Shock Compression Technology Applied to CCS Applications

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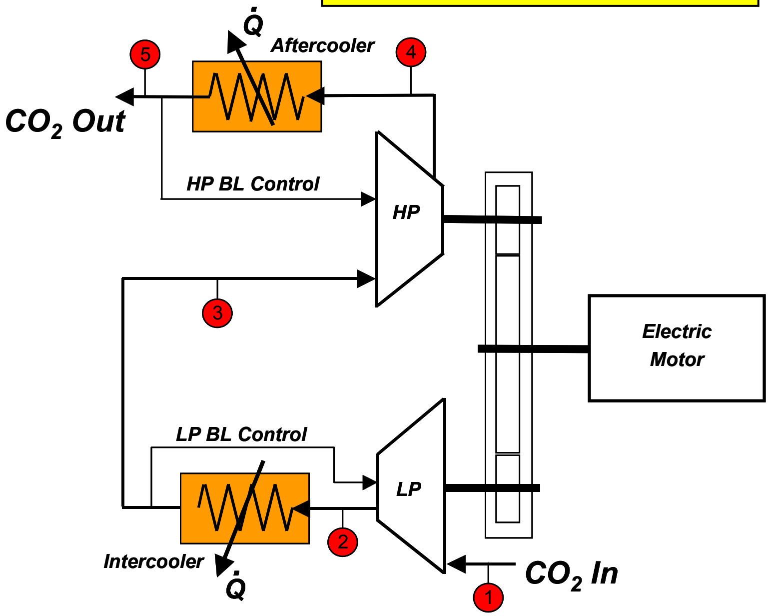
Typical System Performance Requirements - CCS

- IGCC & PC retrofits (geologic carbon sequestration)
  - PR ~ 100:1 (suction pressure ~ 15 psia)
  - Two comparably loaded stages
  - Stage efficiency ~ 85%
  - Mass flow range ~ 30%

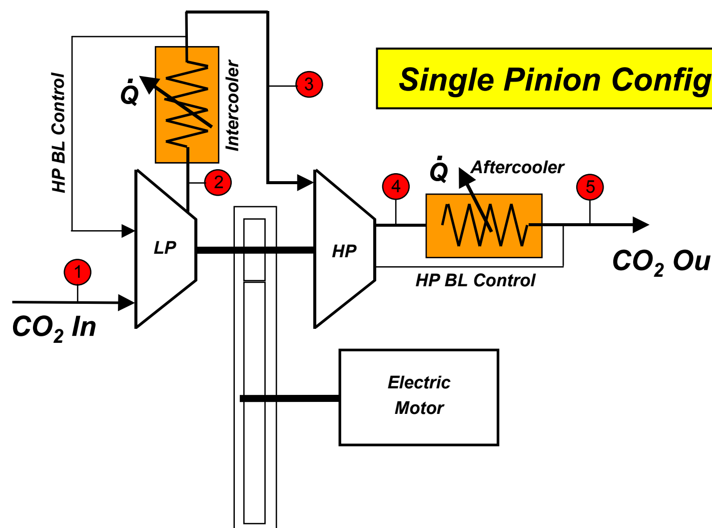
Property Summary by Station – 3,000 hp

Property	Station 1	Station 2	Station 3	Station 4	Station 5
P (psia)	14.6	150.7	144.6	1,489.7	1,460.8
T (F)	100.0	480.8	91.8	489.8	194.7
ρ (pcf)	0.1082	0.6613	1.1277	6.7633	12.7410
a (fps)	898.3	1138.7	873.2	1144.5	855.7
V (fps)	179.2	113.9	174.2	114.5	50.0
P_t (psia)	15.0	151.7	148.3	1,499.3	1,465.7
T_t (F)	100.0	481.9	95.0	491.0	195.0
Mass (pps)	12.4				12.4

