Fifth Annual Conference on Carbon Capture & Sequestration

Steps Toward Deployment

Session: Advanced Capture

Conceptual Design of a Supersonic CO_2 Compressor

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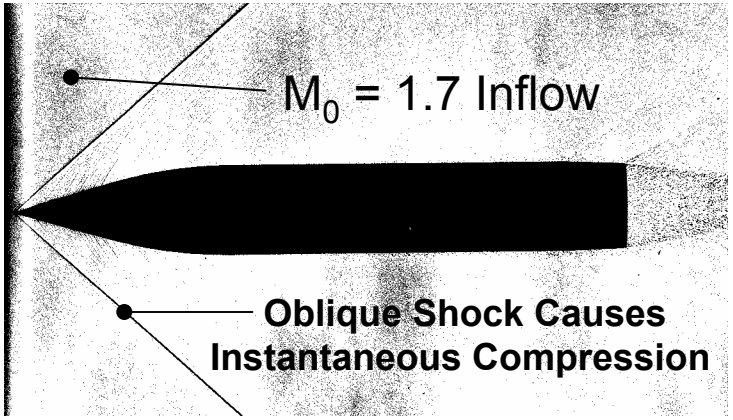
Basic Aero-Physics

- Supersonic Flight Inlets More Efficient Than Most Land Based Compressors

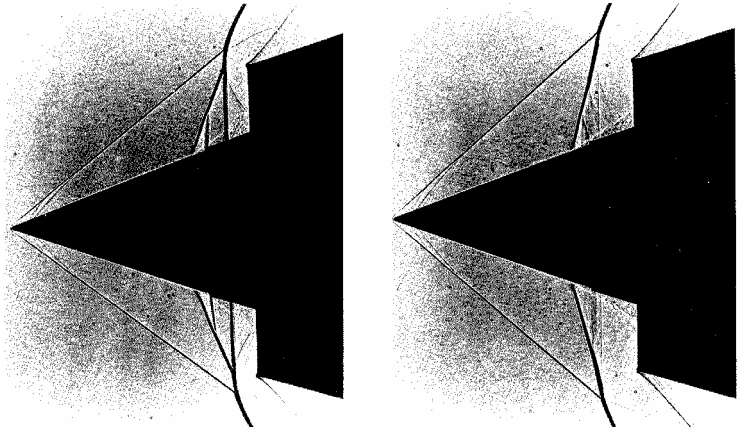
- Inlet Performance Characteristics and Aero Design Tools/Techniques Well Proven Over Past 50 yrs

- Flight Inlets Form Basis for Supersonic Compressor
  - Apply Proven Flight Inlet Design Practice to "Wheel Mounted" Supersonic Inlet Systems
  - Develop Systems to Integrate Flight Inlet Design Features Into Stationary Gas Compression Systems
  - High Stage PR's Well Suited to CO_2 Compression Applications

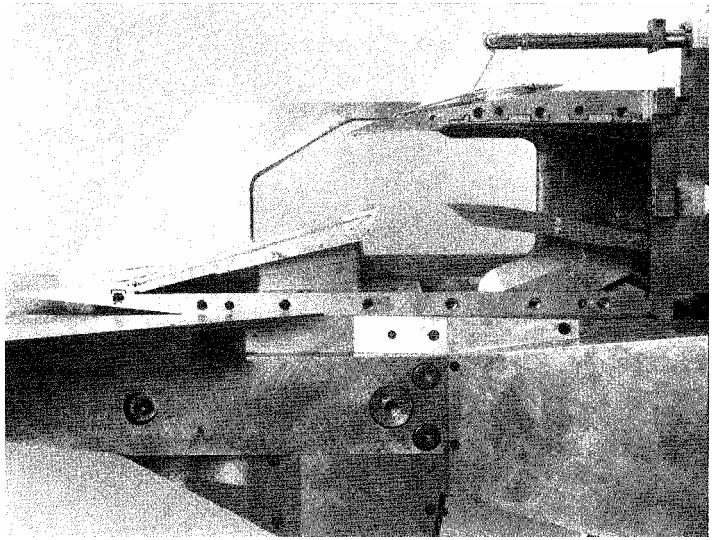
Shock Waves to Supersonic Inlets



Schlieren Photo of Projectile with Shocks



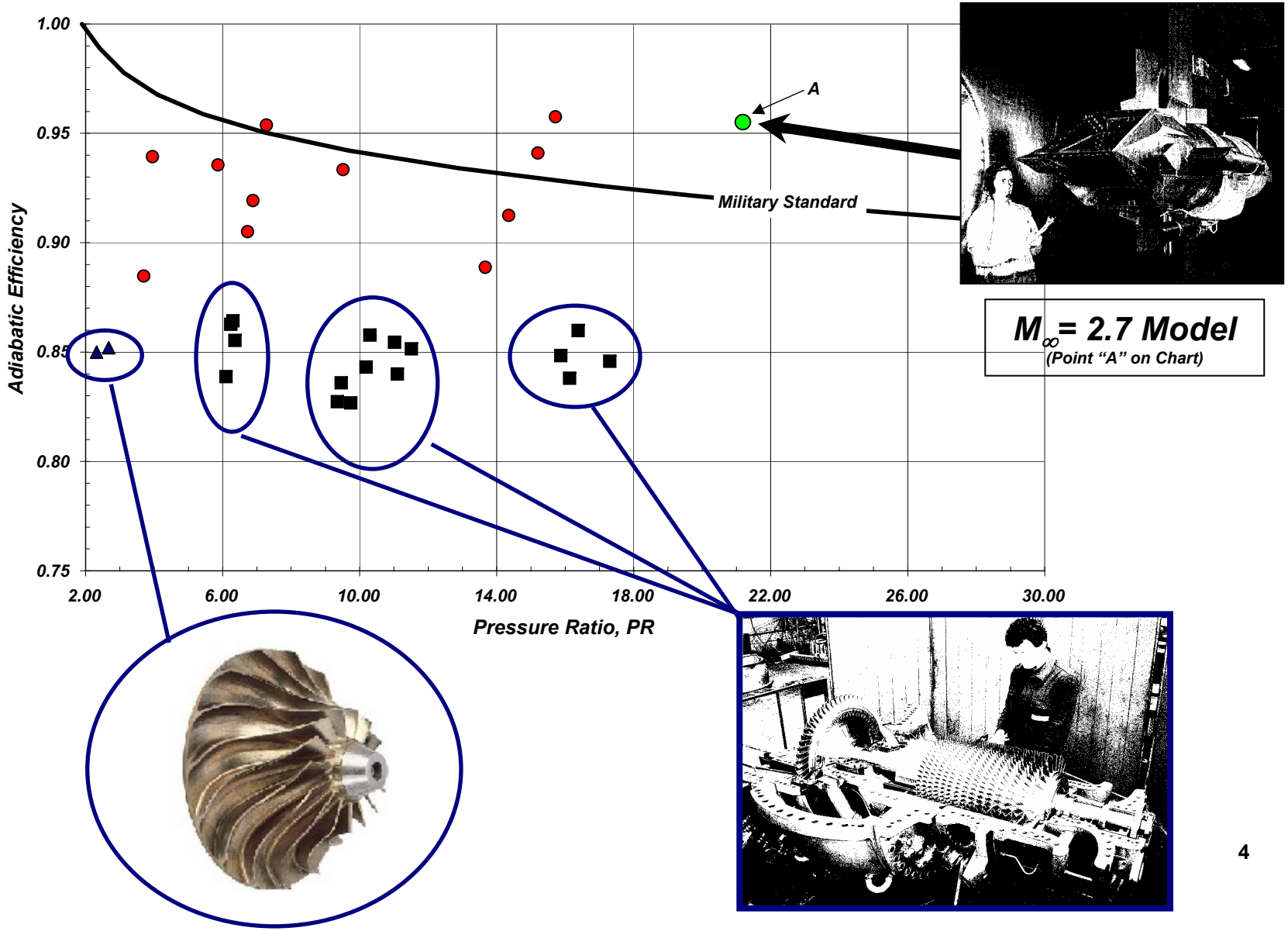
Schlieren Photo of Inlet Center-body and Cowl with Shocks



