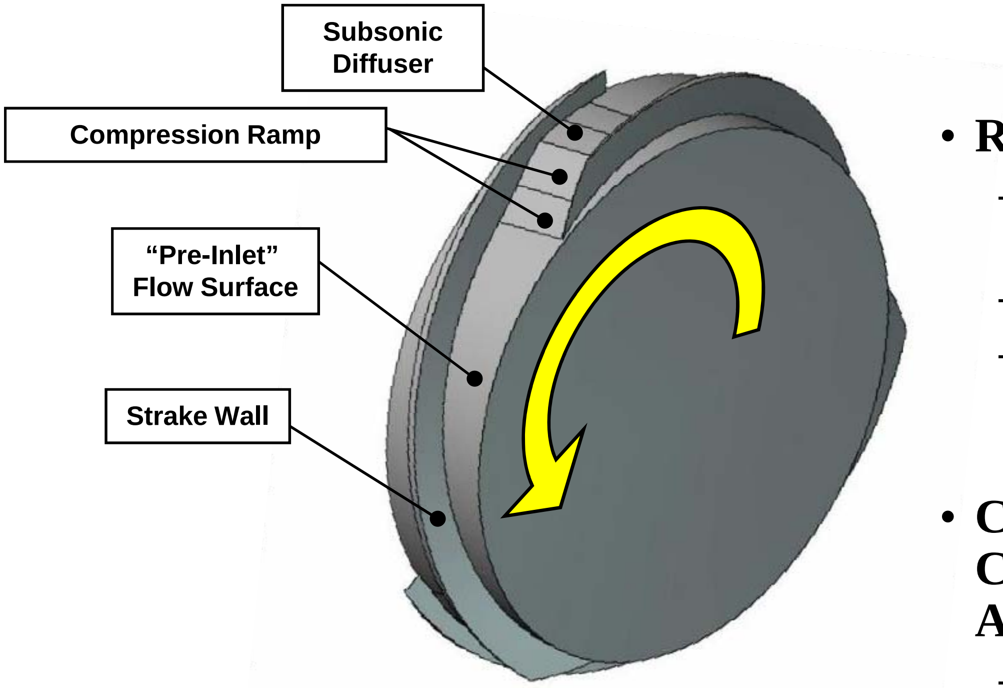


Supersonic F-15 Inlet



Rampressor Rotor

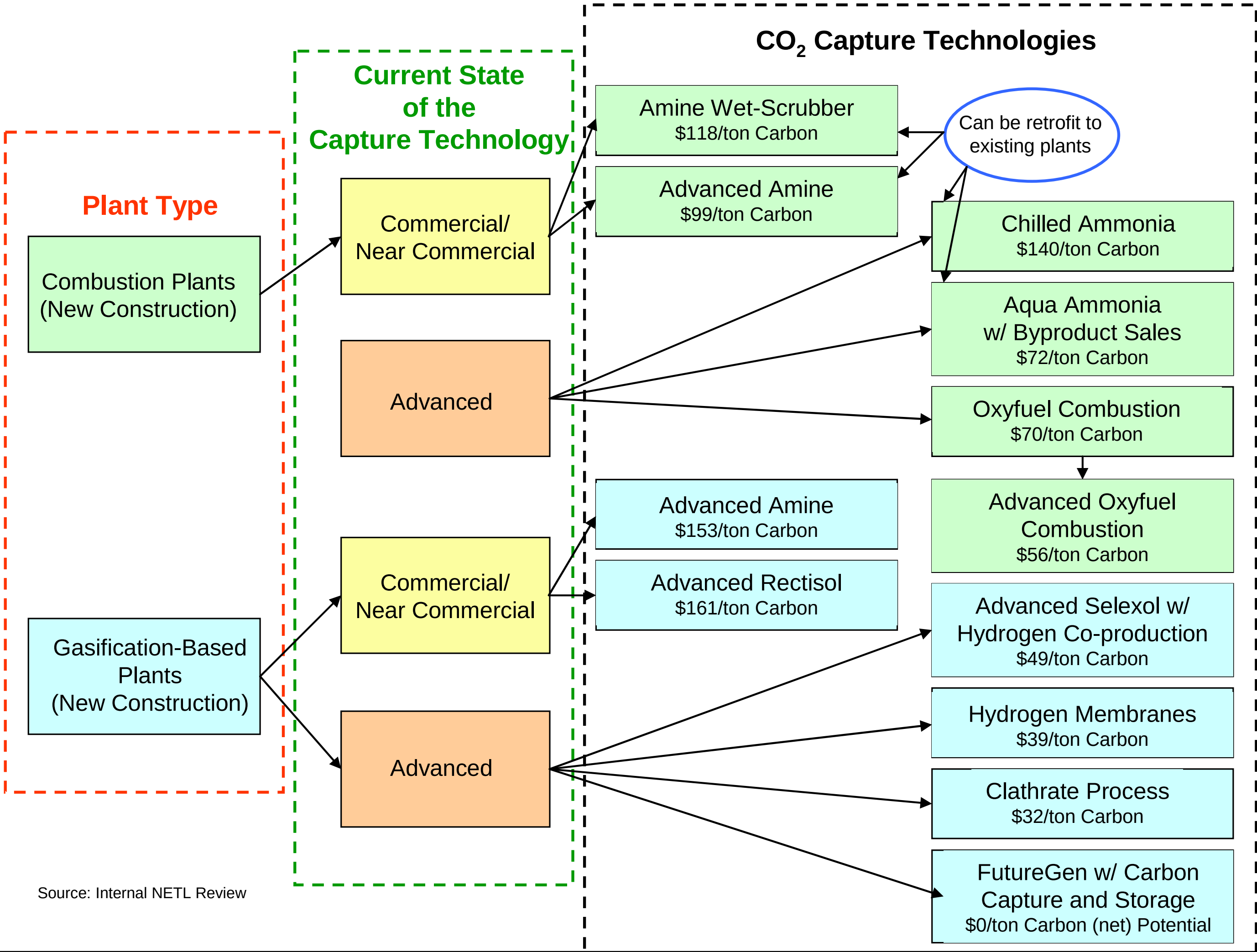
Typical Rotating Supersonic Flow Path



- **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