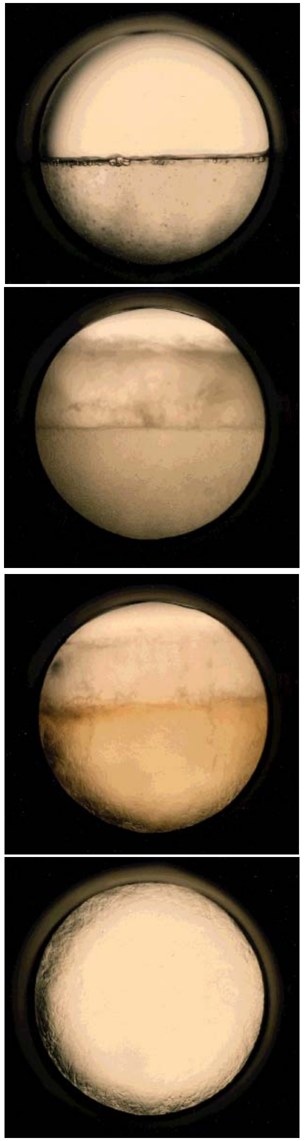
Dual Pinion Configuration



Single Pinion Configuration



PT Diagram & Supercritical Phase



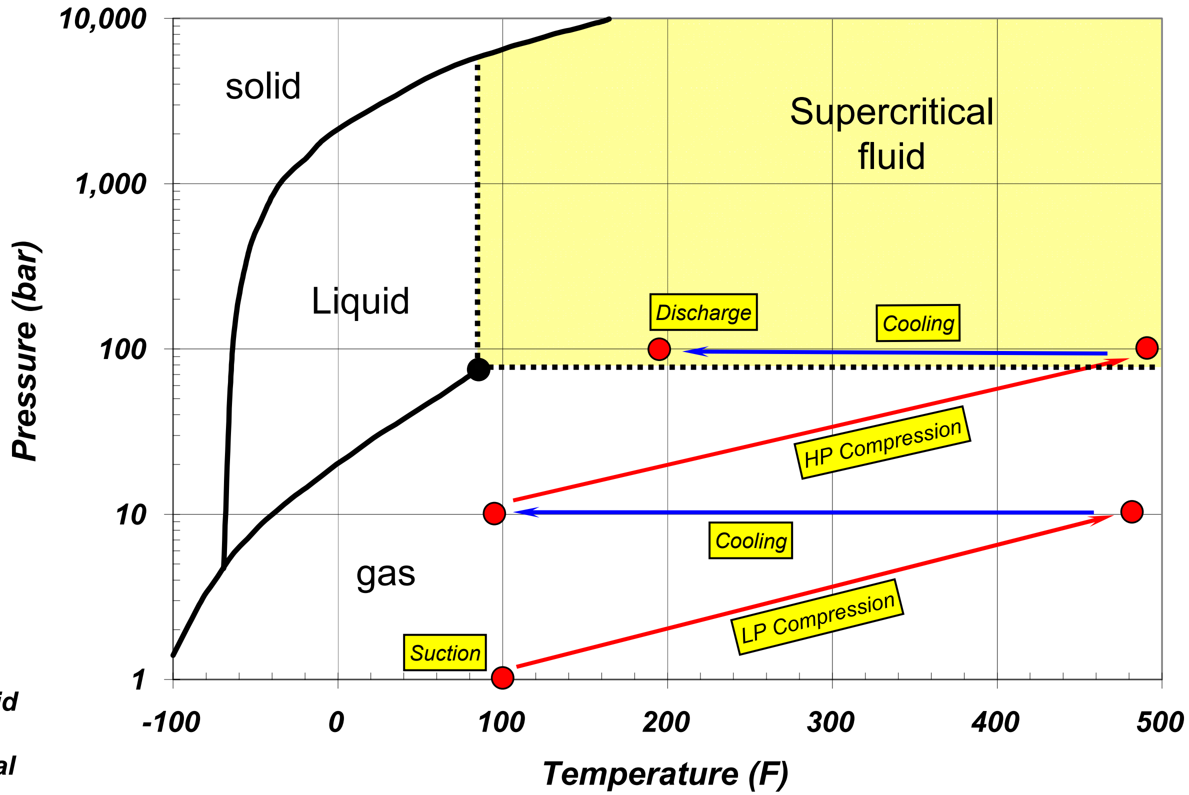
Separate Phases Visible- Meniscus Clearly Observed

Increase in Temperature- Diminished Meniscus

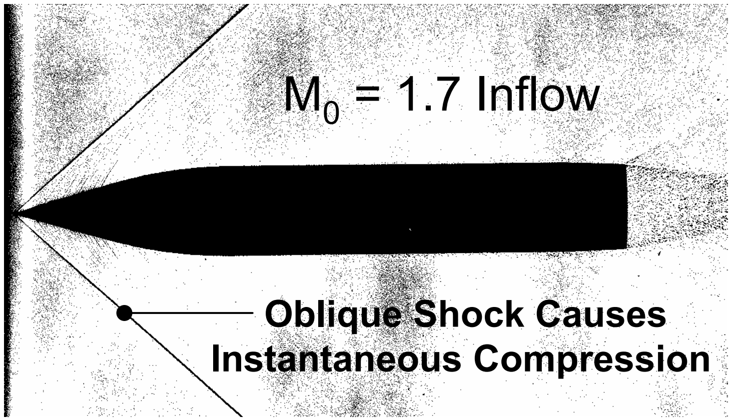
Further Increase in Temperature- Gas & Liquid Densities more Similar

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

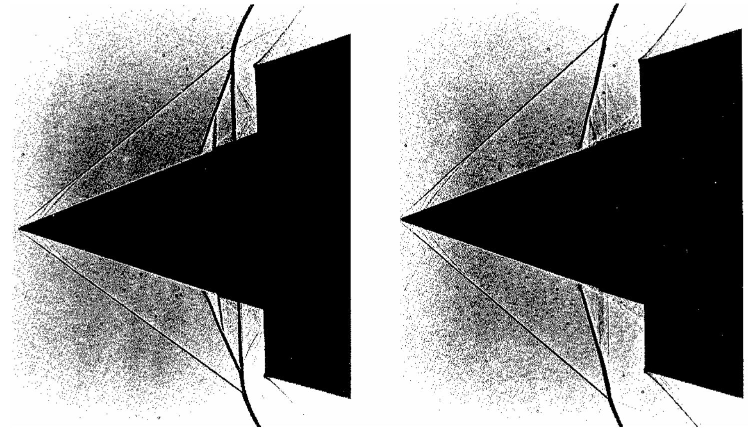
- **Compression process transitions from superheated to supercritical phases**
- **Avoids liquid (sub-cooled) phase**



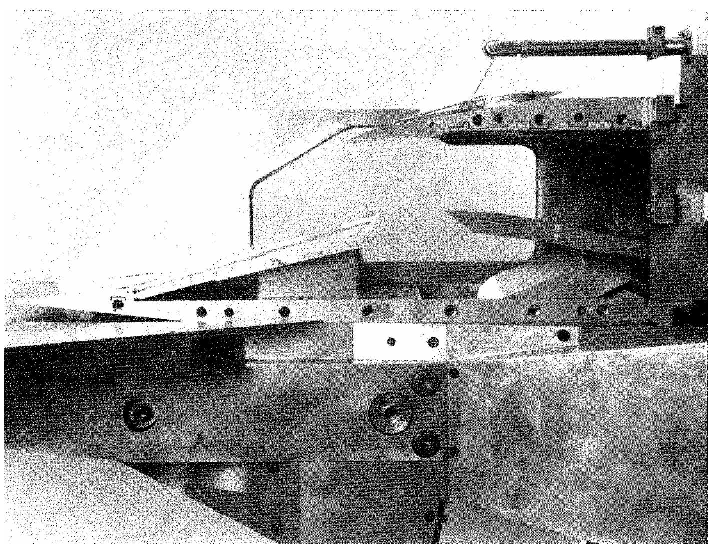
Performance - Shock Waves to Supersonic Inlets



