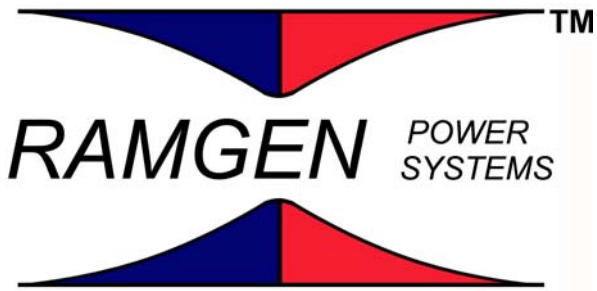
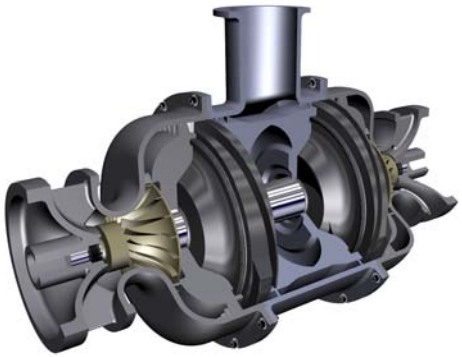
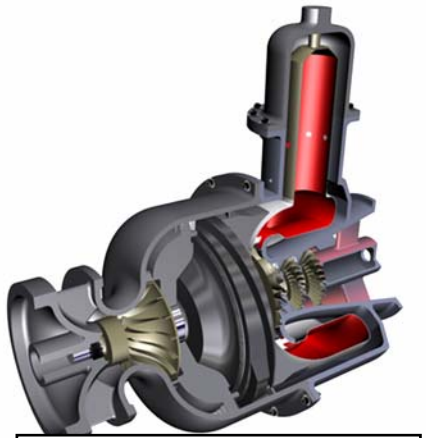


Ramgen Technologies

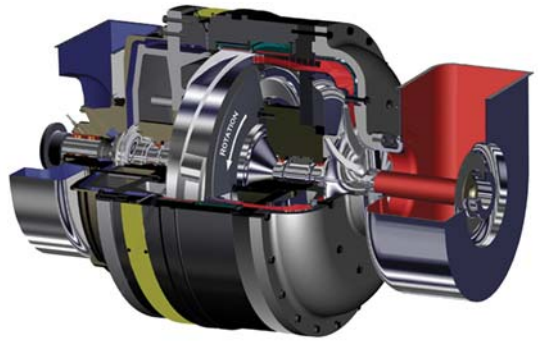
Compression Technology Path



Rampressor™



Ramgen Turbine



Ramgen Engine

- **Increased Efficiency Compression Technology**
- **Aerodynamic and Mechanical Designs At ~3:1 to ~9:1 Pressure Ratios**
- **Rampressor™-Specific Component Layout & Cost**

- **Rampressor™ Integrated With Conventional Combustor & Turbine**
- **Cycle Efficiency Increased Due to Rampressor™ Efficiency**
- **Higher Pressure Ratio Designs (>9:1)**

- **Supersonic Compression And On-Rotor Combustion/Power Extraction Technology**
- **High Overall Cycle Efficiency: High Compression and Power Extraction Efficiencies**

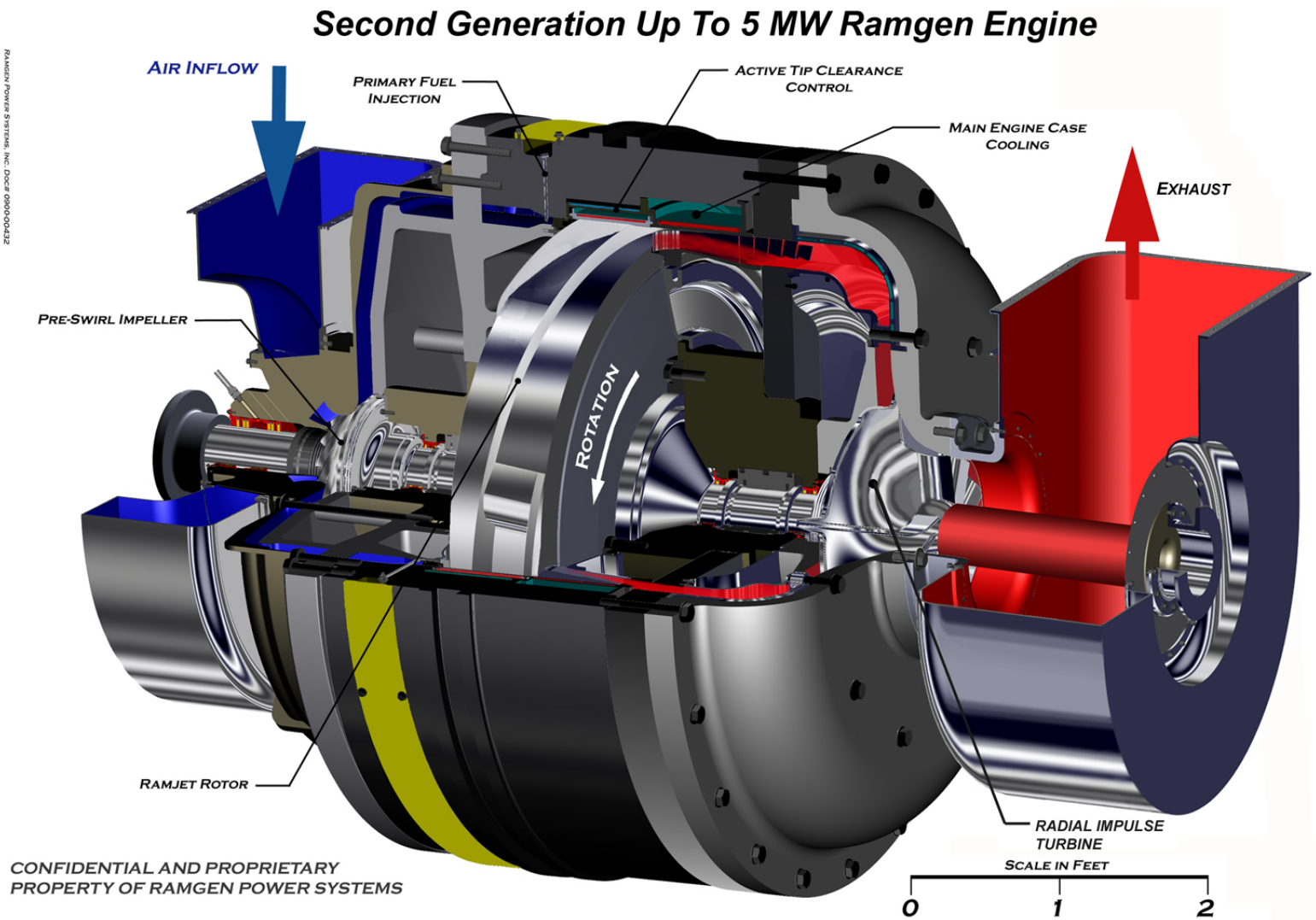
Compression/Power Technology Applications

Rampressor™ →
- Air Compressors
- Turbochargers
- Turbines
- Industrial Processes
- Refrigeration
- Gas Pipeline Boosters

Rampressor Turbine →
- Base Load Power Generation
- Hybrid Fuel Cell
- Waste Fuel Utilization

Ramgen Engine →
- Base Load Power Generation
- Expanded Waste Fuel Utilization

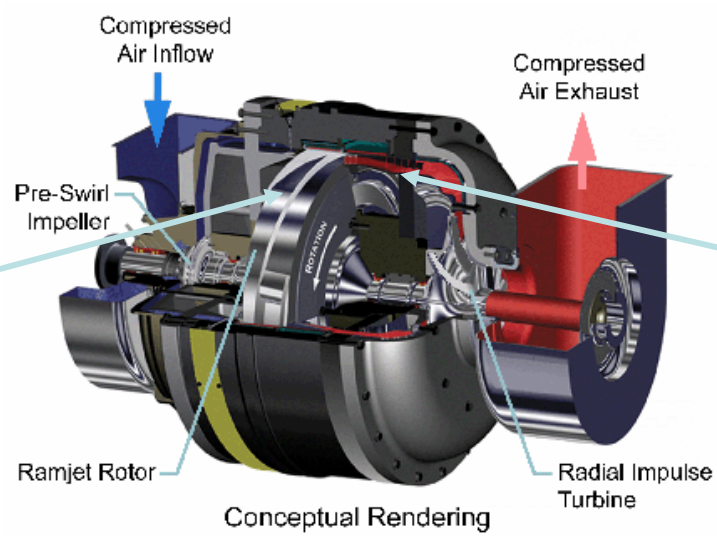
Conceptual Rendering - Engine



2.8 MW Engine Design Review

- Two-day all government design review at NASA-Glenn (April, 2002)
  - NETL, Oak Ridge, NASA, AFRL, Army Research Lab
- Facilitated by third party, Parsons Group
- Followed the “technology readiness level” approach

