CO_2 Compression Using Supersonic Shock Wave Technology

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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

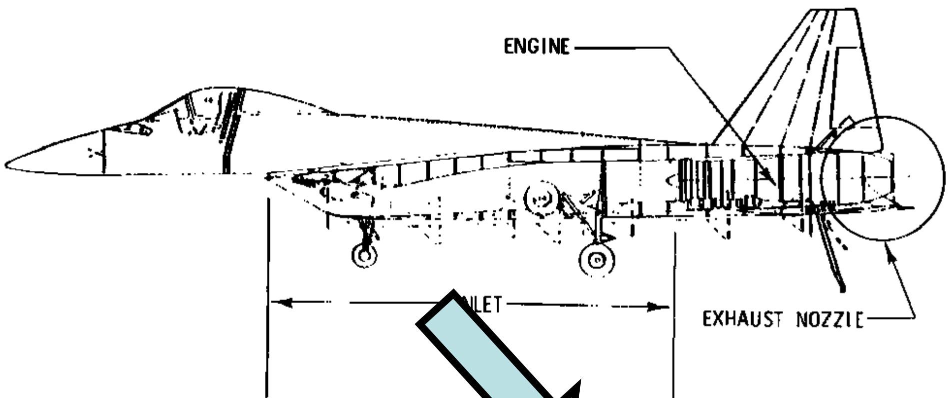
- Privately held since 1993, headquartered in Bellevue, WA
- Development and test of supersonic turbo-components for process gas and power generation applications
- 1998-present, $30 M in private funds and $25.0 M in DOE, DOD and CEC PIER support
- 2008-Dresser-Rand investment of up to $49M to commercialize supersonic compression technology
- Novel technology permits high pressure ratios and efficiencies
- DOE Supporting commercial scale compressor demonstration (10 khp)
- 26 full-time employees
  - Ingersoll-Rand, CAT/Solar, P&W, Boeing, Honeywell, Rocketdyne
  - 3 PhD & 9 MS Degreed Engineers

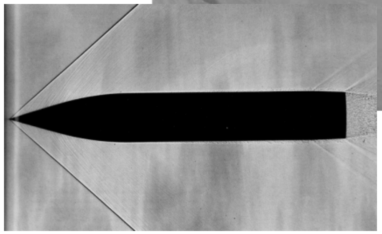
Project Overview

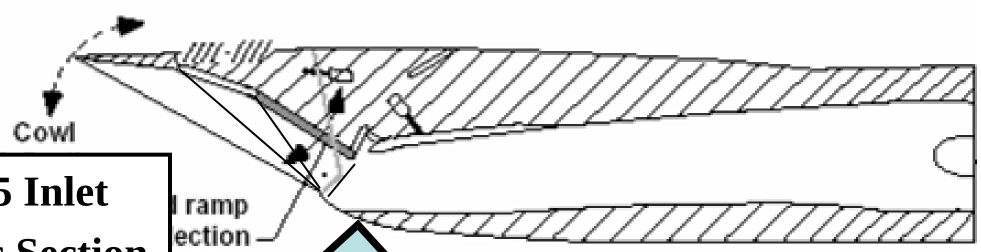
- **Funding (DOE and Cost Share)**
  - **Total Funding – Current Contract $42.2M (DE-FE0000493)**
  - **DOE – $20.0M**
  - **Ramgen – $22.2M**
- **Overall Project Performance Dates**
  - **August 1, 2009 – November 30, 2012**
- **Project Participants**
  - **DOE**
  - **Ramgen**
    - **Dresser-Rand – 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