Schlieren Photo of Projectile with Shocks



Schlieren Photo of Inlet Center-body and Cowl with Shocks



2-D Mixed Compression Inlet Model

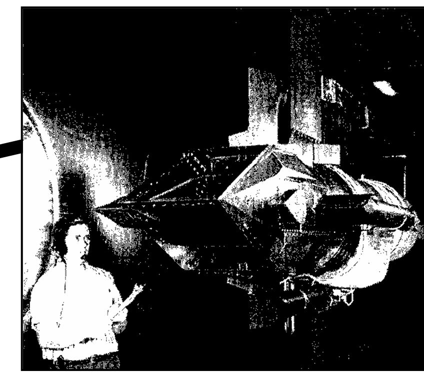
- Initial External Shock System Followed by Internal Shock System
- Throat Bleed Slot For Inlet Starting
- Side Window For Schlieren Photography

Typical Supersonic Inlet Performance

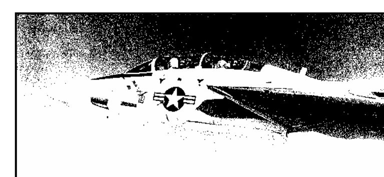
USAF F-15
M_∞= 2.0

Concorde SST
M_∞= 2.0

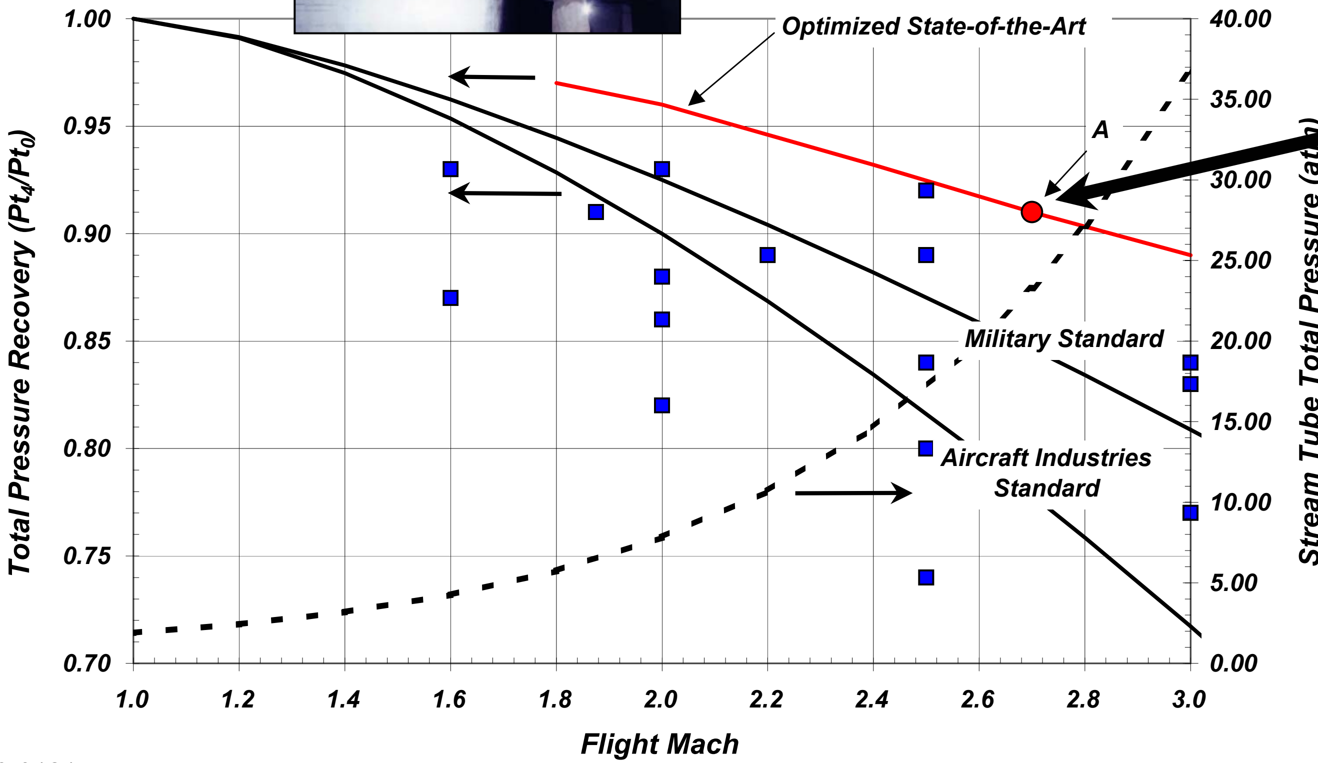
M_∞= 1.5-2.0 Model



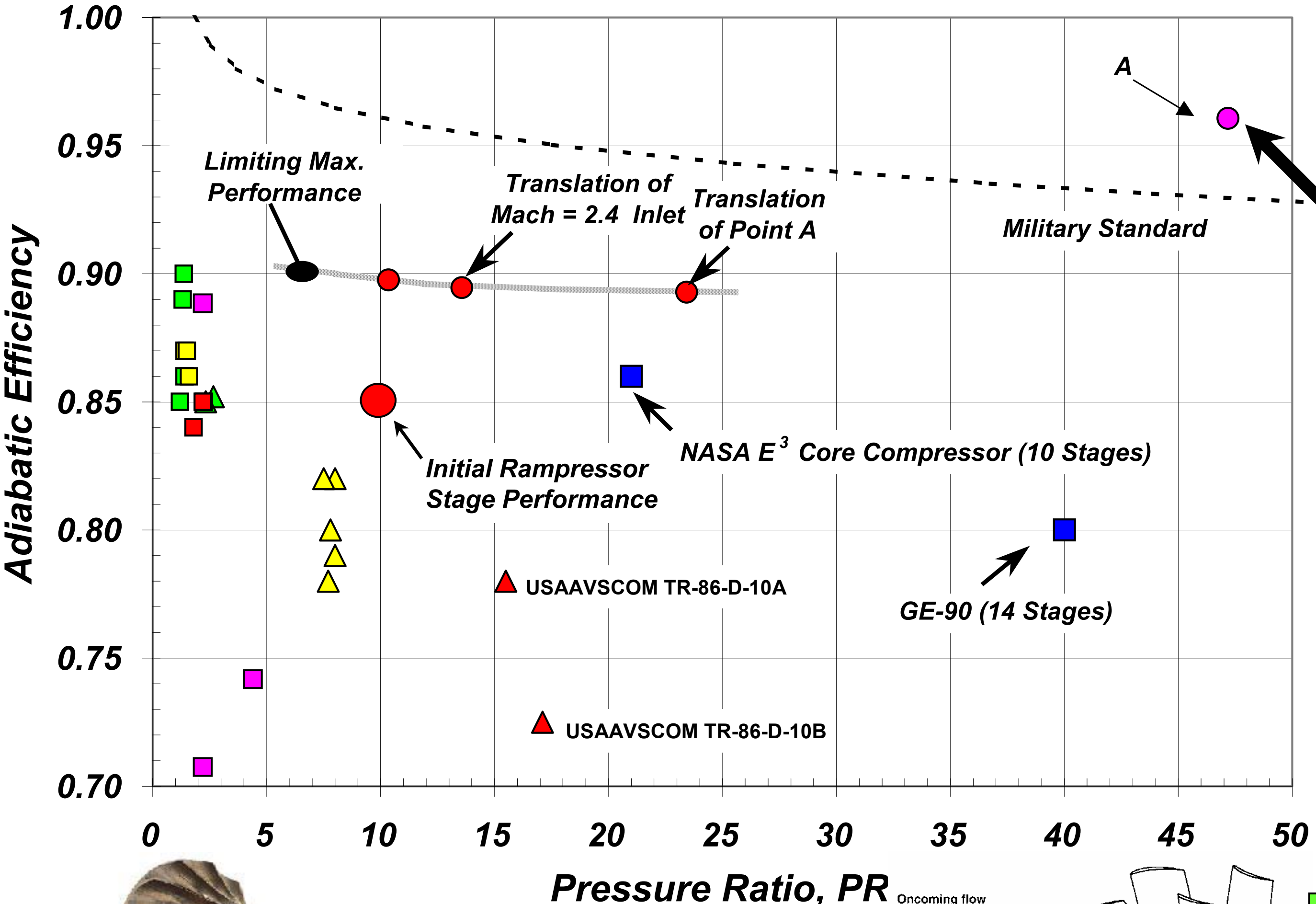
M_∞= 2.7 Model
(Point "A" on Chart)

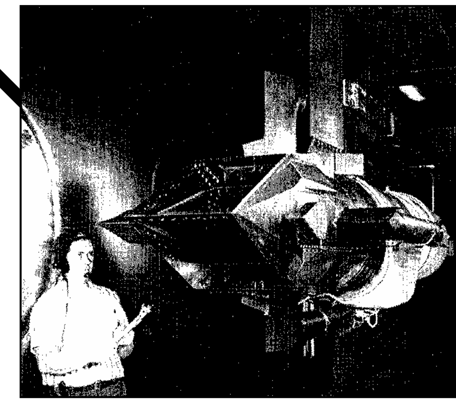


USN F-14
M_∞= 2.4



Supersonic Inlets Are Efficient Compressors

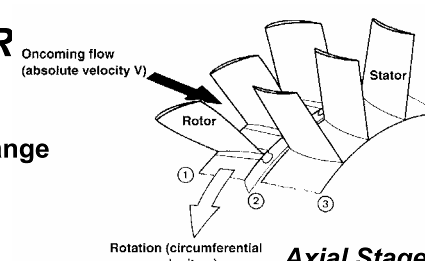




M_∞= 2.7 Model
(Point "A" on Chart)

Centrifugal Stage

- Low PR / High Efficiency /Good Range
- Med PR / Lower Efficiency / Decreased Range
- High PR / Low Efficiency / No Range