Recommendation:
Move forward but develop subsystems separately before full engine integration



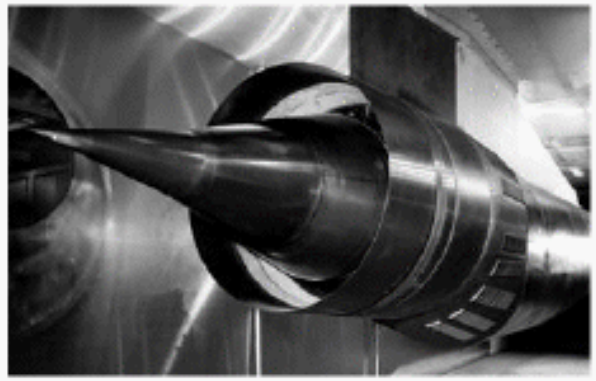
Various Flight Inlet Types For Propulsion

RAMGEN POWER SYSTEMS™

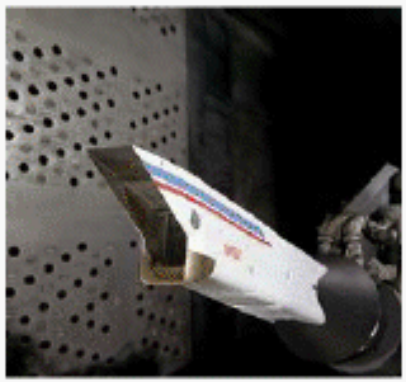
Inlets

Glenn Research Center

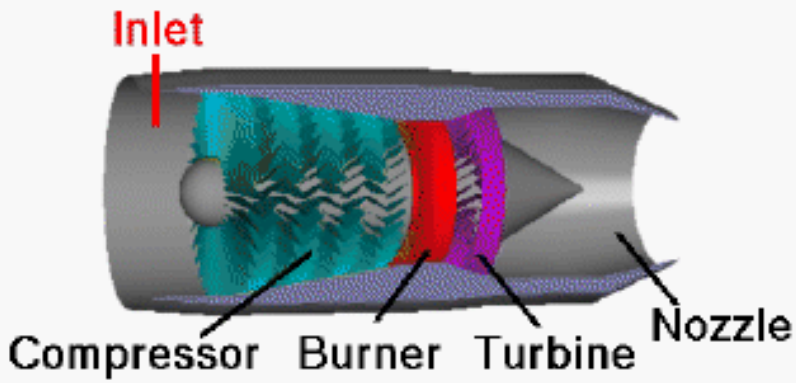
Subsonic



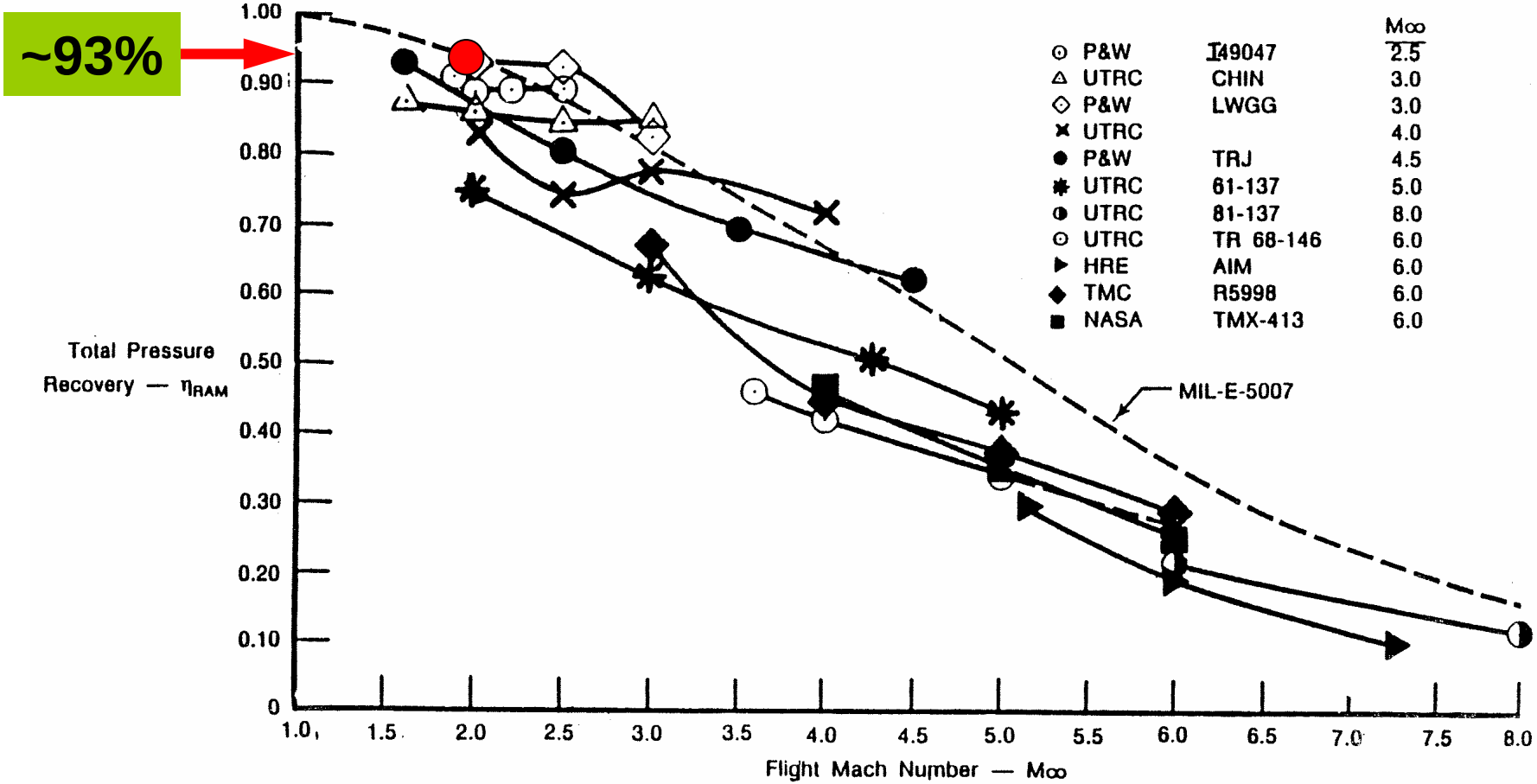
Axisymmetric Supersonic