Capture Technology Drives Operating Conditions



Source: Internal NETL Review

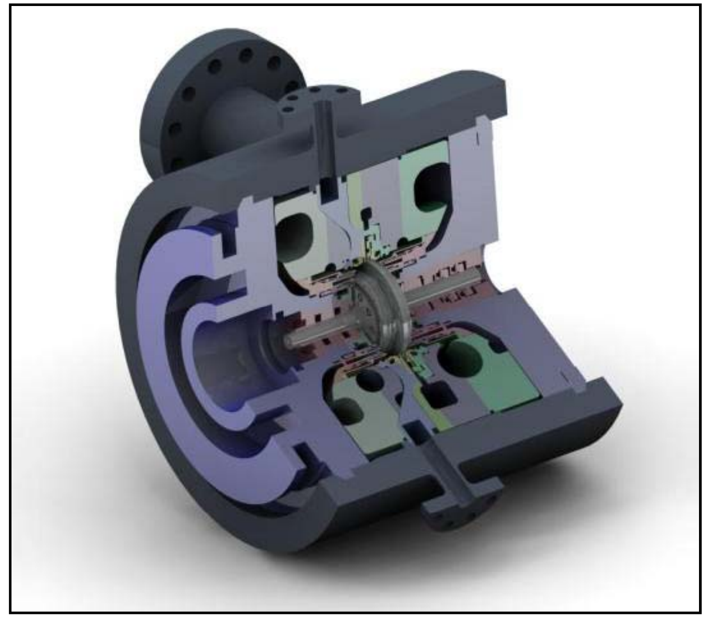
Ramgen technology works with all capture technologies and can provide heat to regenerate solvents/delivery media