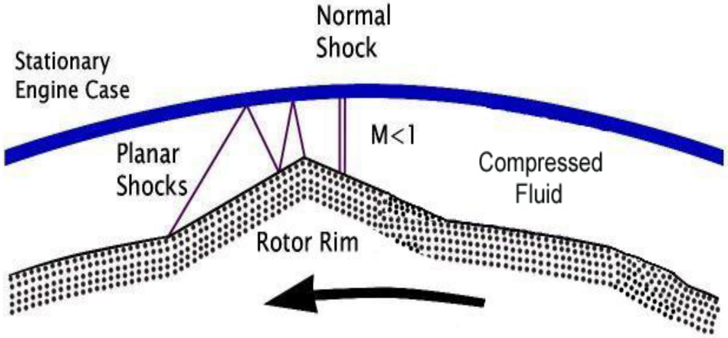
Technology Fundamentals/Background





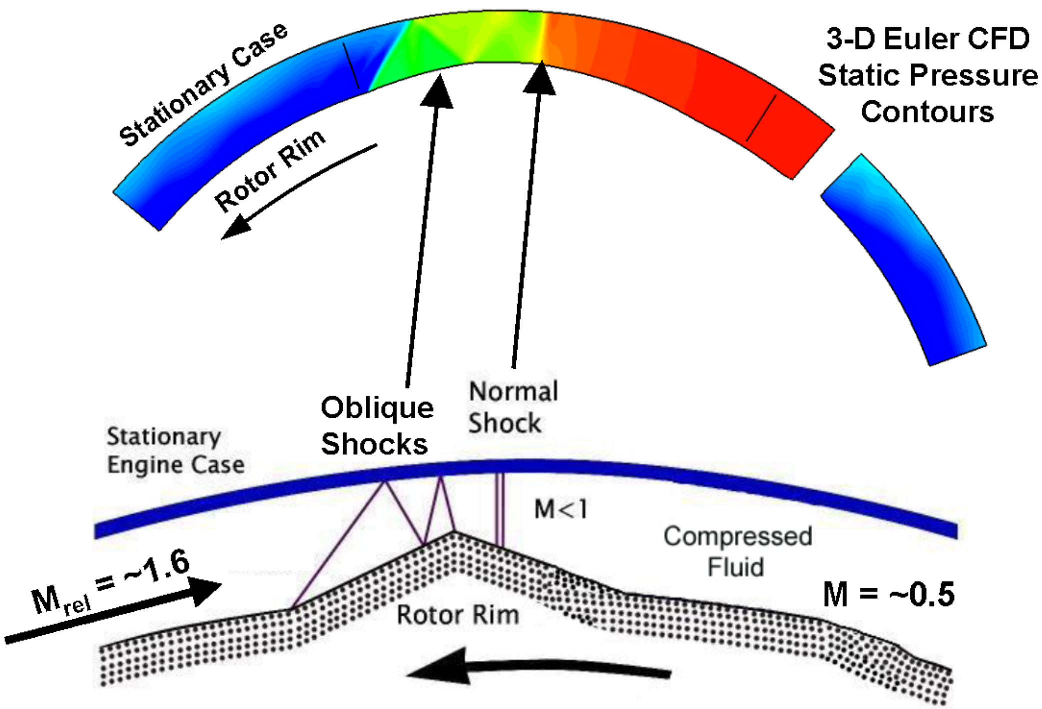


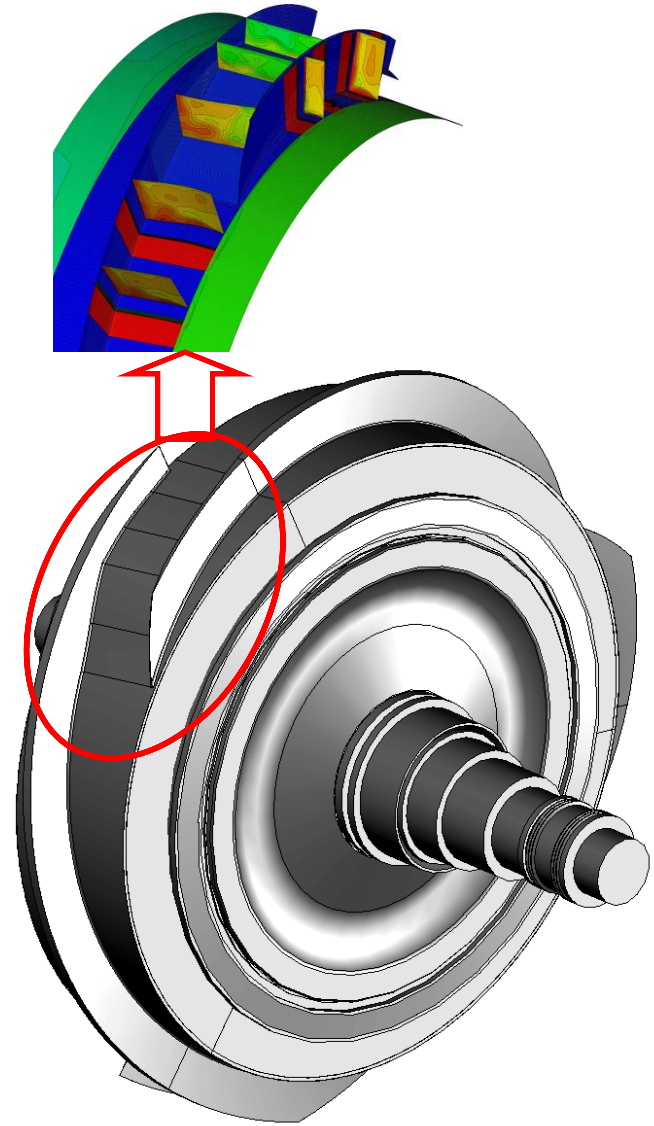
F-15 Inlet Cross Section



Rampressor Rotor

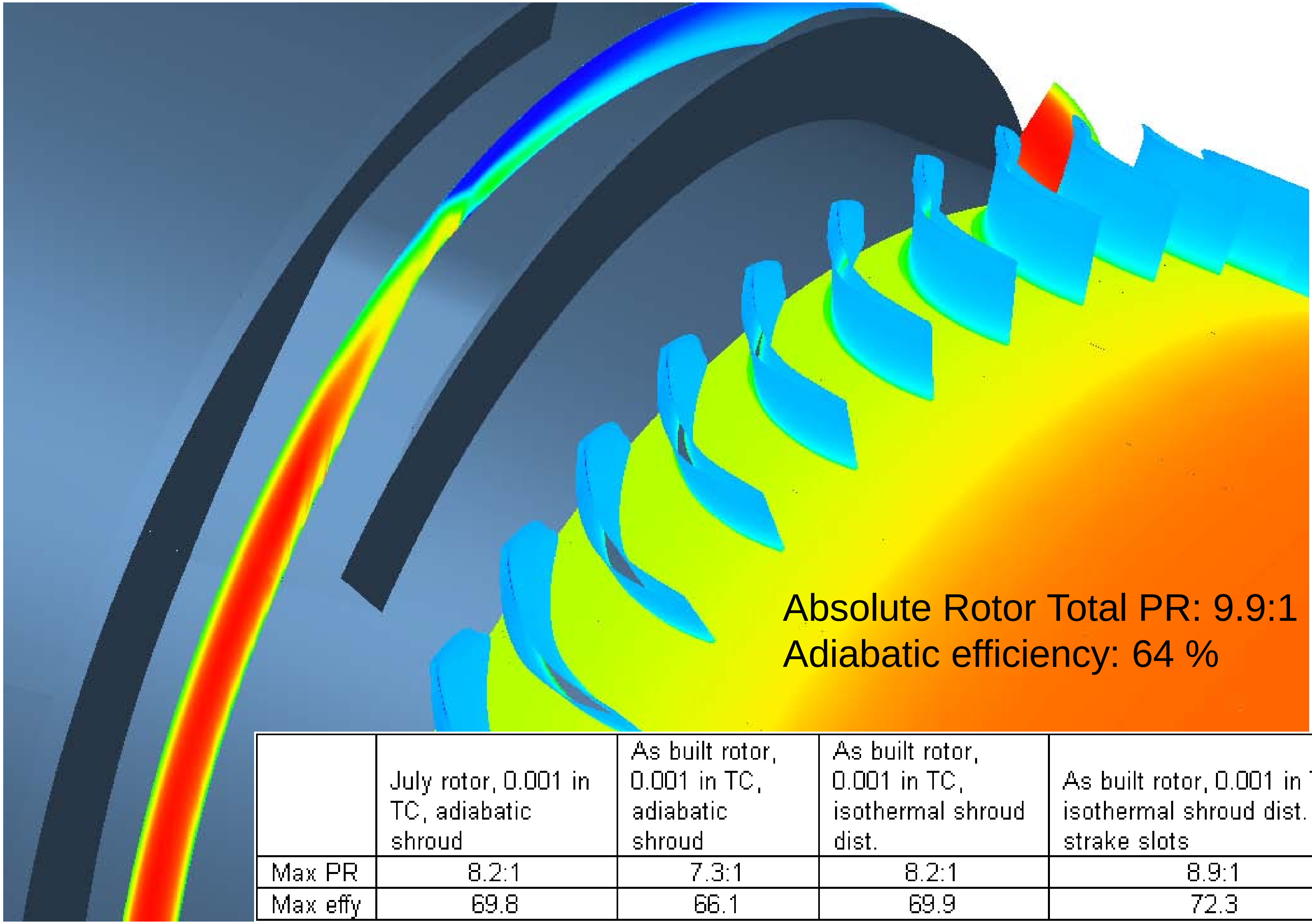
Rampressor 3-D Geometry & Flowfield





- **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**

Effect of IGV Losses on Rotor PR



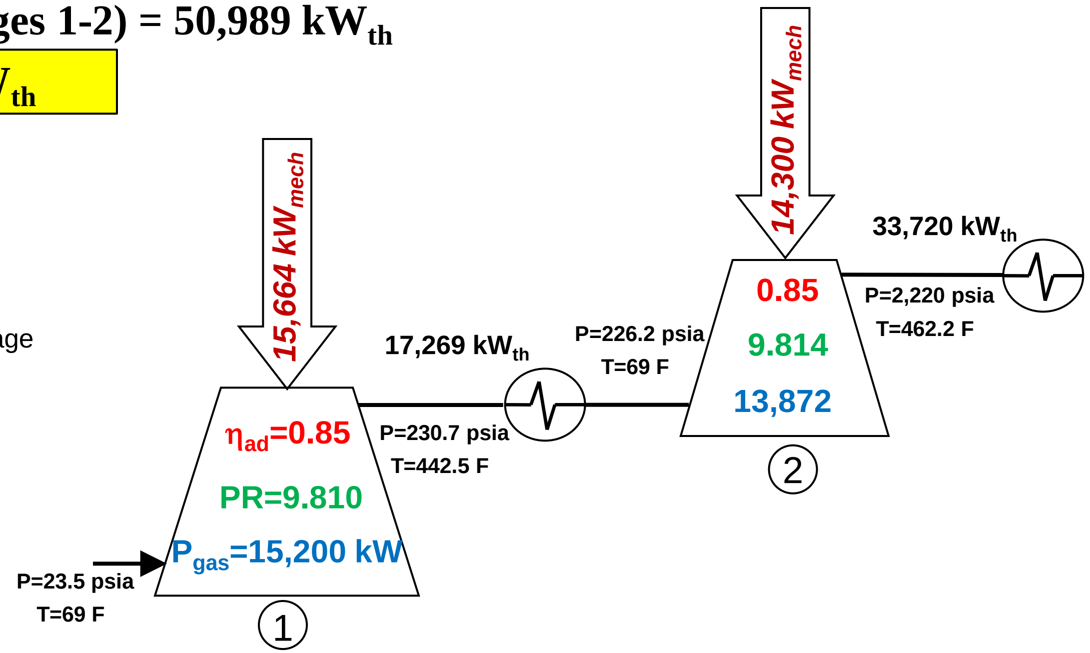
	July rotor, 0.001 in TC, adiabatic shroud	As built rotor, 0.001 in TC, adiabatic shroud	As built rotor, 0.001 in TC, isothermal shroud dist.	As built rotor, 0.001 in TC, isothermal shroud dist., +4 strake slots
Max PR	8.2:1	7.3:1	8.2:1	8.9:1
