CO_2 Compression Using Supersonic Shock Wave Technology

Project NT42651

March 26, 2009

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Ramgen Power Systems

Forward Looking Statement

Some of the information contained in this document contains “forward-looking statements”. In many cases you can identify forward-looking statements by terminology such as “may,” “will,” “should,” “expects,” “plans,” “anticipates,” “estimates,” “predicts,” “potential,” or “continue,” or the negative of such terms and other comparable terminology. Forward-looking statements are only predictions and as such inherently include risks and uncertainties. Actual events or results may differ materially as a result of risks facing Ramgen Power Systems, LLC (“Ramgen”) or actual results differing from the assumptions underlying such statements. These forward-looking statements are made only as of the date of this presentation, and Ramgen undertakes no obligation to update or revise the forward-looking statements, whether as a result of new information, future events or otherwise. Your decision to remain and receive the information about to be presented to you shall constitute your unconditional acceptance to the foregoing.

The Company – Brief Background

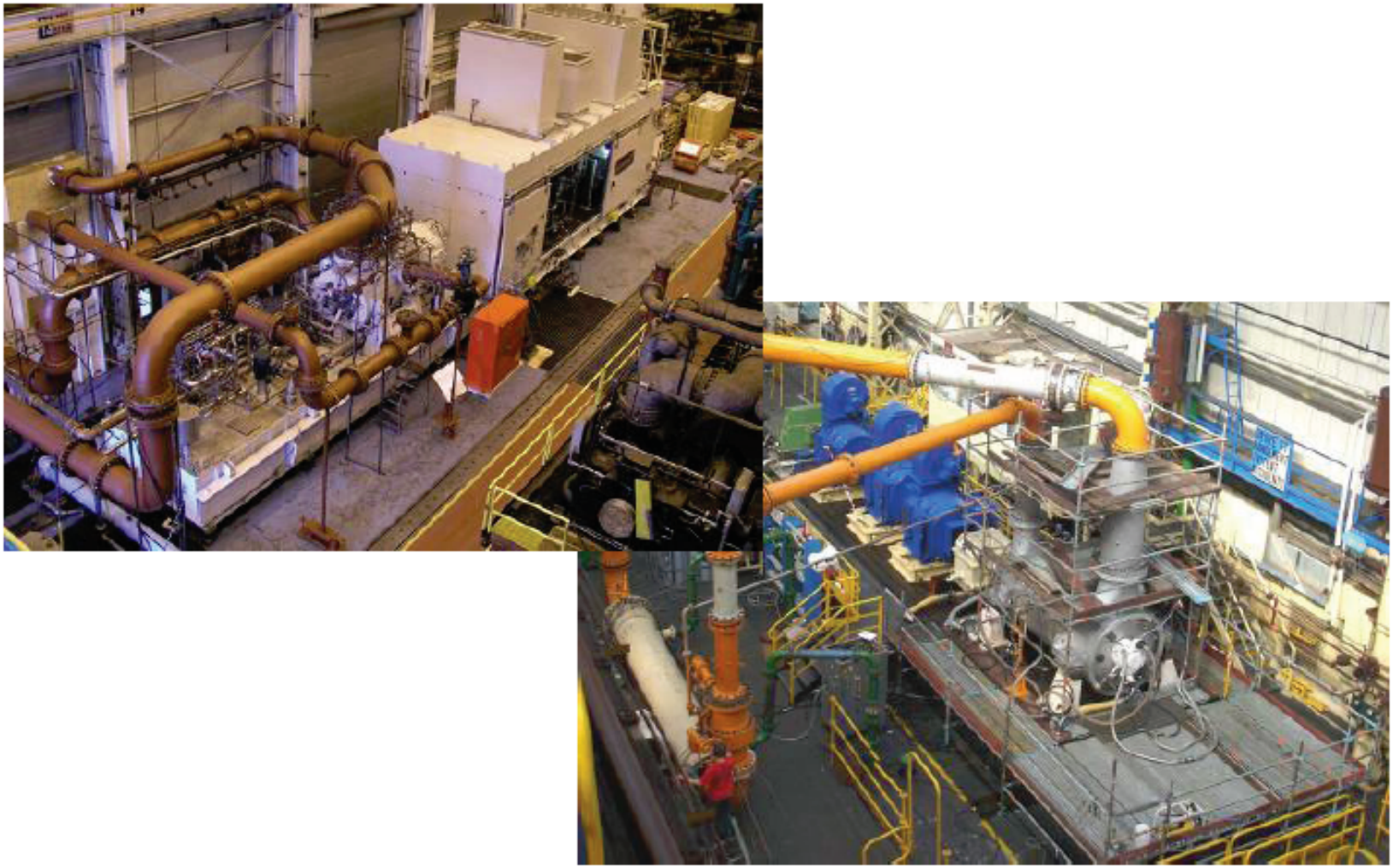
- Privately held since 1993, headquartered in Bellevue, WA
- Development and test of supersonic turbo-components for process gas and power generation applications
- 1998-present, $30 M in private funds and $25.0 M in DOE, DOD and CEC PIER support
- 2008-Dresser-Rand investment of up to $49M to commercialize supersonic compression technology
- Novel technology permits high pressure ratios and efficiencies
- Recent DOE Funded tests validate capability of compression stage
- 26 full-time employees
  - Ingersoll-Rand, CAT/Solar, P&W, Boeing, Honeywell, Rocketdyne
  - 3 PhD & 9 MS Degreed Engineers

Project Overview

- **Funding (DOE and Cost Share)**
  - **Total Funding – Current Contract $16,109,211 (DE-FC26-06NT42651)**
  - **DOE – $9,494,456**
  - **Ramgen – $6,614,665**
- **Overall Project Performance Dates**
  - **May 10, 2006 – January 9, 2011**
- **Project Participants**
  - **DOE**
  - **Ramgen**
    - **Dresser-Rand – Integrated demonstration tests**
    - **Naval Post Graduate School Turbo Machinery Laboratory – static component testing**
    - **Consulting engineering organizations**
- **Overall Project Objectives (SOPO)**
  - **Incorporate lessons learned from previous Ramgen shock compression test programs and recommendations from industry partner Dresser-Rand to define and execute improvements in development plan for large scale demonstration of novel CO_2 compression technology**

