Rotating Detonation Combustion for Gas Turbines – Modeling and System Synthesis to Exceed 65% Efficiency Goal

DE-FE0023983

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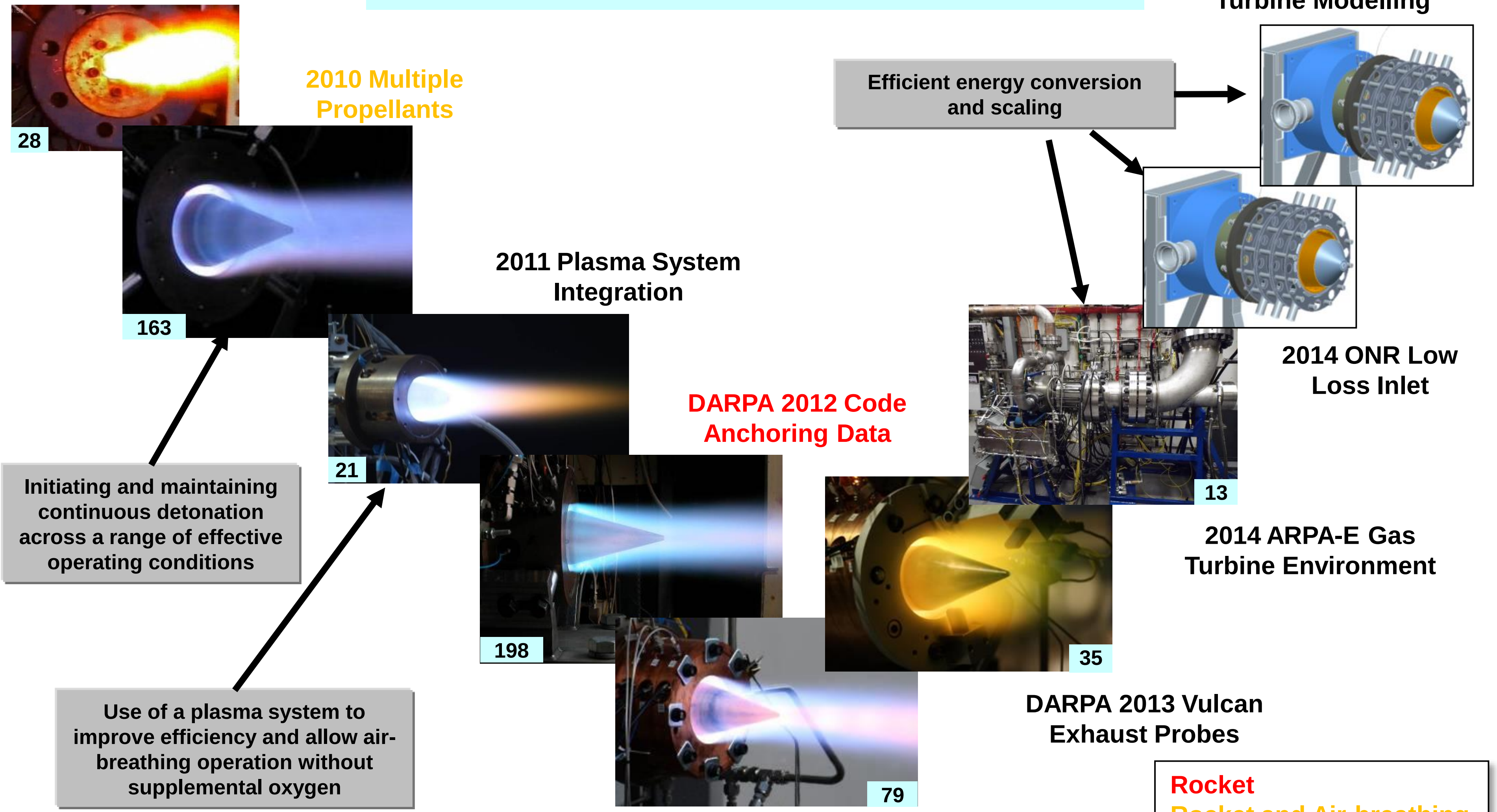
Background: Aerojet Rocketdyne RDE Development Progress

Over 600 Hot Fire Tests to Date



2010 Proof of Concept

2010 Multiple Propellants

2011 Plasma System Integration

DARPA 2012 Code Anchoring Data

DARPA 2013 Liquid Fuel Demonstration

DARPA 2013 Vulcan Exhaust Probes

2014 ARPA-E Gas Turbine Environment

2014 ONR Low Loss Inlet

2015 NETL Gas Turbine Modelling

Initiating and maintaining continuous detonation across a range of effective operating conditions

Use of a plasma system to improve efficiency and allow air-breathing operation without supplemental oxygen

Efficient energy conversion and scaling

Rocket
Rocket and Air-breathing
Air-breathing

Objective of Program

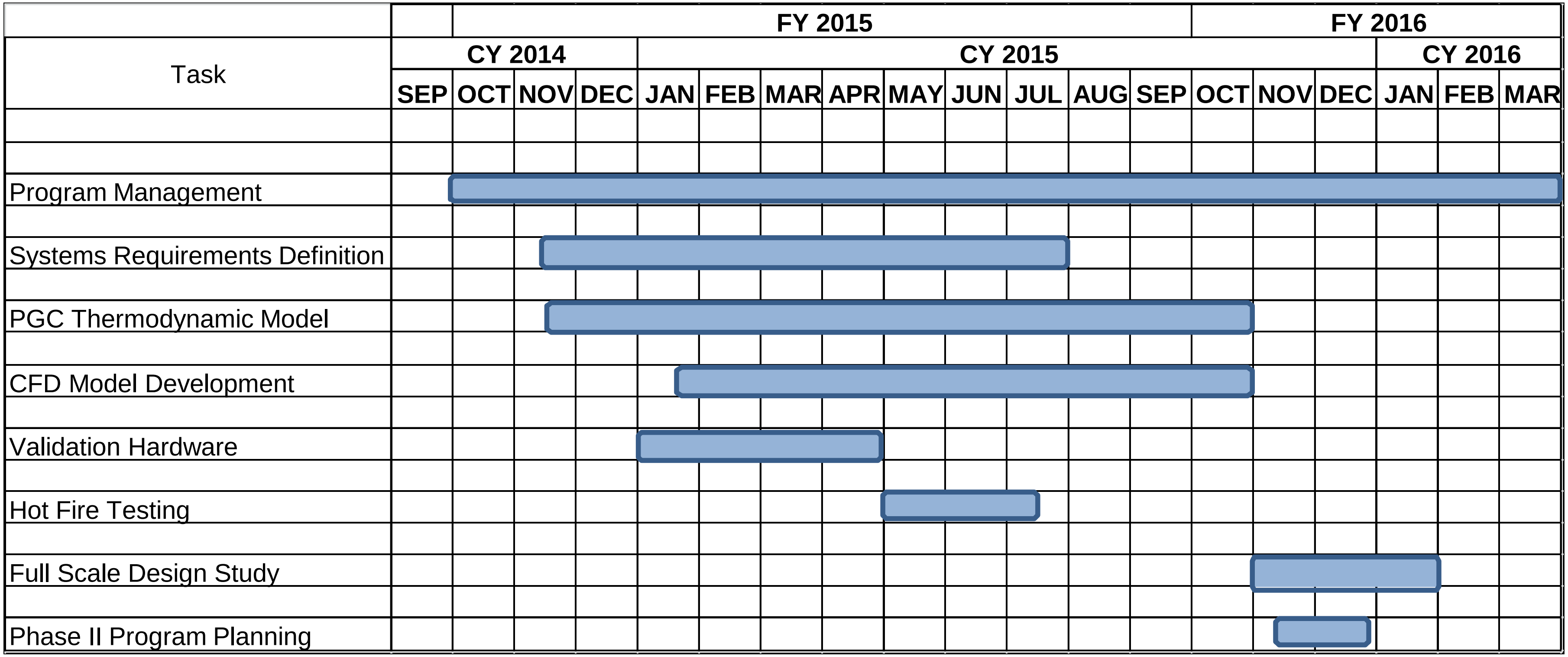
To advance combustion turbine technologies for combined cycle applications…

…by integrating a Rotating Detonation Engine (RDE), pressure gain combustion system with an air-breathing power-generating turbine system to achieve a combined cycle efficiency equal to or greater than 65%.

Five Major Program Steps

1. Develop a **power plant mass and energy balance system model** integrating an RDE with a gas turbine-based power generation system.
2. Define the RDE and the interaction of the RDE with the pieces of the gas turbine system through **component models** encapsulating the operation of these components with real, as opposed to ideal, performance in succinct fashion.
3. **Determine the efficiencies** defined in these component models through unsteady, multidimensional, Computational Fluid Dynamics (CFD).
4. **Validate the CFD models** feeding this system model with in-stream-probe pressure and flow angle measurements of an RDE operating under conditions traceable to gas turbine operation.
5. Employ this system model based on realistic performance for **product system trades** to define the path to an advanced combustion turbine in a combined cycle application capable of meeting or exceeding 65% combined cycle efficiency.