Max effy	69.8	66.1	69.9	72.3

Ramgen 2-Stage Process – Discrete Drive

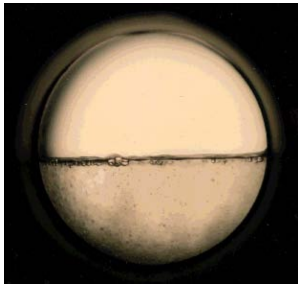
- **Shaft power (stages 1-2)**
  - **– Gas-path power = 29,072 kW_{mech}**
  - **– Total shaft power = 29,964 kW_{mech}**
- **Heat of compression**
  - **– Total rejected into coolers (stages 1-2) = 50,989 kW_{th}**
  - **– Total recoverable[1] = 28,986 kW_{th}**

Notes:

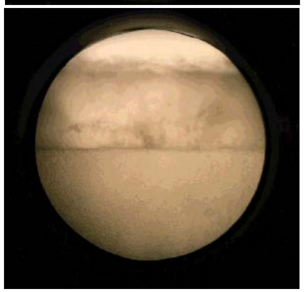
1) 60ºF Cooling Water / 9ºF Approach / 69ºF Interstage
2) Recovery to 200ºF



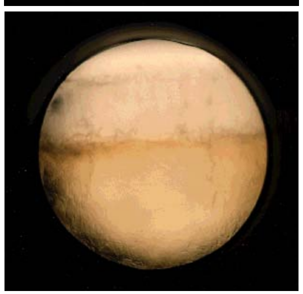
PT Diagram & Supercritical Phase



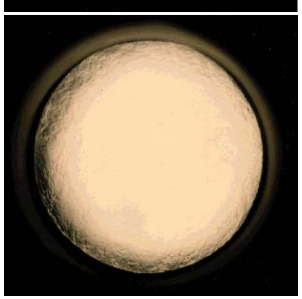
Separate Phases Visible- Meniscus Clearly Observed