Program Targets and Benefits

MAN Turbo CO_2 Compressor

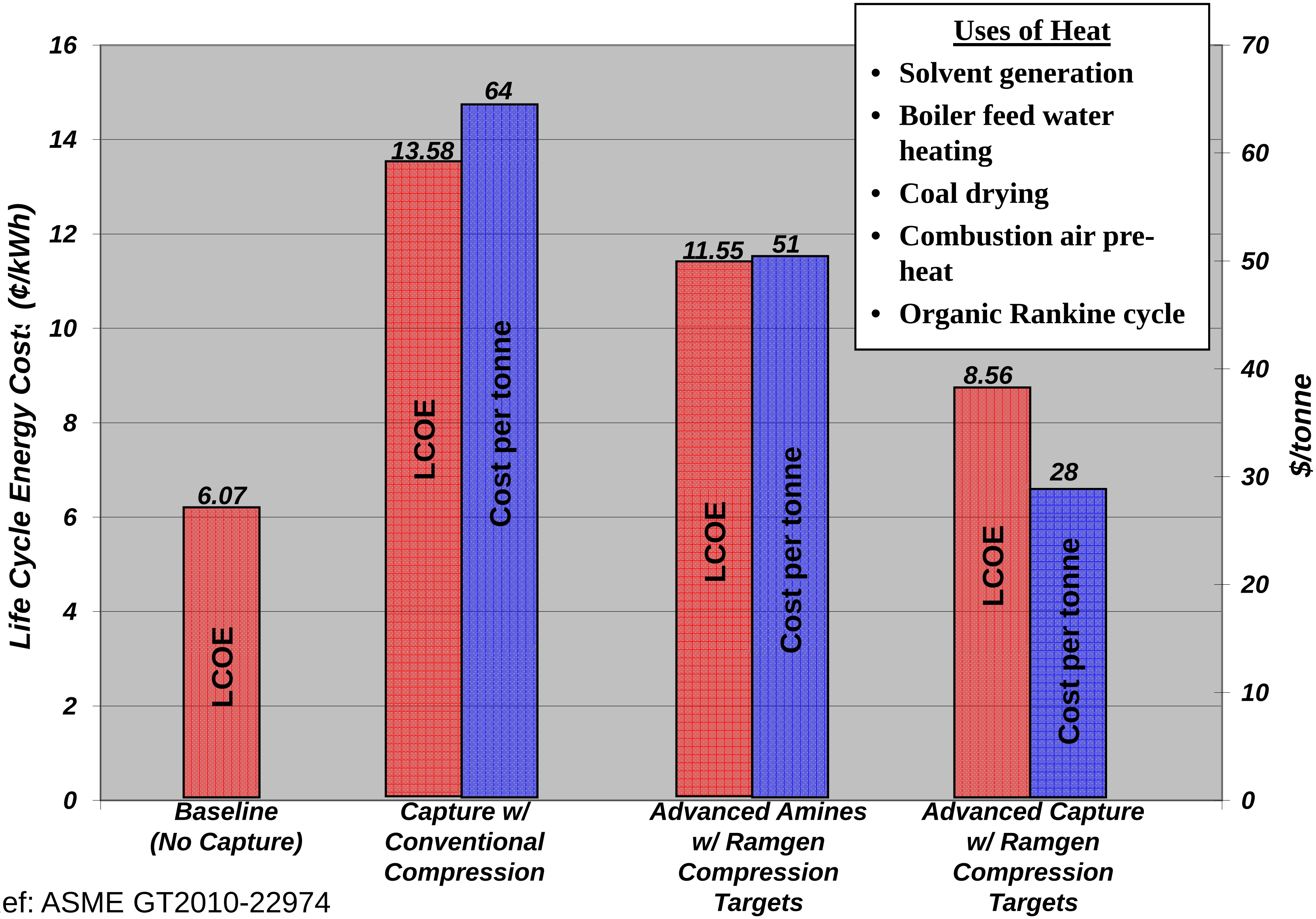
- **10-stage 6000 hp**
  - $8.0 million ⇨$1350/hp
  - Pr 200:1 ⇨1.70 per stage
- **8-stage 20,000 hp**
  - $15.0 million ⇨$750/hp
  - $23.0 million installed⇨$1150/hp
  - Pr 143:1 ⇨1.86 per stage

Ramgen CO_2 Compressor Targets



- **Pr 10+:1 per stage; intercooled**
- **Smaller 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

LCOE with Advanced Capture and Compression



Ref: ASME GT2010-22974

Technical and Economic Challenges

- **Technical challenges – Demonstrating targets**
  - **Test Rig –** new 10MW closed loop CO_2 systems, components, controls, motor, gearbox, VFD
  - **Pressure Ratio/Efficiency –** not proven until demonstrated in test
  - **Maintainability –** mean time between replacement
  - **Turndown** – key operational consideration efficient operation over changing inlet and outlet plant conditions
- **Economic challenges – Realizing reduced LCOE**
  - **Capital Cost –** lowest costs will involve the integrated design of capture and compression
  - **Capture heat of compression** – Each plant has unique opportunities for uses of heat. The system must be integrated into the plant cycle.