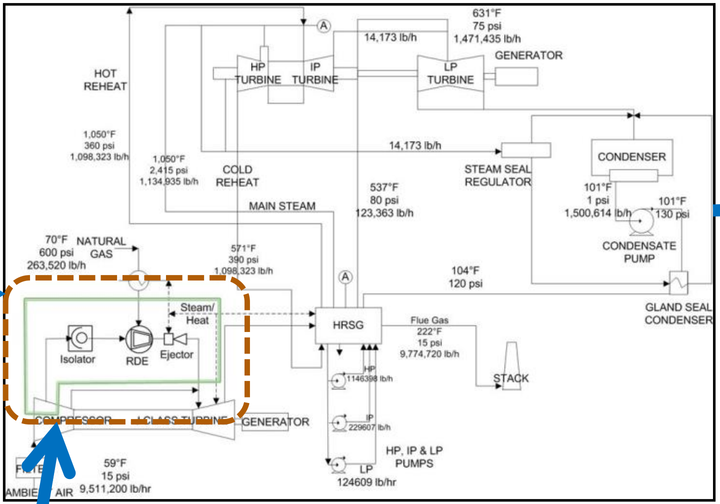
Program Schedule



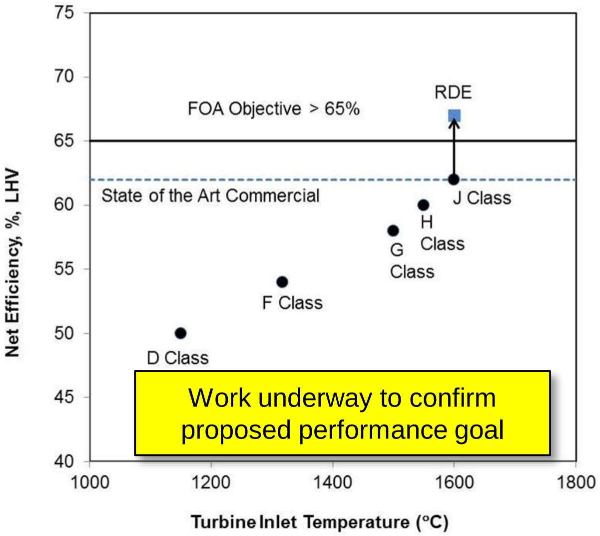
- **Interdependencies require working systems, modeling, analysis and test in parallel**
- **Testing has been completed**

Rotating Detonation Combustion for Gas Turbines – Modeling and System Synthesis to Exceed 65% Efficiency Goal
(Aerojet Rocketdyne, DE-FE0023983)

Task 2: Aspen model of combined cycle power plant developed including model for rotating detonation combustor subsystem.

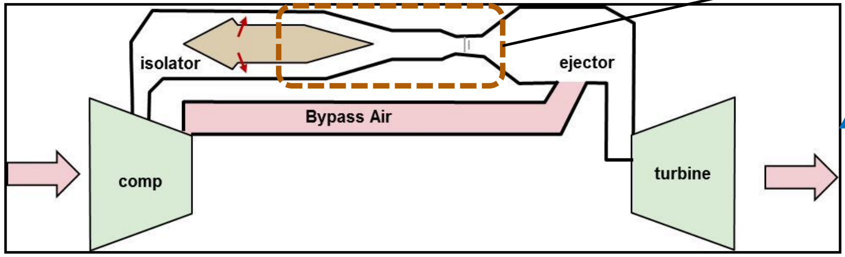


Rotating detonation combustor subsystem

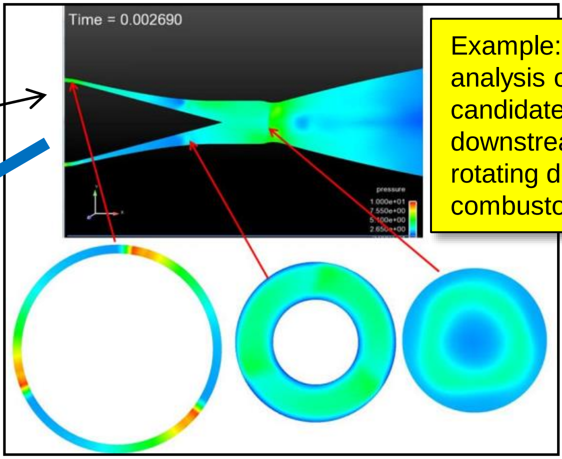


Work underway to confirm proposed performance goal

Rotating detonation combustor subsystem



Task 3: Fortran model of rotating detonation combustor subsystem developed for inclusion into Aspen plant model.

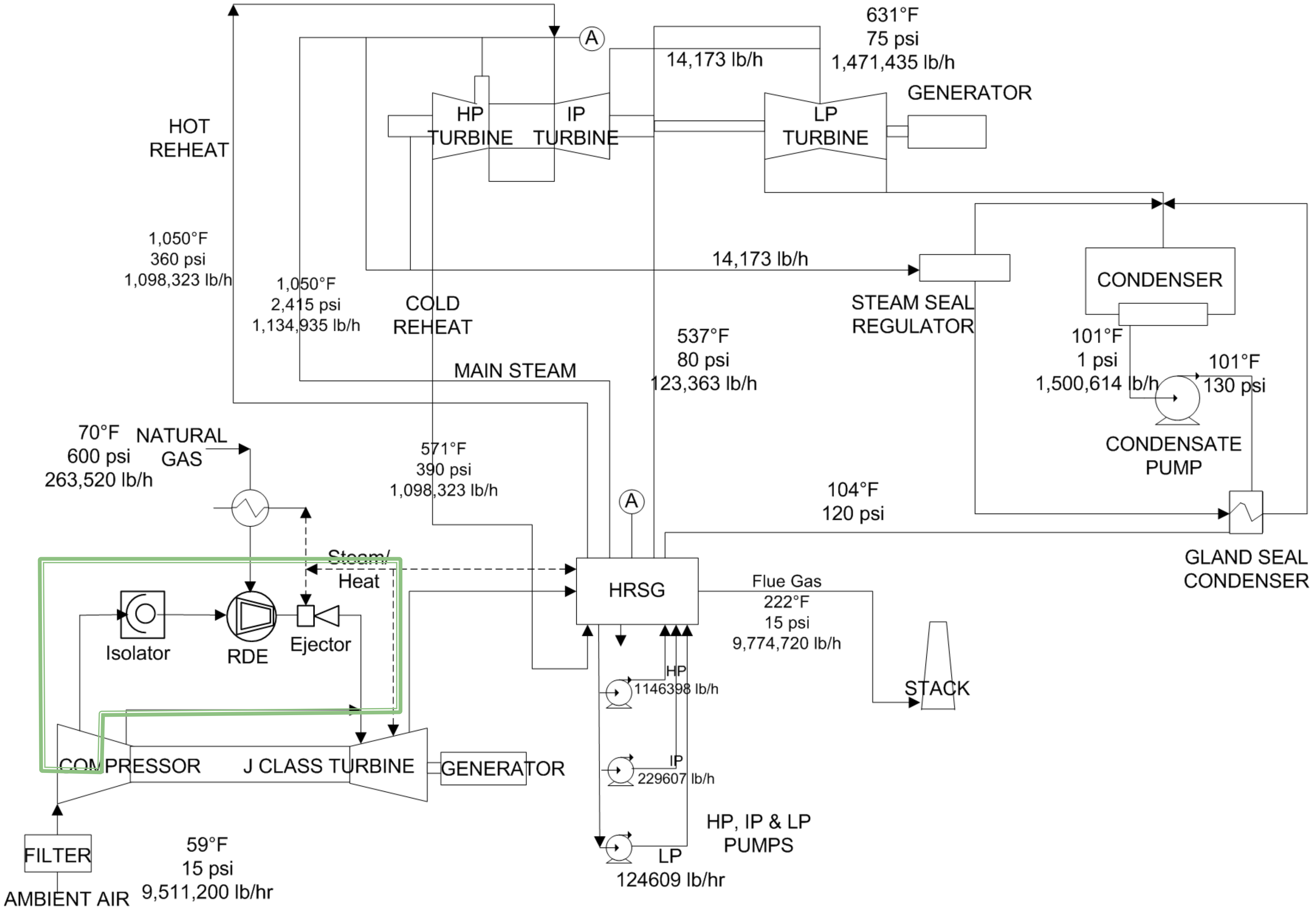


Example: CFD analysis on one candidate geometry downstream of rotating detonation combustor

Task 4: CFD used to explore alternatives for managing rotating detonation flow field from discharge of compressor to turbine inlet. Results reflected in efficiencies used in Fortran model.