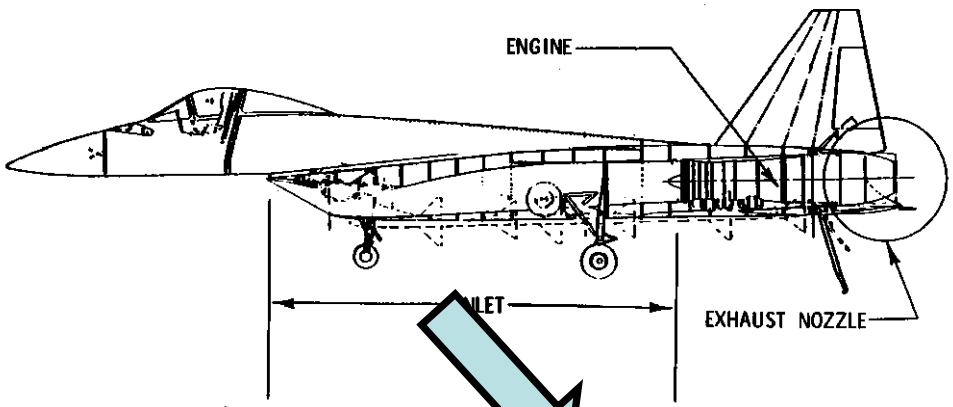
World Class Test Facilities

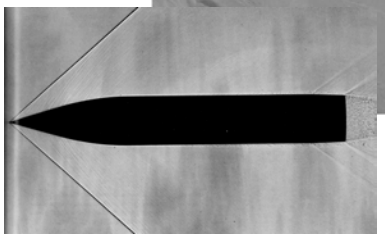
RAMGEN POWER SYSTEMS™

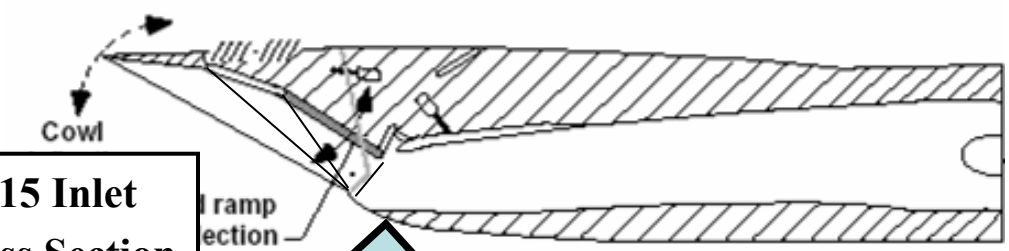


DRESSER-RAND

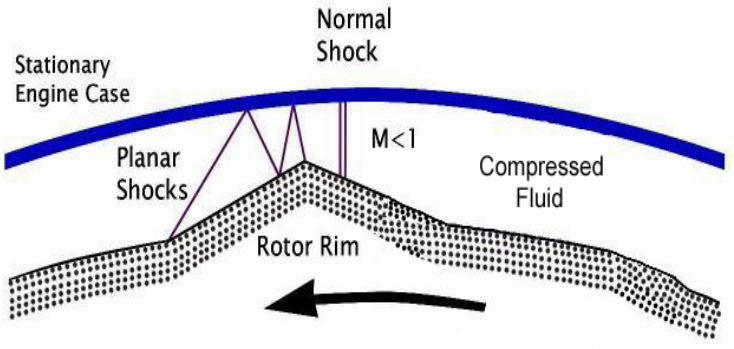
Technology Fundamentals/Background





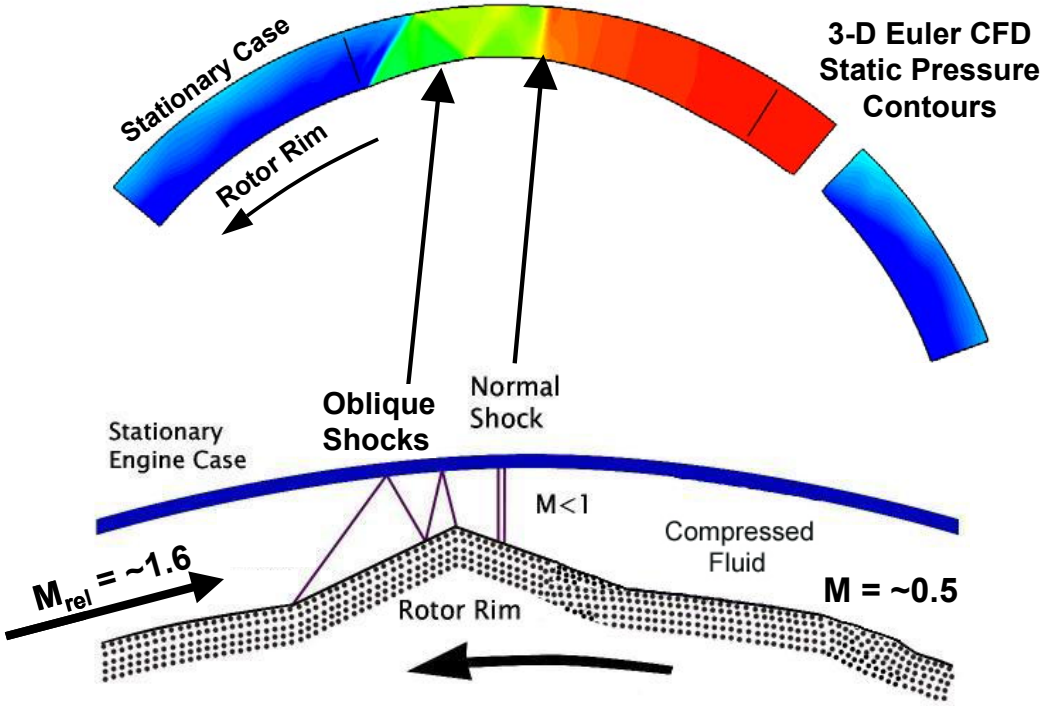


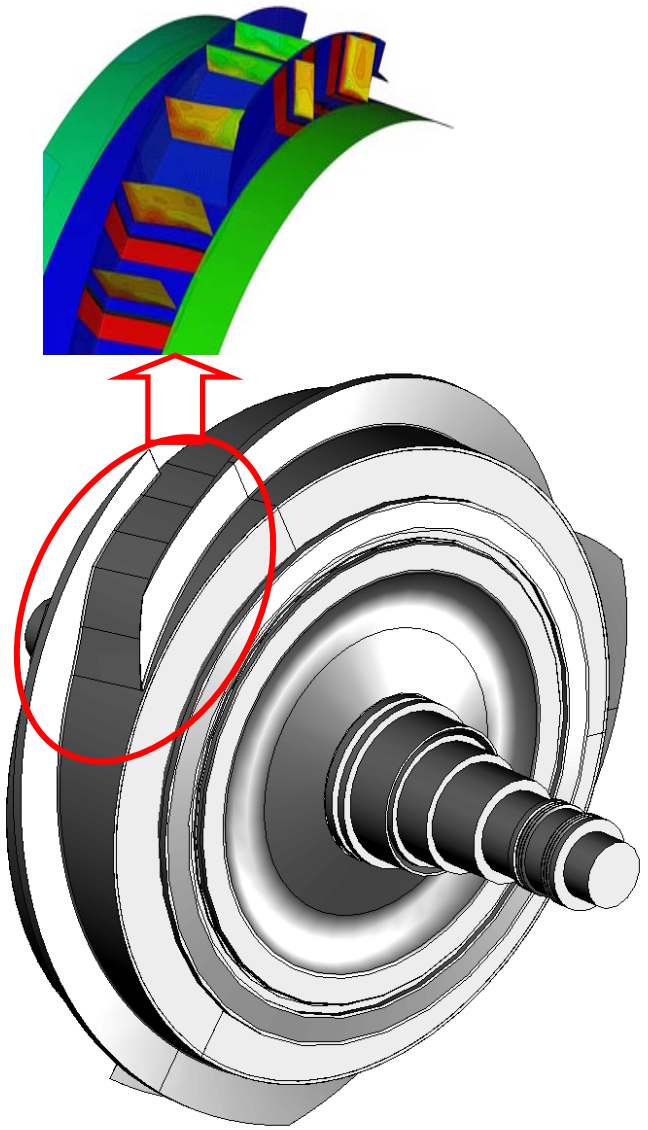
F-15 Inlet Cross Section



Rampressor Rotor

Rampressor 3-D Geometry & Flowfield





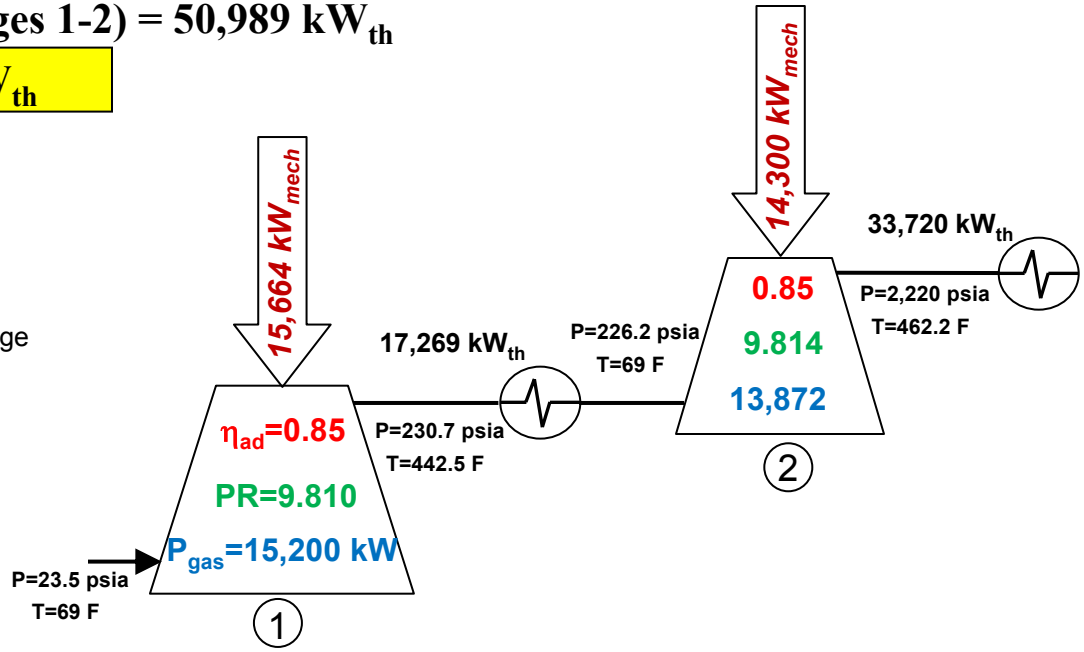
- Compressive flowpaths integrated onto rim of rotor at shallow helix angle
- Strakes form sidewalls for shock compression ducts & separate high pressure discharge from low pressure suction

Ramgen 2-Stage Process – Discrete Drive

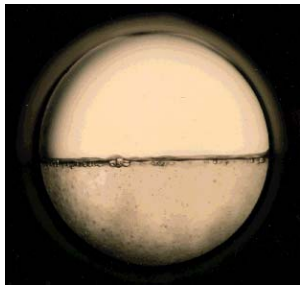
