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

DE-FE0023983

Scott Claflin
Director – Power Innovations

Edward D. Lynch
Fellow – Combustion CFD

Jeffrey Stout
Project Engineer – Combustion Devices

Chandrashekhar Sonwane
Specialist Engineer – System Engineering

Alan Darby
Program Manager – Power Innovations

2016 University Turbine Systems Research Workshop; Blacksburg, Virginia
November 1 - 2, 2016

Our Recent RDE Programs Provide Data Relevant to Gas Turbine Applications

Contract	*Relevant Technology*	*Test Dates*
• **ARPA-e Contract DE-AR0000322:** RDE Combustor for Natural Gas Turbines	Near full scale operation with mixed hydrocarbon fuels at relevant gas turbine conditions	Feb. 2015
• **NETL Contract DE-FE0023983:** Rotating Detonation Combustion for Gas Turbines Phase I	Thermodynamic model development and anchoring with near full scale hydrocarbon test data	July 2015
• **NETL contract DE-FE0023983**: Rotation Detonation Combustion for Gas Turbines Phase II	Definition of the interface environment between the RDE and turbine cascade	Feb. 2017
• **ONR Contract N00014-14-C-0035**: RDE Low Loss Inlet/Injector Manifold	Near full scale, high performance inlet/injector design assessment at relevant conditions	July 2016
• **DARPA/HyPerComp STTR Contract W911QX-13-C-0132:** Modeling and Optimizing Turbines for Unsteady Flow	Effect of dilution air on the thermal environment and detonation behavior. RDE interaction with a turbine cascade	Sept. 2016
• **DARPA Contract HR0011-15-C-0132** HAVOC	Near full scale testing of liquid fuels at relevant conditions	Sept. 2016

Objective of Program

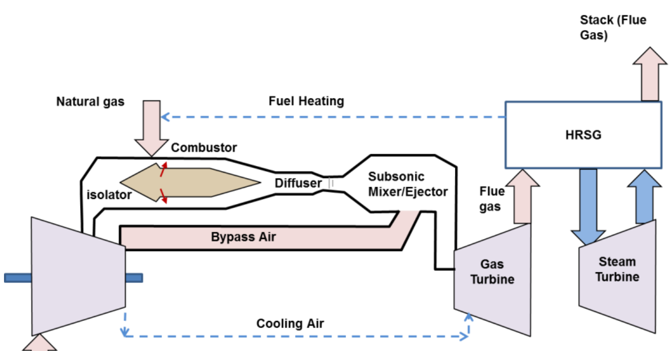
To advance combustion turbine technologies for combined cycle applications…

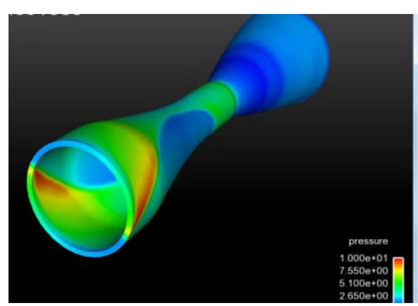
…by integrating a Rotating Detonation Engine (RDE), pressure gain combustion system with an air-breathing power-generating turbine system to achieve a combined cycle efficiency equal to or greater than 65%.

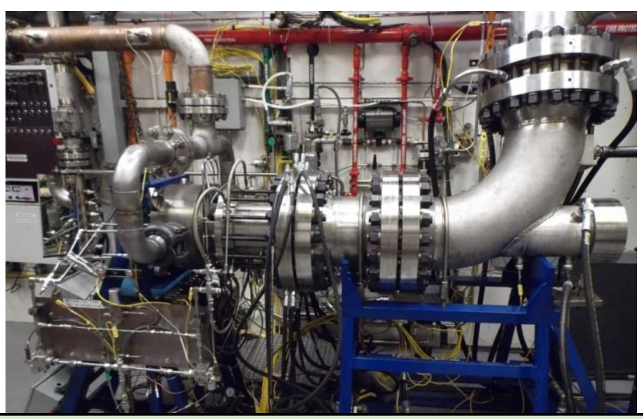
RDE Phase I Program Summary

National Energy Technology Laboratory Phase I (October 2014 – March 2016)

- **$800k Cooperative Agreement with cost sharing from AR, Duke Energy and UTRC**
- **Eighteen month technical effort focused on four primary tasks**
  1) Pressure Gain Combustion (Rotating Detonation) Thermodynamic Analysis
     - Refine current tools for high fidelity analysis of NETL case 13 for NGCC
     - Evaluate NOx reduction strategies
       - Fuel lean combustion, exhaust gas recirculation, rapid quench, exhaust scrubbing, etc.
  2) CFD Model Development
     - Extend current tools to analyze entire rotating detonation system
       - Inlet rectifier - cooled combustor - turbine transition
  3) Hot-fire Testing at Gas Turbine Conditions
     - Determine effectiveness of components using existing ARPA-e hardware
     - Generate data for analytical tool anchoring/validation
  4) Full Scale Design Study
     - Identify scaling and integration issues with fielded gas turbines







Plant and Combustor/Diffuser Model Development

Model Validation Via Hot Fire Testing

Approved for Public Release

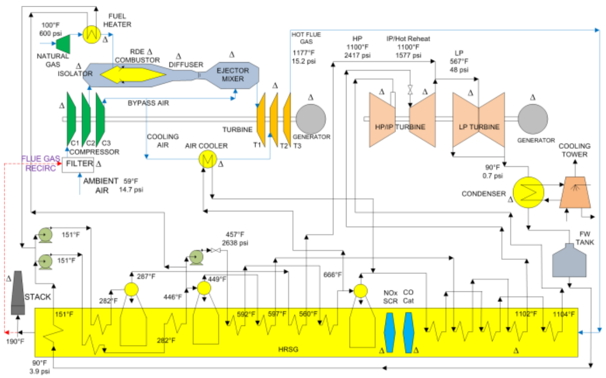
National Energy Technology Laboratory Phase I Contract