Rectangular Supersonic



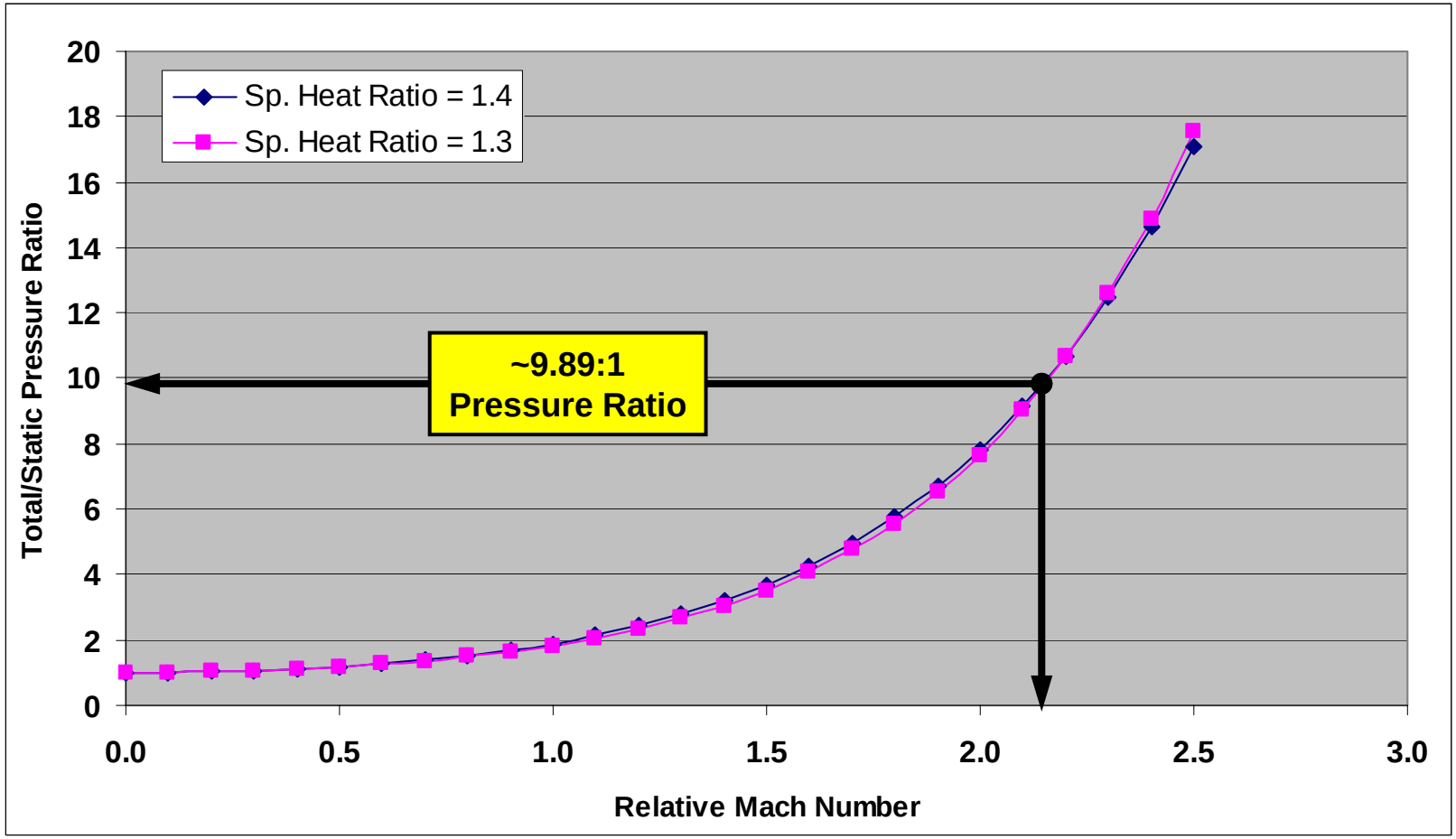
Typical Supersonic Inlet Pressure Recoveries



~93% Inlet Pressure Recovery Typical @ M = 2

A Well Designed Inlet Can Do A Little Better Than MIL-SPEC

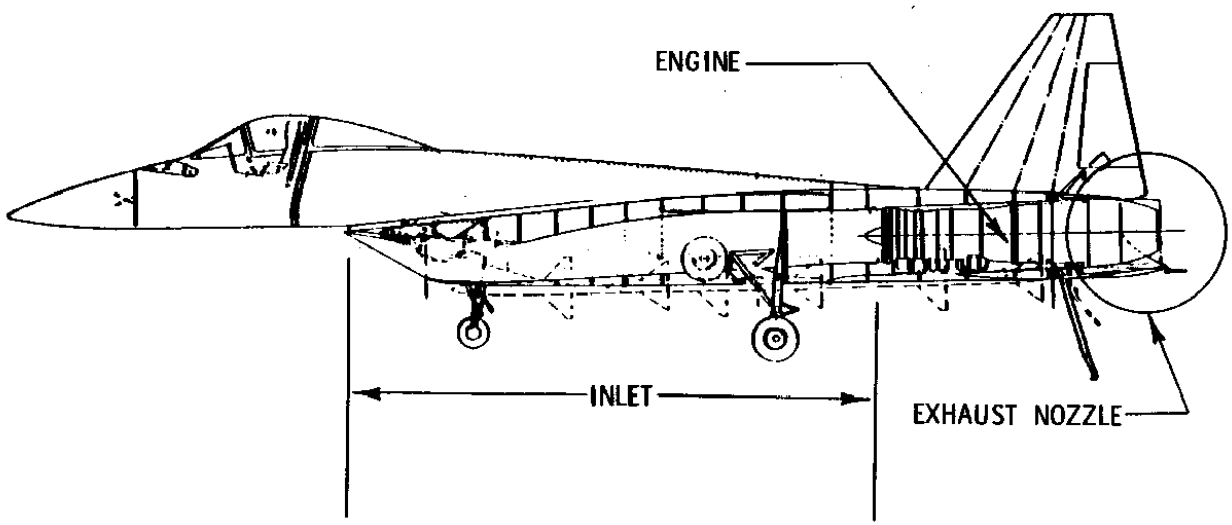
Supersonic Compression vs. Relative Mach



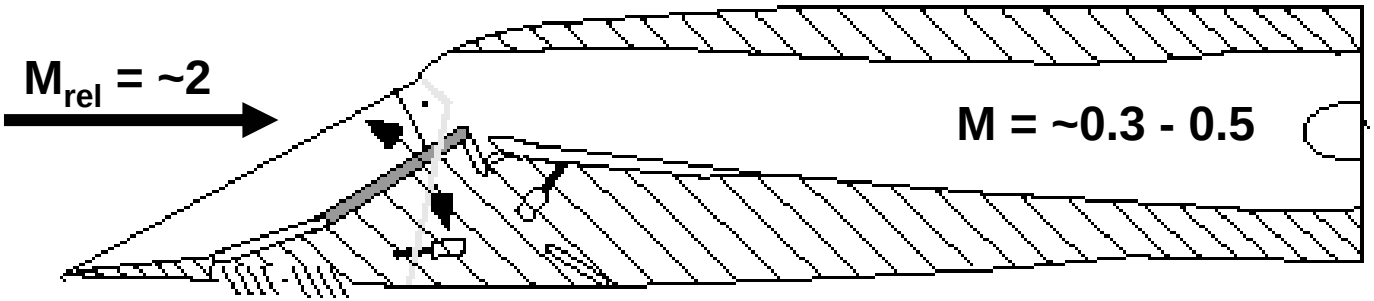
Pressure Ratio Non-Linear With Relative Mach #