- **Shaft power (stages 1-2)**
  - **Gas-path power = 29,072 kW_{mech}**
  - **Total shaft power = 29,964 kW_{mech}**
- **Heat of compression**
  - **Total rejected into coolers (stages 1-2) = 50,989 kW_{th}**
  - **Total recoverable[1] = 28,986 kW_{th}**

Notes:

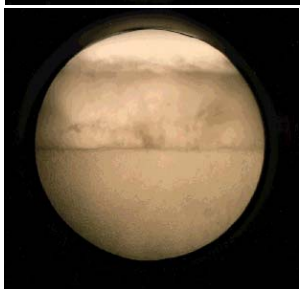
1) 60ºF Cooling Water / 9ºF Approach / 69ºF Interstage
2) Recovery to 200ºF



PT Diagram & Supercritical Phase



Separate Phases Visible- Meniscus Clearly Observed

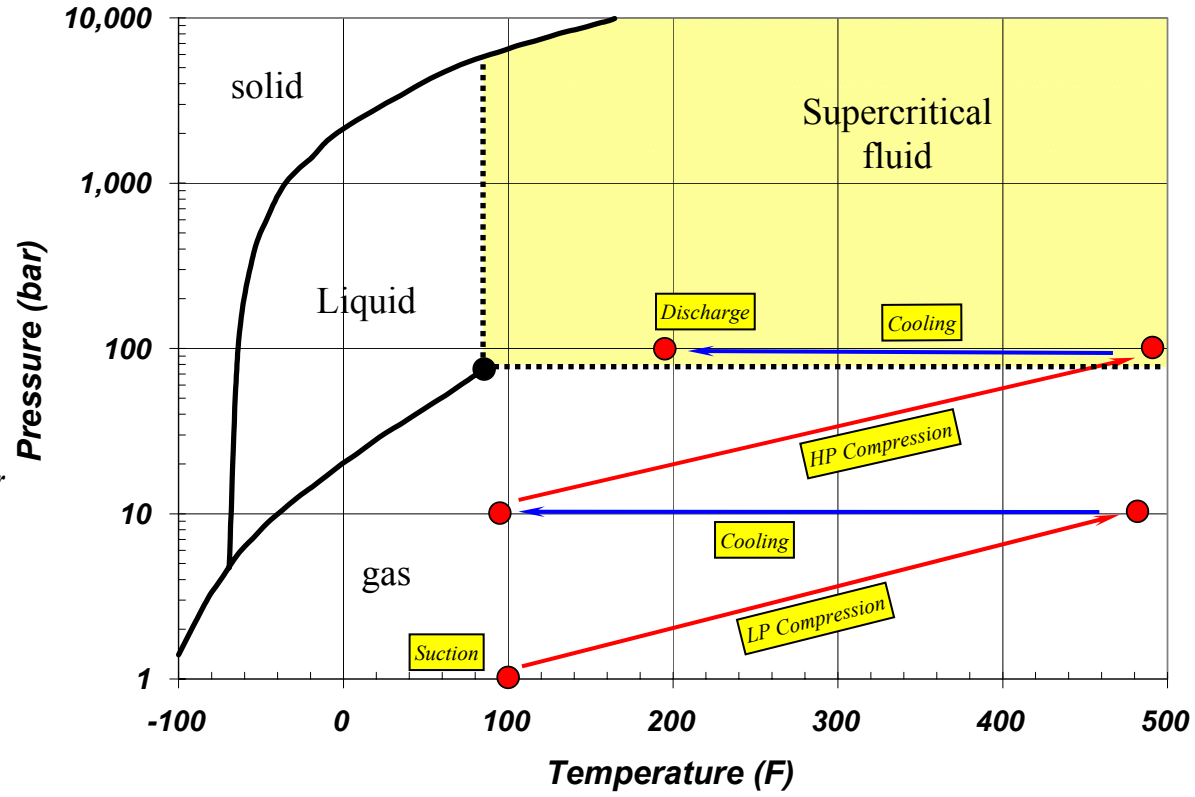


Increase in Temperature- Diminished Meniscus

Further Increase in Temperature- Gas & Liquid Densities more Similar

At Critical P & T- Distinct Gas & Liquid Phases no Longer Visible "Supercritical Fluid" with Properties of Both Liquids & Gases