Objective:

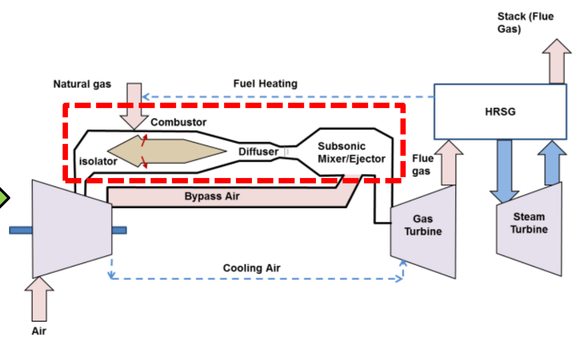
- Develop and validate a system model of rotating detonation combustion in a Natural Gas Combined Cycle Power Plant

Approach:

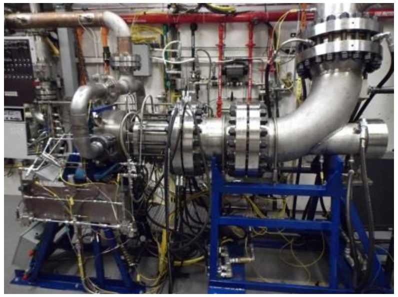
- Develop thermodynamic models of the compressor, RDE and turbine
- Refine CFD models of the inlet rectifier, RDE (including NOx) and turbine interface
- Develop and hot fire test an inlet rectifier and RDE at relevant conditions



A Natural Gas Combined Cycle system model that has been anchored with RDE test data



An RDE component and interface model that has been anchored with test data

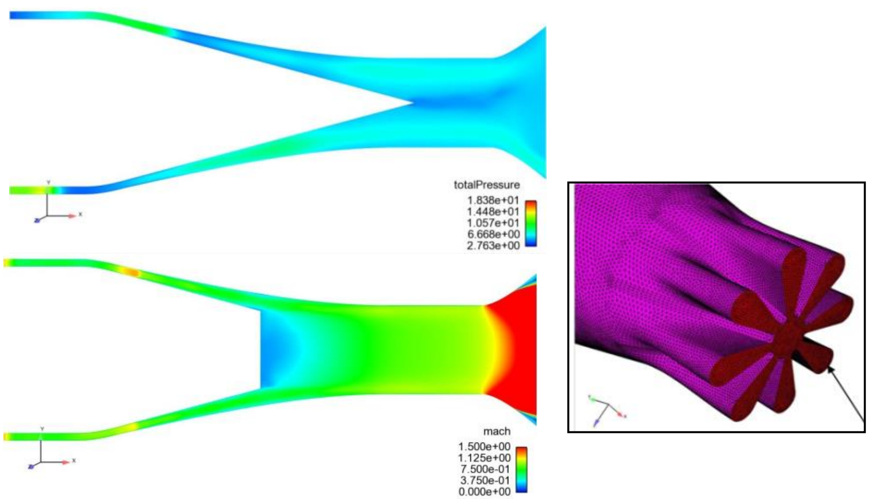


9.4 inch RDE test facility – 66 tests

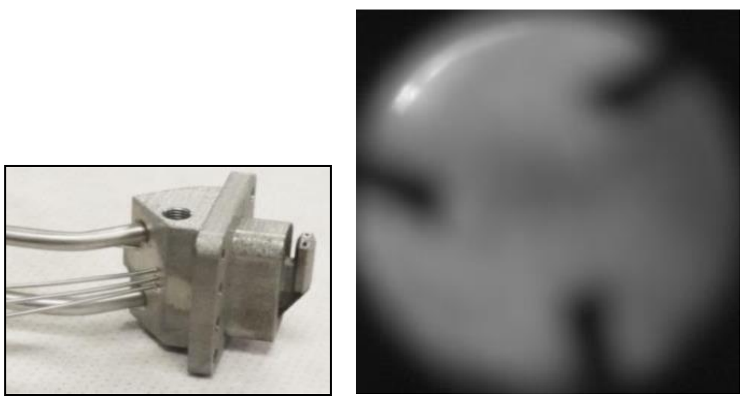
National Energy Technology Lab
Phase I Contract

Results:

- **Comprehensive model of an RDE-powered gas turbine was developed**
  - **RDE specific interfaces were defined and modeled**
  - **CFD analysis identified multiple potential schemes for minimizing losses associated with interfacing the unsteady RDE with a turbine cascade**
  - **66 hot-fire tests with air/natural gas at gas turbine conditions (OPR 16) was ultimately successful but yielded limited data.**
- **RDE gas turbine model was integrated into a natural gas combined cycle power plant system model and plant parameters were quantified**