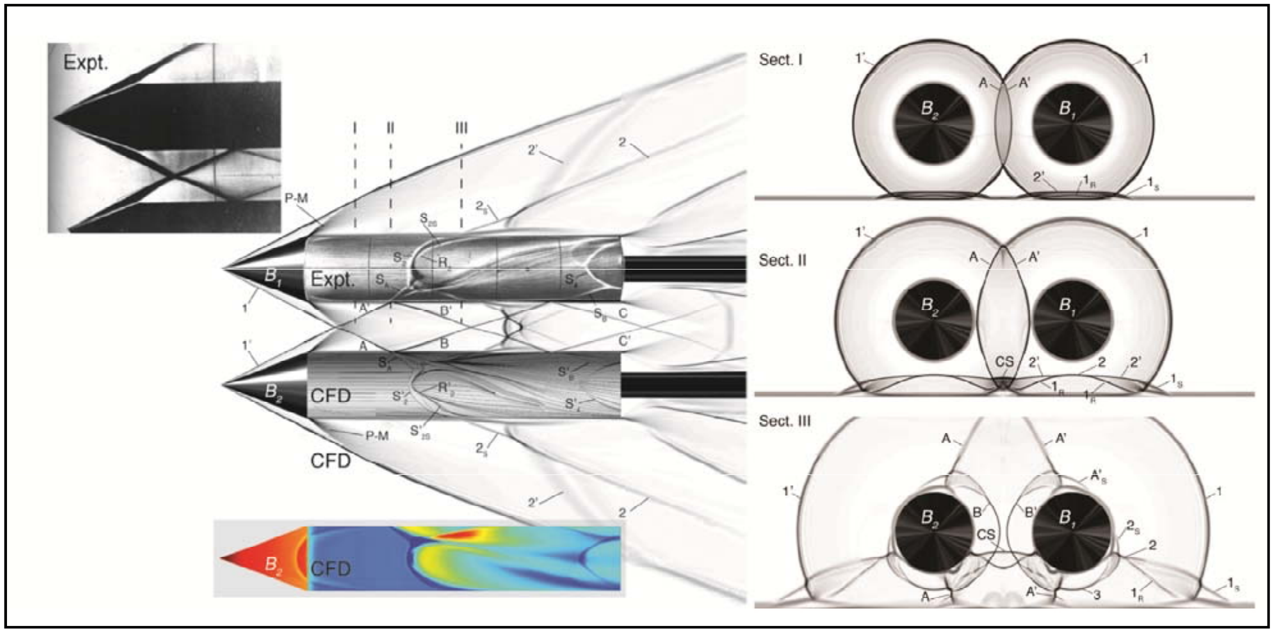
Project Status

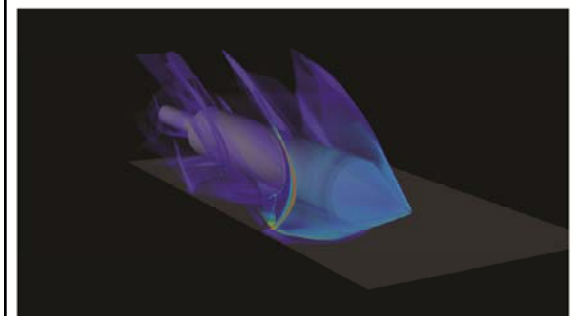
Project Schedule – CO_2 Compressor

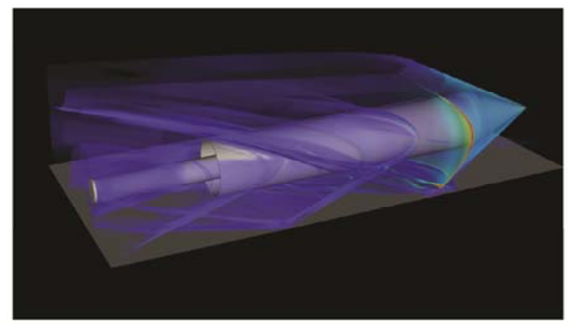
- **10 MW Test Facility Complete - *Fall 2011***
- **Full Speed Test Rotor Runs Complete - *Winter/Spring 2012***
  - 10 MW VFD, Motor, Gearbox, Couplings and Bearing Systems validated
- **Build 1 compressor testing - *September 2012 and continuing***
  - Demonstrated 7.7:1 pressure ratio and supercritical CO_2 in a single stage
- **Build 1 compressor test completion - *July 2013***
- **Build 2 compressor design underway – *September 2013***
  - Oakridge National Laboratory Supercomputer utilized for CFD optimization studies
  - Flowpath configuration identified
  - Static hardware in design development
- **Build 2 test – *Q1 2014***