Supersonic Inlets Produce Significant Compression

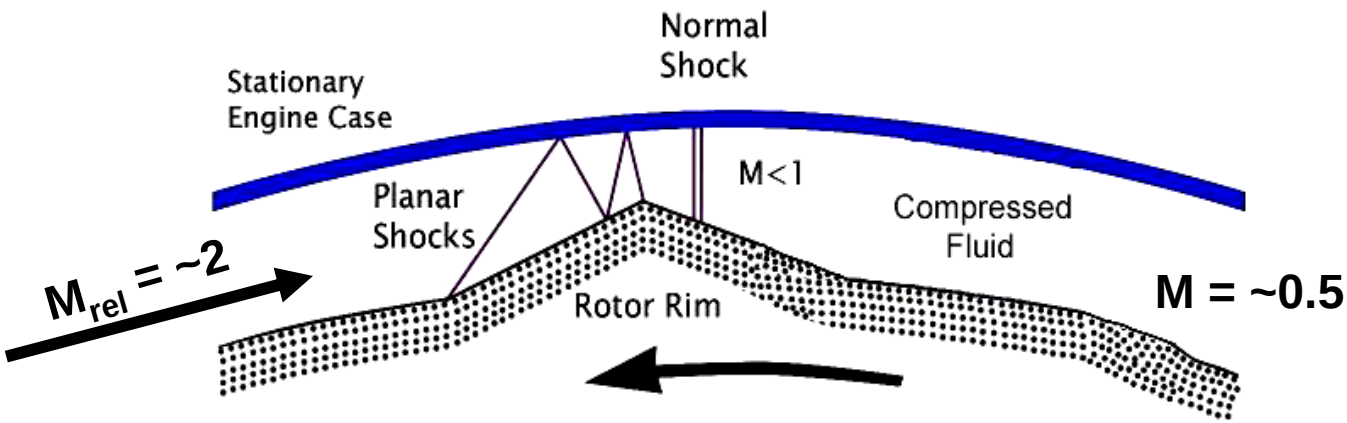
Typical Supersonic Inlet: F-15



Rampressor Rotor Design

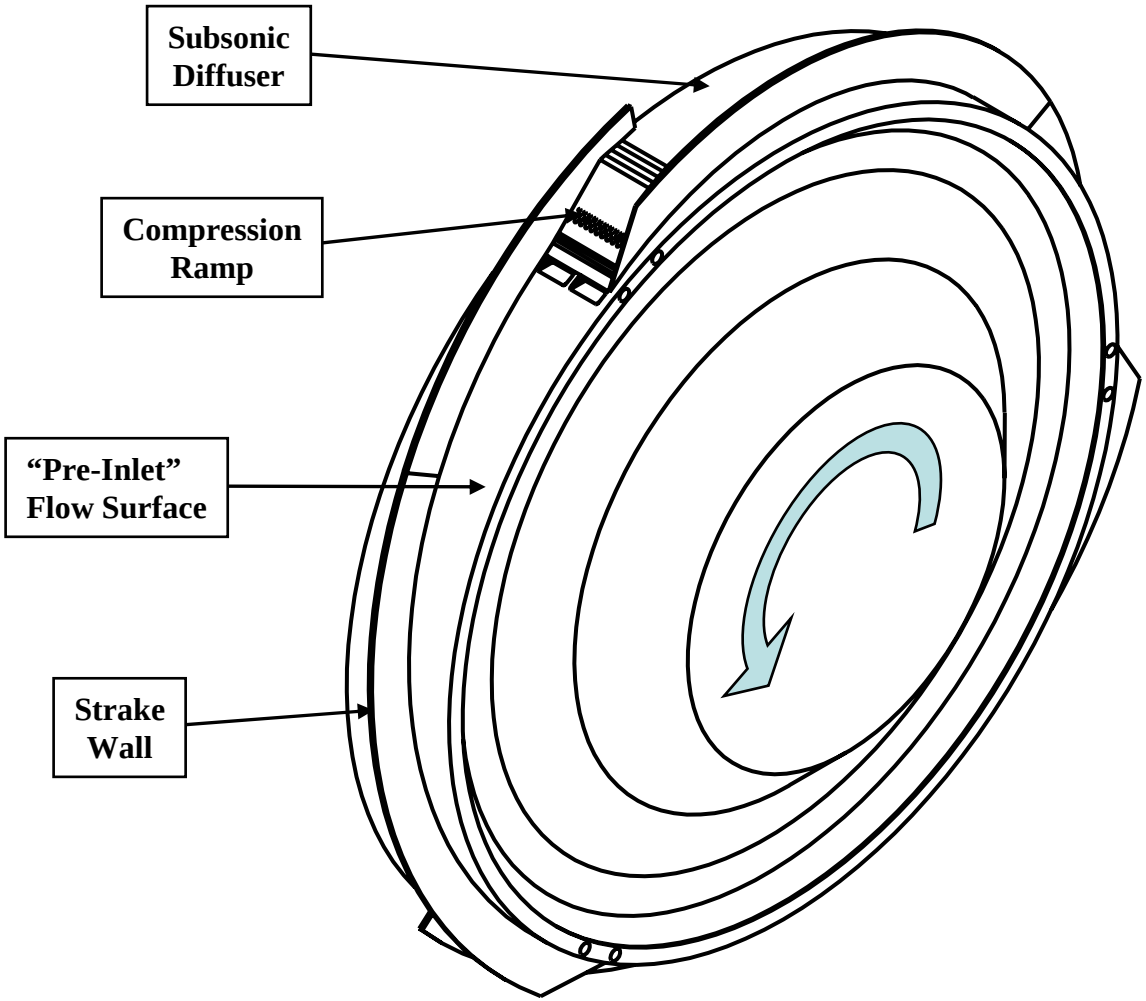


Supersonic F-15 Inlet



Rampressor Rotor

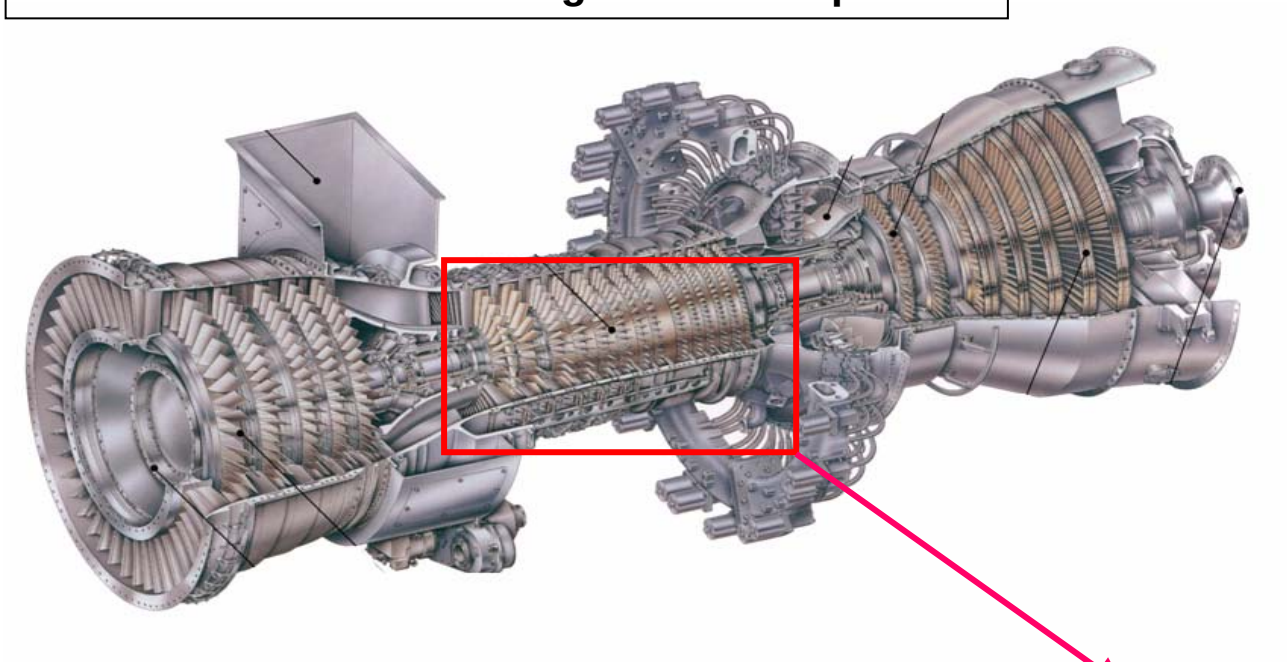
Typical Rotating Supersonic Flow Path



- **Rotor Flow Path:**
  - **3 Supersonic Compression Inlet Flow Paths On Disk Rim**
  - **High Efficiency, Compact Compression**
  - **Minimal Number of Leading Edges**
- **Combination of Supersonic Flight Inlet & Conventional Axial Flow Compressor Aerodynamics**

Gas Turbine Tech. Insertion Opportunity

Gas Turbine with Multi-stage Axial Compressor

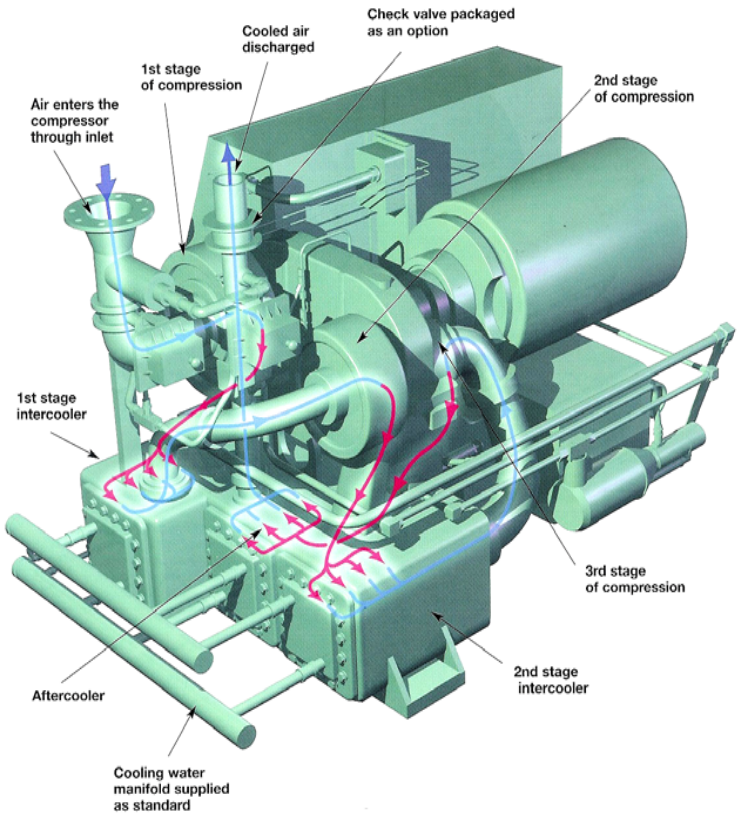


Replace or “De-stage” Gas Turbine Compressors with a Single Stage High Pressure Ratio Rampressor