Task 3.0 – Thermal Models of Pressure Gain Combustion Components and Plant Systems

RDE Combined Cycle Power Plant



RDE Model For Integration Into Plant System Model (Aspen)

1) Compressor

J class

2) RDE Combustor Tap-off

No loss

3) Isolator

Friction

Heat loss

Shock isolation (cfd)

2) - 3) Compressor pressure pulse interaction

No loss

4) RDE Combustor

Constant volume

Deflagration bypass

5) Combustor Exit Choke

6) Ejector

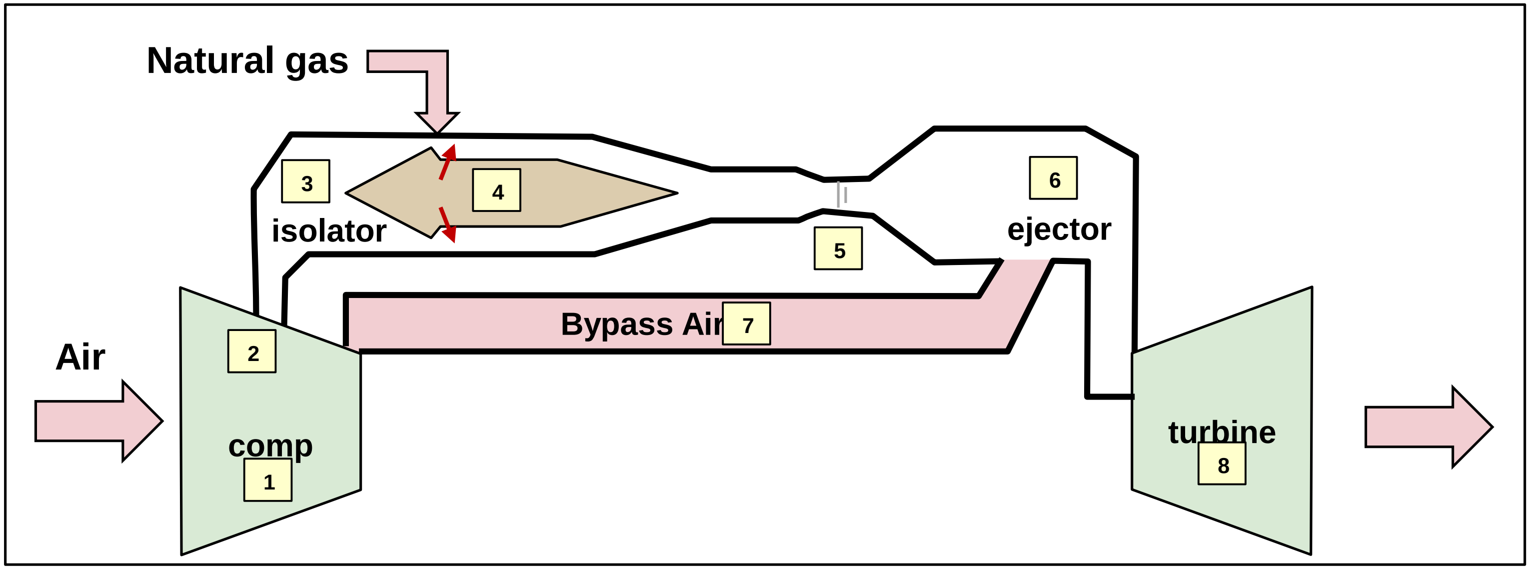
Shock primary to subsonic at Mach X

Stream thrust averaged mixing

7) Bypass Duct

8) Turbine

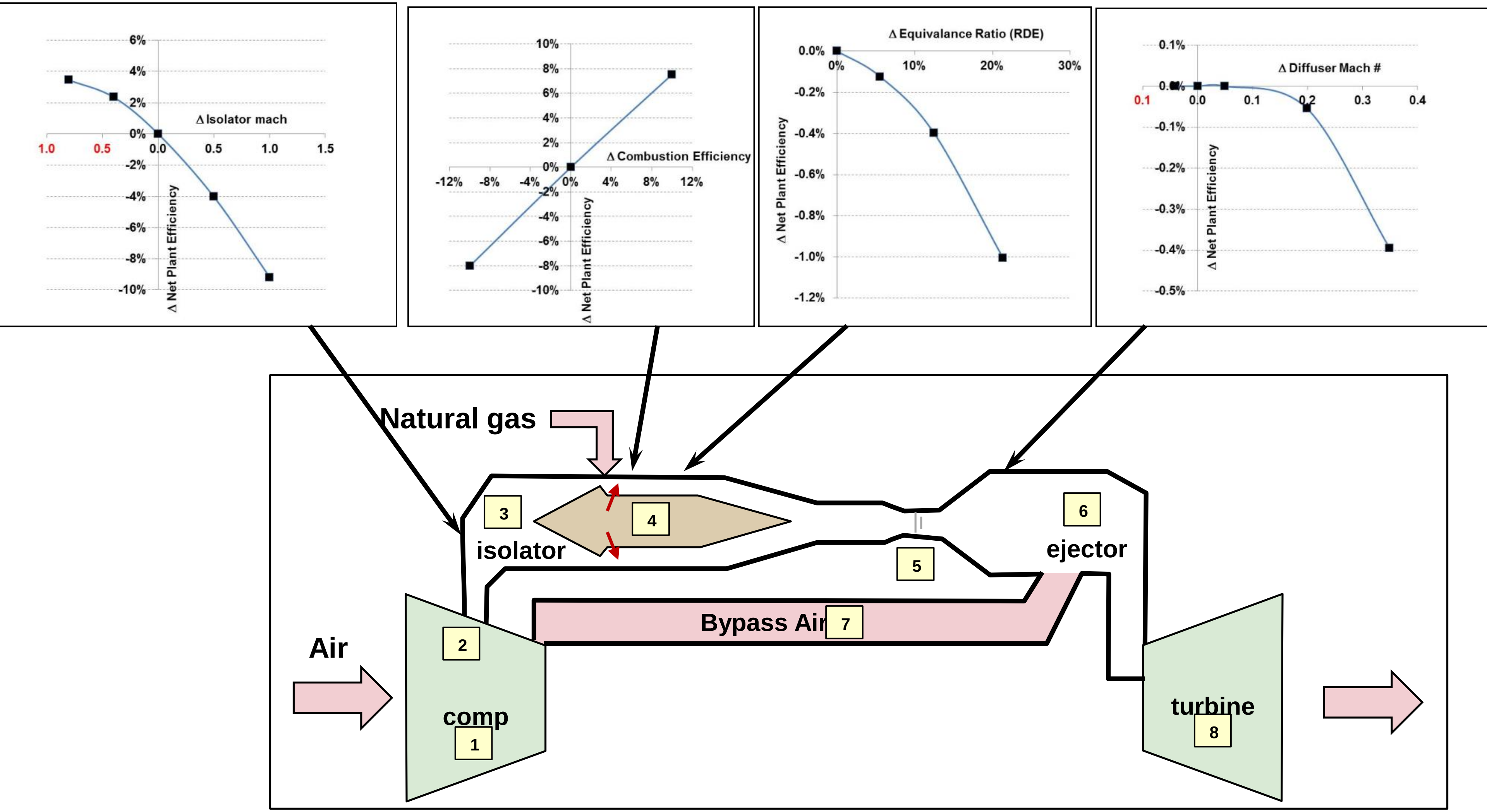
J class



Baseline Assumptions for Plant Model

- 90% Combustion Efficiency (10% of fuel does not combust)
- Natural Gas Fuel (93.1% CH_4, 4.3% C_2H_6, 1.6% N_2, 1% CO_2)
- Turbine
  - Inlet Temperature 2,950 F, Pressure 350 psi
  - Isentropic Efficiency 87.5%
  - Exhaust to Hot Reheat Steam Generator (HRSG) 14 psi
- Compressor
  - Inlet 59 F, 15 psia
  - Outlet to RDE combustor, 180 psi and 683 F
  - Efficiency 85%
- Bypass Ratio = 0 (All air goes to RDE combustor)
- RDE Flow Equivalence Ratio = 0.45
- Steam Turbine & HRSG
  - 38% gross efficiency
  - Three Stage Turbine
  - Flue Gas exhaust 14 psi and 190 F

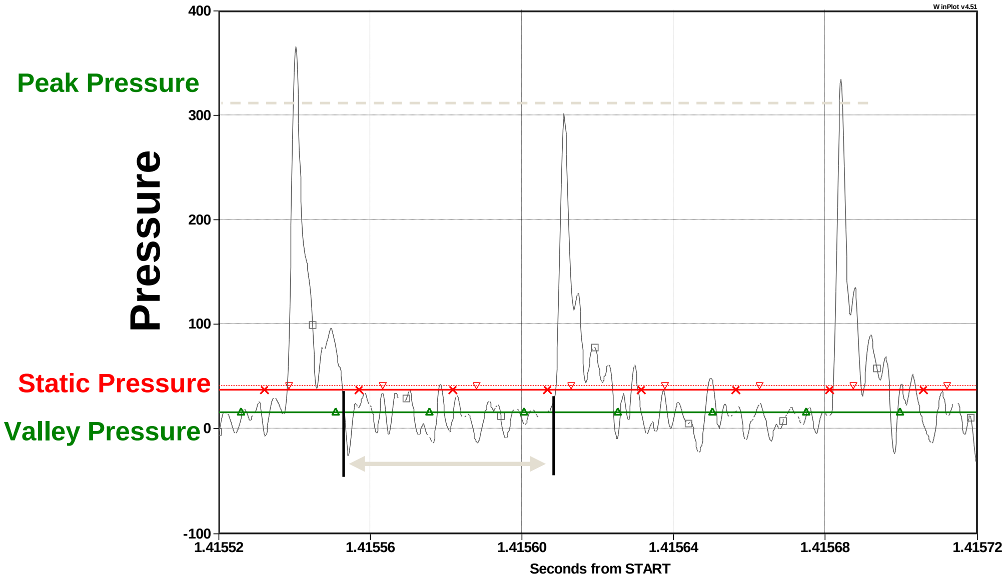
System Analysis Determines the Sensitivity of RDE-Specific Parameters on Plant Efficiency