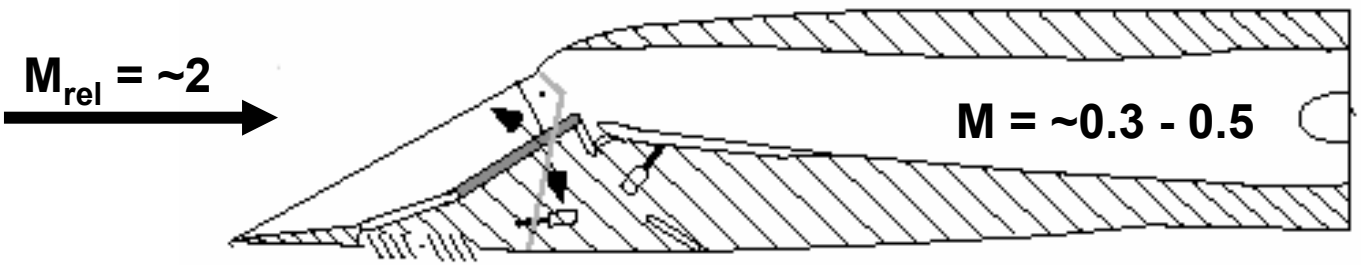
2-D Mixed Compression Inlet Model

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

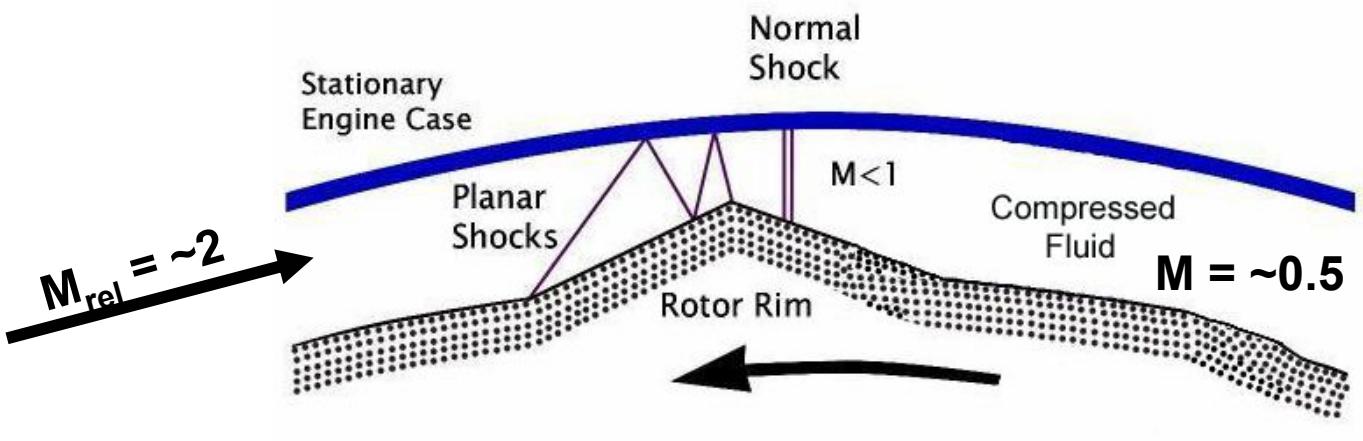
Supersonic Inlets = Efficient Compressors