Rampressor Rotor

Replace or “De-Stage” Conventional Compressors

3-Stage Intercooled Compressor Package

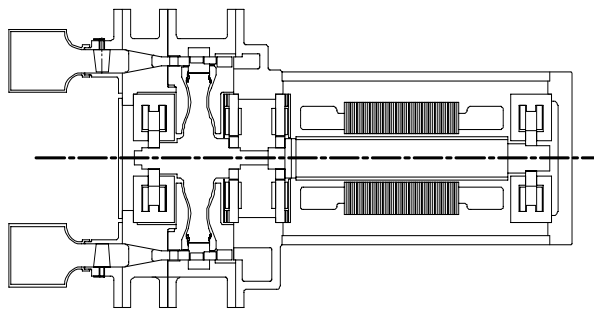


Single-Stage Rampressor

Replace stages with Rampressor Rotor

Replace with Rampressor

- **Simple single-stage design**
- **High speed direct drive**
- **Magnetic bearings**
- **Useable heat recovery**
- **Eliminates:**
  - **2nd & 3rd stage(s)**
  - **Speed increaser gearbox**
  - **Intercooler(s)**
  - **Lube oil system**



Rampressor™ Demonstration Program

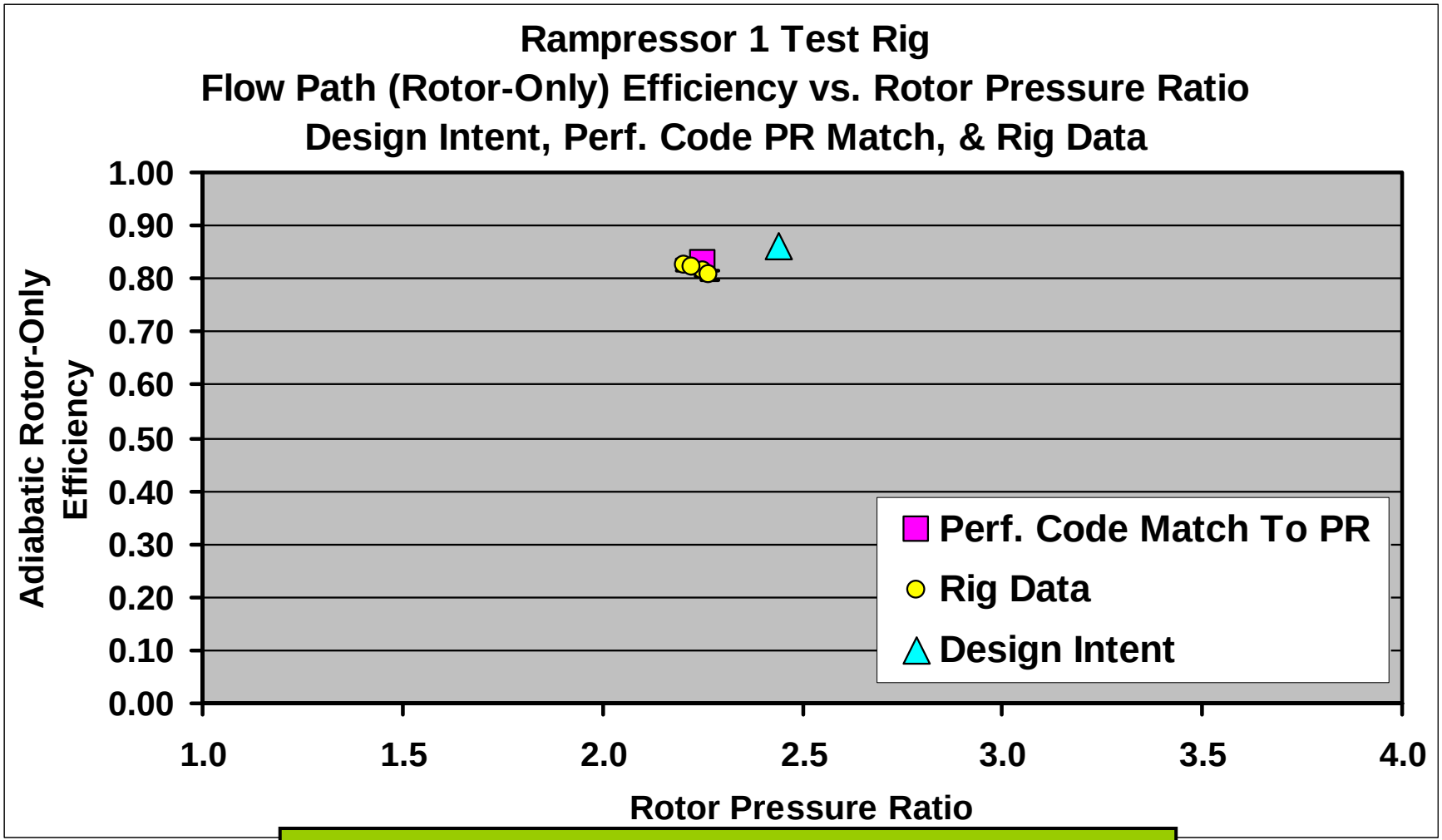
- **Goals:**
  - Demonstrate Rampressor Rotor Operation
    - Supersonic Compression
  - Characterize Rotor Efficiency
- **How:**
  - Design & Build Rotor Test Apparatus
  - Conventional Compressor Test Rig Design
  - Characterize Rotor-Only Efficiencies
- **Where:**
  - Boeing Nozzle Test Facility (NTF)
  - Boeing Field, Seattle
- **When**
  - Installation April ‘03
  - Testing To Start August ‘03
  - Through 1st Quarter of CY04

Test Rig Assembly

Boeing Test Cell

Rotor

Rampressor 1 Preliminary Test Results



Test Rig Data Matching Well With Predictions

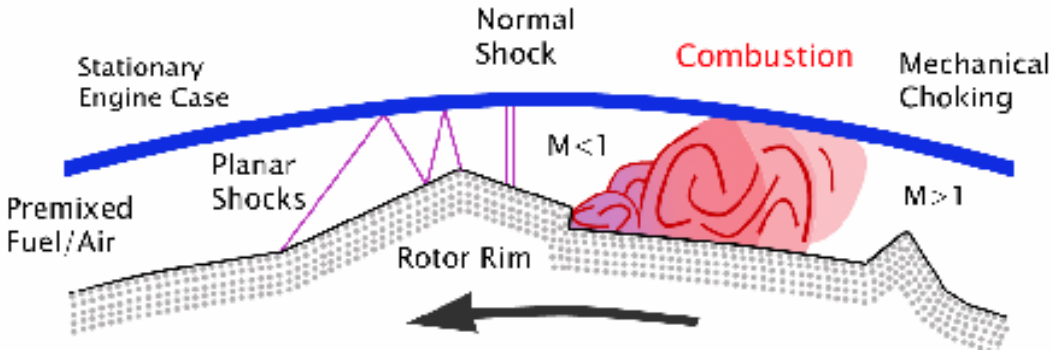
Rampressor 1 Test Rig Status

- **Achieved Full Rotor Speed**
  - Mechanical Systems Now Working Adequately
  - **Achieved Design Rotor-relative Mach Number (M = 1.6)**
- **Started All 3 Rotor Inlets**
  - Have Not Experienced Instabilities, Surge, Or Inlet-to-inlet Variations
  - **Benign Surge Characteristics => Very Good Thing**
- **Near Design Pressure Ratio/Mass Flow Point**
  - **Operating As A Compressor!**
  - Working To Increase Rotor Efficiency & Pressure Ratio
- **Have Not Optimized All Available "Knobs" To Increase Pressure Ratio, Mass Flow, and Efficiency**
  - Rotor Geometry, Tip/Case Clearance, Bleed Amounts And Locations, RPM, Etc.: Additional Rotor Available For Changes/Upgrades/Etc.