Increase in Temperature- Diminished Meniscus

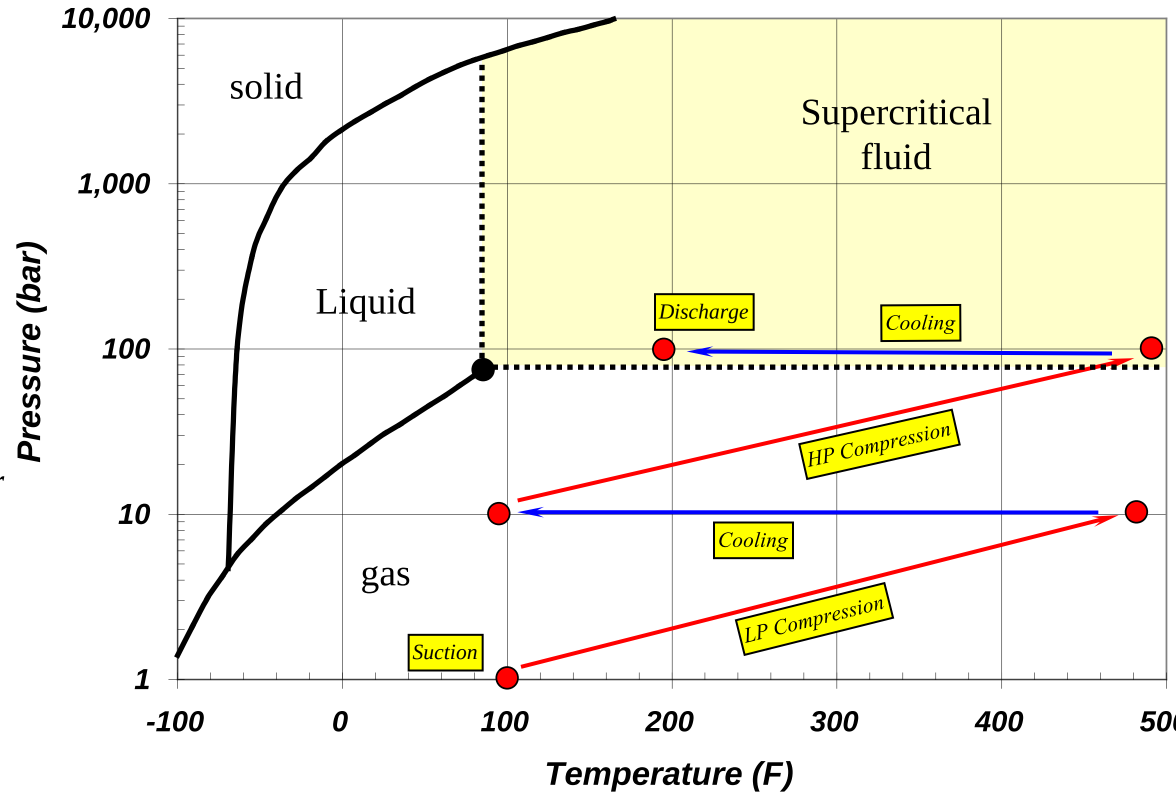


Further Increase in Temperature- Gas & Liquid Densities more Similar

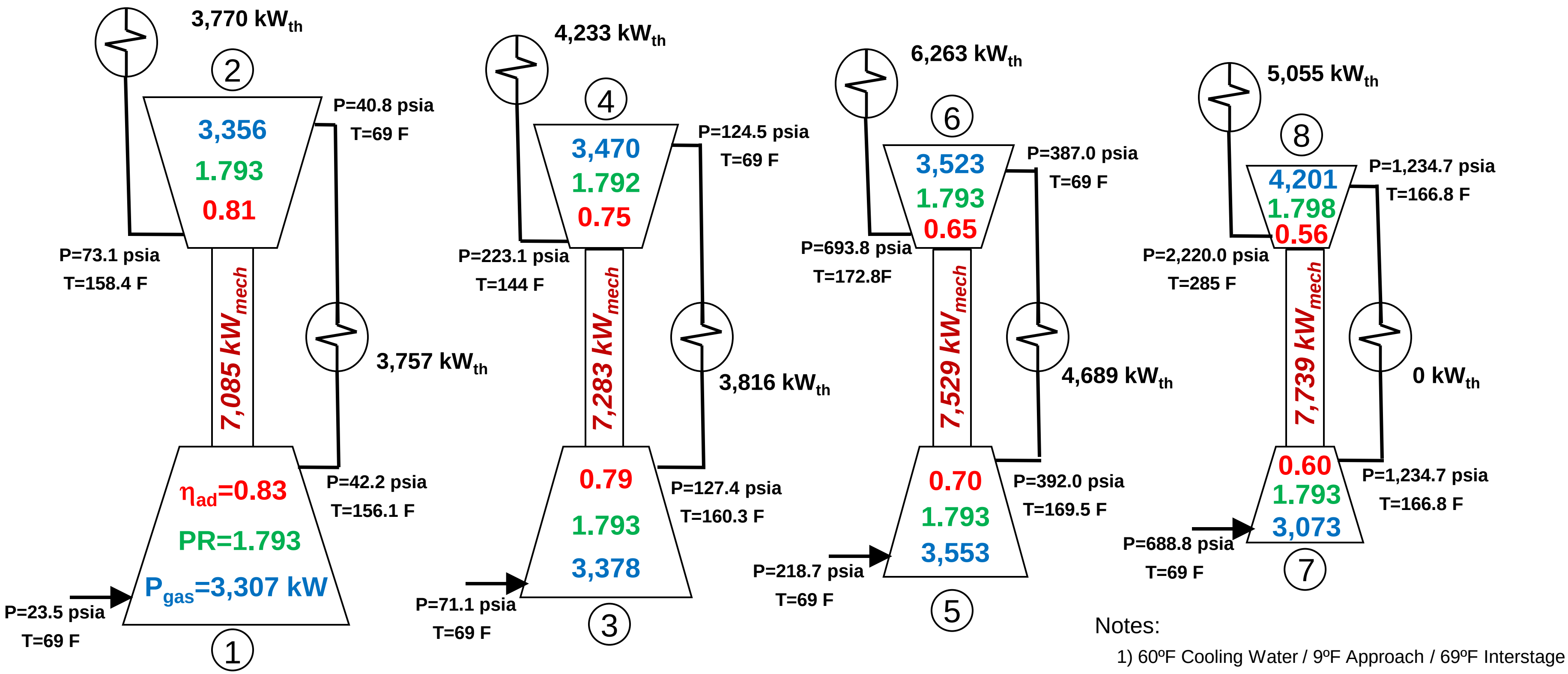


At Critical P & T- Distinct Gas & Liquid Phases no Longer Visible "Supercritical Fluid" with Properties of Both Liquids & Gases