Rampressor Rotor Development

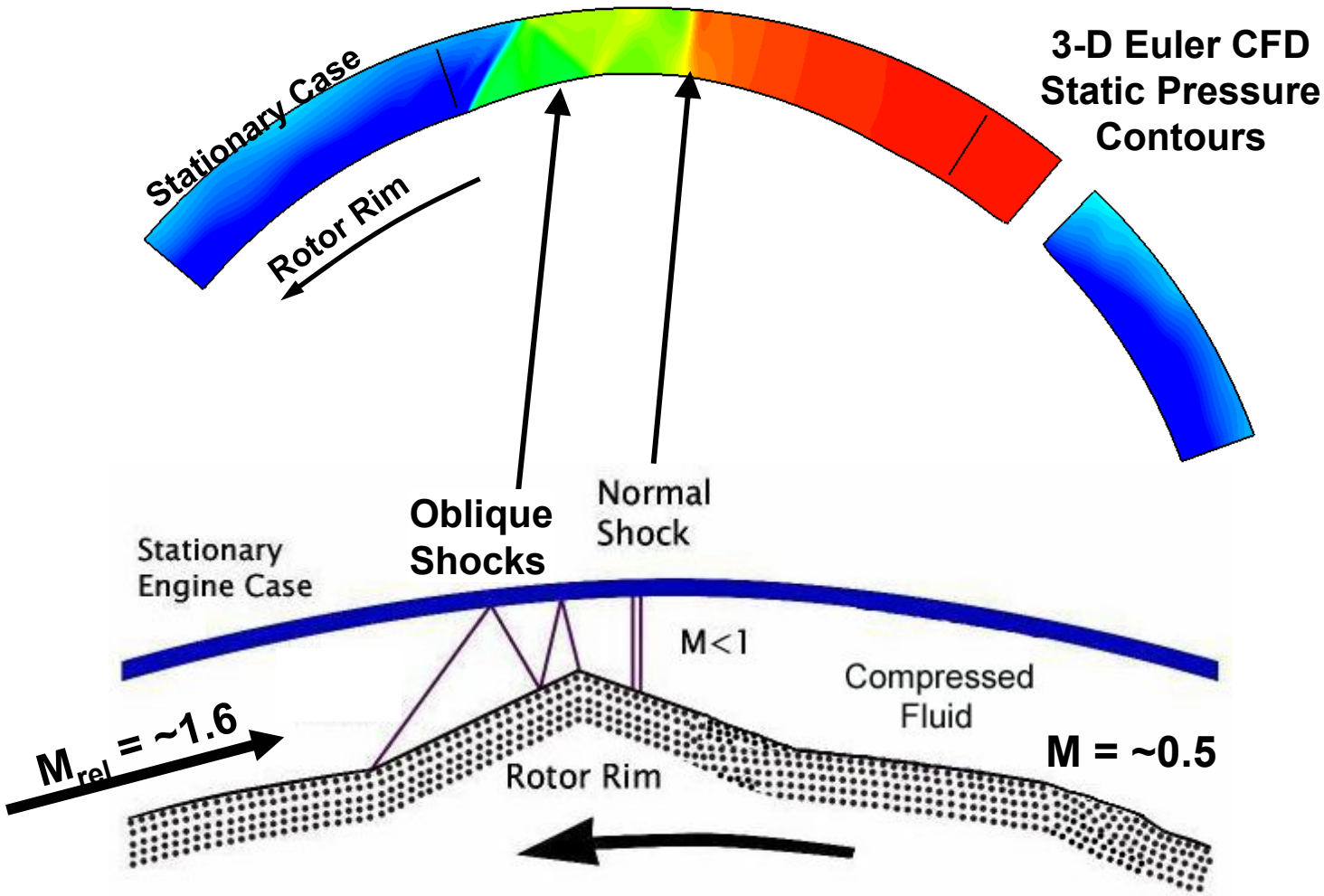


Supersonic F-15 Inlet



Rampressor Rotor

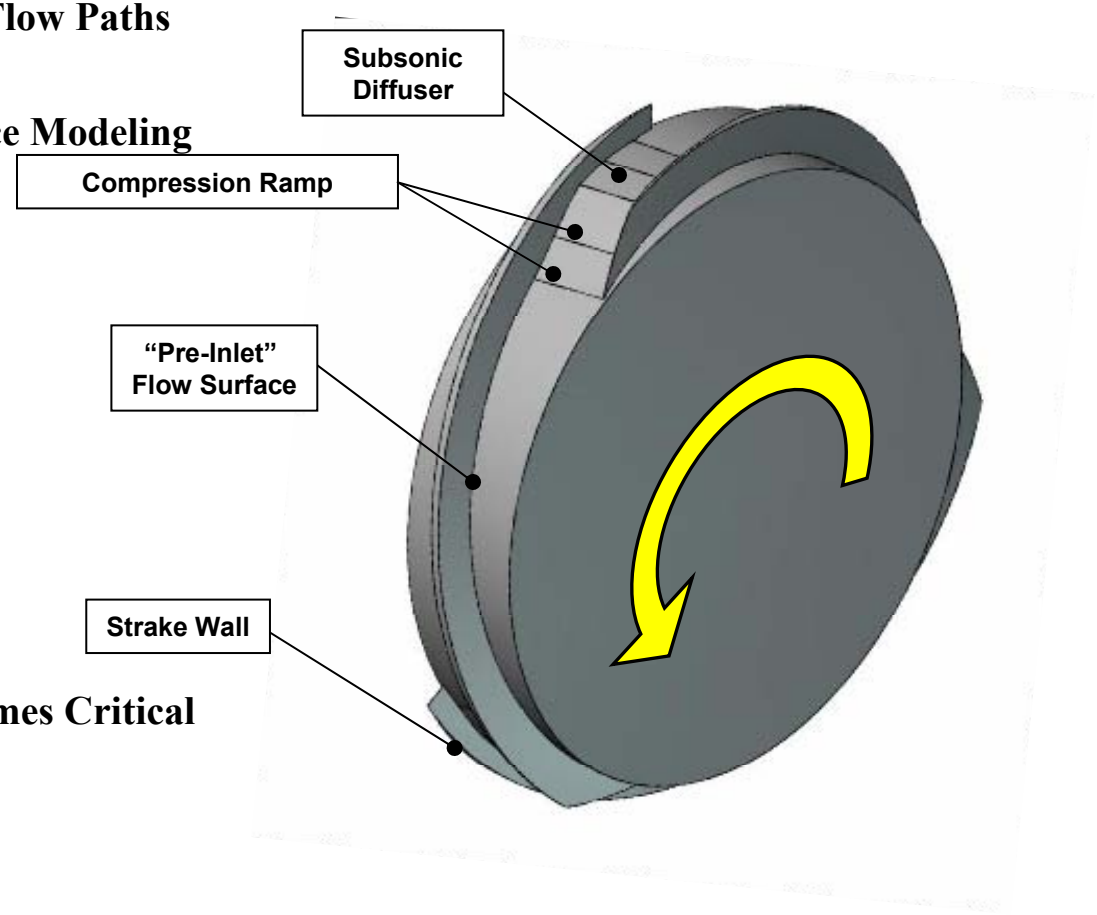
Rampressor 1 Design



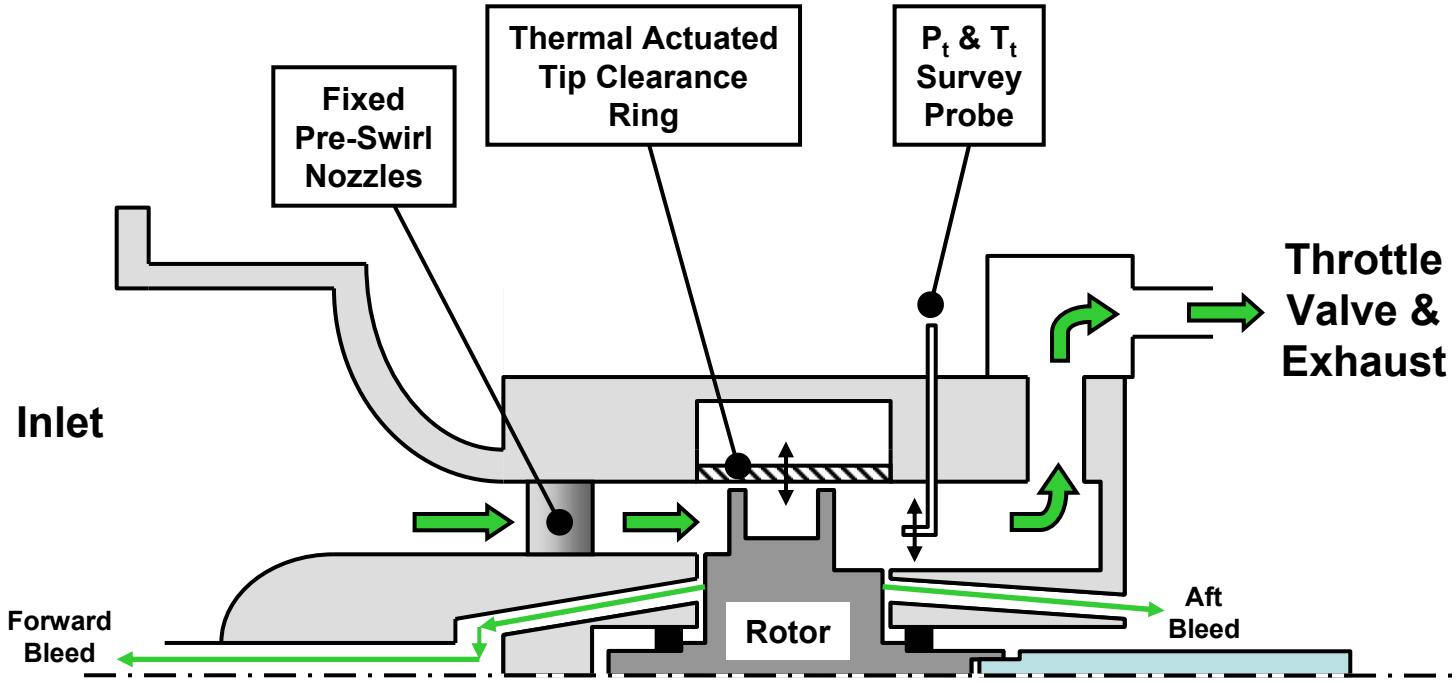
Rotating Supersonic Flow-Path

- **Rotor Flow Path:**
  - 3 Supersonic Compression Inlet Flow Paths
  - Shallow Helix Angle
  - Flight Inlet Design & Performance Modeling Techniques Applicable

- **System Features Required**
  - Bleed System Required
    - System Starting
    - Performance Optimization
  - Tip Gap Control
  - Rotor Discharge
    - Diffusion/Deswirl Design Becomes Critical