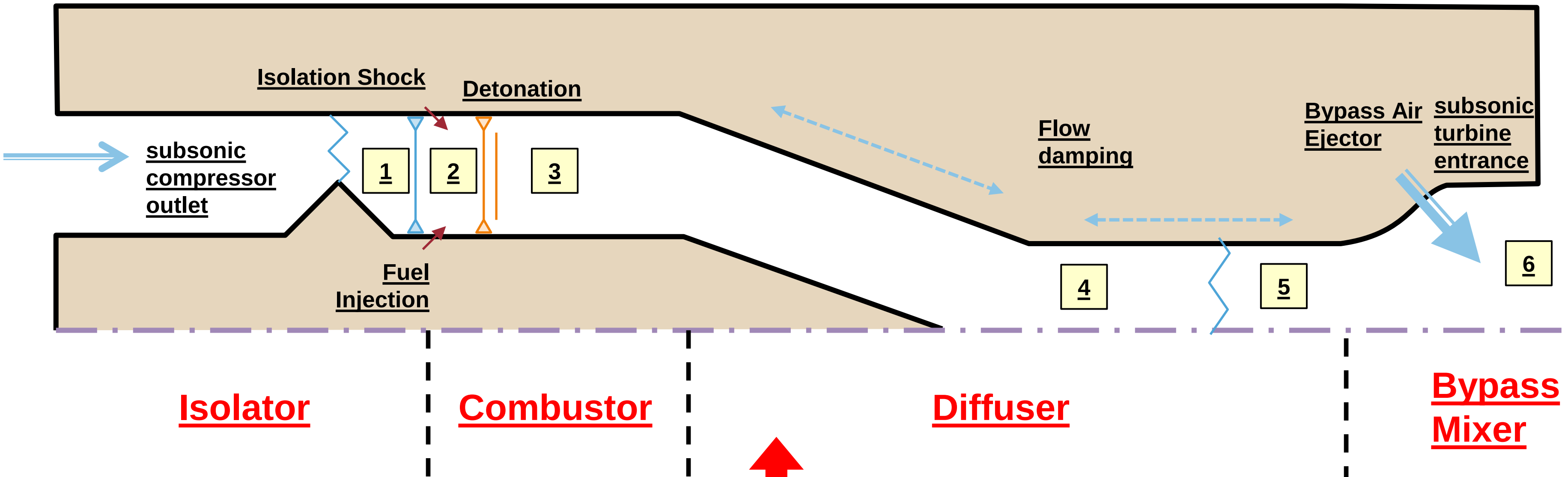


3-D CFD analysis to determine minimal loss approaches to interfacing and RDE with a turbine cascade



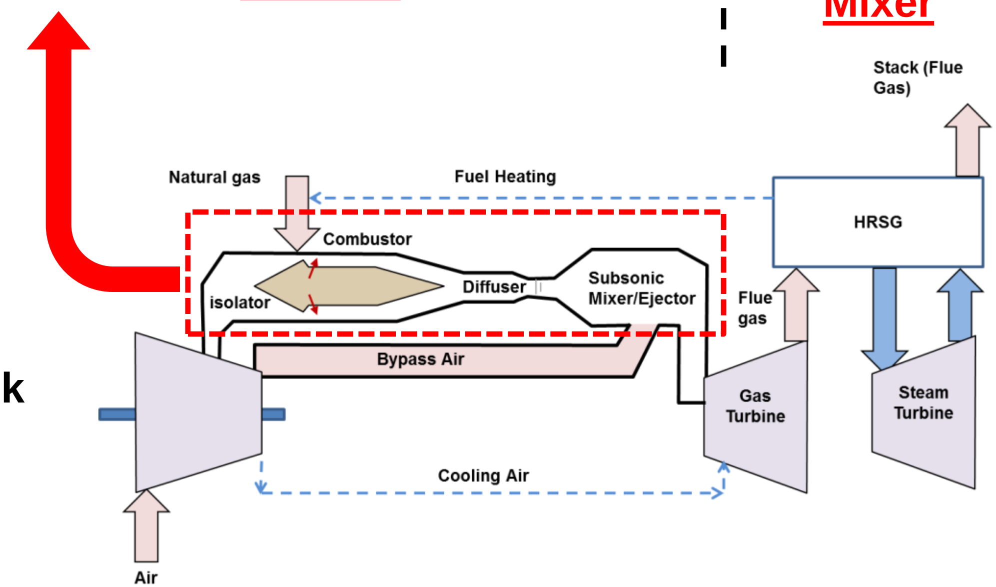
Hot-fire testing with a cobra probe to determine operating limits and hot gas velocity vectors

Performance Model Components



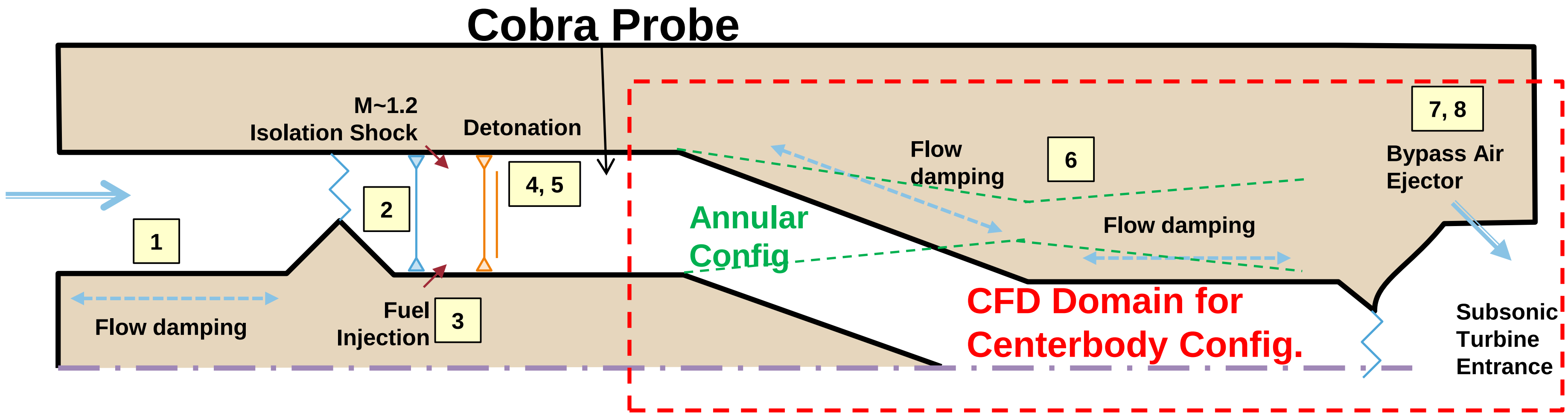
Trade Study Parameters:

1. Isolation shock strength
2. Equivalence ratio
3. Detonation efficiency
4. Flow compression ΔPt
5. Flow transition normal shock
6. Bypass mass flow / mixing



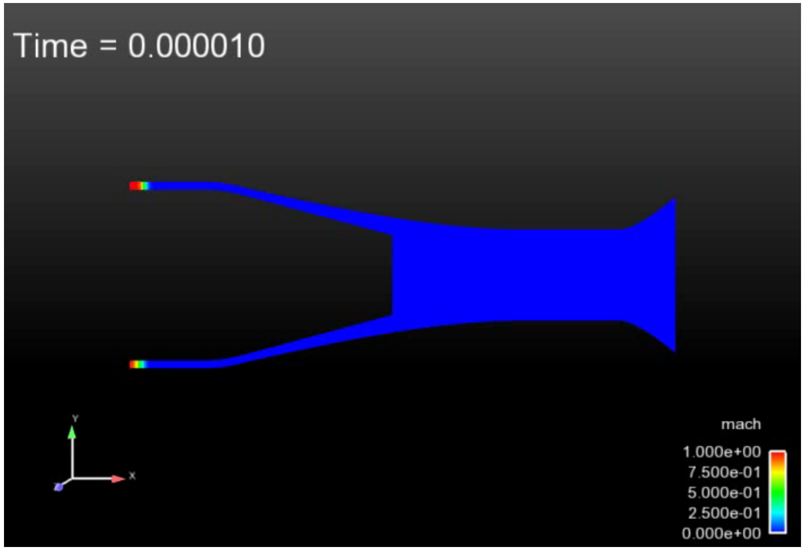
Approved for Public Release

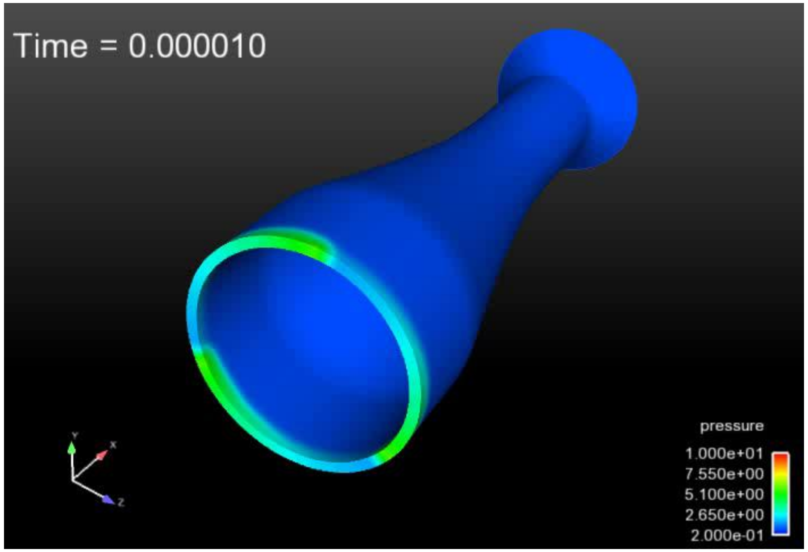
Design Space Examined to Date for Flow Smoothing of Exhaust