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



Advantages Over Conventional Designs



Notes:

1) 60ºF Cooling Water / 9ºF Approach / 69ºF Interstage

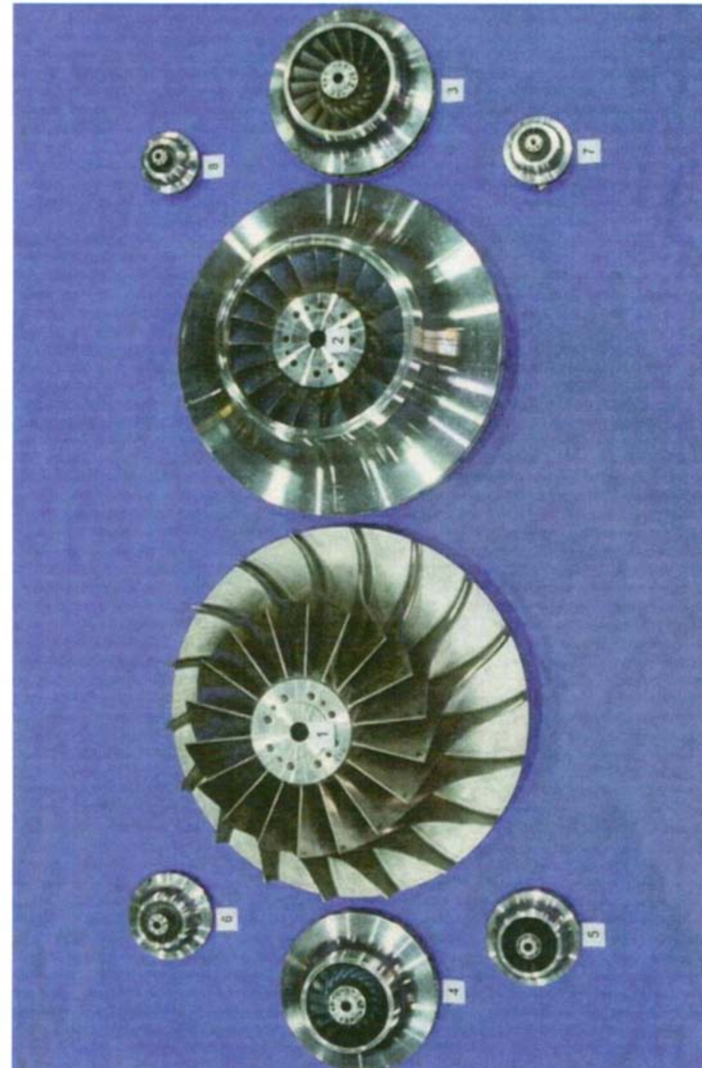
2) Recovery to 200ºF

- 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

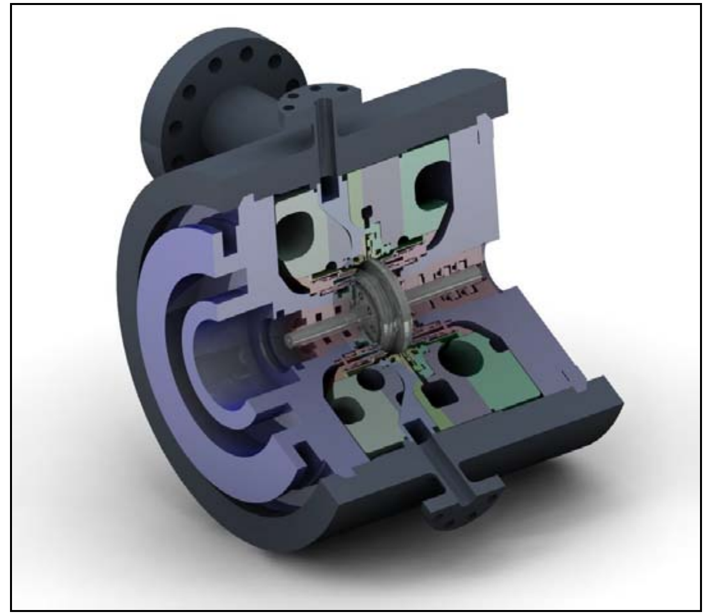