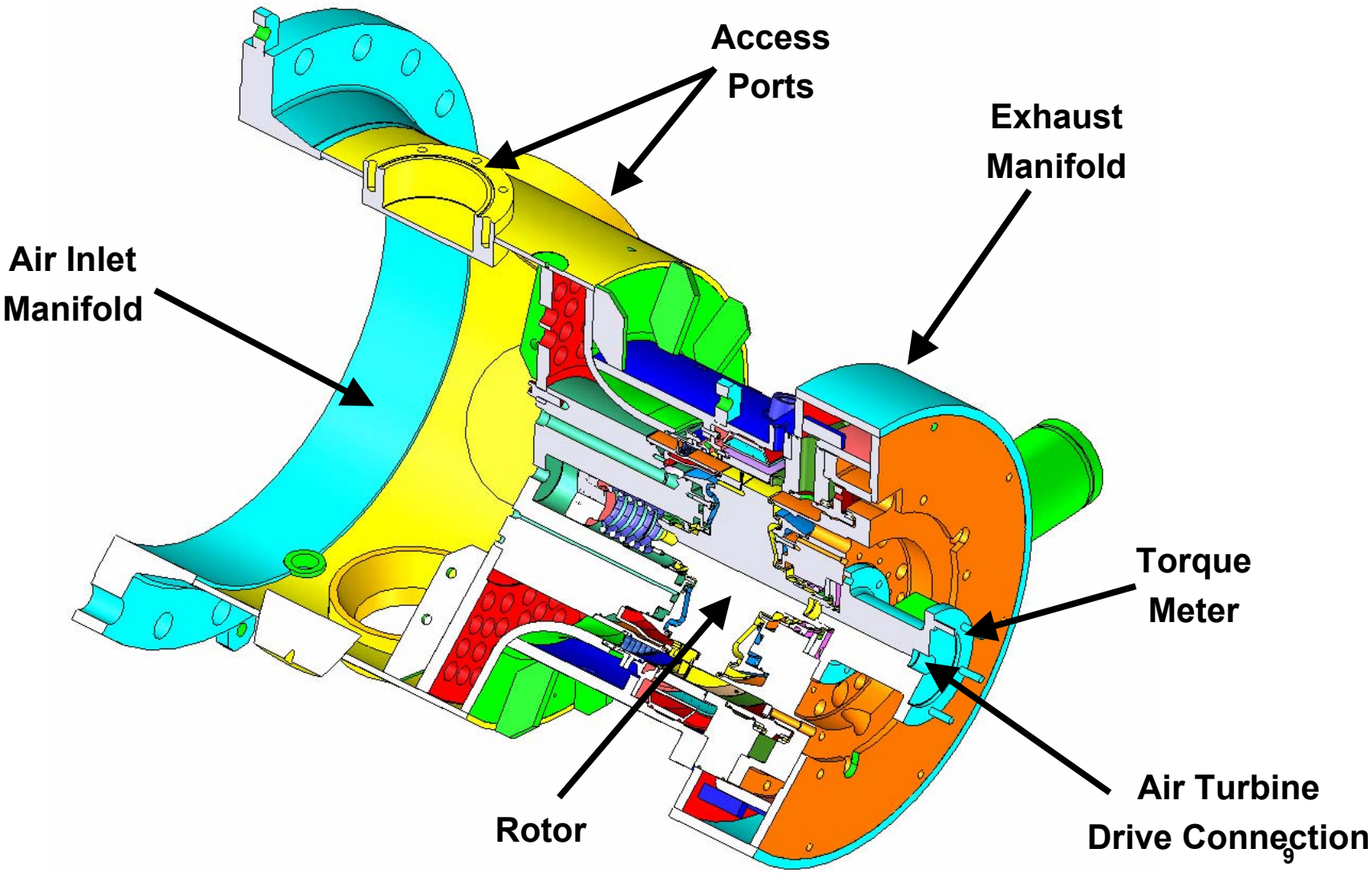


Simplified Test Rig Cross-Section

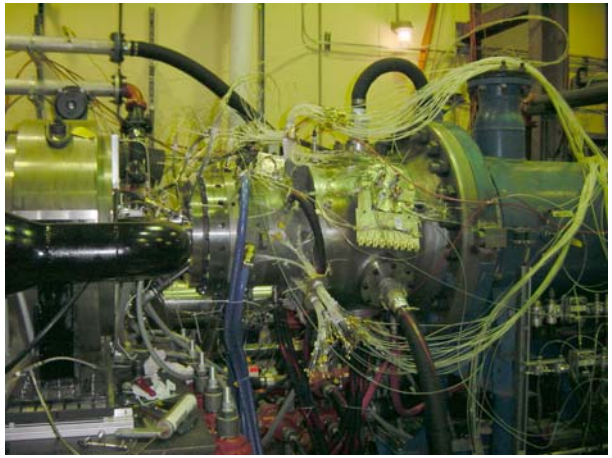


- **Rotor-Only Test Rig**
  - Upstream/downstream components not optimized for minimal loss
  - PSN pressure loss characterized and discounted from rotor performance
  - Exhaust diffusion/de-swirl losses not measured