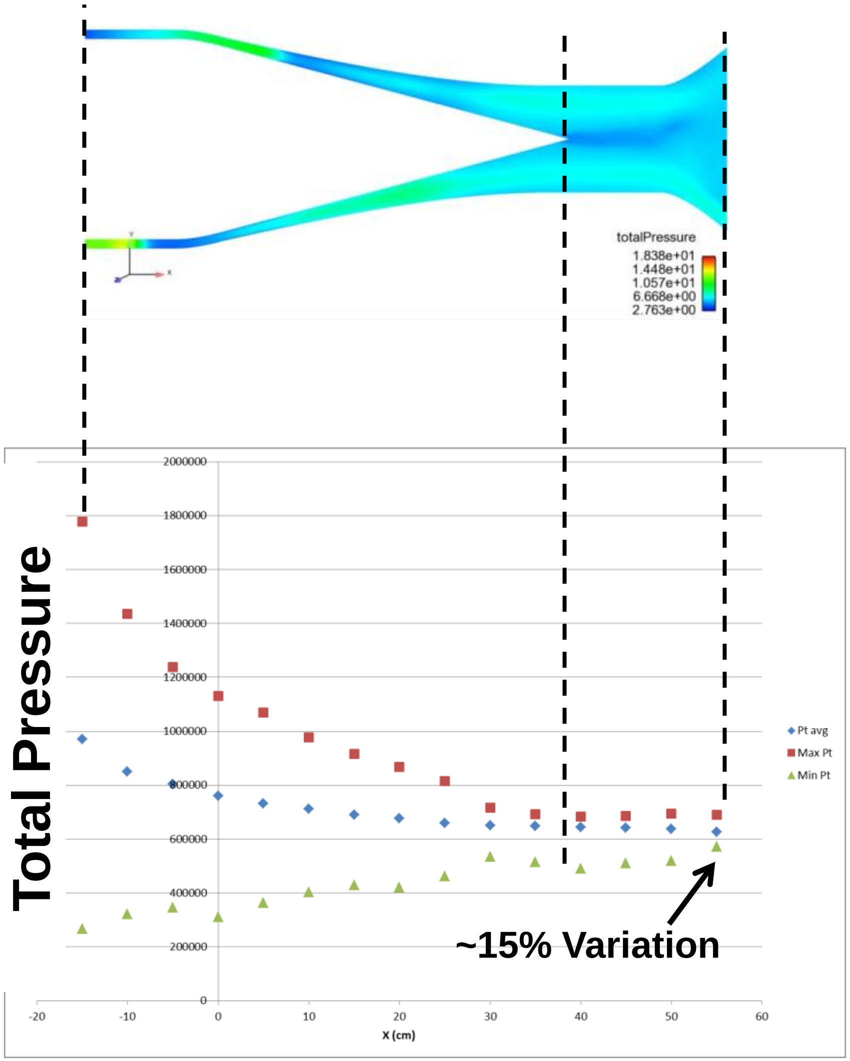
- **Configurations Evaluated Relative to Smoothing of Total Pressure and Swirl Angle**
- **Types of Configurations Considered**
  1. Centerbody/Boattail configuration contracting then expanding the exhaust flow to the annulus axis
  2. Cases evaluated with and without ejector mixing of bypass flow
     - Similar to Nordeen/Schwer configuration evaluated with Euler CFD and presented at 2015 JPC
  3. Purely annular configurations
  4. Annular configurations with enhanced three-dimensional mixing
  5. Smoothing of flow through magnetogasdynamics

Reduction in Flow Nonuniformity Seen with Centerbody Configuration





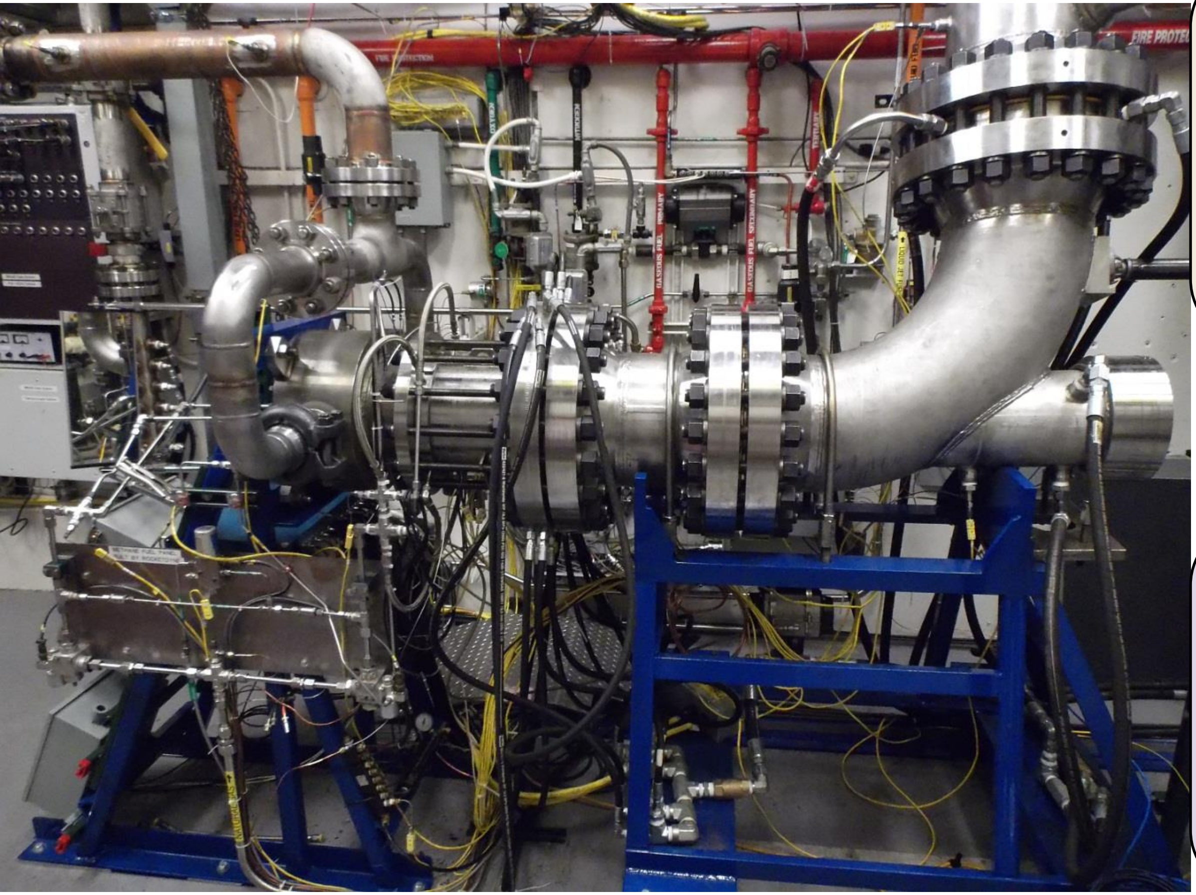
Best Centerbody Configuration to Date



Conclusions from Detailed CFD Analyses

- Centerbody configuration can reduce variation in swirl angle sufficient to largely eliminate unsteady turbine losses
  - Currently at too high total pressure loss
- Mixing in bypass flow requires some azimuthal vortex creation
- Purely annular configuration cannot achieve large degrees of smoothing without transfer of momentum between high and low momentum RDE exit flow through mechanical or external body force means
- Current direction focuses on downstream loss process
  - Improving bypass flow mixing
  - Determining optimal turning angles for centerbody configuration
  - Increasing uniformity to allow moving to higher back pressures before unstart
- High detonation temperature drives NOX formation
  - 1-D Kinetics prediction indicate time scale for expansion still too long to prevent NOX formation