CFD Development at Oak Ridge National Labs

- Shockwave rotor development greatly accelerated by the ORNL Supercomputers



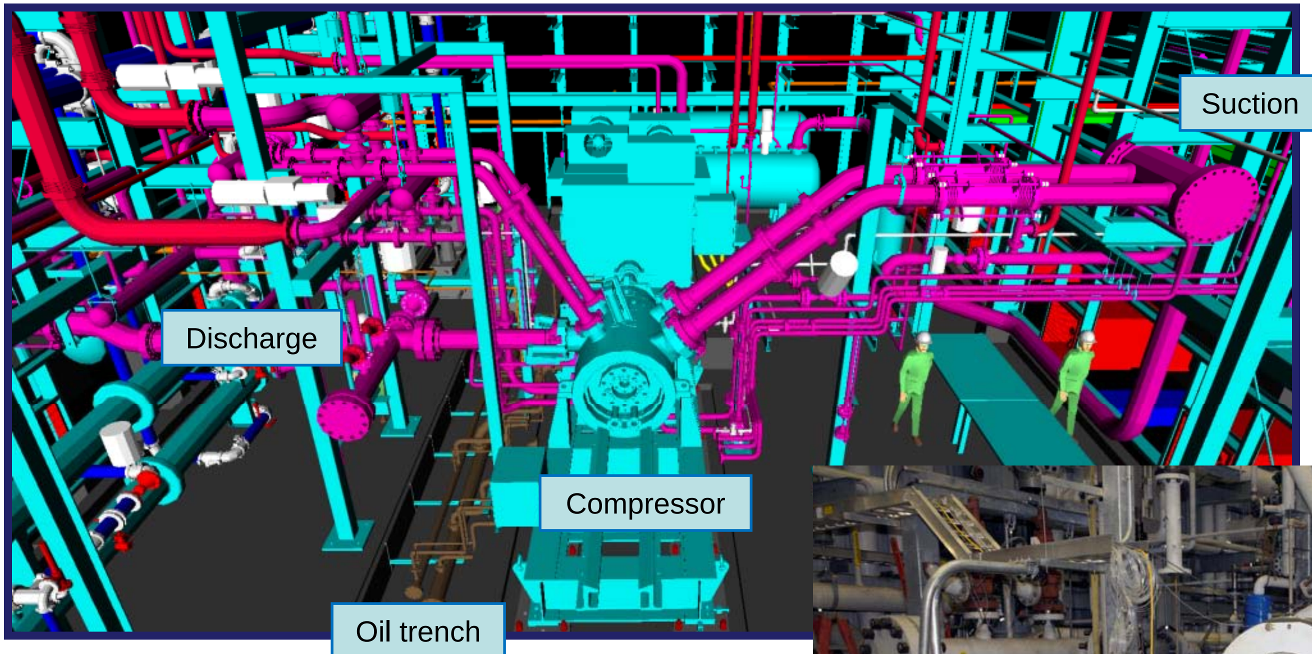




- Ramgen executed 200,000 core run to analyze 800 configurations in 18 hours

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