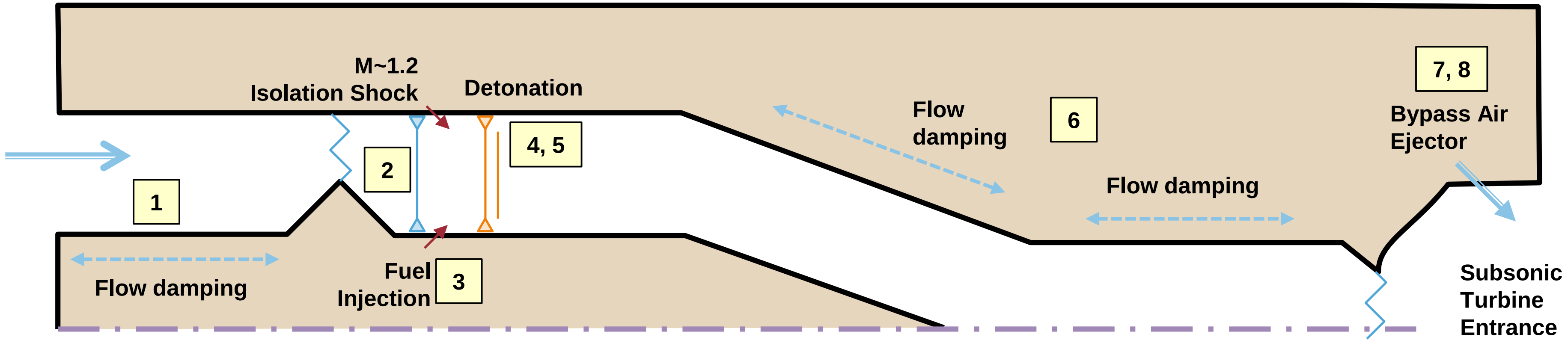
Task 4.0 – CFD Integrated Component Modeling

Integration Challenge Of RDE Combustion

- **Non-uniform flow both temporally and spatially.**
- **Optimum turbine performance requires steady flow.**
- **Smoothing detonation pulse creates pressure loss.**
- **Challenge is balancing pressure loss of flow smoothing with turbine unsteady performance loss.**



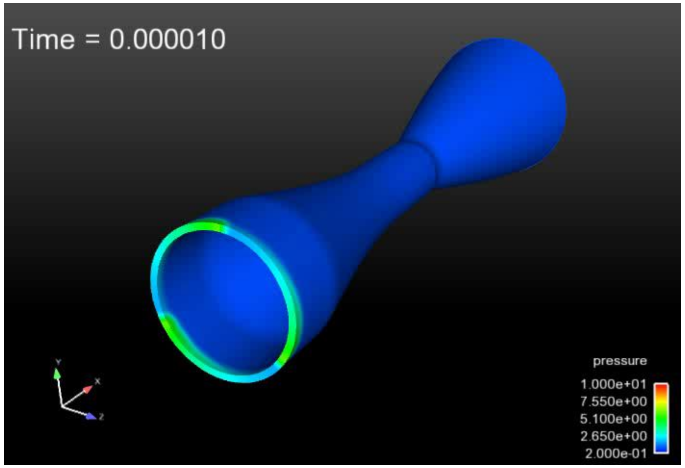
RDE Flow Path For Trade Study



Trade Study Parameters:

1. Isolator flow damping
2. Isolation shock strength
3. Equivalence ratio
4. Deflagration pre-burn
5. Detonation leak flow
6. Flow damping
7. Bypass mass flow
8. Bypass injection total pressure

CFD: Combustion can downstream of RD combustor

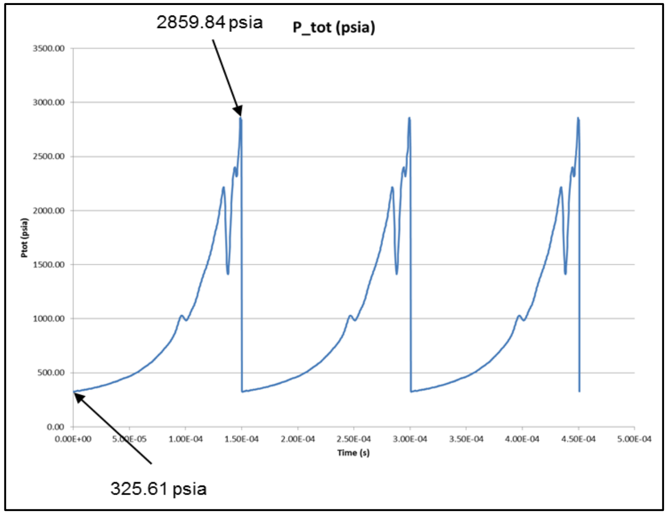


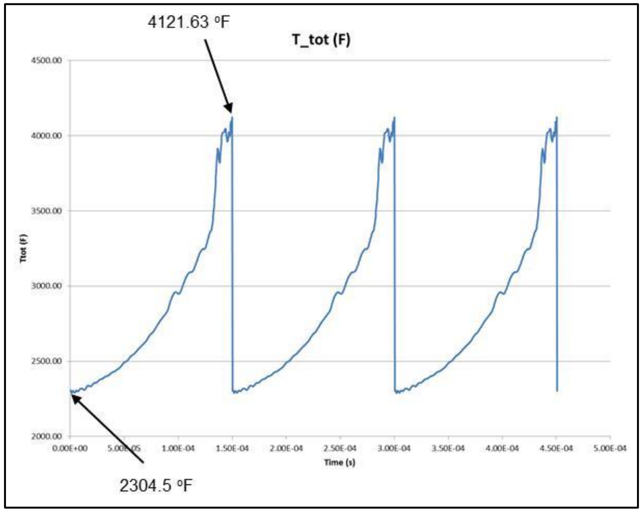
RDE Pressure and Temperature vs. Time for CFD Design Trade Study

To date, four broad classes of exhaust design configurations have been considered:

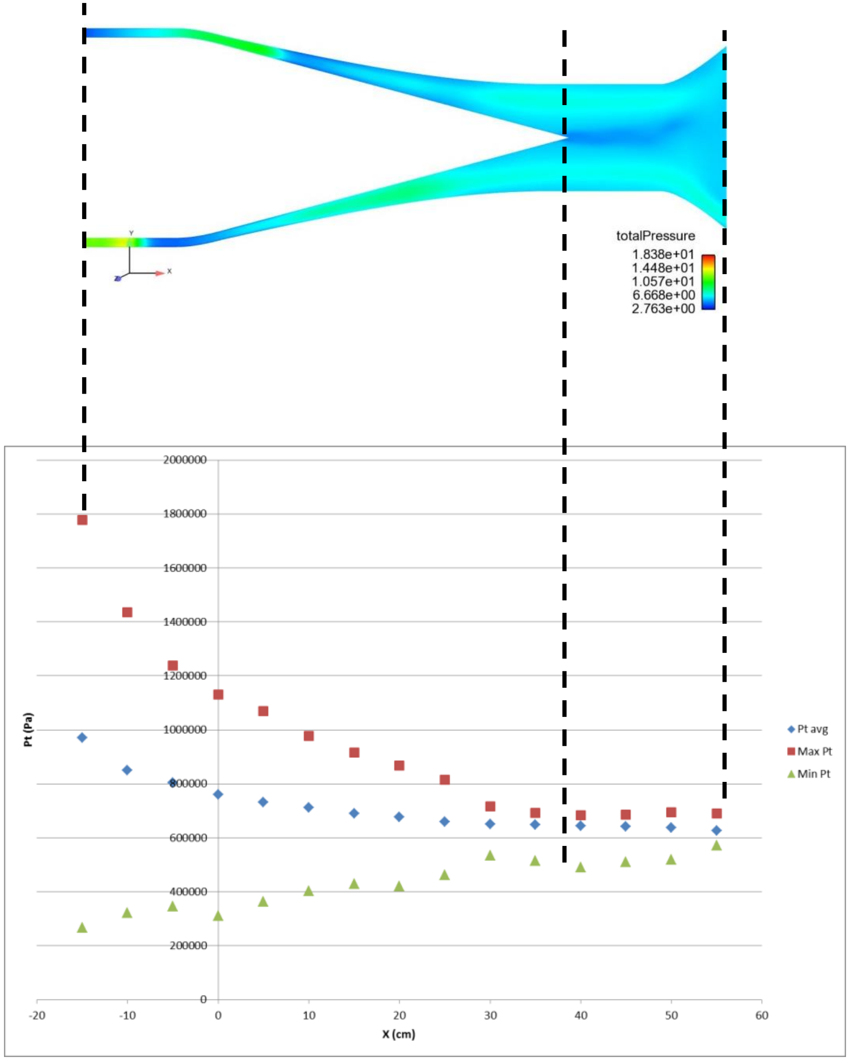
1) A configuration contracting then expanding the exhaust flow to the annulus axis.
2) Purely annular configurations.
3) Annular configurations with enhanced three-dimensional mixing.
4) Smoothing of the flow through magnetogasdynamics.