Validation Testing Leveraged Existing Ø9.4-inch RDE



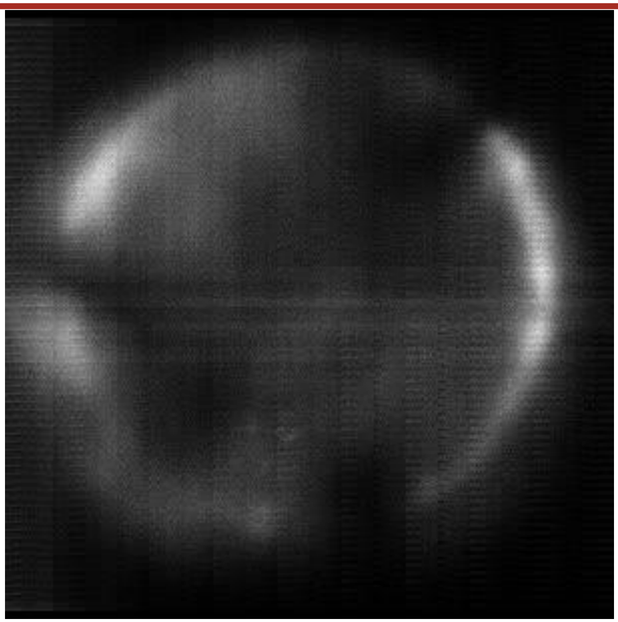
Test Objective: Obtain RDE exhaust dynamic pressure measurements that can be used to validate component thermodynamic models

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

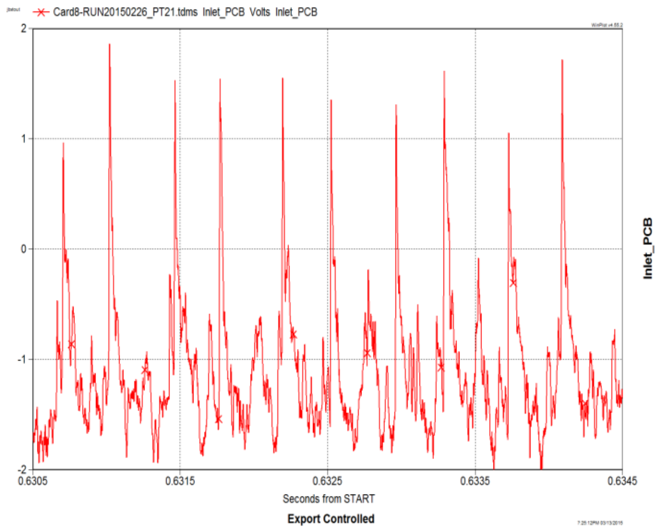
- **Facility and RDE built up by AR & ARPA-E at UTRC Jet Burner Test Facility**
  - **Capable of 10 lbs/sec heated air, 764°F**

9.4-inch 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

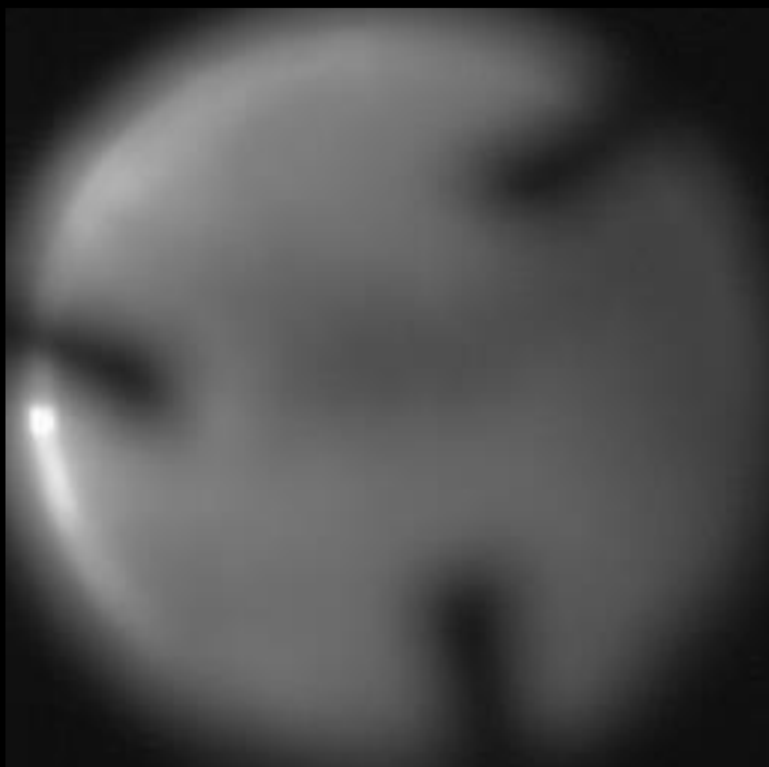


High magnitude pressure spikes indicate efficient detonation.