- **Compression process transitions from superheated to supercritical phases**
- **Avoids liquid (sub-cooled) phase**



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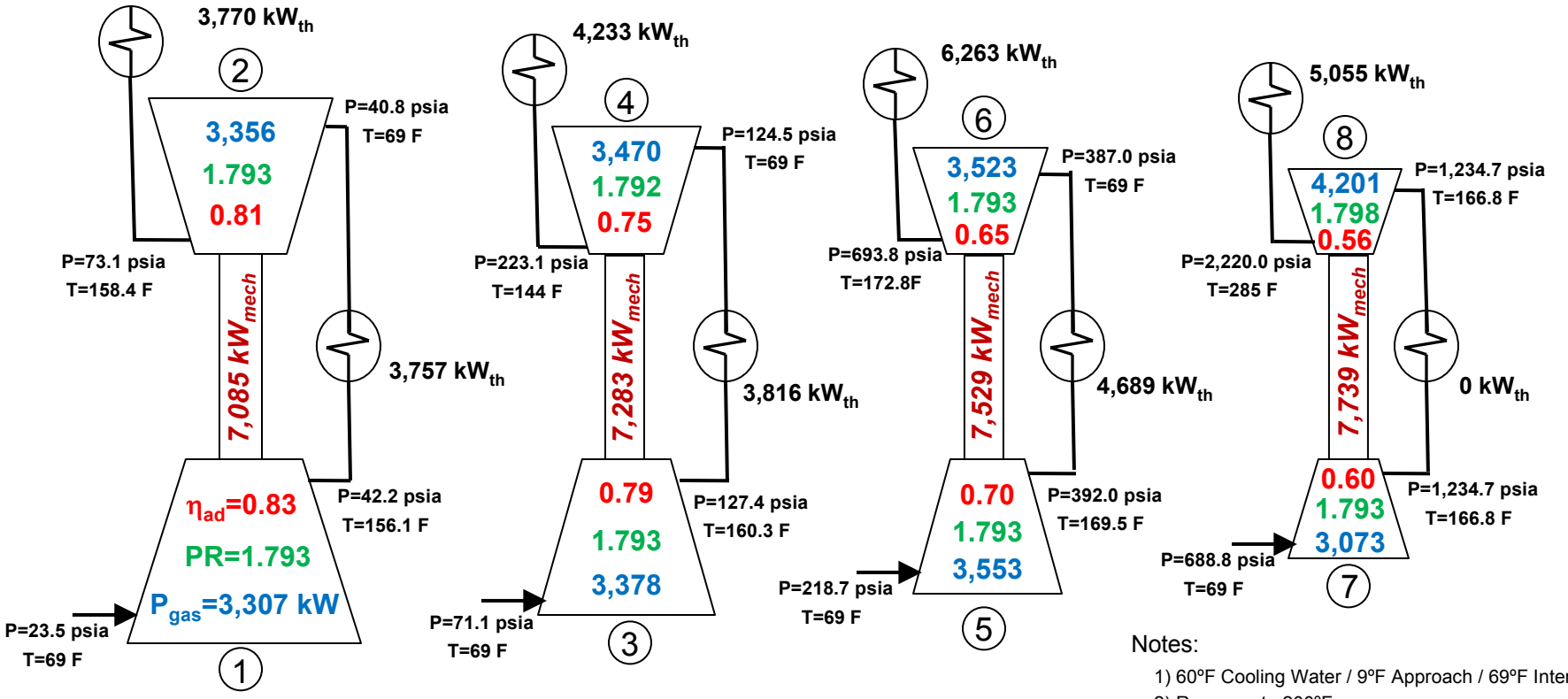
Advantages Over Conventional Designs



Notes:

1) 60ºF Cooling Water / 9ºF Approach / 69ºF Interstage
2) Recovery to 200ºF

- **Shaft power (stages 1-8)**
  - **Gas-path power = 27,862 kW$_{mech}$**
  - **Total shaft power = 29,636 kW$_{mech}$**
- **Heat of compression**
  - **Total rejected into coolers (stages 1-8) = 45,614 kW$_{th}$**
  - **Total recoverable^2 = 224 kW$_{th}$**

- **Ramgen (stages 1-2)**
  - **Total shaft power = 29,964 kW$_{mech}$**
  - **Total recoverable^2 = 28,986 kW$_{th}$**

Conventional Design Practices

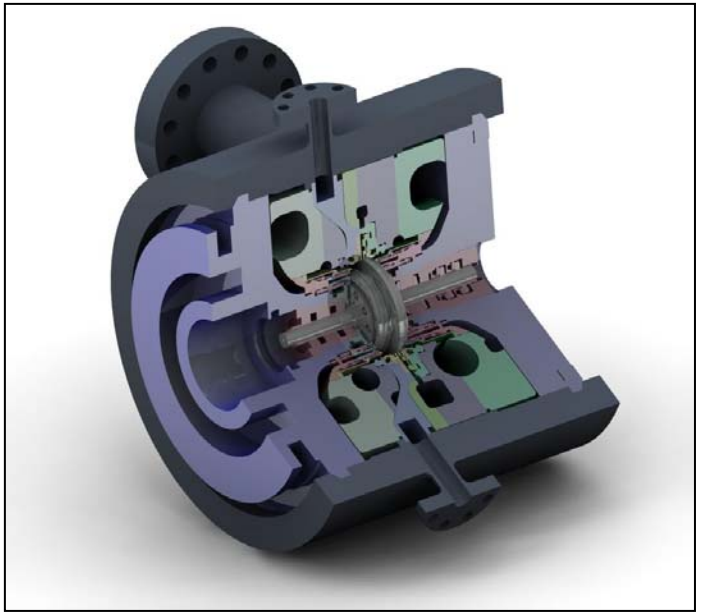
- **Combined PR, turndown and specific speed effects limit maximum achievable stage pressure ratios (PR ~1.7 – 1.9)**
- **Increasing suction pressure and rotor pair speed matching results in decreasing rotor sizes through system**
- **Decreased rotor sizes result in decreased efficiency – Reynolds number effects become dominant**