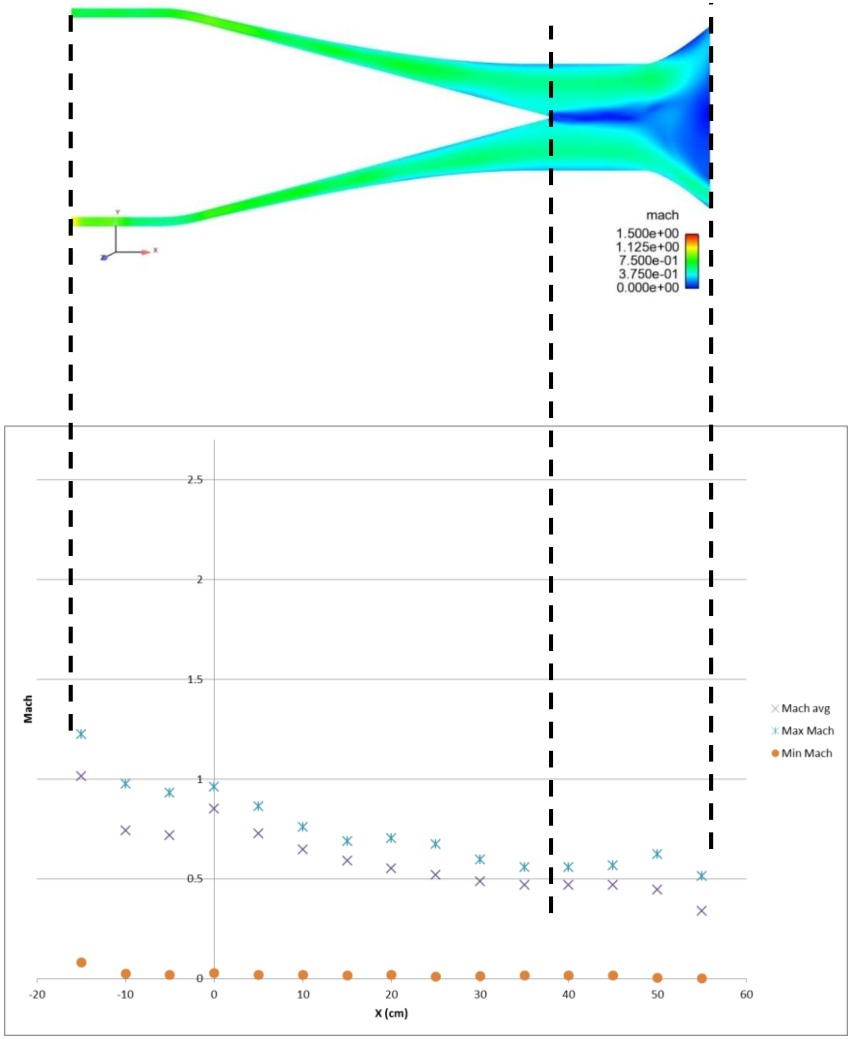
Preexisting RDE exit flow solution with ethylene and air propellants was used as an entrance boundary condition.



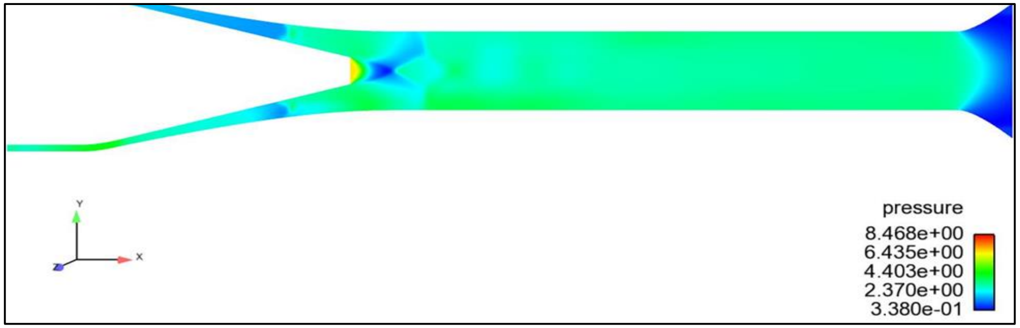


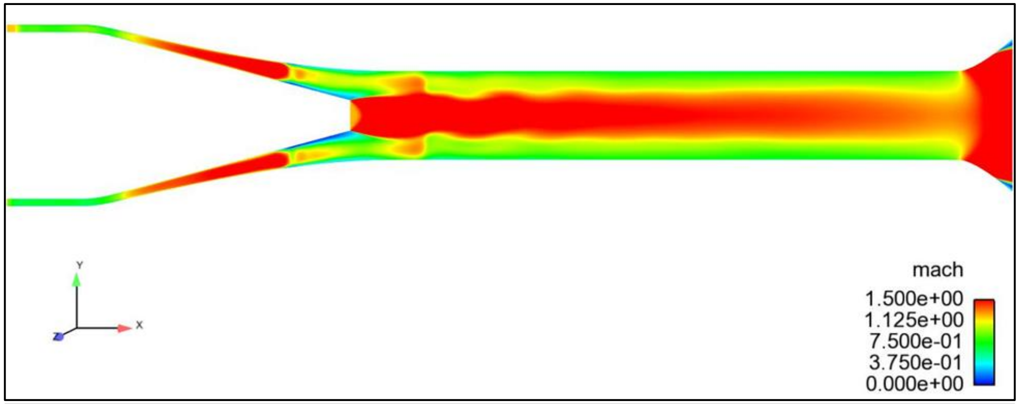
Contours for an Attenuator with a 15 degree Cone, Three Pulses, and Six Atmosphere Back Pressure

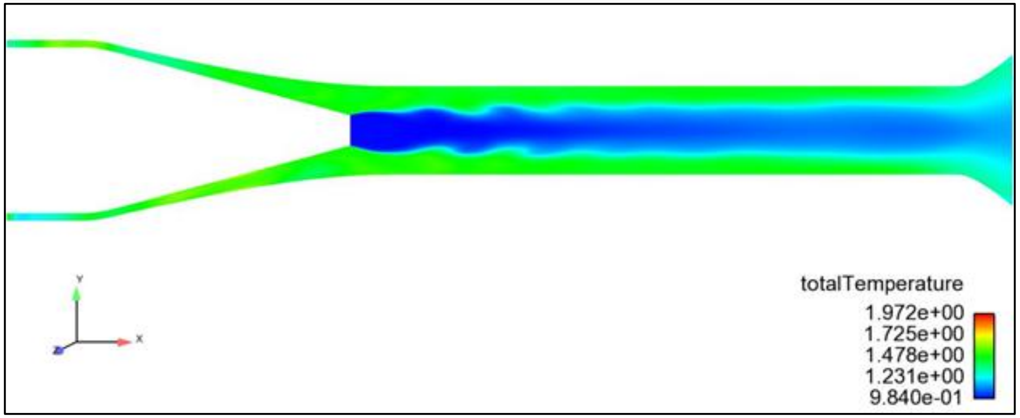




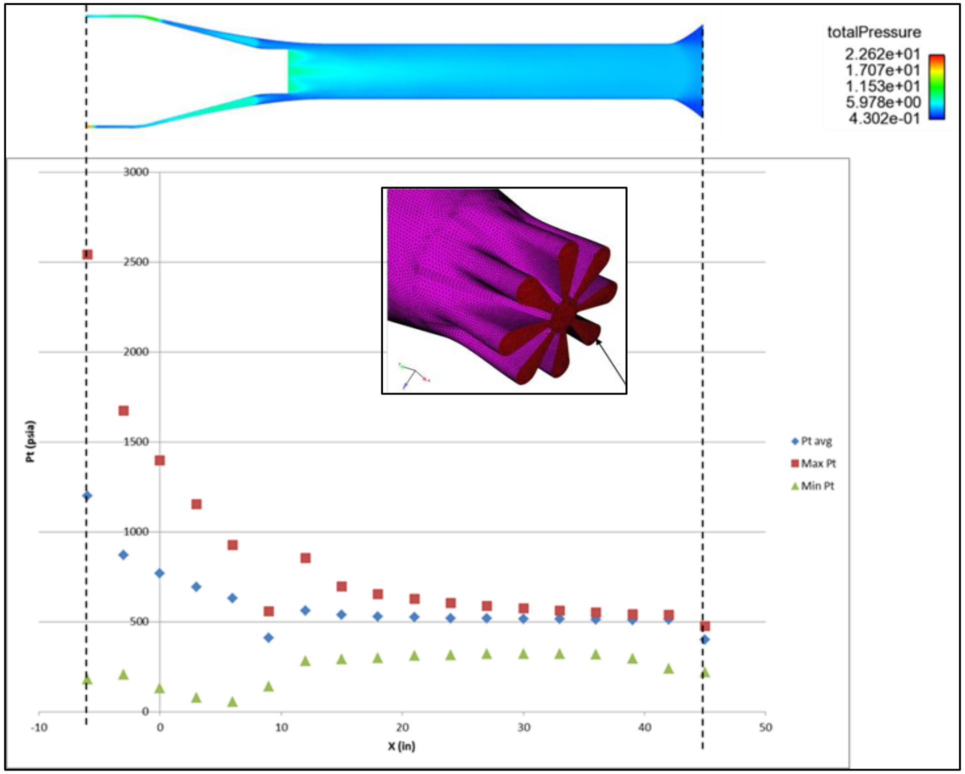
Contours for Initial RDE Plus Constant Area Ejector