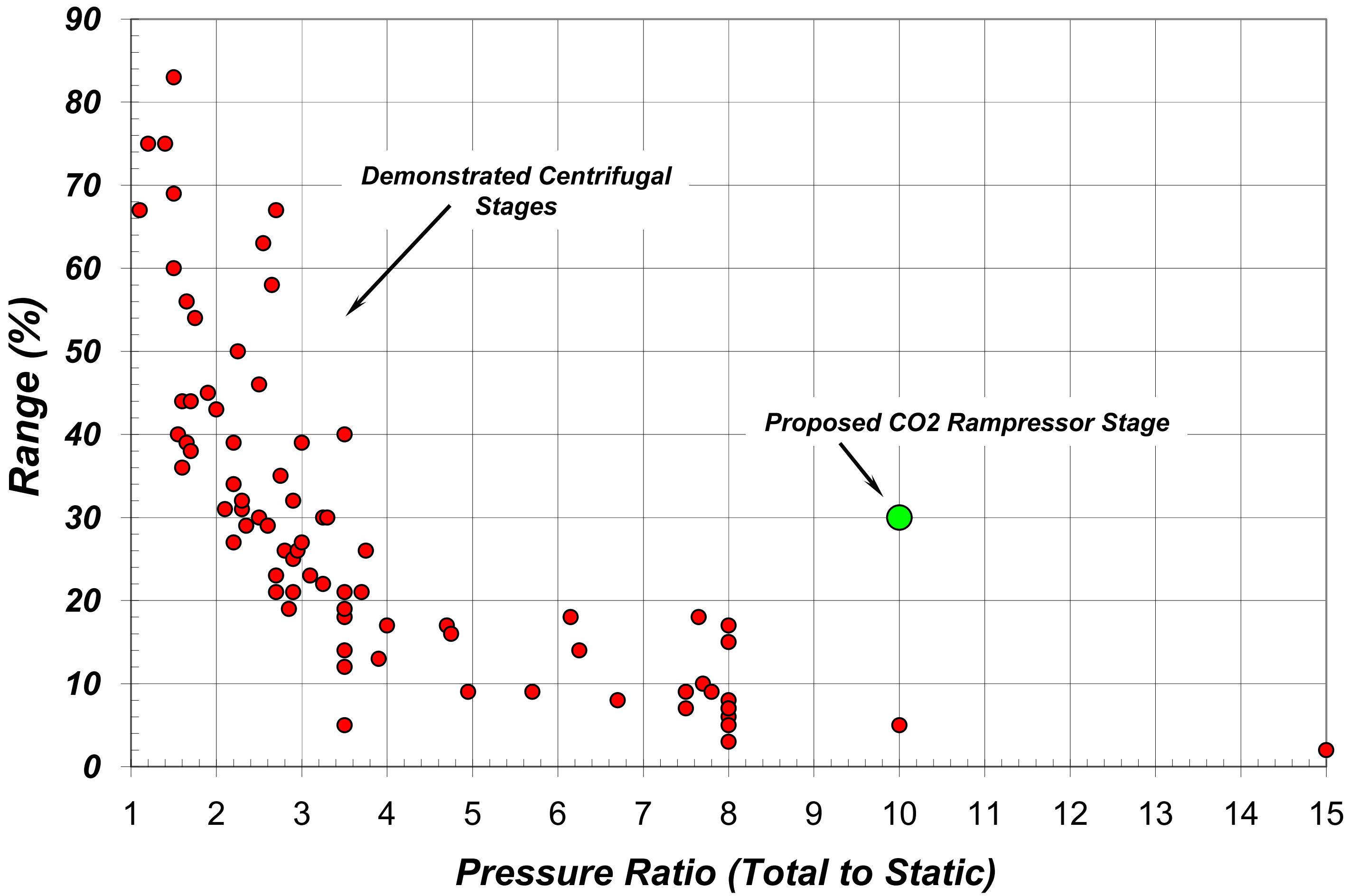


Axial Stage

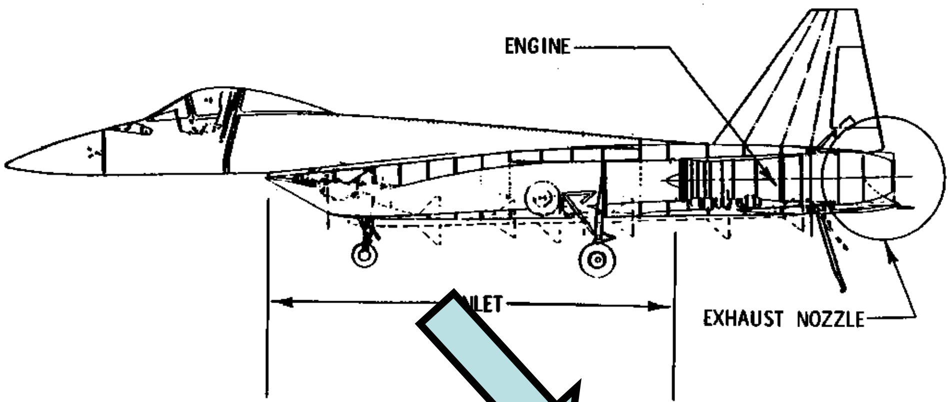
- Lightly Loaded / Subsonic
- Increased Loading / Transonic
- Advanced Highly Loaded
- Multi-Stage Axial Compressors
- Supersonic Axial Stages

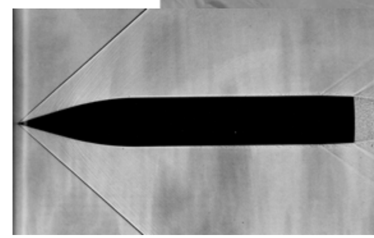
Range / Turndown Strong Function of PR

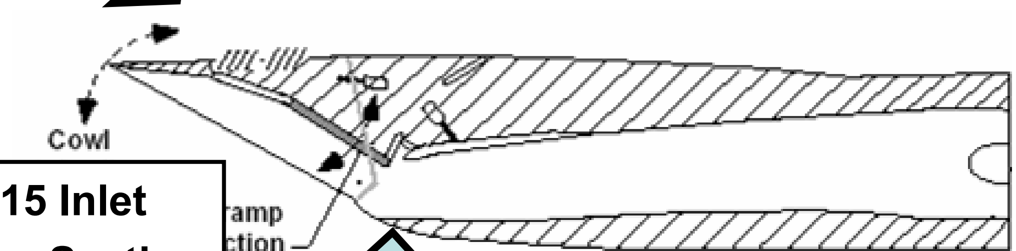
- **Rampressor achieves high stage PR & efficiency with improved range compared to centrifugal stages**