Benefits - Reduce CC(C)&S COE Penalty

MAN Turbo CO_2 Compressor

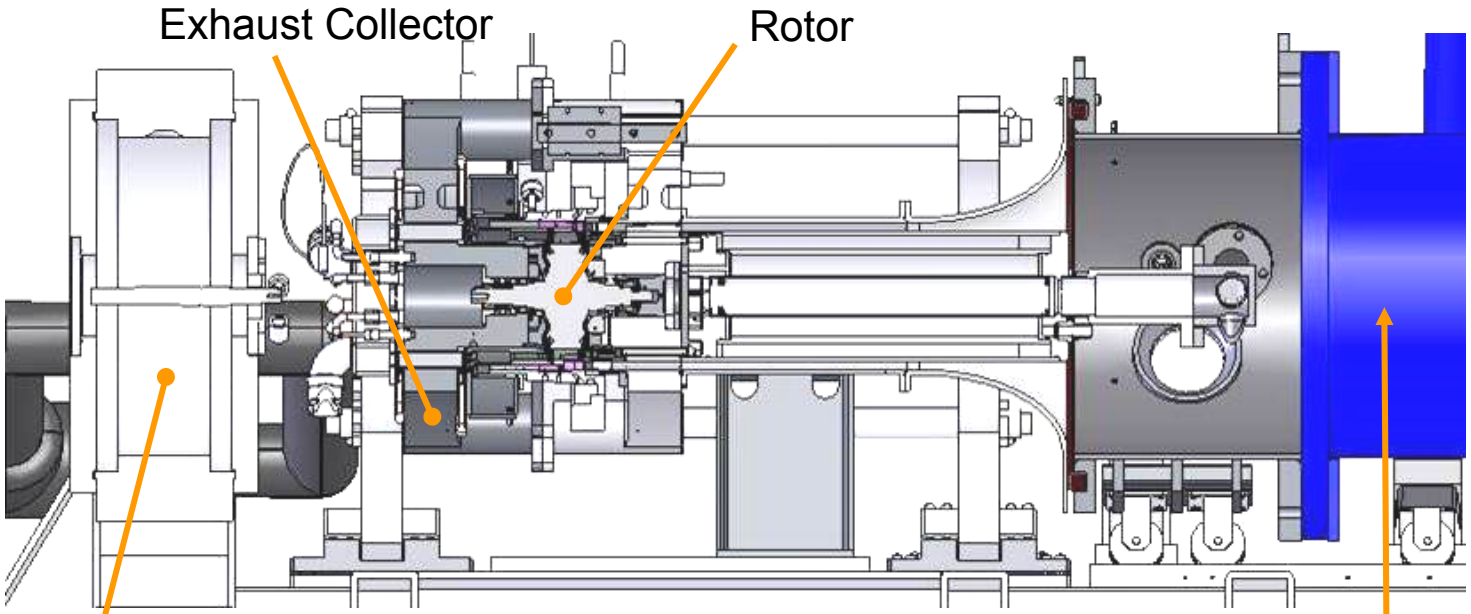
- 10-stage 6000 hp
  - $8.0 million ⇨$1350/hp
  - Pr 200:1 ⇨1.70 per stage
- 8-stage 20,000 hp
  - $15.0 million ⇨$750/hp
  - $23.0 million installed⇨$1150/hp
  - Pr 143:1 ⇨1.86 per stage

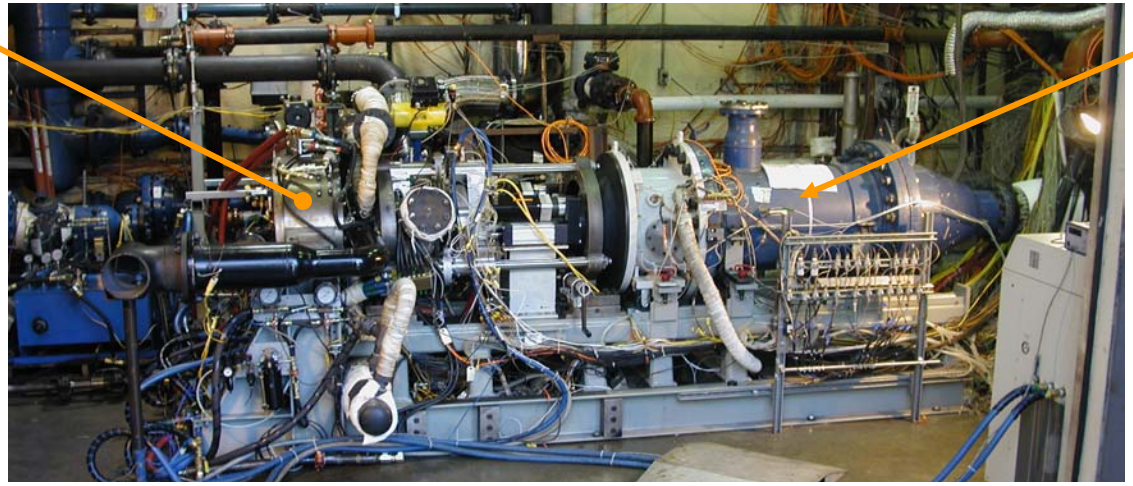
Ramgen CO_2 Compressor



- Pr 10+:1 per stage; Intercooled
- 1/10th the physical size
- 50-60% 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

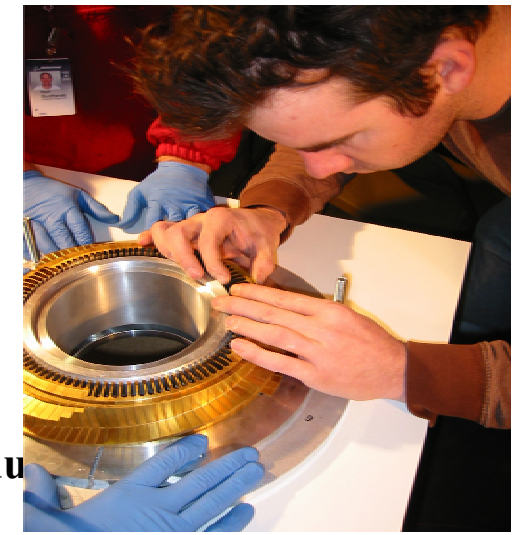
Progress/Current Status – Rampressor 2





Ram 2 Results

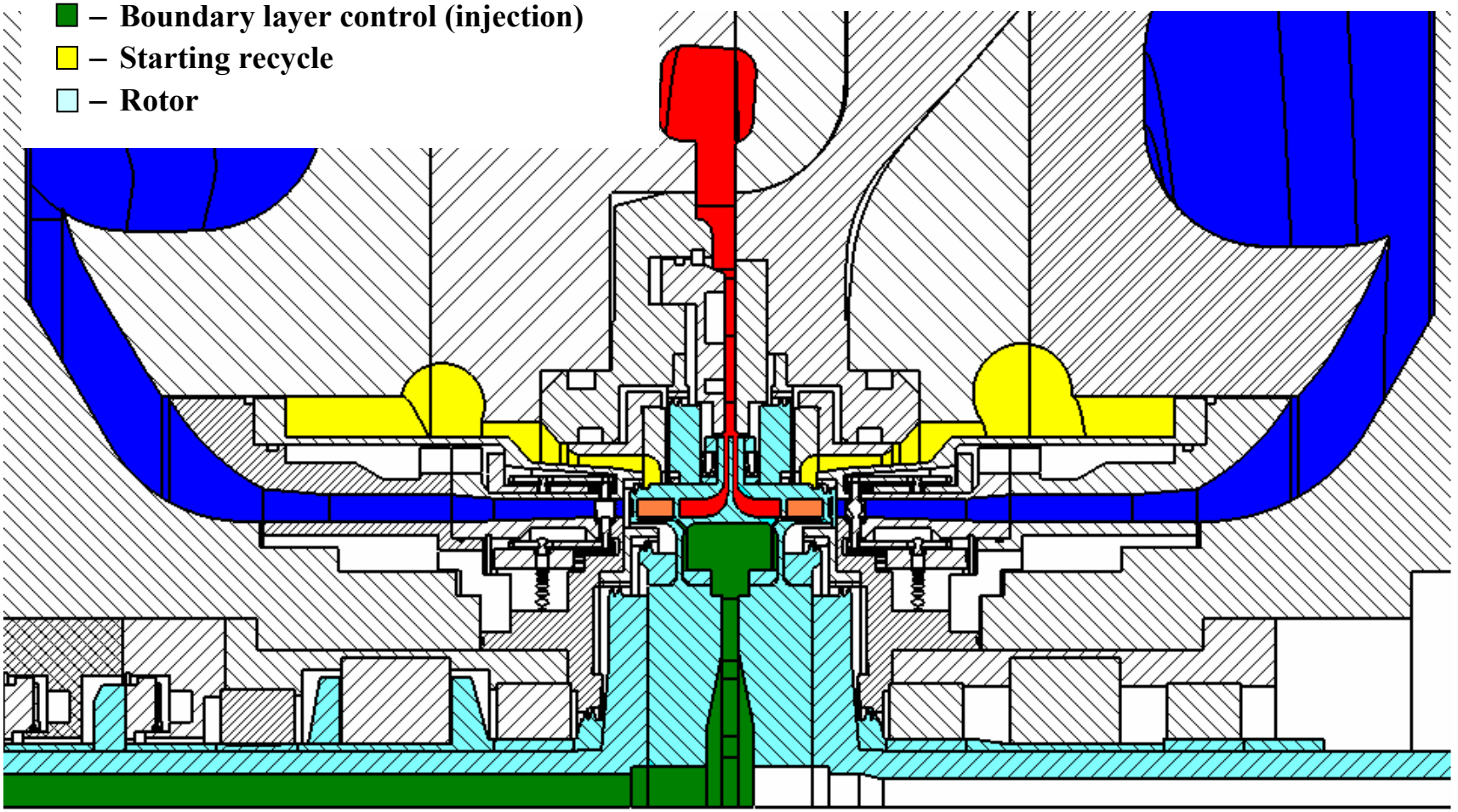
- **Achieved breakthrough rotor pressure ratio of ~7.9:1**
- **Demonstrated tip speeds up to ~2,200 ft/s and $M_{rel's}$ up to ~ 2.7**
- **Full flow path 3-D viscous CFD modeling successful**
- **Performance prediction/design tools match test**
  - Pressure ratio
  - Mass flow
- **Benign surge characteristics**
- **Data gathered for preliminary compressor maps**
- **Developed & demonstrated bearing designs suitable for produ application**
- **Have not optimized all available technology "knobs" to increase efficiency**