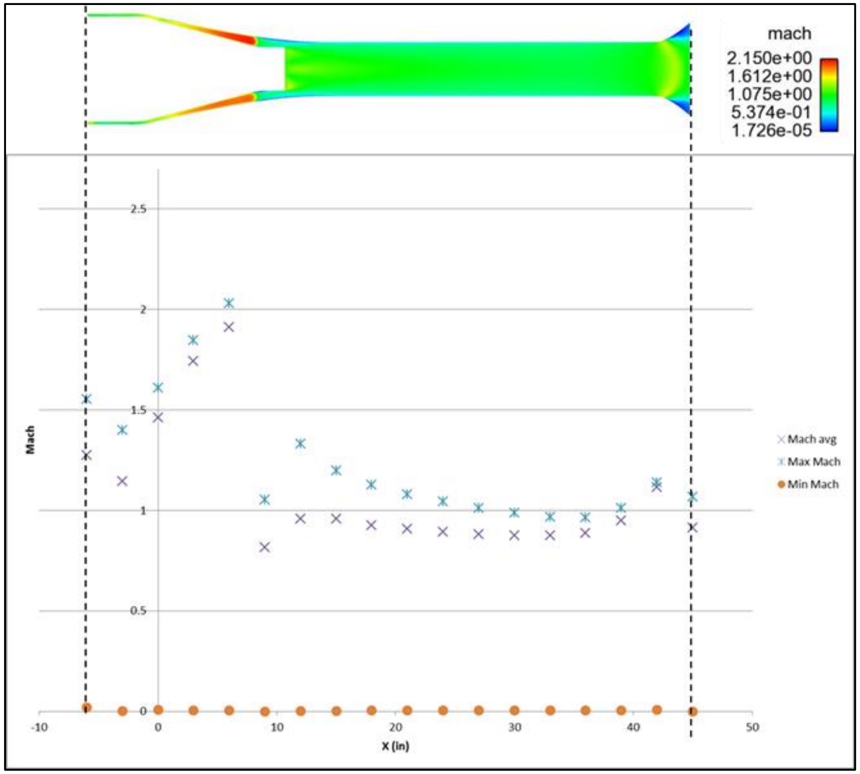






Contours for a Lobed Mixer Ejector





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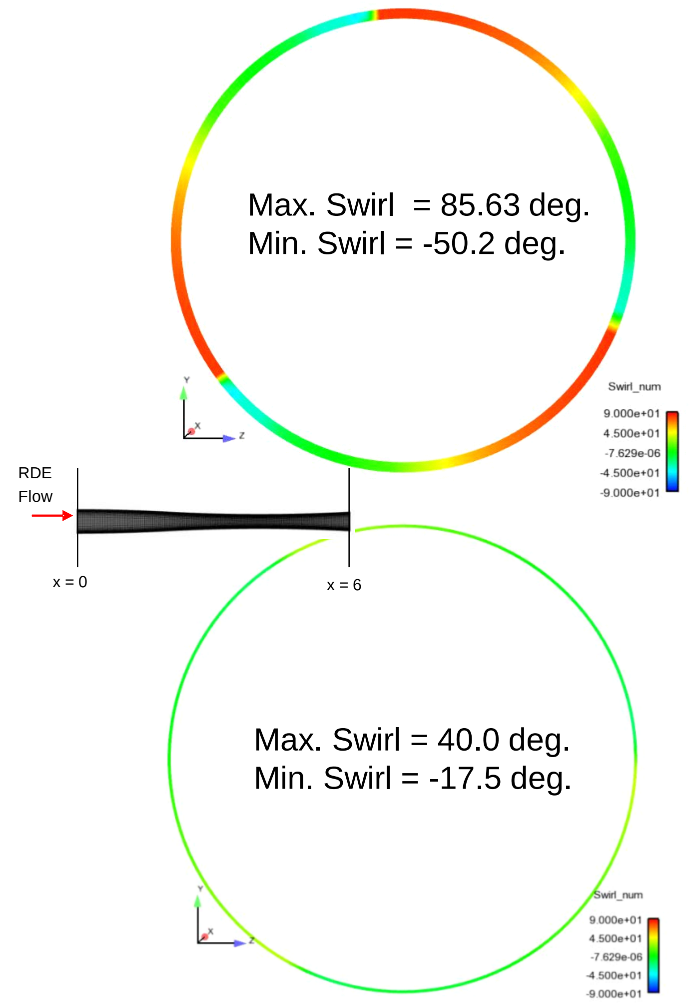
Parameter Profiles for Annular Attenuator

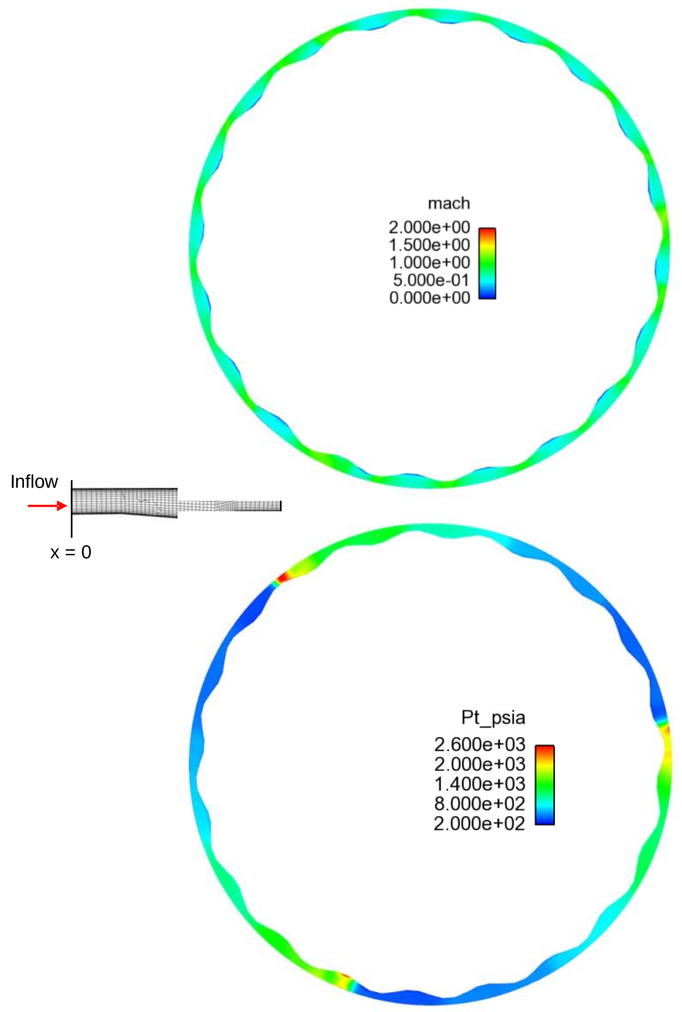
Straight Annulus Swirl Number



Max. Swirl = 85.63 deg.
Min. Swirl = -50.2 deg.

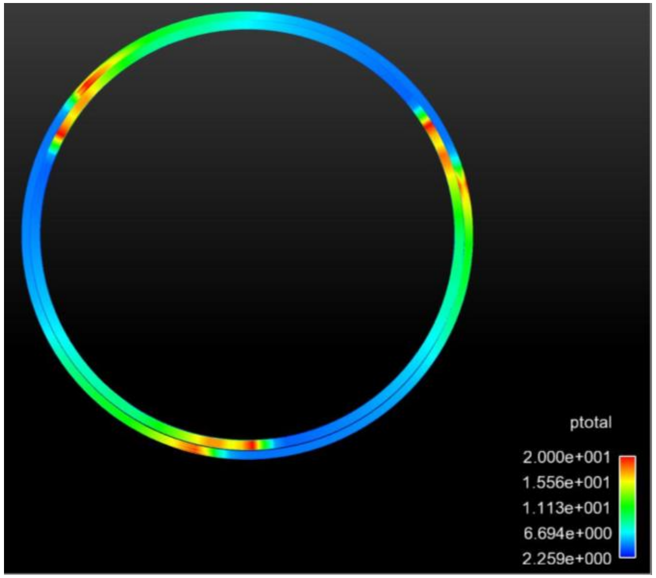
Max. Swirl = 40.0 deg.
Min. Swirl = -17.5 deg.

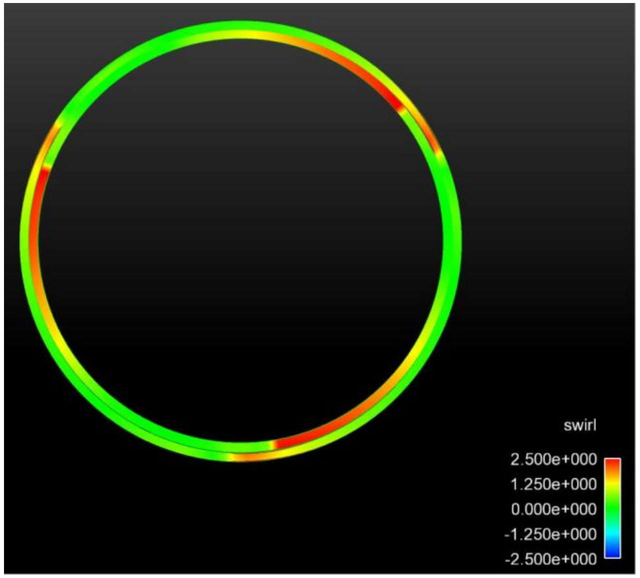
"Zig-Zag" Annulus Mach and Presssure

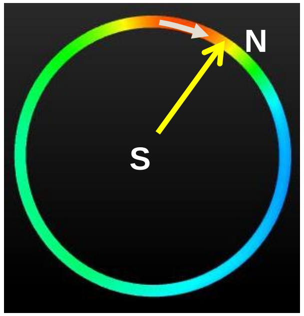


Profiles for Magnetohydrodynamic (MHD) Attenuator

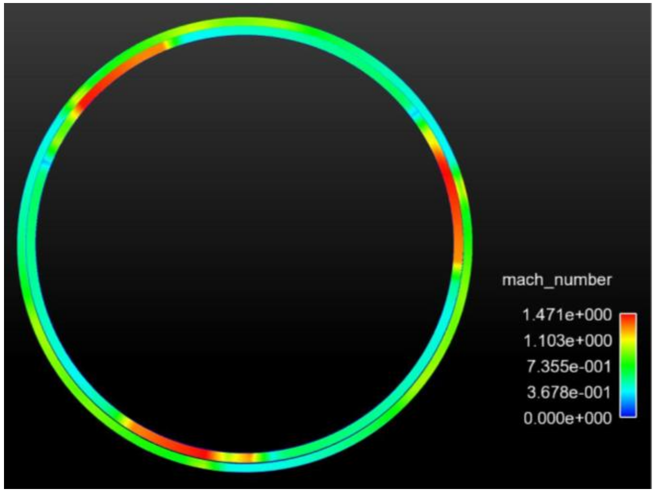
Entrance (Inside) and Exit (Outside) Planes