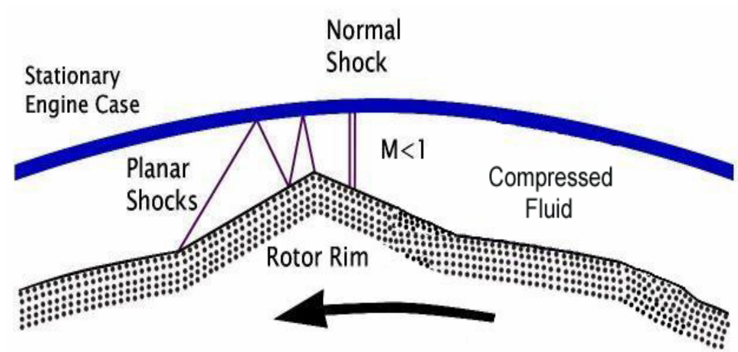
Development of Rim Compression Concept





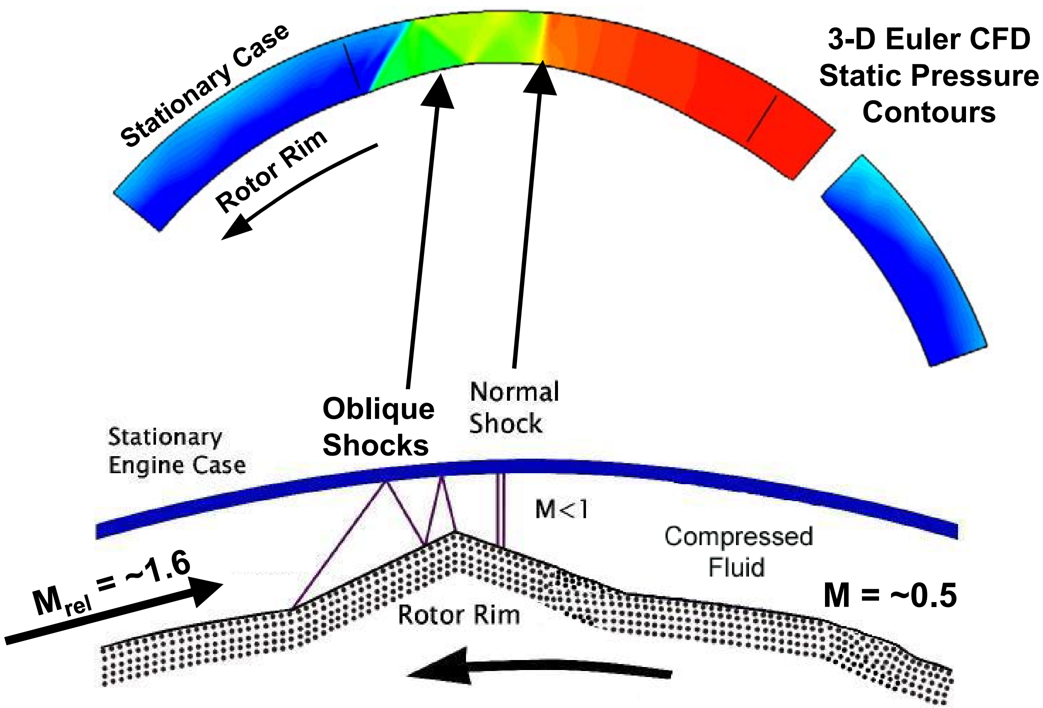


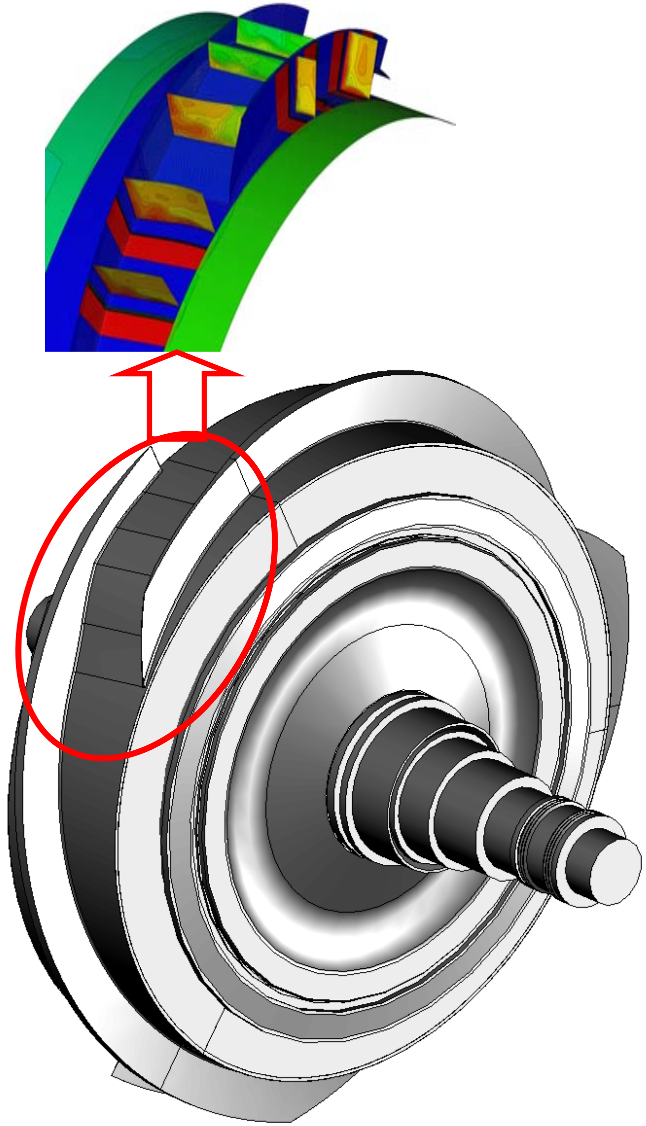
F-15 Inlet Cross Section



Rampressor Rotor

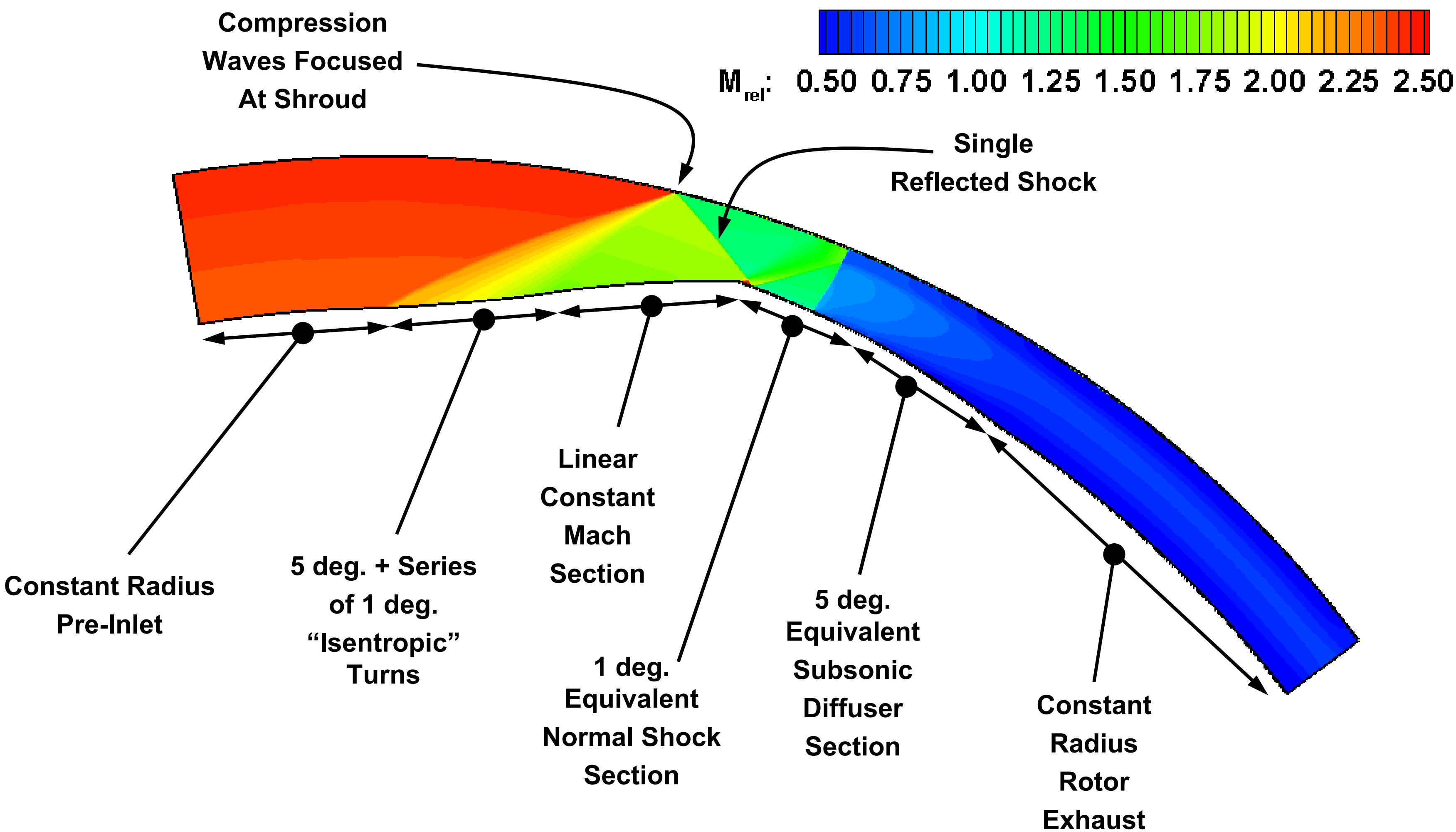
Rampressor 3-D Geometry & Flowfield





- **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**

Ideal-Inviscid 2-D Inlet Design

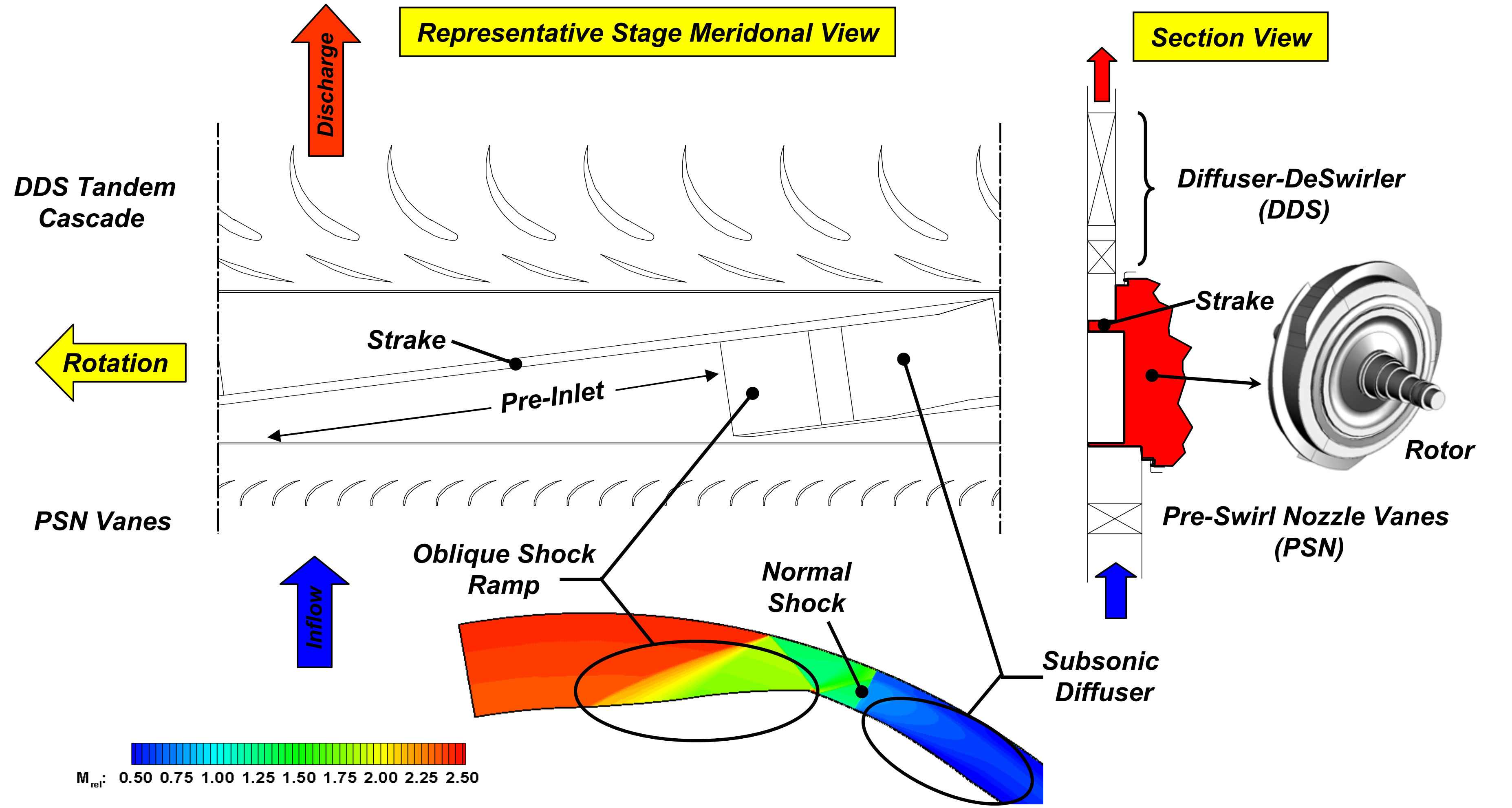


- **2-D Inviscid Used To Determine Starting Geometry for 3-D Viscous Simulations**

PSN – Rotor Flow Visualization

Loss Modeling - Stage Components

- **Design point PR assumes conventional static components & supersonic shock compression with on-rotor active BL control**



Design Point Pressure Ratio & Efficiency

- **Design point PR assumes conventional static components & supersonic shock compression with on-rotor active BL control**
- **Efficiency projections include all key loss mechanisms & cycle charges**
- **RPS 1D design tool (CADRE) integrates component performance inputs & uses real gas properties (NIST) to determine station by station property variation & integrated system performance**

	CO2 Demo Unit Performance Metrics		Industry Standard Basis for Ramgen's Metrics	Future Growth Potenial