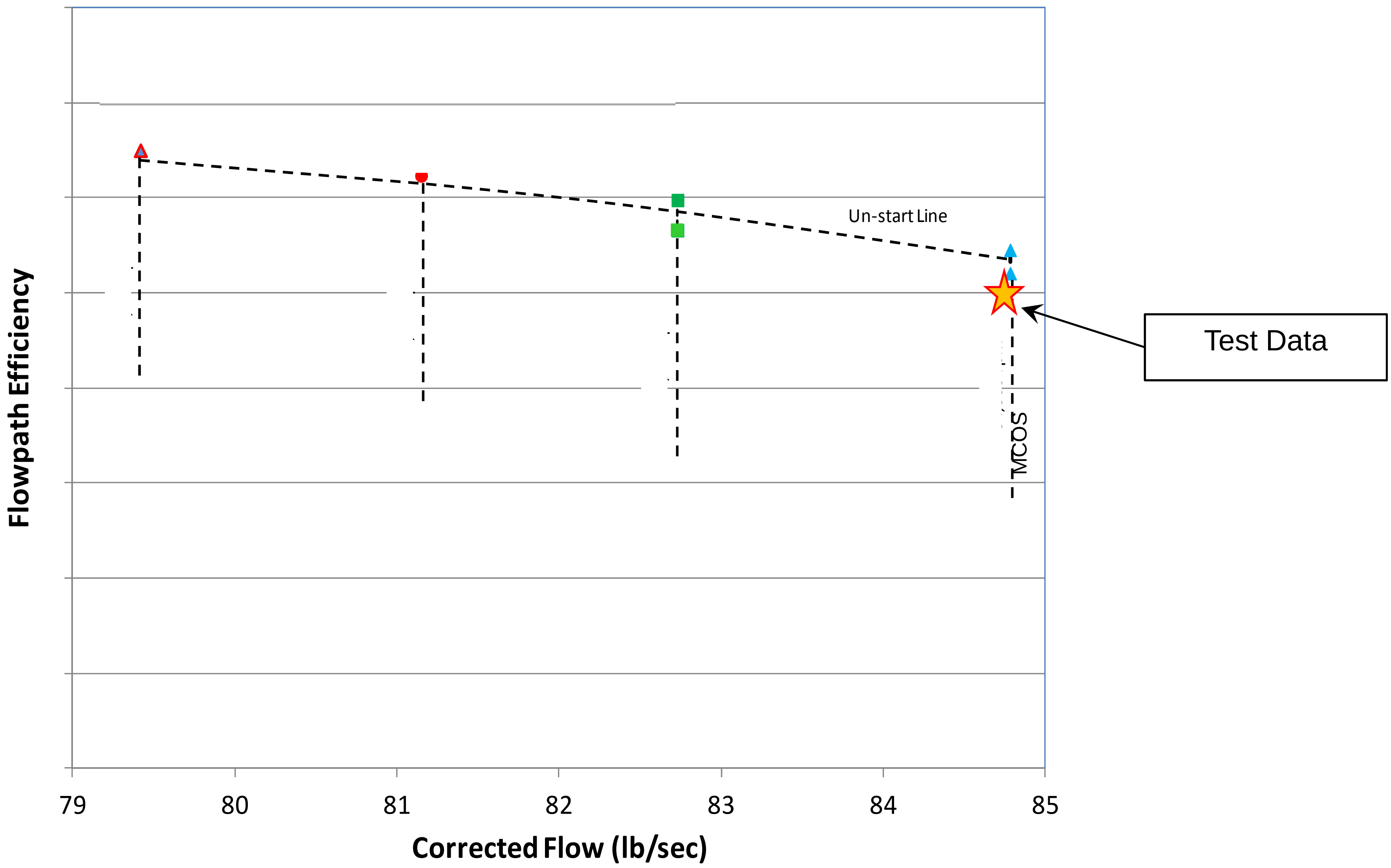
HP CO2 Build 1 Comparison of CFD and Test

	CFD Prediction 210 psia suction	Test Data 6/27/13 135 psia suction
Suction Corrected Mass Flowrate (lb/sec)	84.8	82.5
Bleed Flow-rate (factor from target)	1.0	1.8
Pressure Ratio	8.37	7.74
Discharge Temperature (factor from target)	1.0	.997