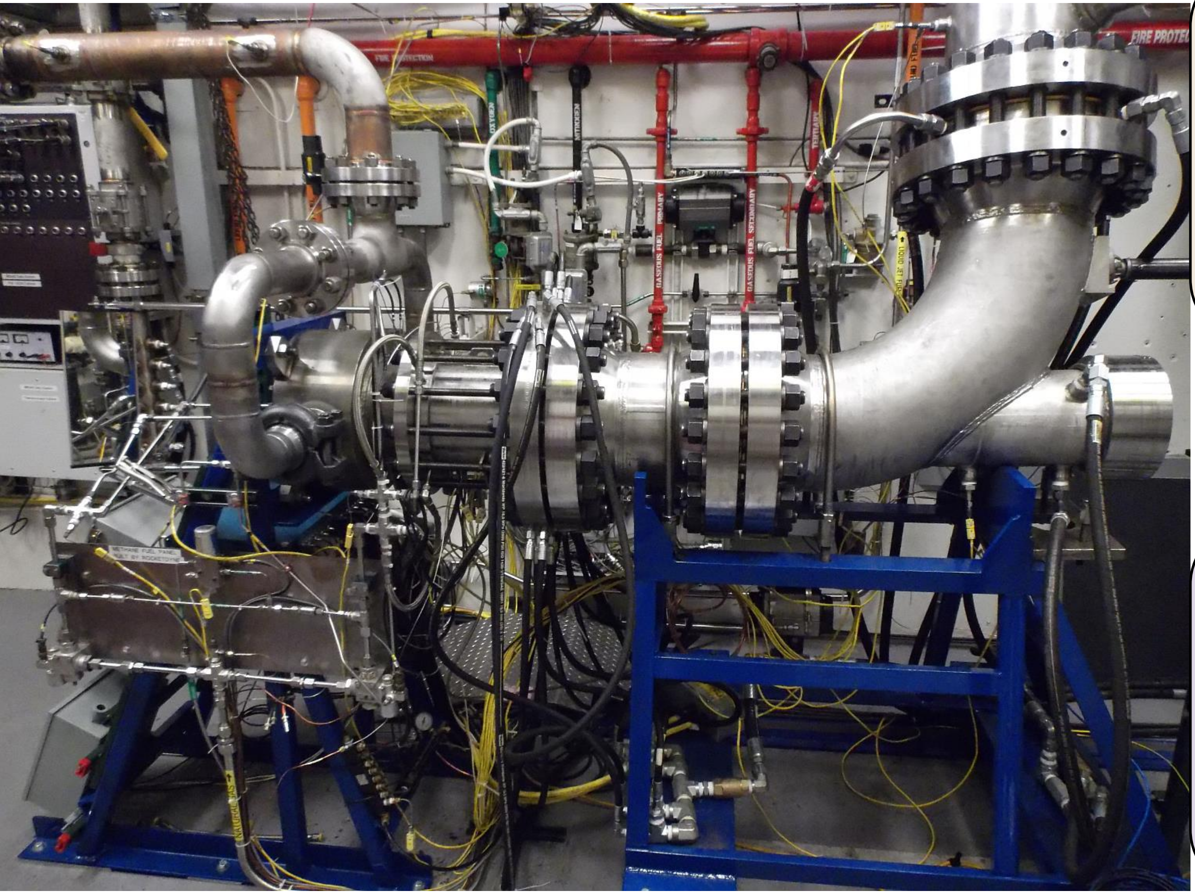
Retarding or Accelerating force depending on the swirl direction (JxB).



The MHD system was successful in reducing the variation in the total pressure, bringing the Mach number down to subsonic, and reducing the swirl variation

Task 5.0 – Test Data Validation Hardware Development

Validation Testing Used 24 cm ARPA-E Hardware



Test Objective: Obtain RDE exhaust dynamic pressure measurements that can be used to validate component thermodynamic models.

Approach: Use angle-of-attack "cobra" pressure probe with high frequency sensors to measure per-pulse time-resolved exhaust flow angle.

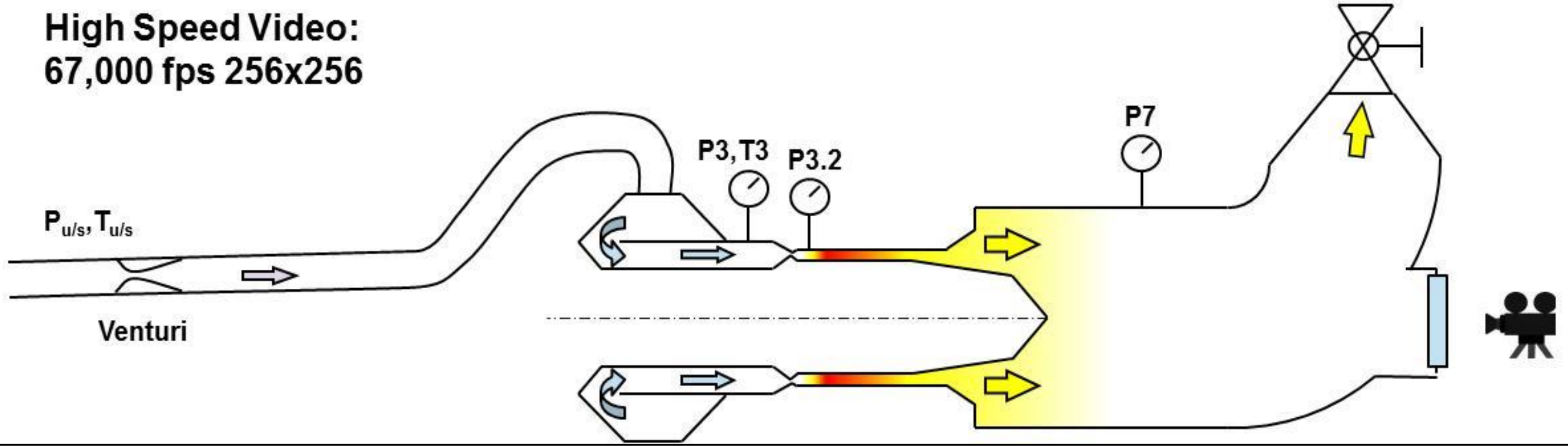
Instrumentation (in Addition to the Cobra Probe) for the Hot-fire Test Program

81 channels,
low speed, 1kHz

7Ch High Frequency Data: 1.25 MS/s
PCB pressure at P3, P3.2
+3 more PCB for cobra probe
2 Ion gauges

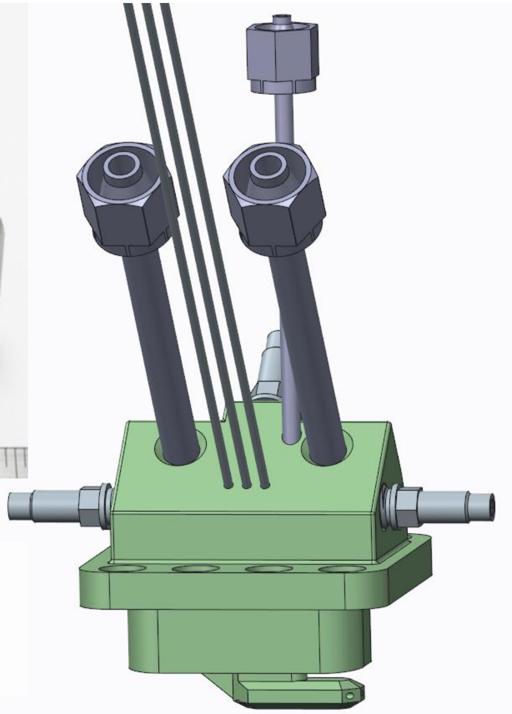
Chamber Static Pressure	Air Venturi U/S Pressure	Air Venturi Throat Pressure	Air T/A Feed Pressure	Air Inlet (outer) CTAP Pressure	Fuel Venturi U/S Pressure	Fuel Inlet Pressure #1	Fuel Inlet Pressure #2	Contraction Section Pressure	Air Venturi U/S Temperature	Air T/A Feed Temperature
PT111	PT201	PT202	PT204	PT254	PT303	PT304	PT305	PT902	TC201	TC204
PSIA	PSIA	PSIA	PSIA	PSIA	PSIA	PSIA	PSIA	PSIG	deg_F	deg_F