High Speed Video Shows Wave Behavior

9 o’clock to 3 o’clock Slapping Mode (5 Cycles)



One-Directional Spinning Mode (4 Cycles)

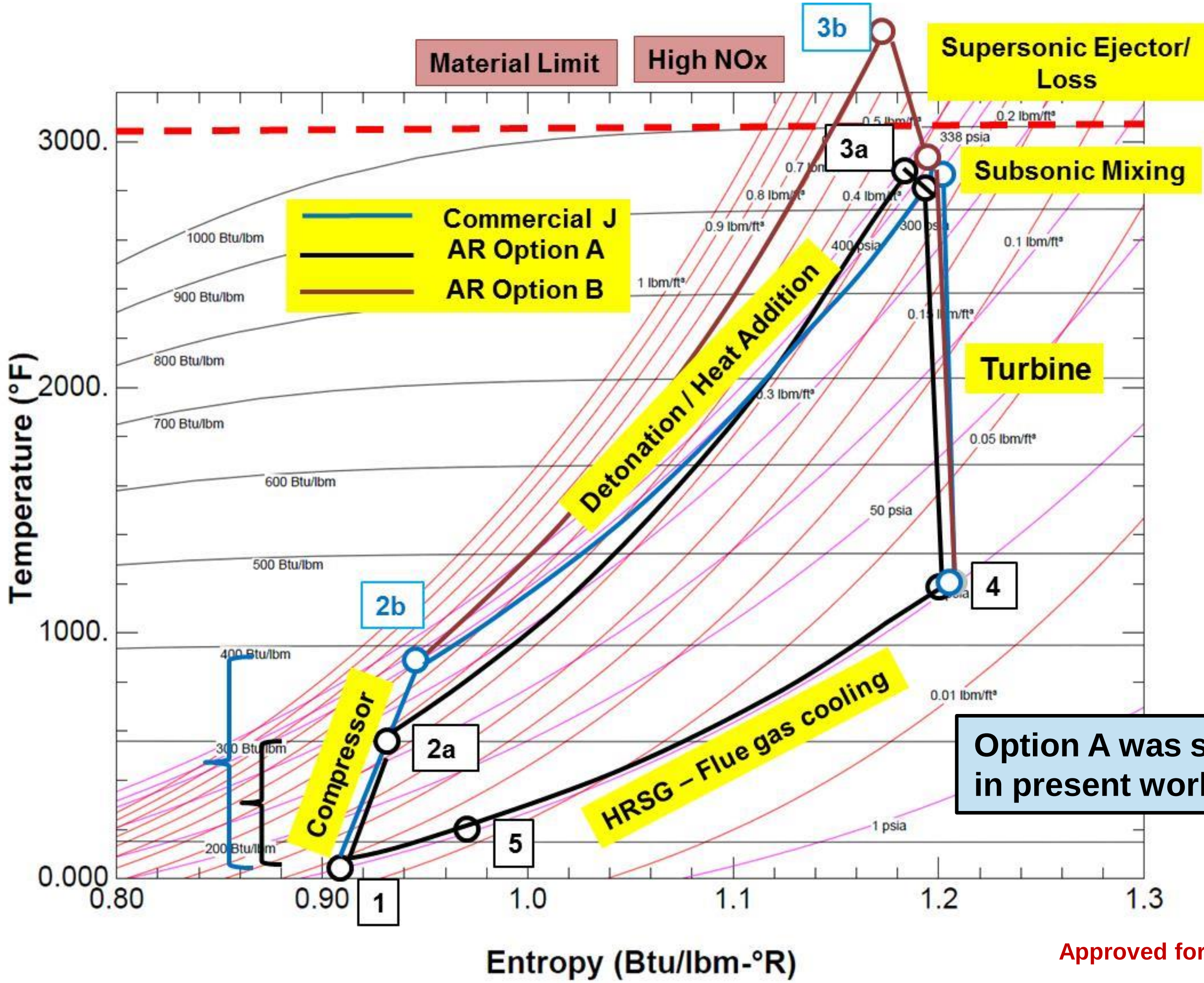
Test Program Summary

- 9.4” RDE tested to find robust detonation condition similar to turbine conditions (OPR 16: temperature and pressure)
  - Difficult to get good detonation with NG/air, particularly with low loss inlet
- Calibration approach and data analysis technique yielded questionable cobra probe results
  - Exhaust flow swirl angle is required to validate CFD models
- Gained a better understanding of relation between detonation cell size and combustor geometry

Approach for Developing Performance Models

- Developed a **power plant mass and energy balance system model using AspenPlus** integrating an RDE Combustion System with a gas turbine-based power generation system
- Defined the RDE Combustion system and the interaction of the RDE with the gas turbine system through **component models** encapsulating the operation of these components with real, as opposed to ideal, performance in succinct fashion
- Developed **Capital Cost** spreadsheet for all components using NETL's guidelines in QGESS (Quality Guidelines for Energy System Studies)
  - Capital cost commercial combustor replaced by RDE
  - Capital cost of Steam Island cost was updated
- Estimated **Fixed and Variable Operating Cost** using NETL's guidelines in QGESS
- Estimated **cost of electricity (COE)** using NETL's QGESS guidelines
- Changes to the size and cost power plant component to the upstream and downstream of combustion system is insignificant (e. g. Compressor, Turbine and Steam Island)

T-S diagram: Options with and without Booster Pump



Supersonic ejectors introduce significant losses.