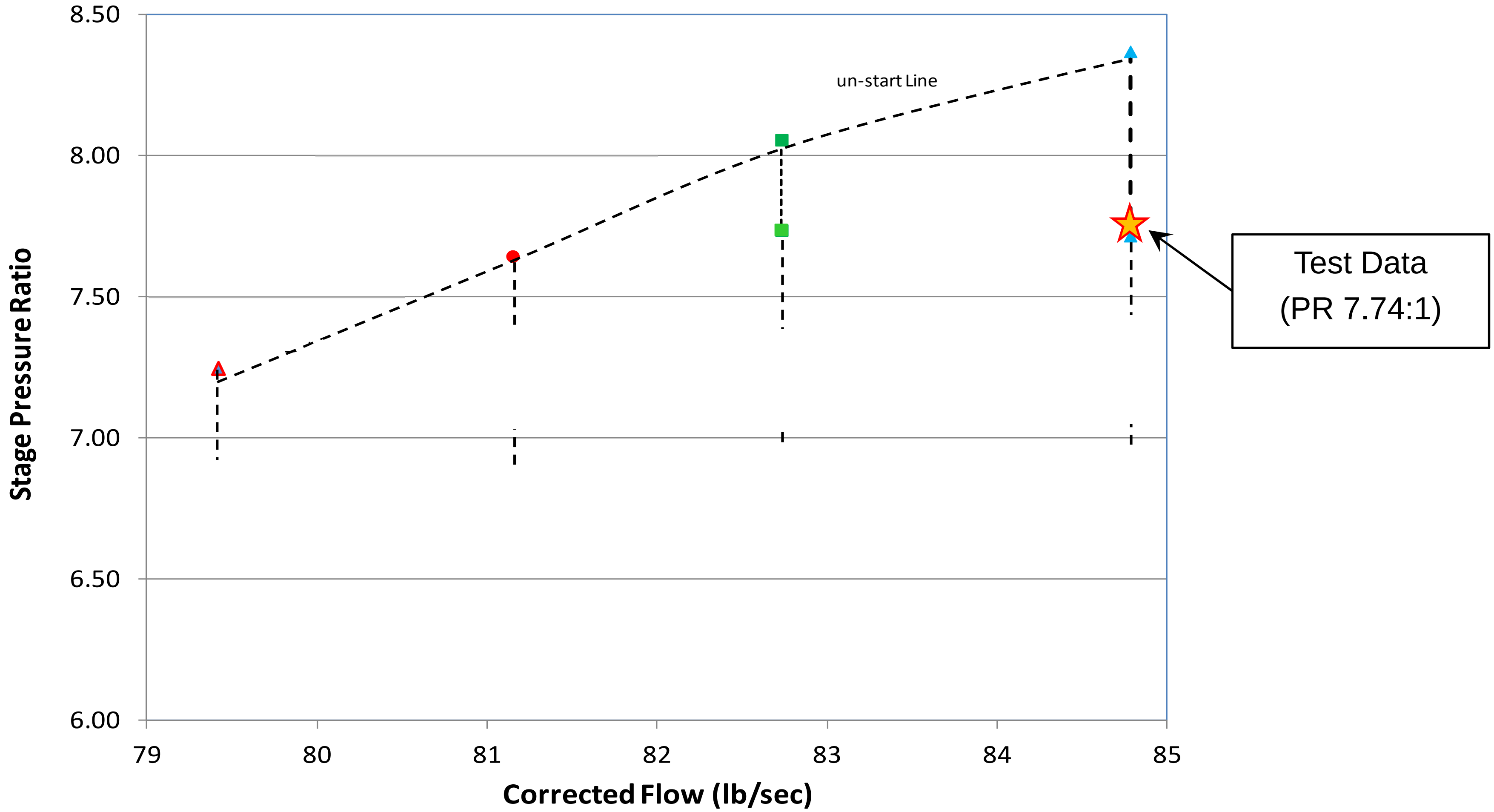
Test data thus far is showing very good agreement with pre-test predictions.

Additional testing and mechanical configuration changes are expected to improve matching even further.