	Stage 1	Stage 2		
PSN Total Pressure Recovery	**97.0%**	**95.4%**	97%	97%
Rotor	**82.6%**	**82.5%**		87%
Pre-Inlet Pt Recovery	96.0%	96.0%		94%
Tip Leakage Pt Recovery	97.0%	97.0%		97%
Shock Compression Pt Recovery	89.2%	89.3%	95.50%	95.50%
Boundary Layer Control Power Loss	2.0%	2.0%	1%	1%
DDS Total Pressure Recovery	**95.8%**	**96.7%**	96%	96%
Rotor Only Pressure Ratio (total/total)	**10.92**	**10.87**		
Rotor Only Adiabatic Efficiency	**88.7%**	**88.7%**		93%
Stage Pressure Ratio (total/total)	**10.11**	**10.11**		
Stage Adiabatic Efficiency	**85.4%**	**85.4%**		89%

Critical Background Activities

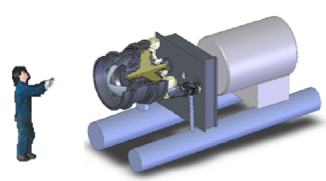
- **Rampressor 1**
  - Began Q2 2002 / completed Q1 2004
  - Designed for inlet M_{rel} ~ 1.6, achieved PR ~ 2.3
  - Validated design tools with PR, mass flow & efficiency
  - Demonstrated multi-flowpath starting & stable operation
  - Operated in controlled supply & self aspirated modes
  - Illustrated wide turndown potential & benign surge characteristics
- **Rampressor 2**
  - Began Q1 2004 / completed Q2 2007
  - Test schedule required release of rotor aero design prior to completion of design optimization – result: low PR & efficiency compared to potential