Rampressor 1 Test Rig Assembly



Rampressor 1 Assembly & Integration



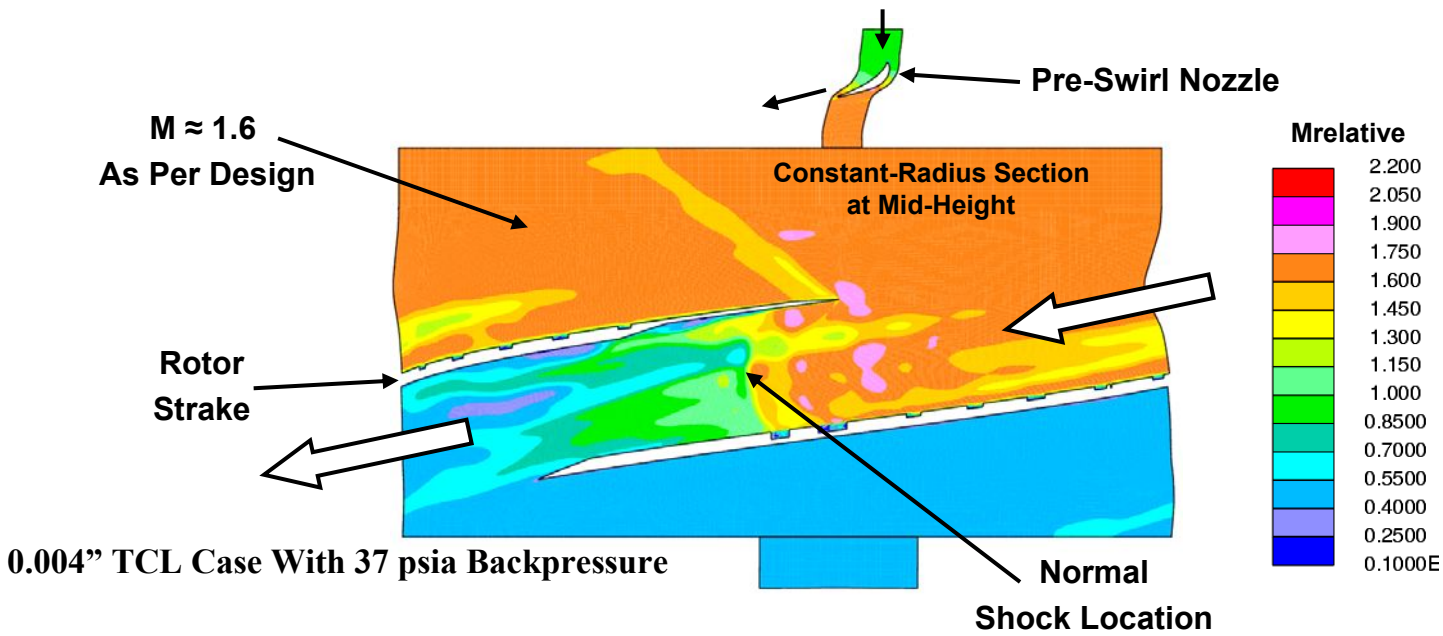
Test Assembly

Tip Clearance Calibration

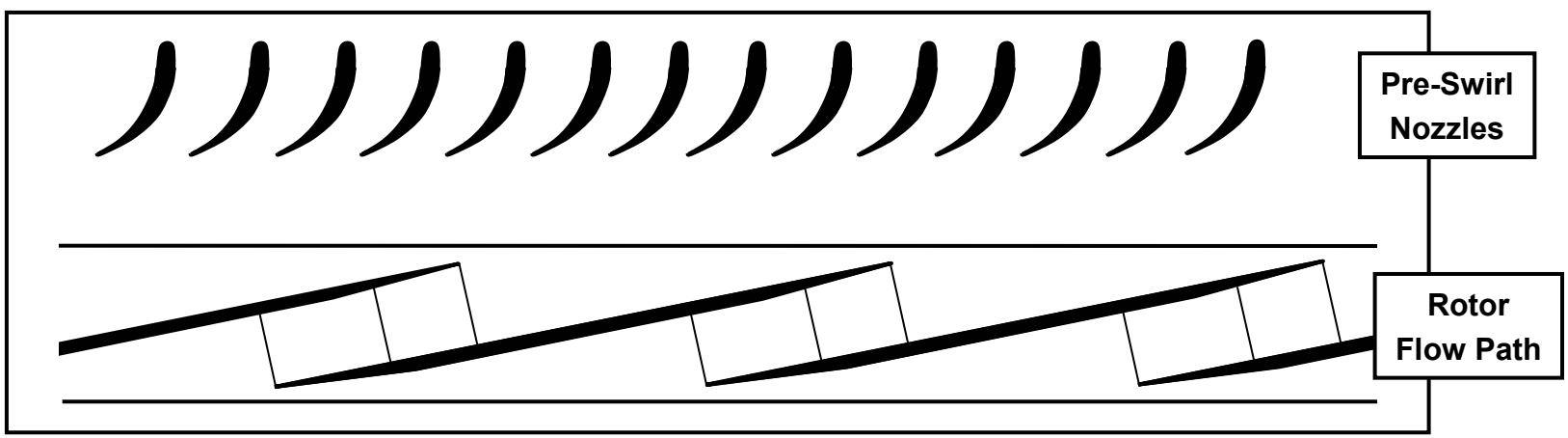
Rotor Spin Pit Proof Testing

Rotor Bleed Hole Patterns

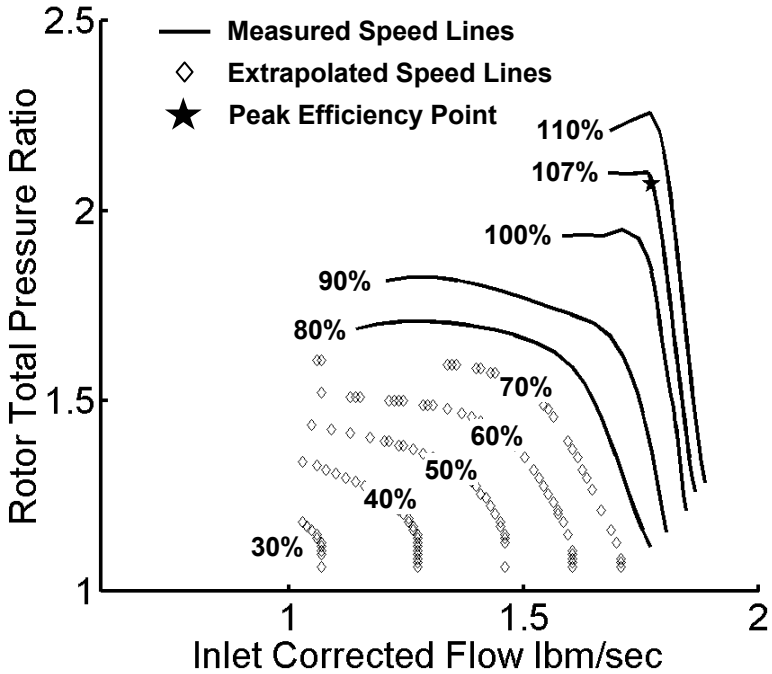
Rampressor 1 Compressor Typical CFD Results