Test results fully traceable to CO_2 product

Working HP Stage Cross Section

- **Key stage features**
  - **– Suction (inflow)**
  - **– Discharge (outflow)**
  - **– Boundary layer control (injection)**
  - **– Starting recycle**
  - **– Rotor**



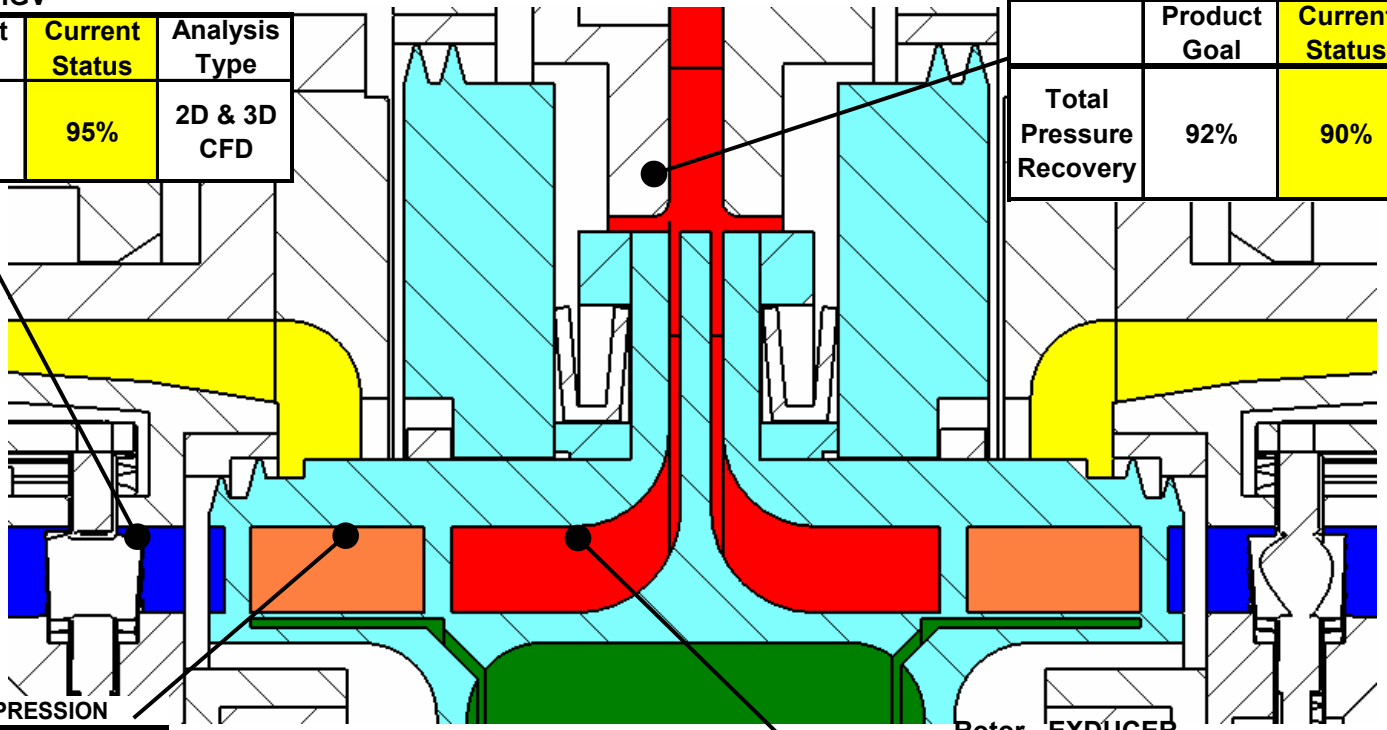
Demo Unit Performance Status

IGV

	Product Goal	Current Status	Analysis Type
Total Pressure Recovery	97%	95%	2D & 3D CFD

Stationary Diffuser

	Product Goal	Current Status	Analysis Type
Total Pressure Recovery	92%	90%	2D & 3D CFD