  - Designed for inlet M_{rel} ~ 2.4 -2.7, achieved significant rotor PR – data analysis ongoing
  - Validated design tools & techniques for Mach no's traceable to proposed CO_2 product
- **Rotor Flowpath Performance Improvement Program**
  - Identified & demonstrated techniques to achieve target product rotor performance levels using 3D viscous CFD validated by RP-1 & RP-2

Notional Family of Frame Sizes

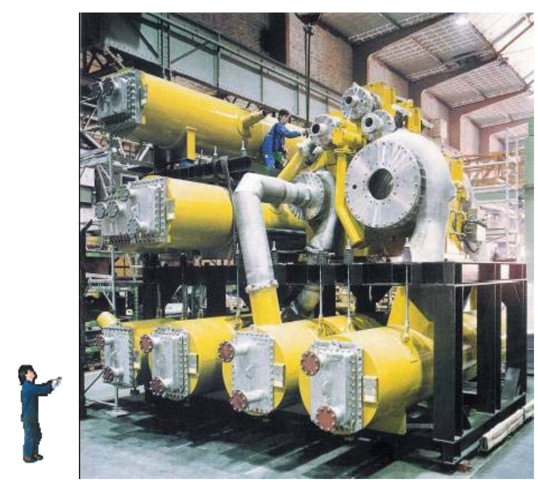
- **Highly scalable design supports wide range of system sizes and capacities**
- **Decreased stage count results in dramatic reduction in size compared to conventional multistage axial**

Frame	Nominal Power (hp)	Nominal Capacity (lb/hr)	Pressure Ratio	Stages	LP Dia. (in)	HP Dia. (in)
1	3,000	44,280	100	2	13.7	7.8
2	6,000	88,560	100	2	18.9	7.8
3	10,000	147,600	100	2	24.4	7.8
4	15,000	221,400	100	2	29.9	9.2
5	20,000	295,200	100	2	34.5	10.6
6	30,000	442,800	100	2	42.3	13.0

- **Comparative size illustration – Ramgen 2 stage 10,000 hp system vs. conventional multi-Stage geared cetrif. 8 stage 10,000 hp system**



Ramgen: PR=100 / 10,000 hp / 2 Stage



Multi-Stage Centrif: PR=200 / 6,200 hp / 10 Stage

QUESTIONS?