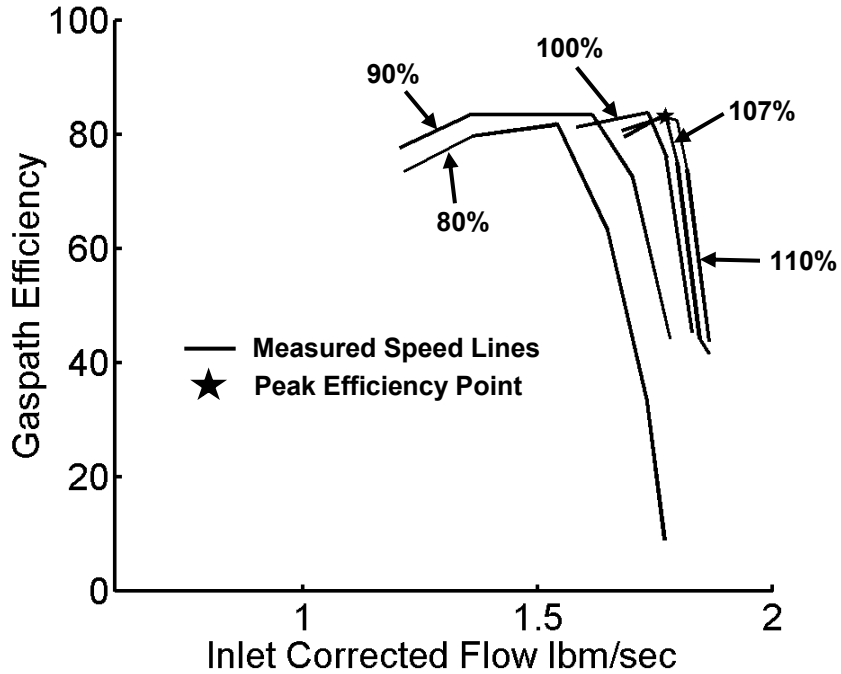


0.004" TCL Case With 37 psia Backpressure



RP-1 Compressor Maps

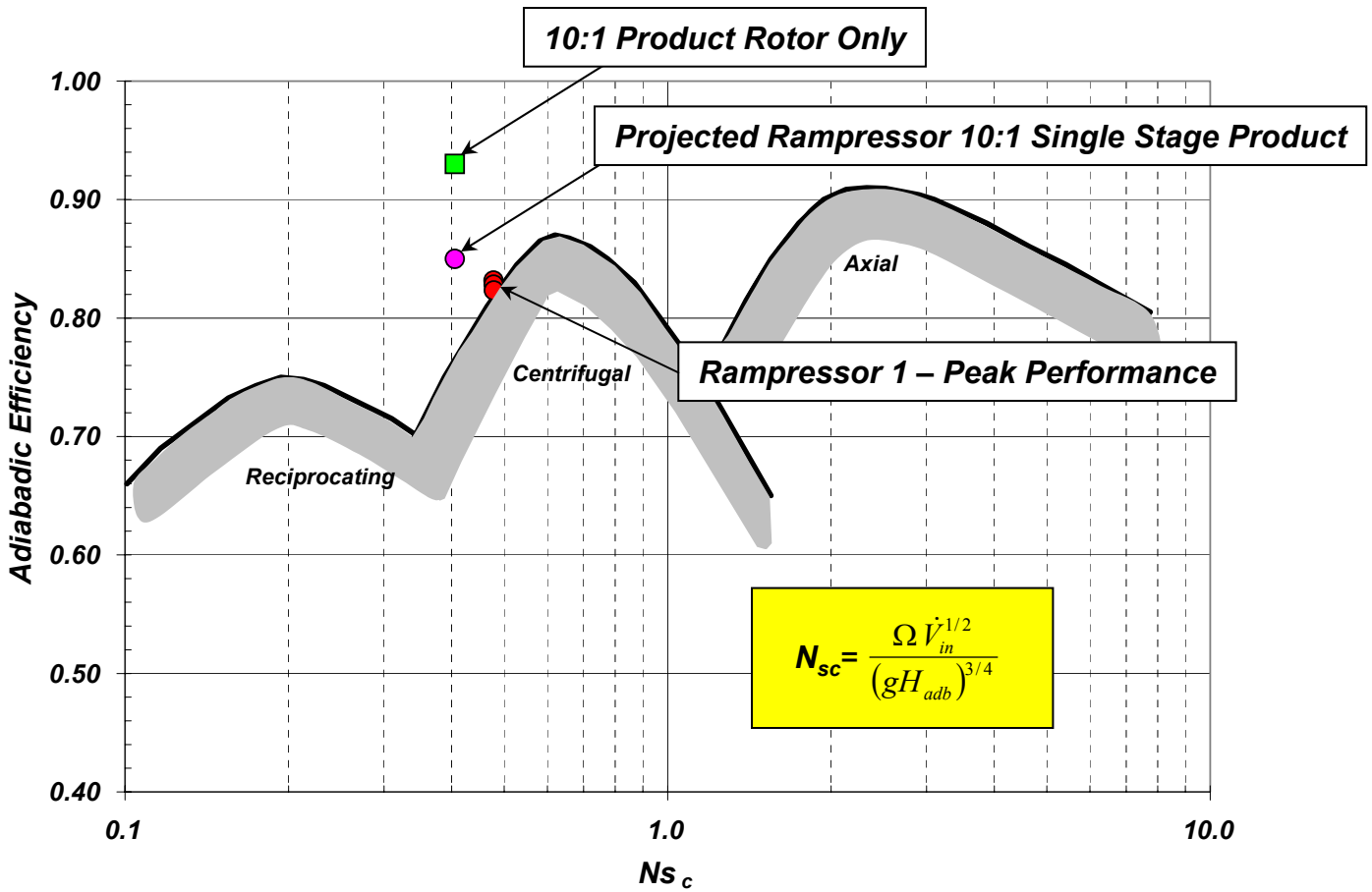




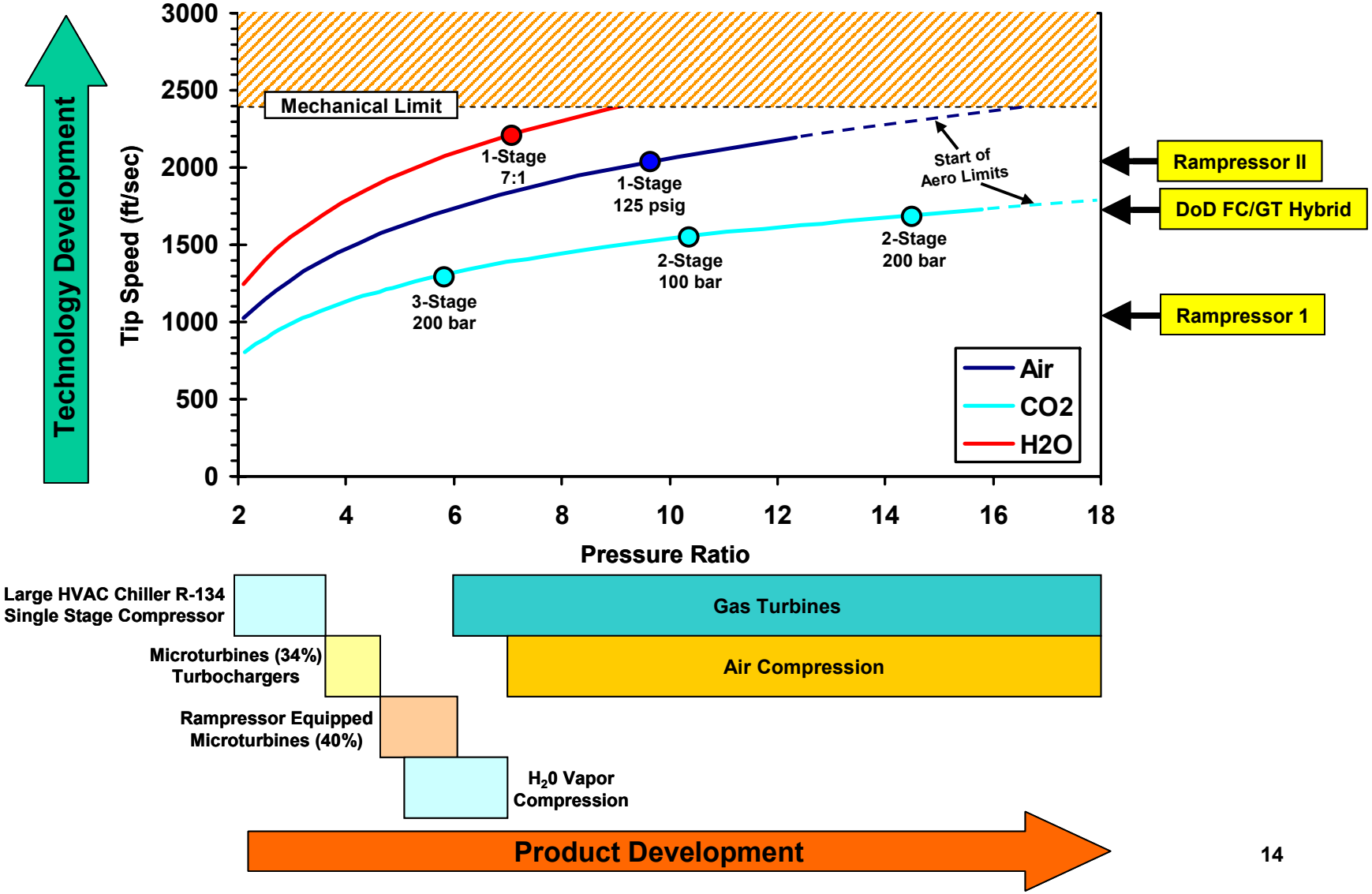
- **Rampressor Has Significant Off-Design Capabilities**
  - **Pressure ratio**
  - **Mass flow**
  - **Gaspath/rotor efficiency**
- **Proof-of-Concept Results**
  - **Incomplete compressor map - more complete maps with additional test rigs/CFD modeling/product prototype demonstrations**
  - **Efficiency and pressure ratio will be improved with product development**

Rampressor Stage Performance

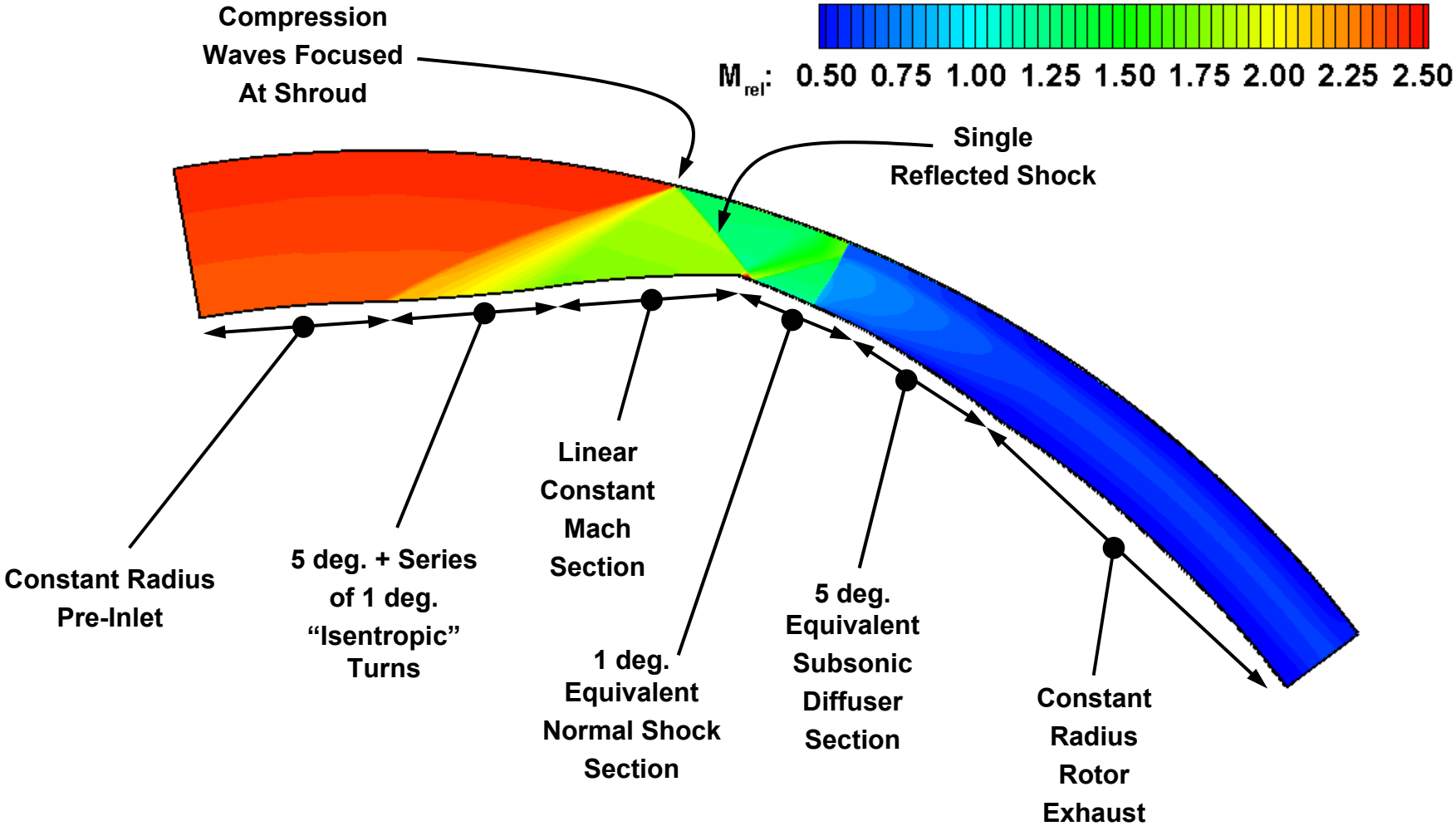
- **Standard Dimensionless Specific Speed Definition**
- **Representative Performance Ranges - Various Compressor Types**
- **Current Rampressor System Concepts N_{sc}~ 0.3 – 0.8**