CFD/Test Comparison of Efficiency



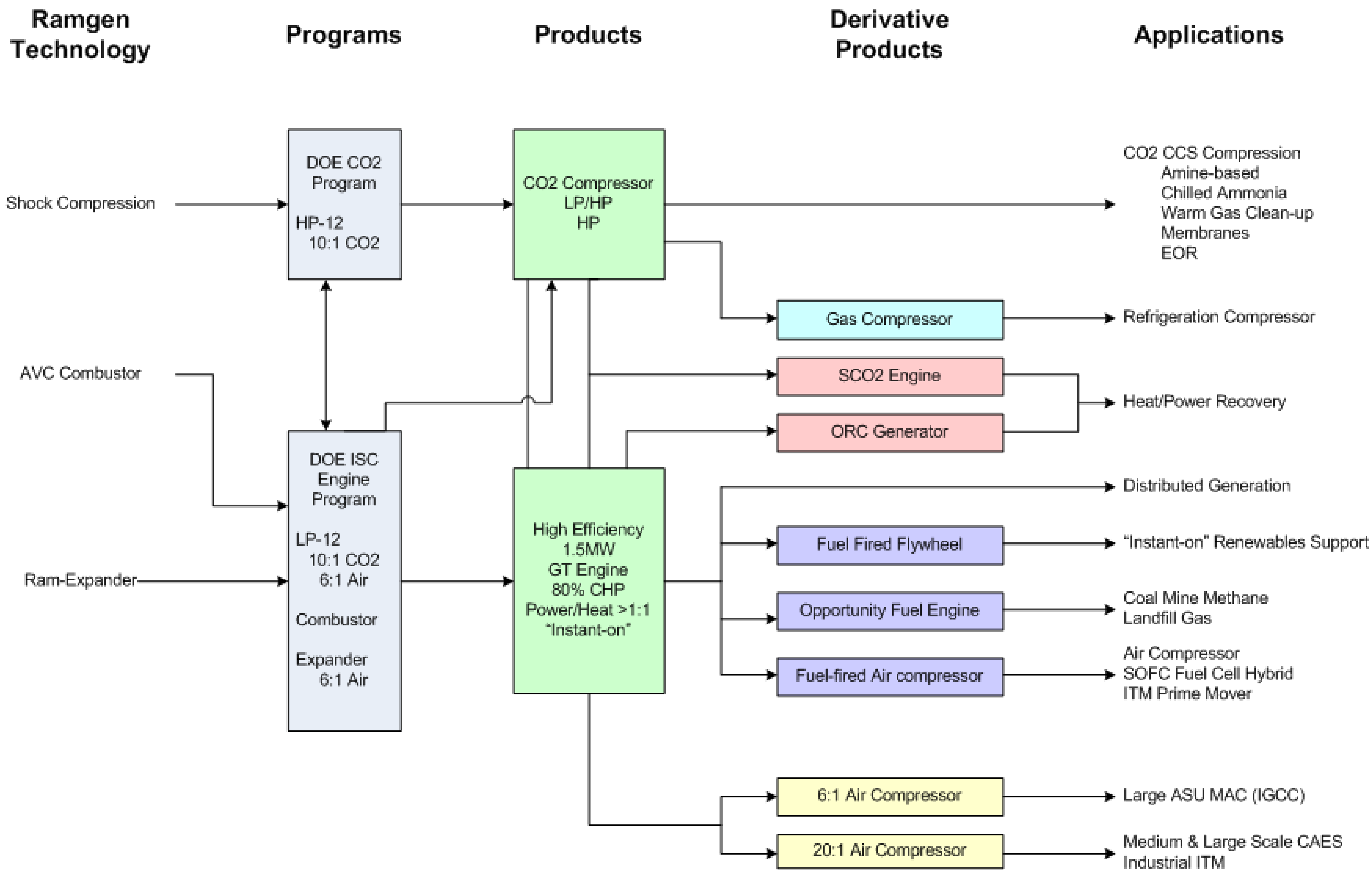
CFD/Test Comparison of Pressure Ratio



- **Measured pressure ratio is 7.74 versus prediction of 8.37**

Future Testing and Commercialization

Technology Development Roadmap



contacts:

Aaron Koopman
aaron.koopman@ramgen.com
(425) 828-4919 ext 235

Pete Baldwin
pete.baldwin@ramgen.com
(425)-736-7272 (c)
www.ramgen.com