High Speed Video:
67,000 fps 256x256

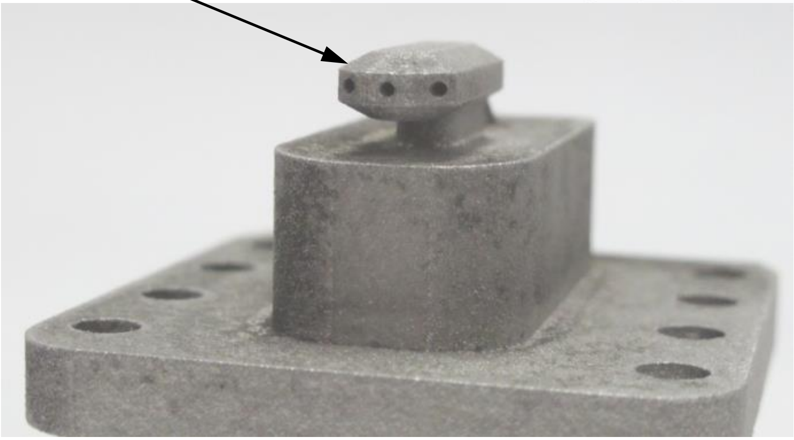


Cobra Probe Design Took Advantage of Additive Manufacturing

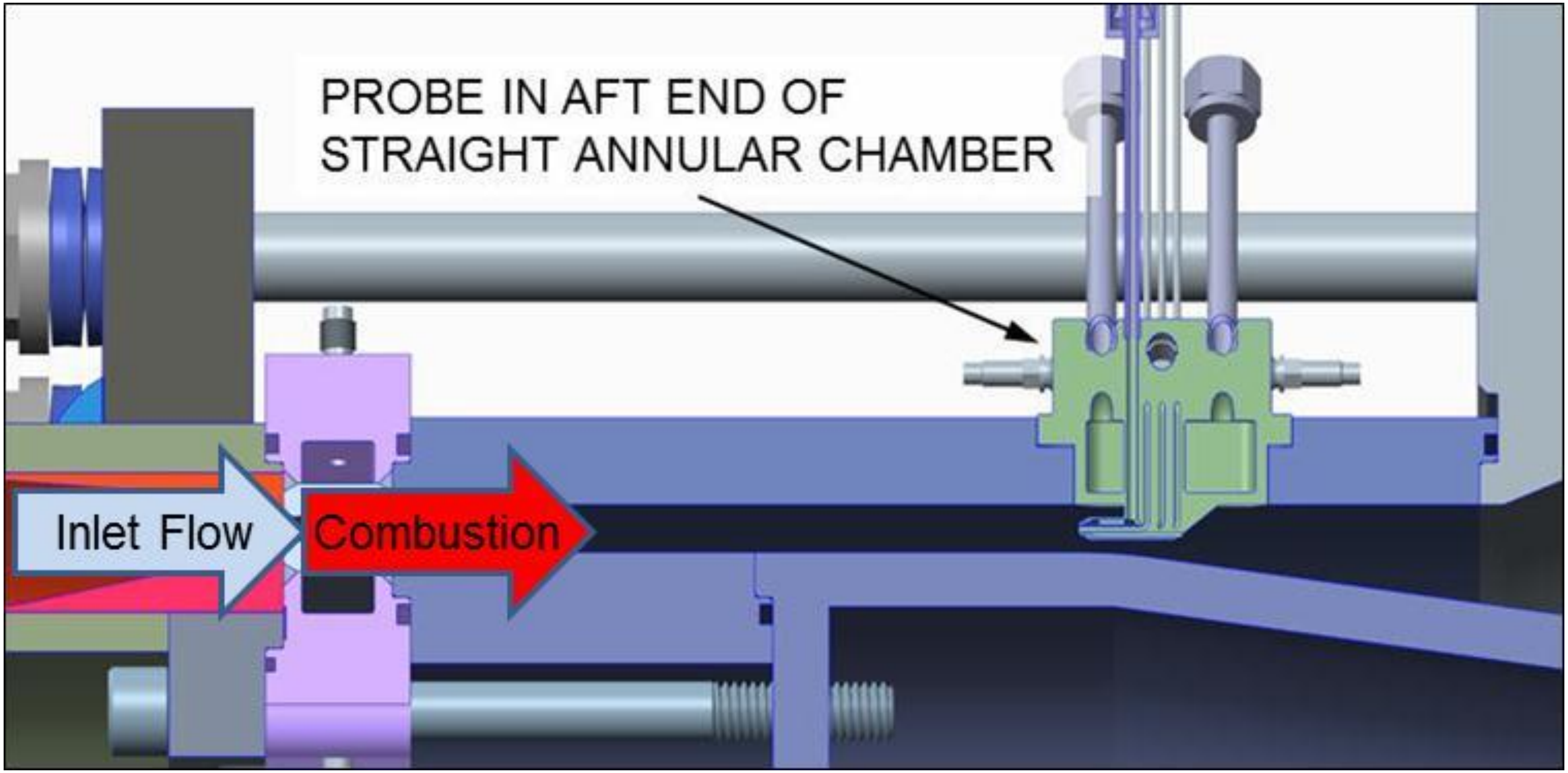
- Obtained time-resolved per pulse flow angle of attack with high frequency pressure sensors.
- Also can extract time resolved total pressure.



PROBE HAS
FACETED TIP TO
MEASURE AoA

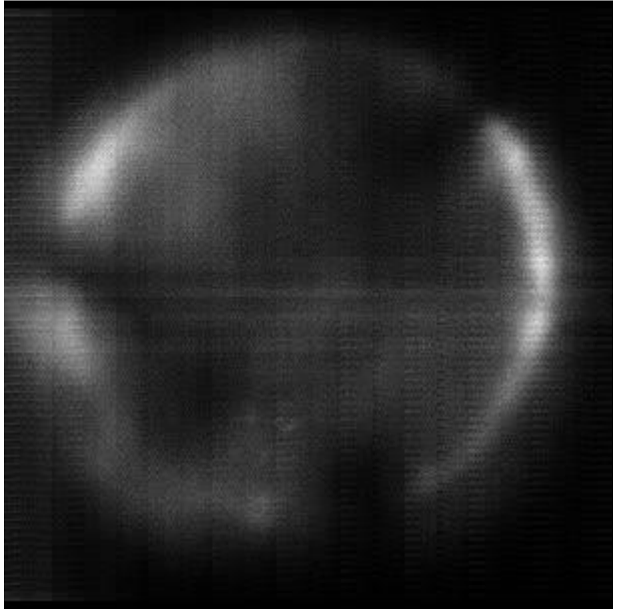


Orientation of the Cobra Probe in the Combustion Chamber



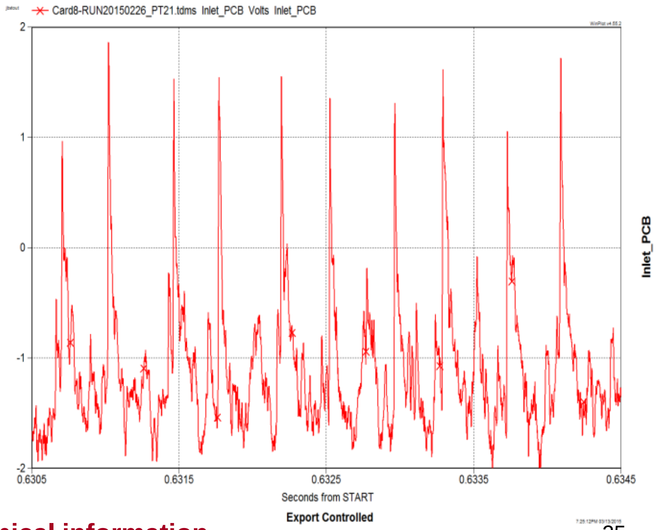
24 cm RDE Hot-Fire Test Results

- 66 Hot-fire Tests
- Three different fuels tested
    - Methane (41 tests)
    - 35/65 hydrogen/methane mixture (9 tests)
    - 70/30 hydrogen/methane mixture (16 tests)
- Equivalence ratio from 0.75 to 1.05
- Inlet air temperature from 310 to 764 degrees F
- Back pressure from 50 to 246 psia
- Air flow rate from 6.1 to 8.7 lbs/sec
- Detonation wave velocities > 3,300 feet/sec



Analysis of the test data is in progress

High magnitude pressure spikes indicate efficient detonation.



Summary and Next Steps

- **Under the NETL "Rotating Detonation Combustion for Gas Turbines" contract, Aerojet Rocketdyne is assessing the potential of incorporating a rotating detonation engine into a Natural Gas Combined Cycle power plant.**
  - AspenPlus cycle analysis of RDE-based power plants is on-going.
    - RDE potential performance gains can be achieved but system interfaces must be carefully engineered to minimize losses.
  - CFD modelling is being used to assess methods for interfacing the unsteady exhaust of an RDE with a conventional turbine.
  - Hot-fire testing of a 24 cm air/methane RDE at gas turbine conditions has been completed.
  - Analyses are on-going.

- **Synthesis of the analysis and hot-fire results into a full scale system design study has been initiated.**

- **Final results will be reported in early 2016.**