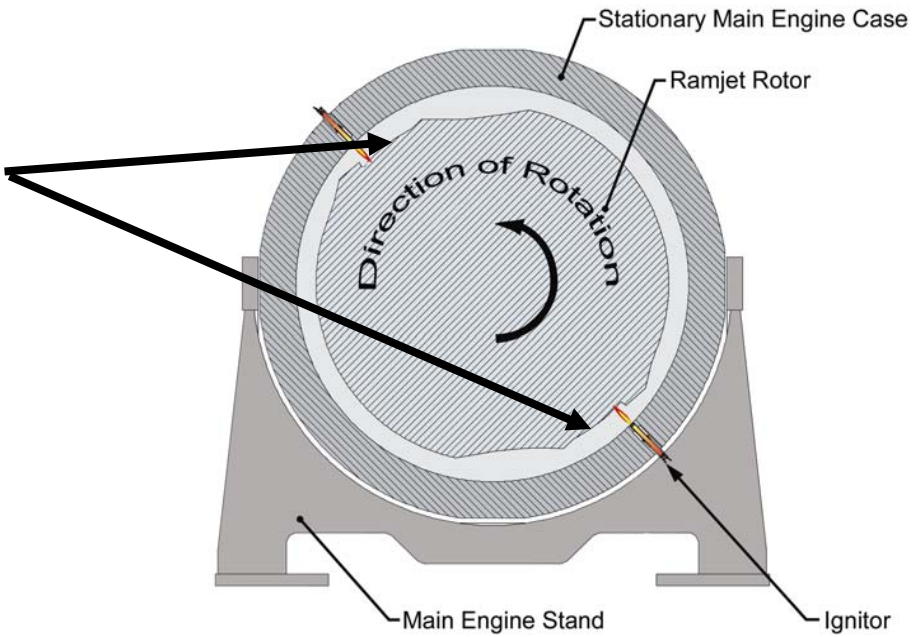
- **Overall Operation of Rotor Aerodynamics Is As Designed/Intended**
  - **Analytical/Numerical Design Tools Have Basic Validation: Validation Continuing With Test Data Generation**

Rotating Ramjet Flowpath

Rampressor™
(with combusion)