Benefits - Reduce CC(C)&S COE Penalty

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**

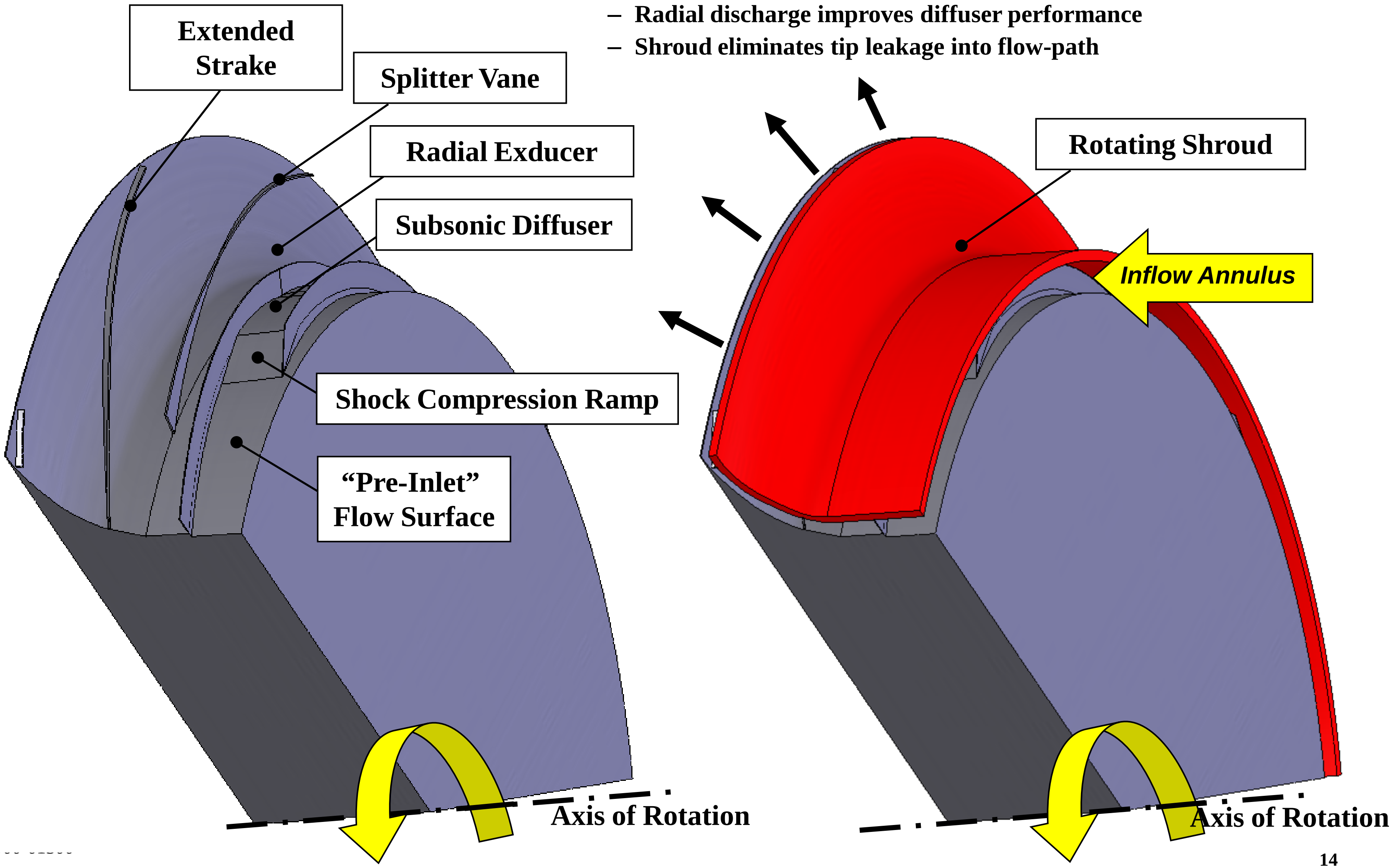
Ramgen CO_2 Compressor



- **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**

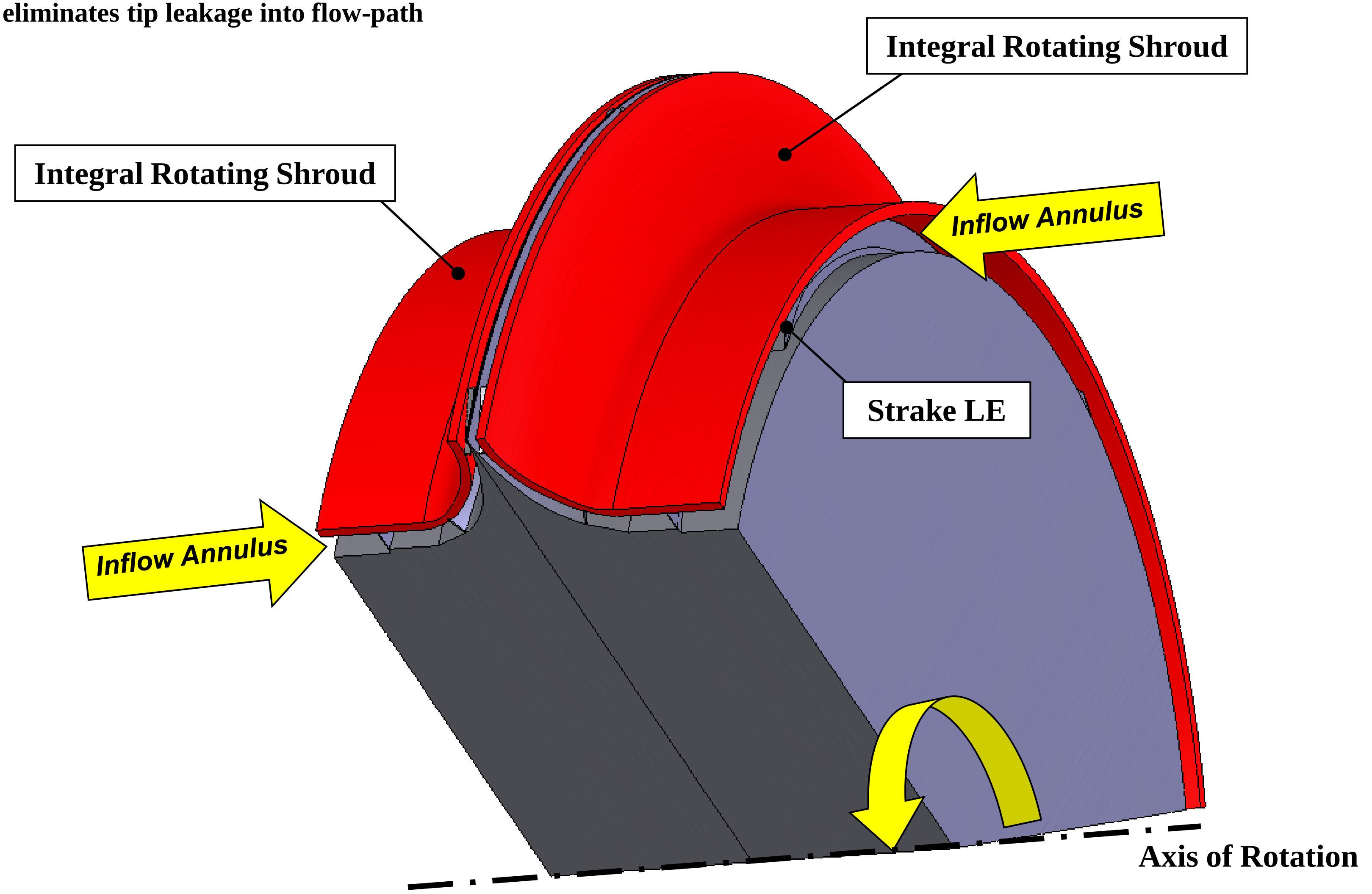
Rotor Design Evolution – Radial Discharge