Rotor - SHOCK COMPRESSION

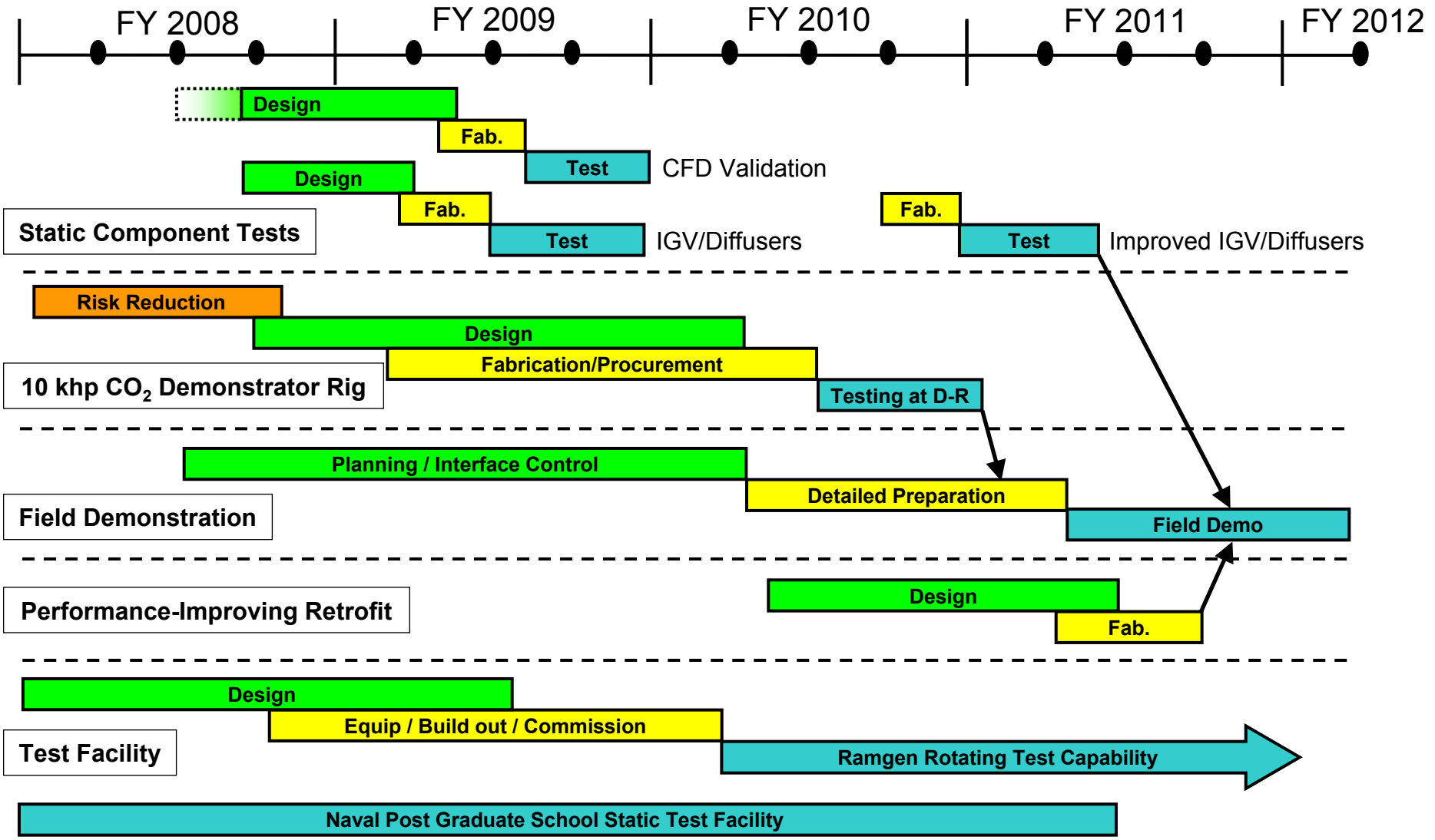
	Product Goal	Current Status	Analysis Type
Total Pressure Ratio	5.38	5.05	2D CFD

Rotor - EXDUCER

	Product Goal	Current Status	Analysis Type
Total Pressure Ratio	2.1	1.9	2D & 3D CFD

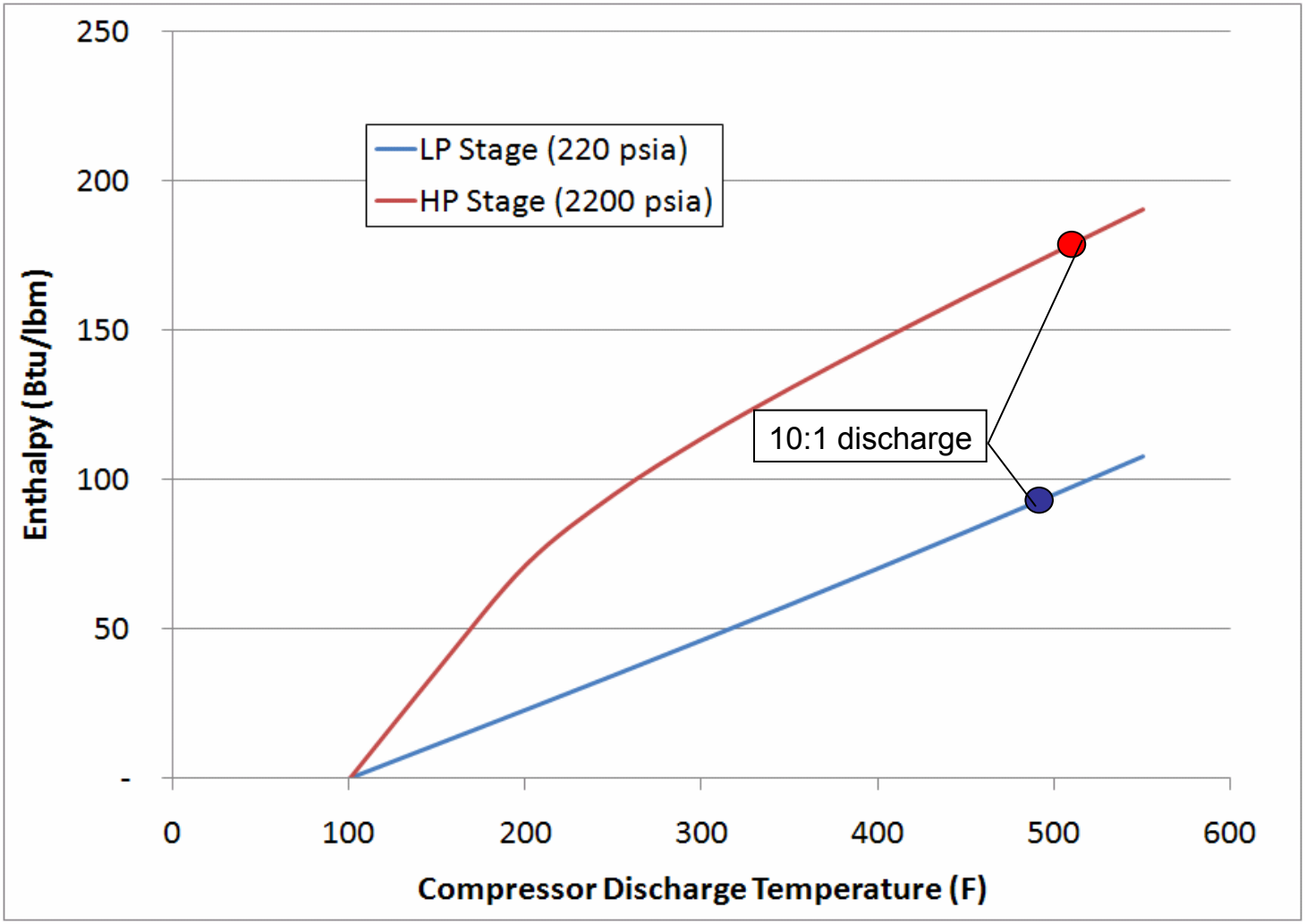
2D & 3D CFD Aero Analyses Indicate Component Performance Levels Are Near Product Levels