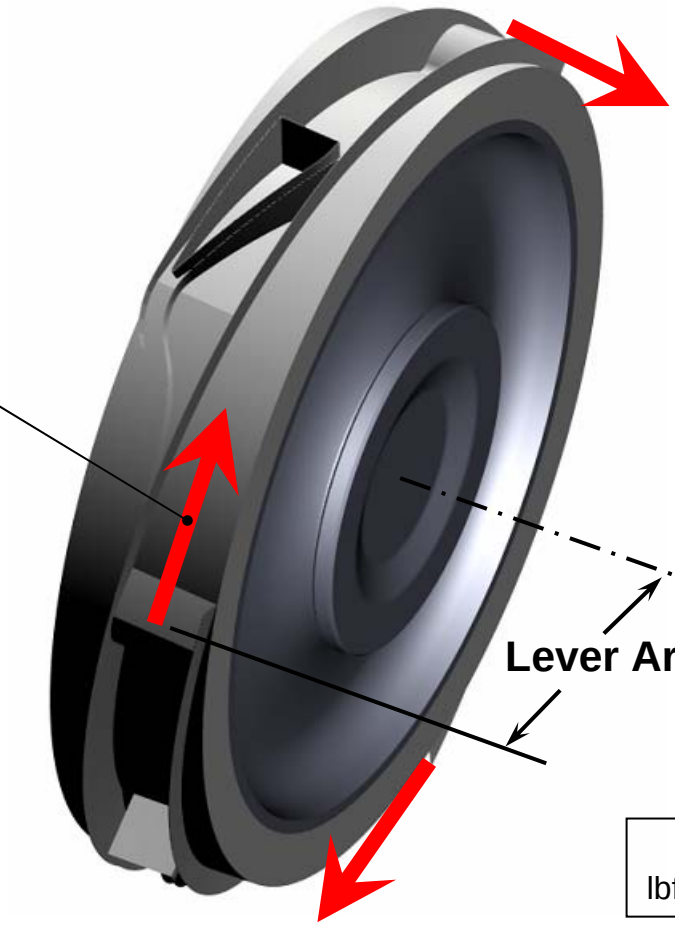


Rotating Ramjet Flowpaths
On Rim of High Speed Disc



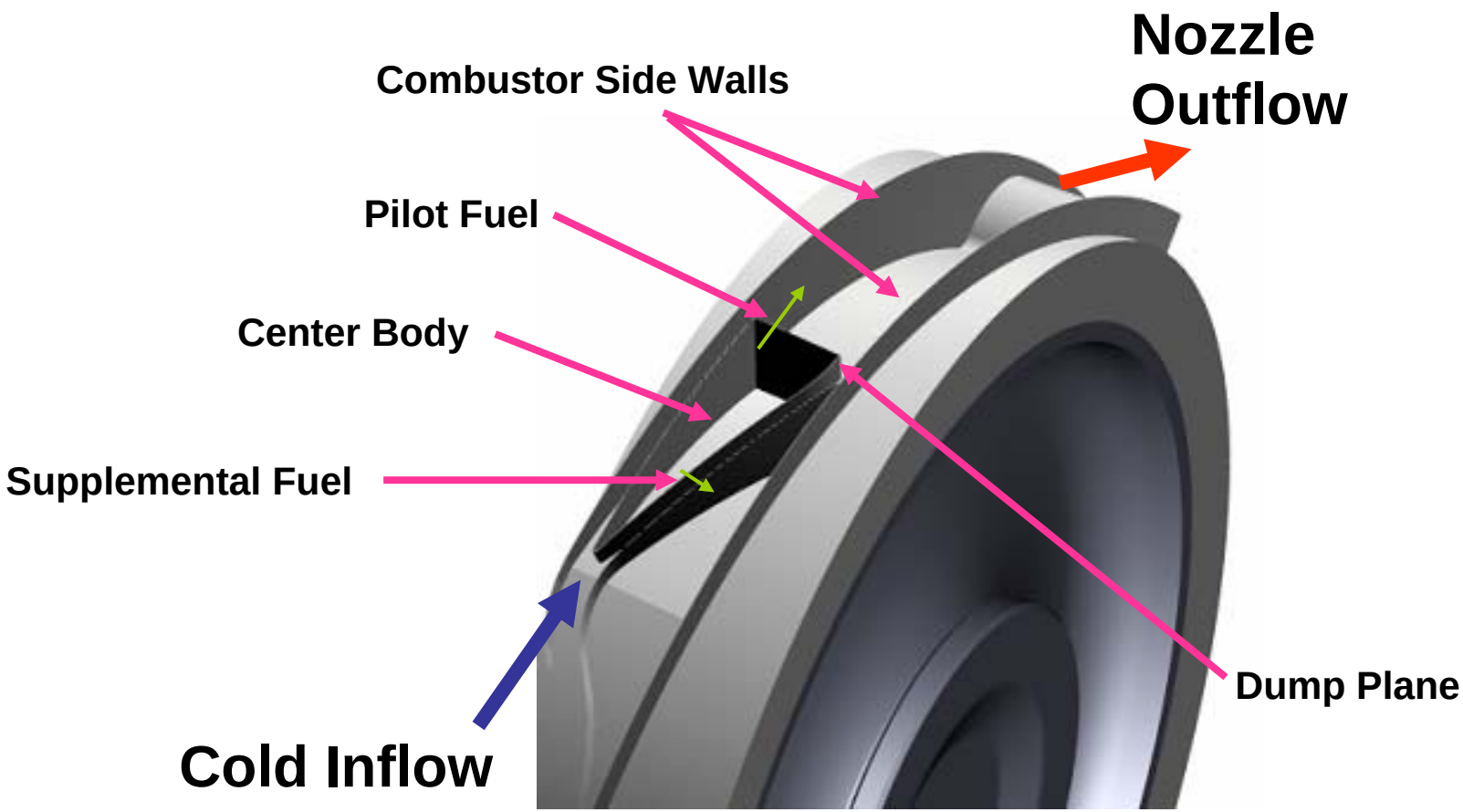
Engine Rotor

- **Ramjet Power = Thrust *x* Lever Arm *x* Rotation Rate *x* No. Ramjets**



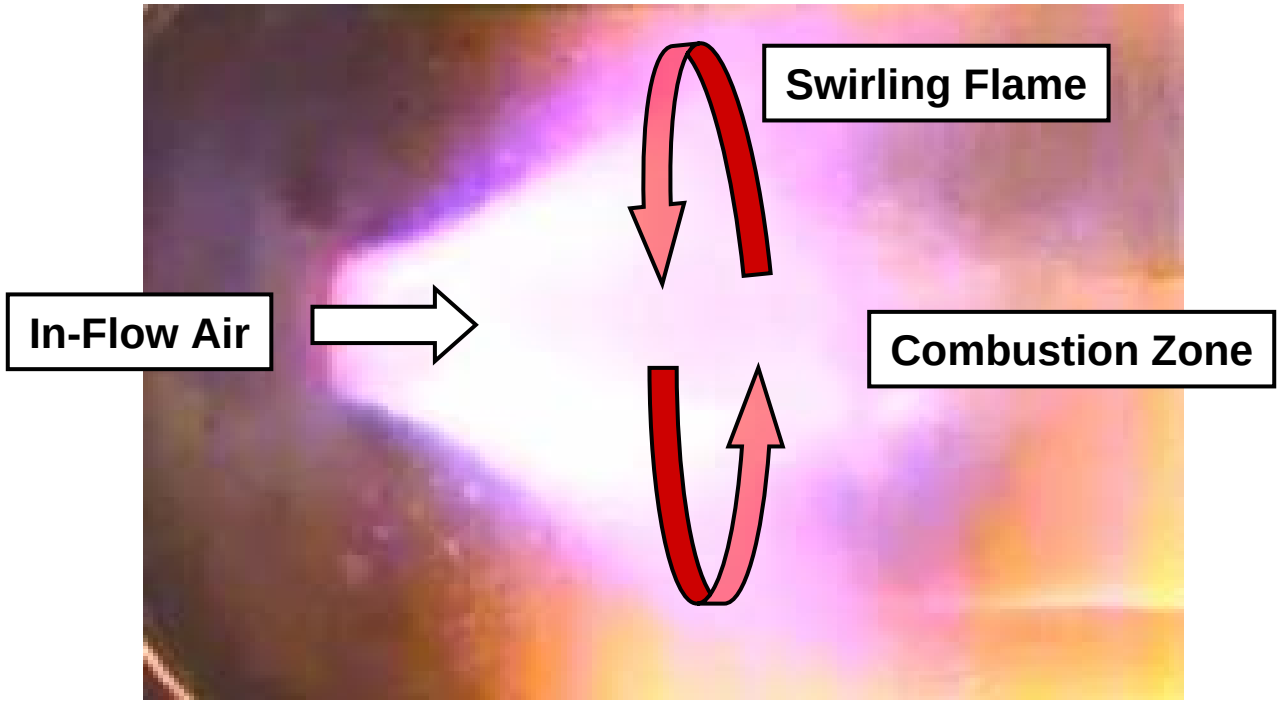
Dimensional Example:
lbf ***x*** ft ***x*** rad/s ***x*** # Jets = ft-lbf/sec

Combustor Details



Conventional Swirl-Stabilized Combustor

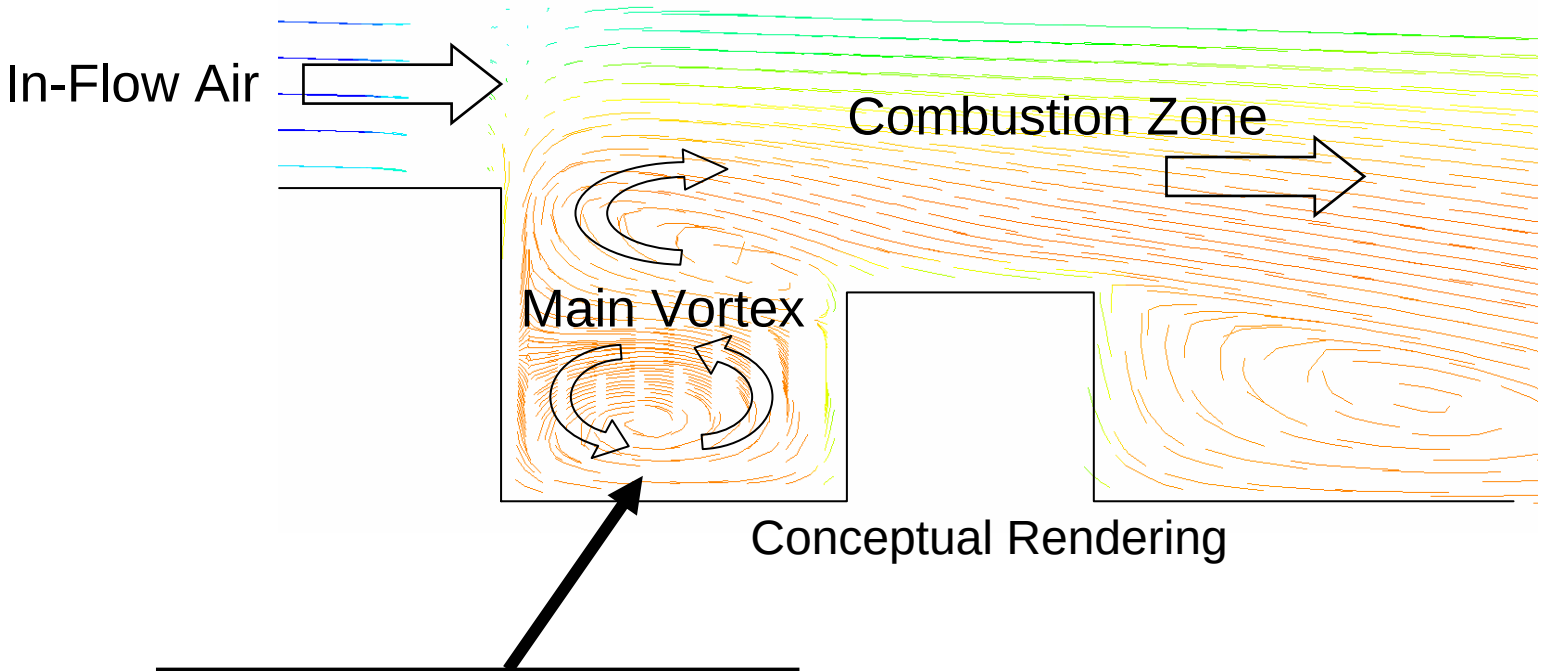
- Most Gas Turbine Combustors and Industrial Burners
- Flame Stability is Dependent on Main Flow



Flame is Unstable at Reduced Temperatures

Advanced or “Trapped” Vortex Combustion ?

- No Swirl Vanes Required For Flame Stability
- Main Vortex is Stationary in a Controlled Cavity