Rampressor Applications vs. PR/Tip Speed



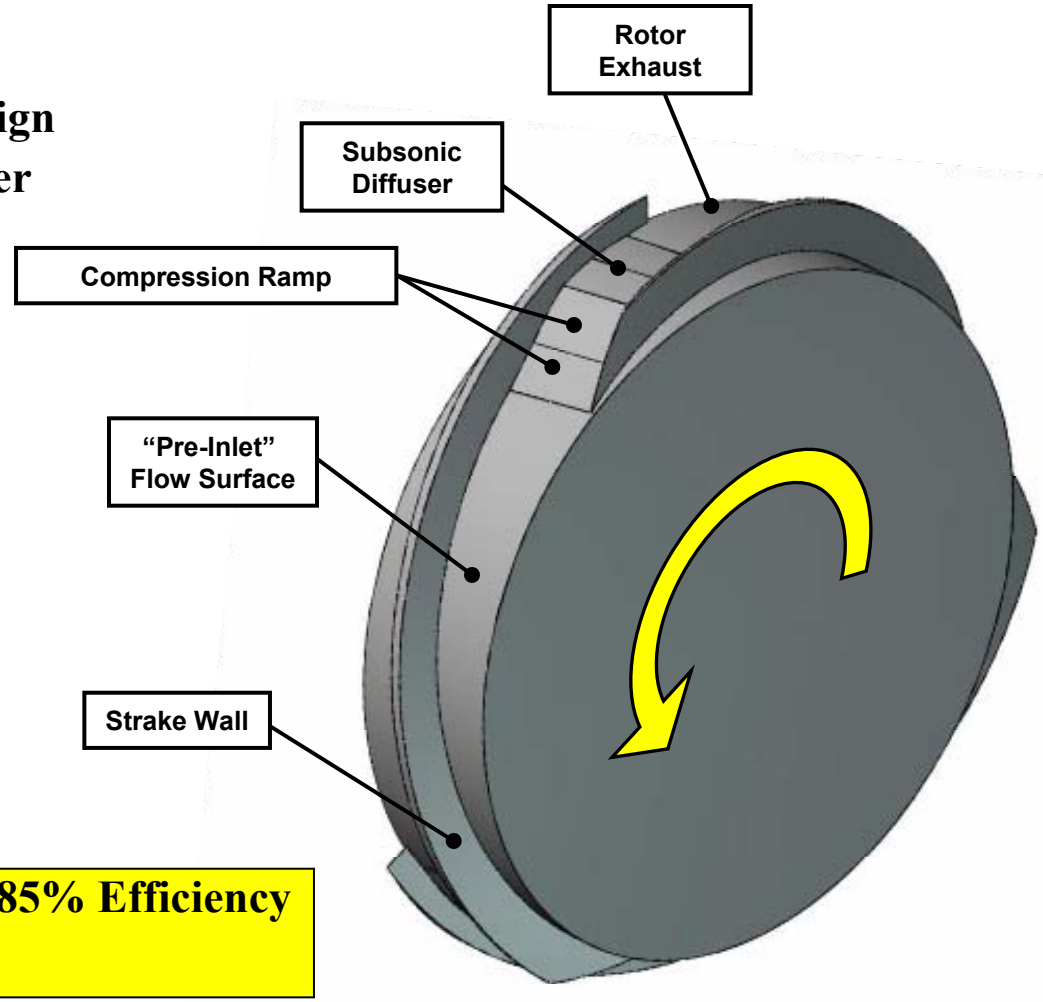
Ideal-Inviscid 2-D Inlet Design, PR~10:1



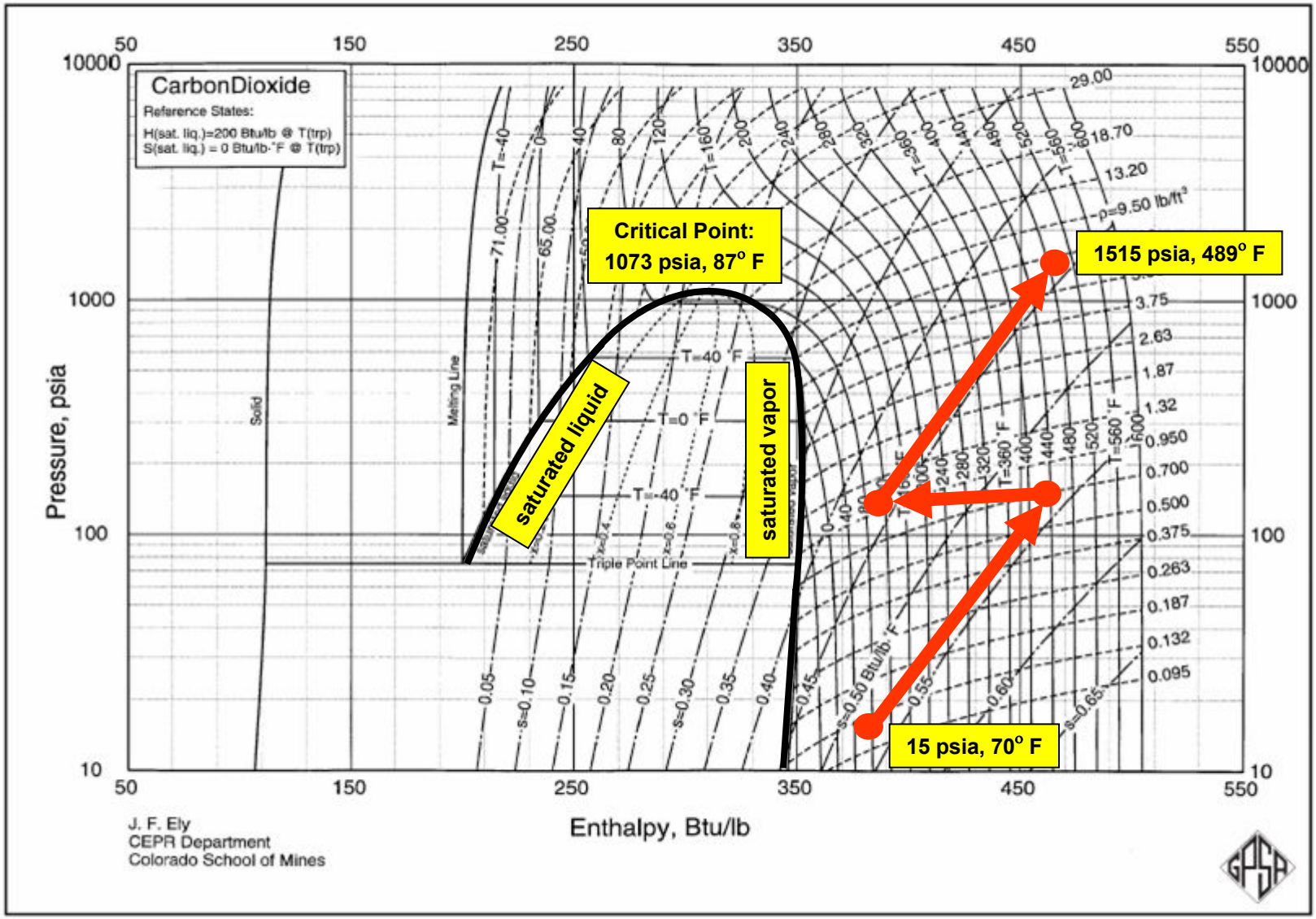
- 2-D Inviscid Used To Determine Starting Geometry for 3-D Viscous Simulations