Future Testing/Commercialization



Ramgen Heat Recovery - Availability

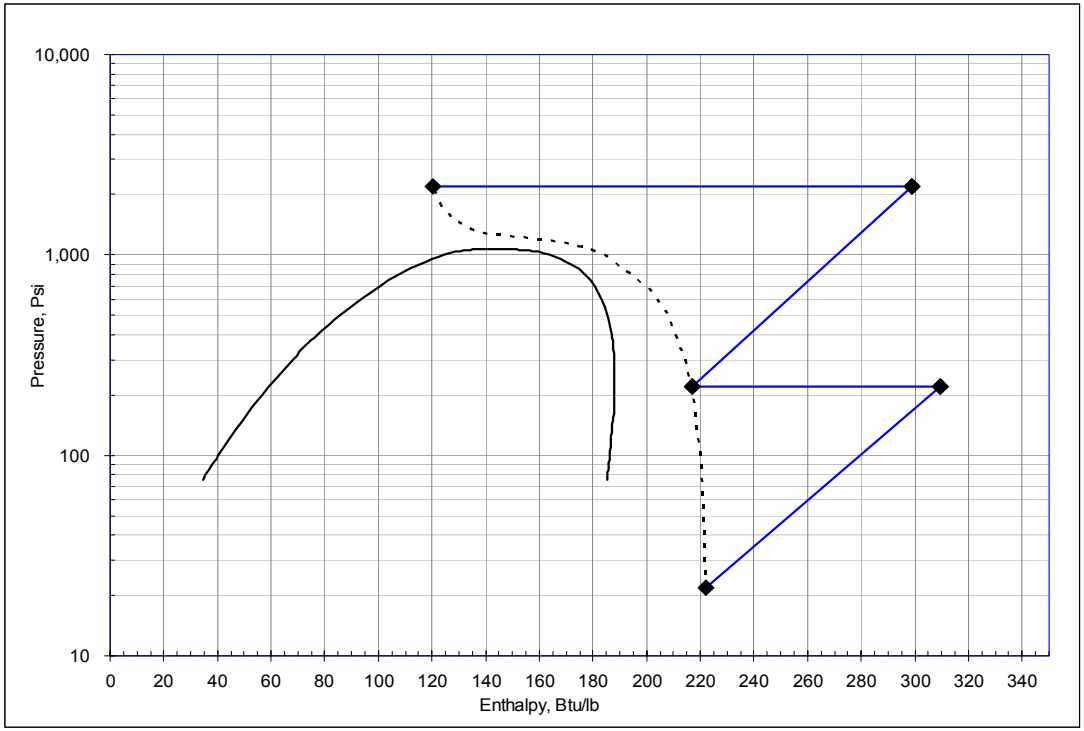
- HP stage has significantly more heat available due to non-ideal nature of CO_2



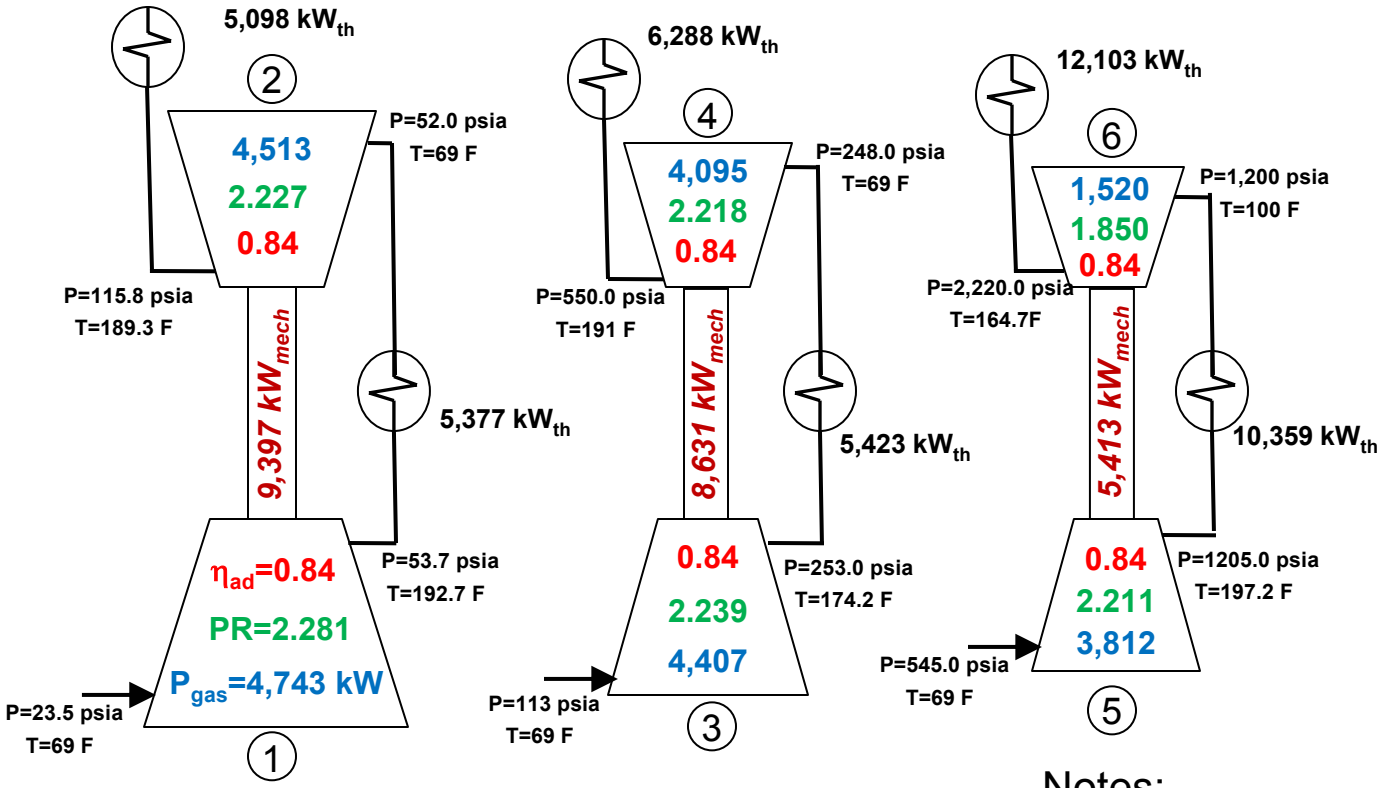
Ramgen Heat Recovery - Amount

	Low Pressure Stage 22 - 220 psia	High Pressure Stage 220 - 2200 psia
Compressor Shaft Input Work	90.6 Btu/lbm	87.0 Btu/lbm
Discharge Temperature	489 °F	509 °F
Lower Recovery Temperature	100 °F	100 °F
Recovered Heat	92.4 Btu/lbm	178.8 Btu/lbm
Recovered Heat/Compression Work	102%	205%

- **Heat available in the HP hot discharge CO2 is more than double the compressor shaft work**
- **153% of the combined LP + HP shaft work is available as heat in the discharge CO2**



6-Stage Process (DOE Baseline)



- **Shaft power (stages 1-6)**
  - **Gas-path power = 23,090 kW$_{mech}$**
  - **Total shaft power = 23,441 kW$_{mech}$**
- **Heat of compression**
  - **Total rejected into coolers (stages 1-6) = 44,648 kW$_{th}$**
  - **Total recoverable[2] = 0 kW$_{th}$**

Notes:

1) 6 stage concept assumed in DOE
1) 60ºF Cooling Water / 9ºF Approach / 69ºF Interstage
2) Recovery to 200ºF
3) Constant Stage η=0.84