- Shrouded rotor - radial discharge
  - Radial discharge improves diffuser performance
  - Shroud eliminates tip leakage into flow-path



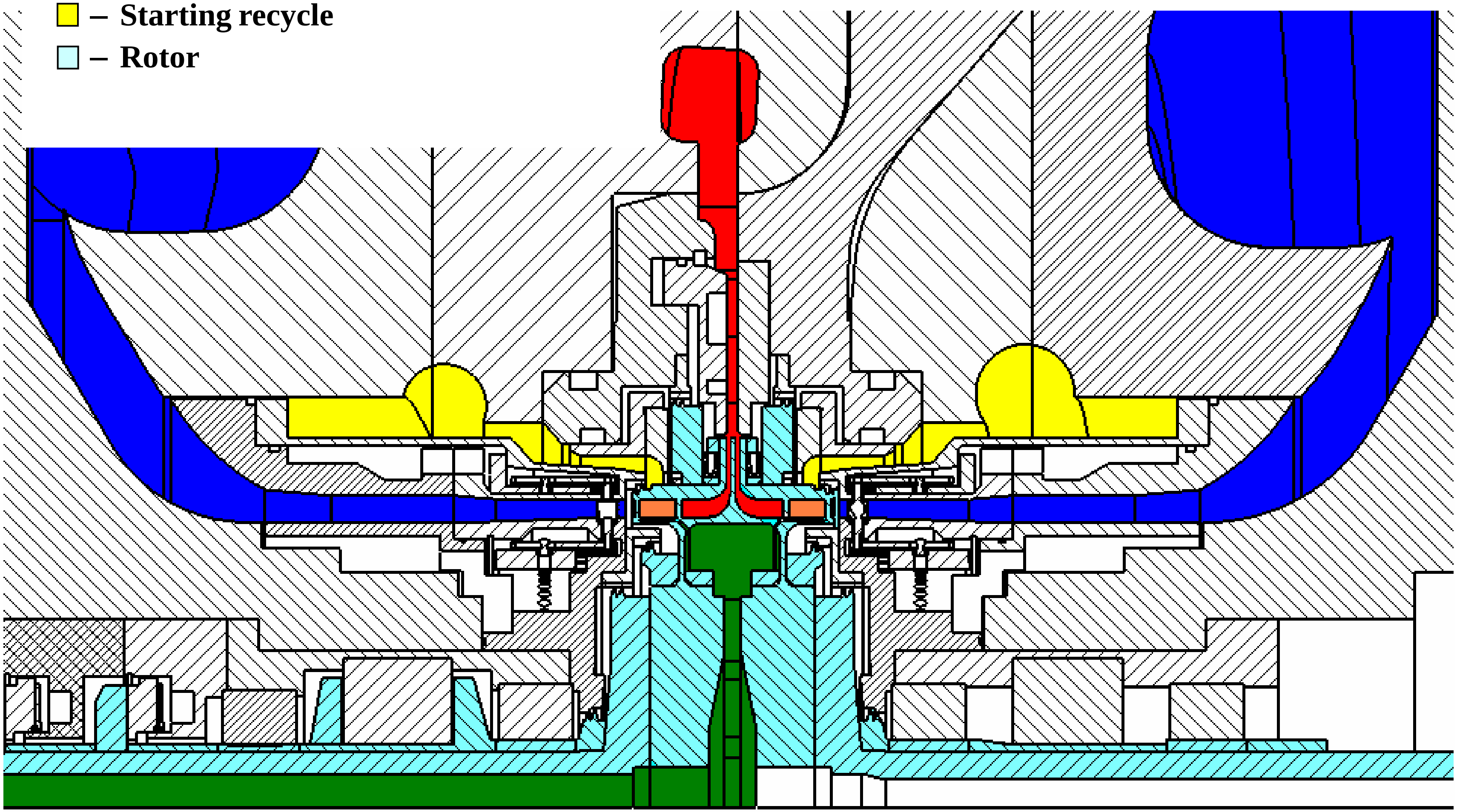
Dual Entry – Back to Back Configuration

- **Shrouded back-to-back rotor**
  - **Eliminates rotor thrust –significant for HP stage**
  - **Shroud eliminates tip leakage into flow-path**



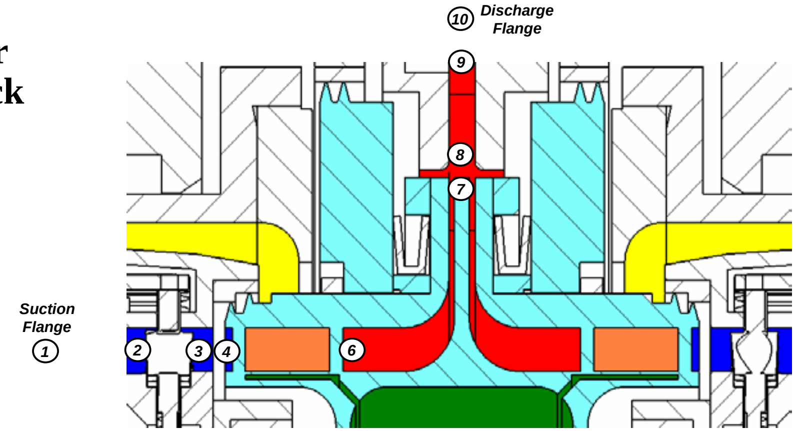
HP Stage Schematic

- **Key stage features**
  - **■ – Suction (inflow)**
  - **■ – Discharge (outflow)**
  - **■ – Starting recycle**
  - **□ – Rotor**