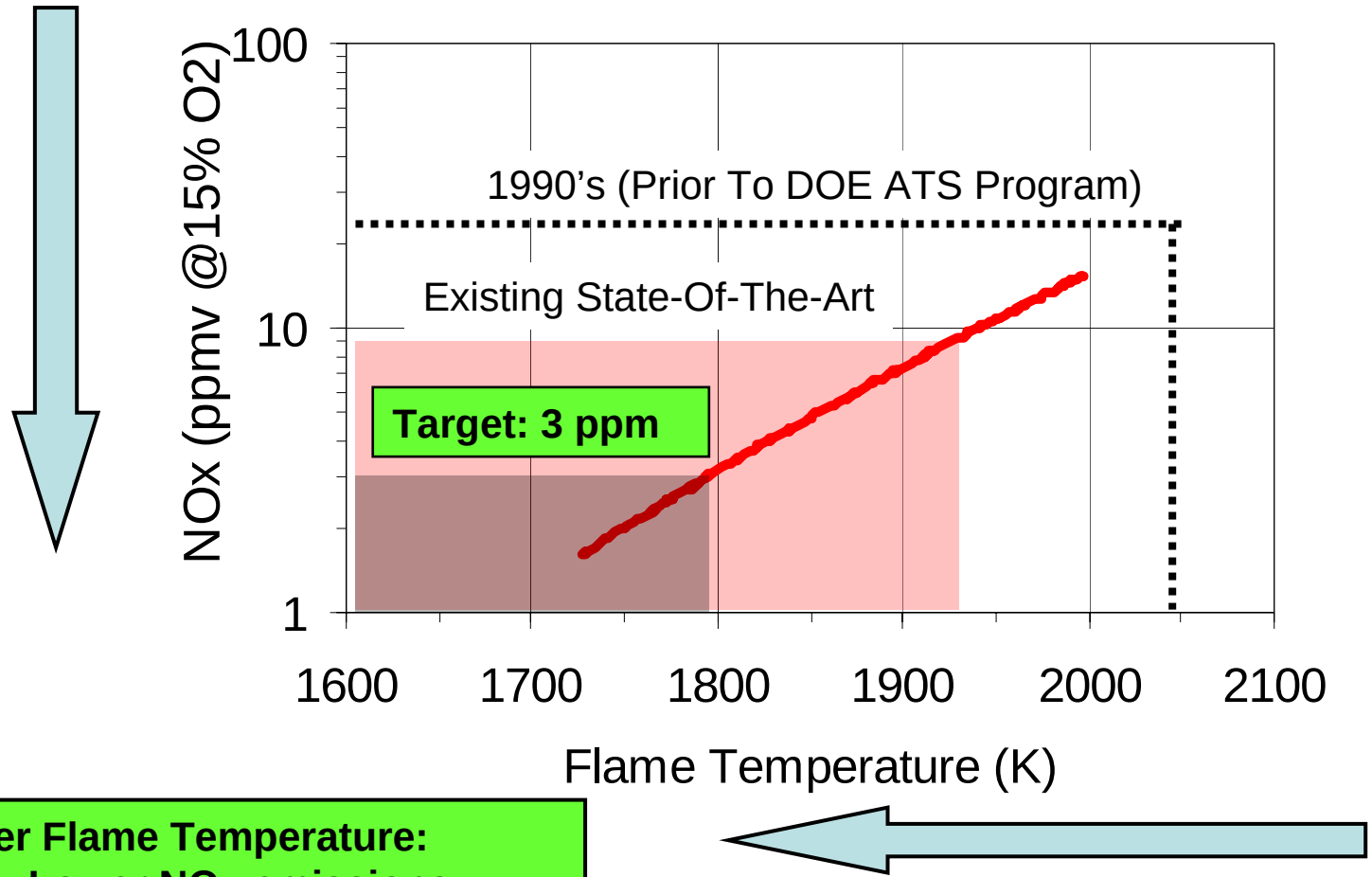


Advanced Vortex Combustor (AVC)

- AVC has seen wide exposure at WPAFB and DOE NETL
- GE, Williams Engines and others are pursuing commercial applications
- Ramgen, DOE and CEC are teamed to develop low NOx design

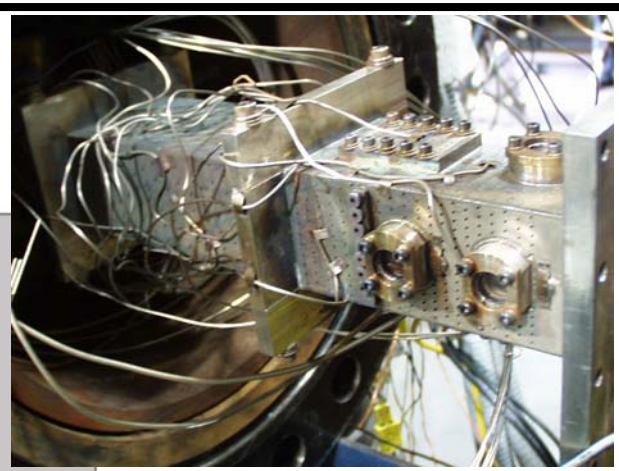
- Flame is Independent of Main Flow for Greater Stability
- Greater Combustor Turndown
- Potential to Achieve Very Low Single Digits NOx

NOx for Industrial Ground-Based Combustion Turbines

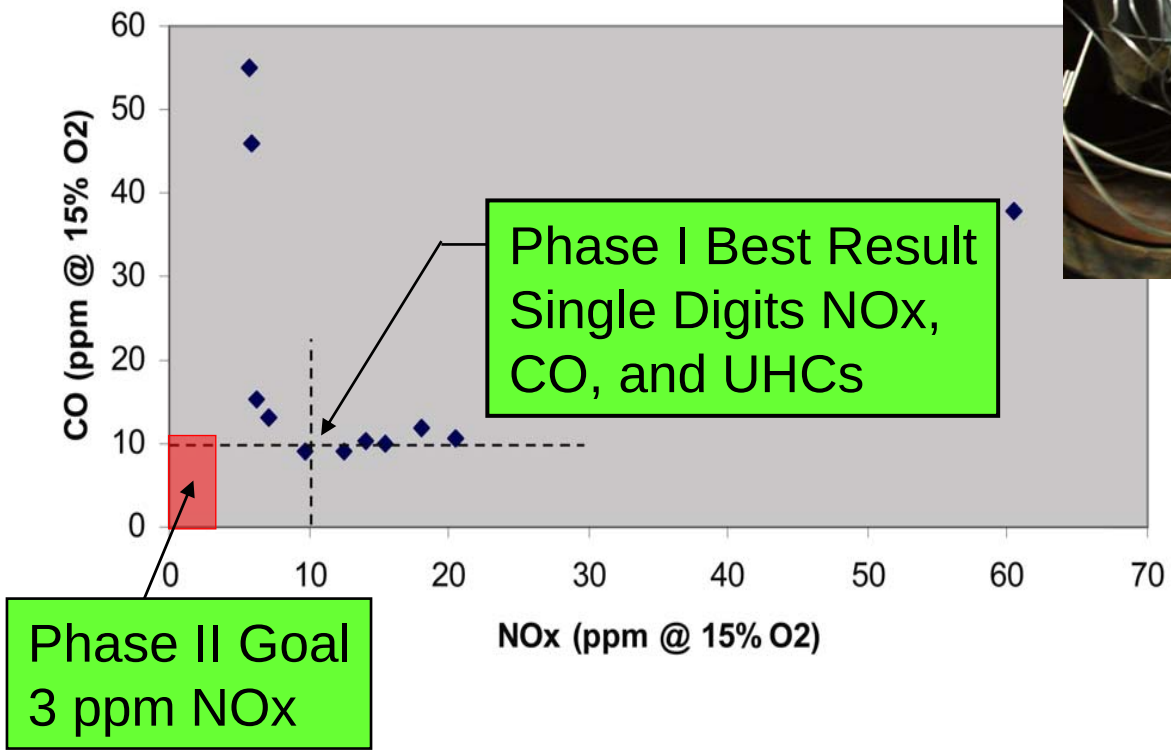


Lower Flame Temperature:
- **Lower NOx emissions**
- **More Unstable Combustion**

Phase I AVC Proof-of-Concept Natural Gas Burning Demonstration

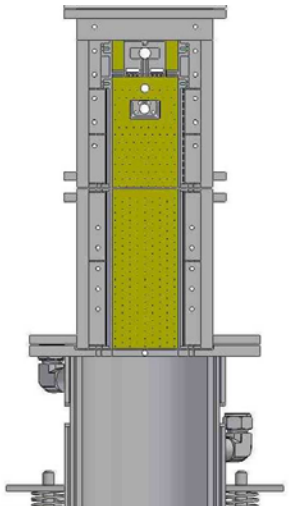


AVC Combustor

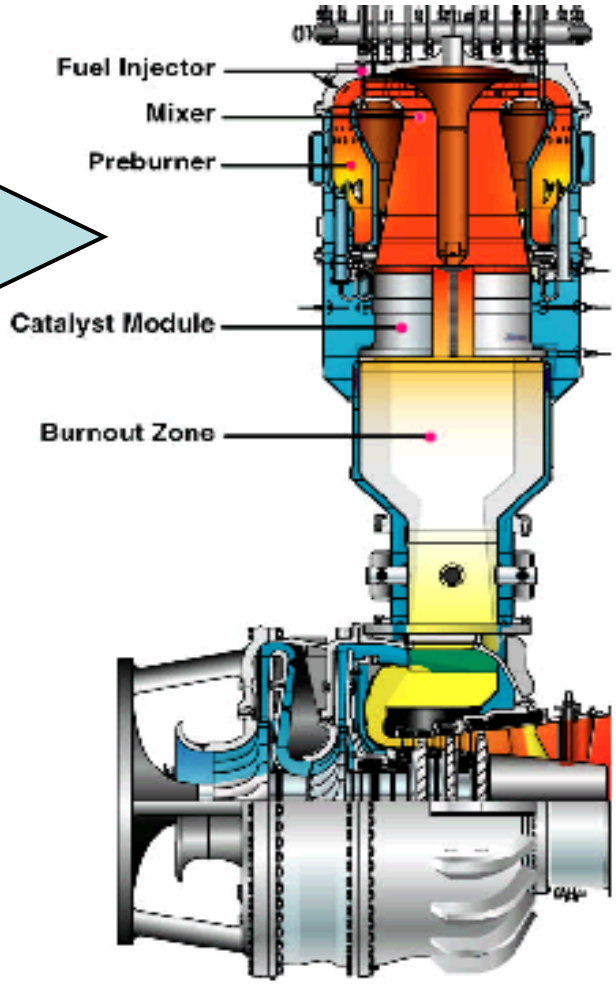


Ramgen is First to Demonstrate Single Digit NOx with AVC

AVC Gas Turbine Demonstration



AVC Retrofit



Kawasaki 1.4MW Gas Turbine

Example: Demonstrate 3ppm NOx
Without Expensive Xonon Catalyst

Compression Product Development