Rampressor-2 Rotor Design

- Nominally Mach 2.4 Relative Inlet Design
  - Mean Radius Relative Mach Number
- Pre-Swirl/Pre-Whirl = 0.69
  - On The Mean Inflow Radius
- Stake Wall Has 8 degree Helix Angle
- Pre-Inlet Rim 4.782” Radius
- Strake Diameter Nominally 5.460”
- Throat Radius Nominally 5.150”
- Inlet Aspect Ratio ~2.0
  - Throat AR ~ 4.4
- Inlet Contraction Ratio
  - Nominally 2.19
- Rotation Rate of 41,837 RPM @ 50º F
- **Nominal 10:1 Pressure Ratio and Mid 85% Efficiency (rotor only)**



Ramgen 2-Stage CO_2 Compressor

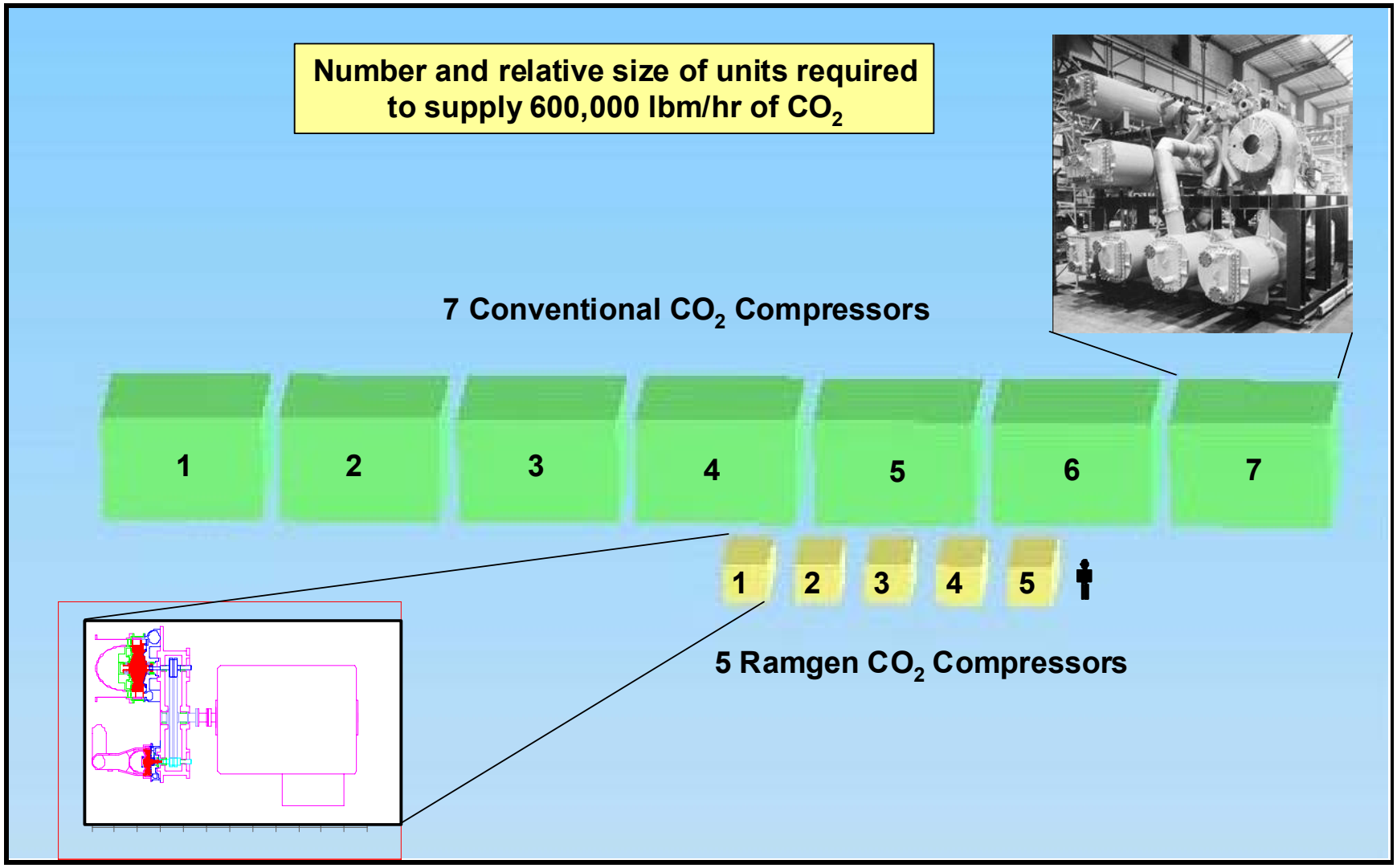


System Comparisons

- **High PR Supersonic Stages Offer Significant Reduction in Stage Counts Compared to Conventional Turbo-Machinery Designs**
  - **PR's of 45:1 – 200:1 Achieved with 2-3 Supersonic Stages**
  - **Rampressor Designs Result in Comparable Isothermal Efficiencies**
  - **Use of Conventional Designs Requires 6-10 Stages for Comparable PR's**
  - **Increased Stage Pressure Ratios Result in More Recoverable Heat of Compression**

	Rampressor Systems			*Conventional Systems*	
Case	***1***	***2***	***3***	***4***	***5***
No. of Stages	*2*	*2*	*3*	*6*	*10*
Pressure Ratio	*45*	*200*	*200*	*45*	*200*
Inlet Water Temp (K)	*303*	*300*	*300*	*303*	*303*
P_{in} (kPa)	*187.5*	*99.9*	*99.9*	*187.5*	*99.9*
P_{out} (kPa)	*8,377*	*19,989*	*19,989*	*8,377*	*19,989*
Mass Flow (kg/s)	*89.51*	*10.56*	*10.56*	*89.51*	*10.81*
Volumetric In-Flow (m^3/s)	*29.02*	*6.31*	*6.29*	*29.00*	*6.52*
Drive Power (kW)	*28,614*	*5,130*	*4,538*	*28,818*	*4,695*
BHP/100	*61.62*	*49.79*	*44.04*	*62.90*	*45.57*
Isothermal Eff.	*0.7342*	*0.6733*	*0.7612*	*0.7169*	*0.7357*

Size Advantage of Supersonic Compressor



Conclusions

- Rampressor 1 Tests Demonstrated Basic Operation of Supersonic Compression Rotor
  - Starting
  - Performance at Design Speed
  - Benign Surge/Stall Characteristics
  - Performance at Part Speed
- Minimizing Tip Clearance/Leakage Critical to Optimizing Performance
- Design Tools Demonstrated
  - 1-D Mean-line Analysis
  - 3-D Viscous CFD
- Currently Preparing for Rampressor-2 Test
  - Design Mach Number: 2.4
  - Pressure Ratio: 8:1
  - Mass Flow: ~ 3 lbm/s
- Ramgen Proceeding With Conceptual Design of CO_2 Compressor
  - System Offers Dramatic Size & Cost Advantages Over Existing Compressors
  - 2 & 3 Stage Designs Support Improved Waste Heat Recovery