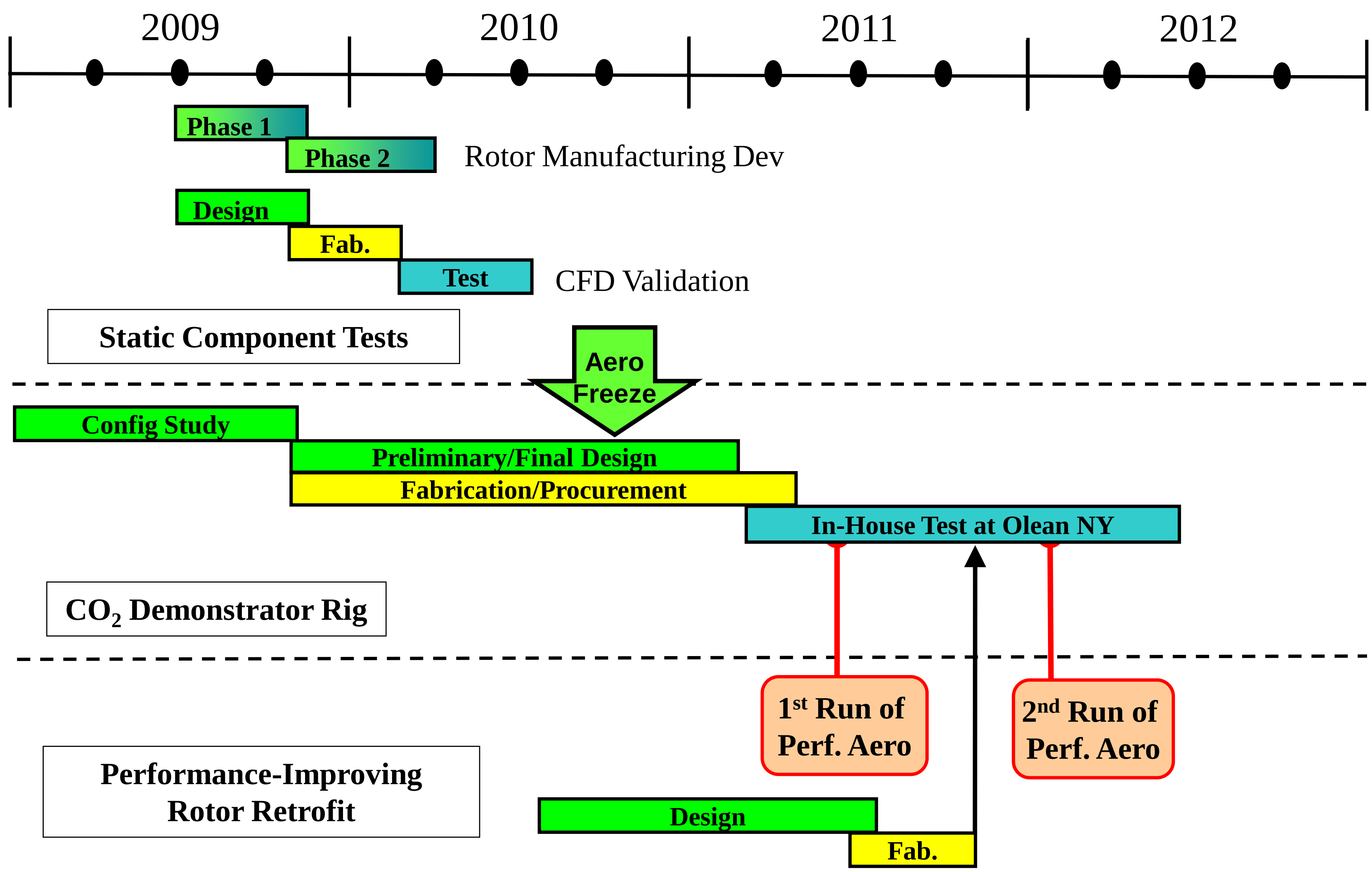
Demo Unit Performance Approaching Goals with DOE Super-Computer Support

- **DOE Support with access to ORNL super-computer resources has been critical to rapid progress in shock compression CFD modeling and optimization**
  - **Details of Ramgen shock compression geometry require large CFD grids**
  - **Capturing critical shock boundary layer interactions complicates simulations**
  - **Need for time-accurate simulations to evaluate aero-stability issues important to system optimization**



						On Rotor - Relative Conditions					
Station Number =>		1	2	3	**4**	**5**	**6**	**7**	8	9	10
		Suction Flange	IGV Inflow	IGV Exit	**Rotor Inflow**	**Ramp Base**	**End Shock Comp**	**Rotor Exit**	Diffuser Entrance	Diffuser Exit	Discharge Flange
Demo – *High*	P_t (psia)	212.0	211.8	208.9	**1,073.5**	**1,019.8**	**968.8**	**2,190.0**	2,520.1	2,319.0	2,289.1
Demo – *High*	Loss Metric		P_{t2}/P_{t1} 0.9991	P_{t3}/P_{t2} 0.9863		**P_{t5}/P_{t4} 0.9500**	**P_{t6}/P_{t5} 0.9500**			P_{t9}/P_{t8} 0.9202	P_{t10}/P_{t9} 0.9871
Demo – *Nominal*	P_t (psia)	212.0	211.8	208.9	**1,073.5**	**1,030.1**	**923.9**	**2,115.0**	2,574.0	2,318.8	2,289.1
Demo – *Nominal*	Loss Metric		P_{t2}/P_{t1} 0.9991	P_{t3}/P_{t2} 0.9863		**P_{t5}/P_{t4} 0.9395**	**P_{t6}/P_{t5} 0.8800**			P_{t9}/P_{t8} 0.9008	P_{t10}/P_{t9} 0.9872
Demo – *Low*	P_t (psia)	212.0	211.8	208.9	**1,073.5**	**1,030.1**	**923.9**	**2,115.0**	2,574.0	2,246.8	2,218.1
Demo – *Low*	Loss Metric		P_{t2}/P_{t1} 0.9991	P_{t3}/P_{t2} 0.9863		**P_{t5}/P_{t4} 0.9395**	**P_{t6}/P_{t5} 0.8800**			P_{t9}/P_{t8} 0.8728	P_{t10}/P_{t9} 0.9872
Current Status	P_t (psia)	212.0	211.8	208.9	**1,073.5**	**1,030.1**	**923.9**	**2,115.0**	2,574.0	2,246.8	2,218.1
Current Status	Loss Metric		P_{t2}/P_{t1} 0.9991	P_{t3}/P_{t2} 0.9863		**P_{t5}/P_{t4} 0.9395**	**P_{t6}/P_{t5} 0.8800**			P_{t9}/P_{t8} 0.8728	P_{t10}/P_{t9} 0.9872

Project Milestones



Questions