Option A was selected in present work

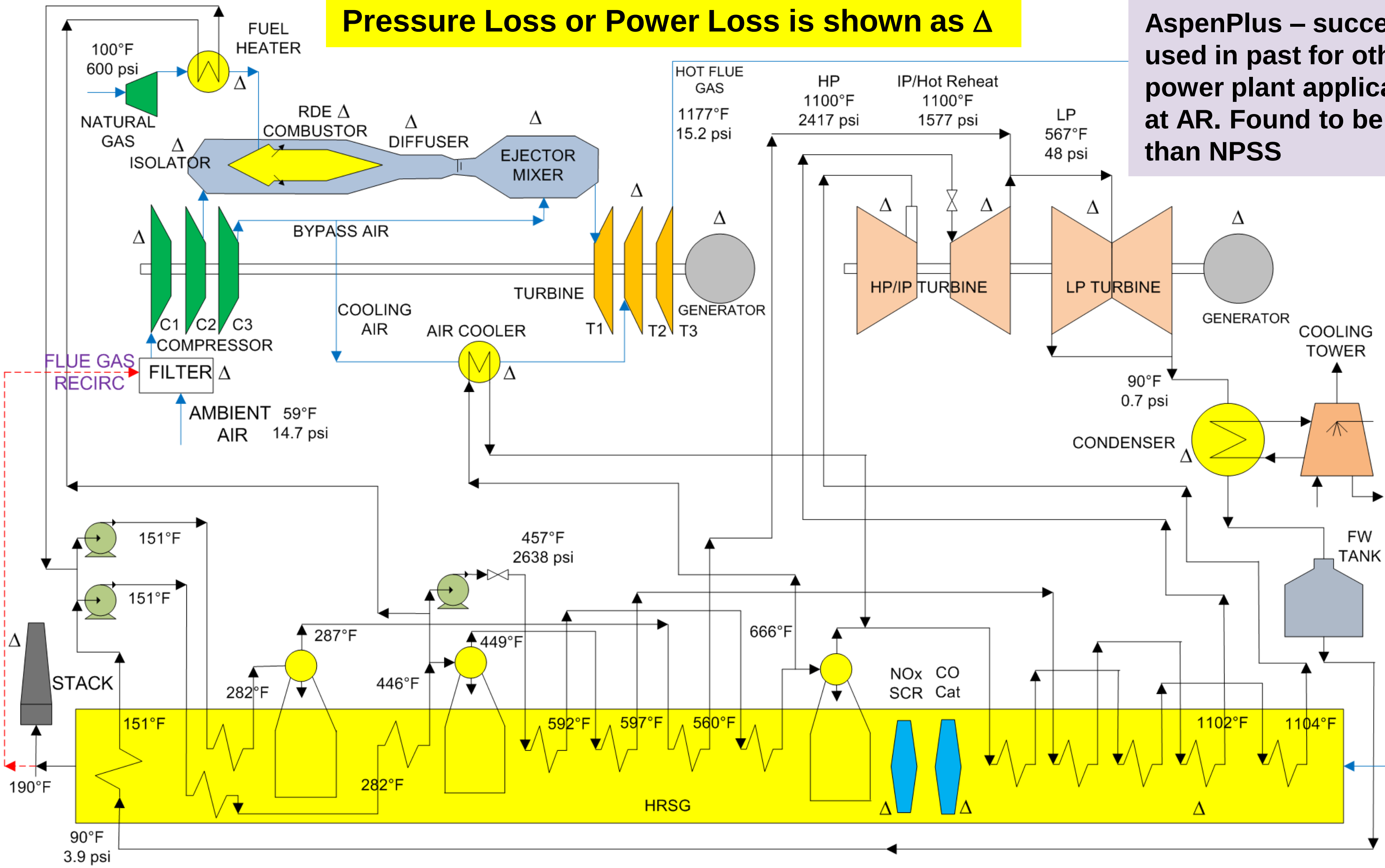
Approved for Public Release

Baseline Cycle Data taken from Case 3a, DOE/NETL-341/061013, Walter Shelton, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants

Process Flow Diagram of RDE based NGCC: AspenPlus

Pressure Loss or Power Loss is shown as Δ

AspenPlus – successfully used in past for other power plant applications at AR. Found to be better than NPSS



MHI's J class turbine uses recycled flue gas to reduce NOx – currently ignored in the present simulation to be consistent with baseline Case 3a, DOE/NETL-341/061013 assumed in the present work

Performance Results: Comparison with State of the Art Power Plant

		IGCC F	Coal SCPC	NGCC F	NGCC H	NGCC J	NGCC RDE
Fuel Type		ILL6 Coal	ILL6 Coal	Natural Gas	Natural Gas	Natural Gas	**Natural Gas**
Total Gross Power	MWe	748	580	650	841	1004	**1096**
Total Auxiliary Loads	MWe	126	30	16	21	22	**23**
Net Power	MWe	622	550	634	820	982	**1073**
Efficiency	**% (LHV)**	**39.0**	**39.3**	**57.4**	**59.5**	**62.6**	**68.3**
CO2 emitted	lb/MWh	1723	1768	780	752	714	**674**
Fuel Use (HHV)	Btu/kWh	8,445	8,379	5942	5736	5448	**4986**
Water Consumed	gpm/MWnet	6.0	7.7	3.5	3.2	2.8	**2.6**
TOC Capital Cost	$/kW	4086	2452	829	756	684	**655**
COE - Total	**mills/kWh**	**101.2**	**81.0**	**57.1**	**54.2**	**50.7**	**47.2**
COE - Fixed O&M	mills/kWh	13.5	9.5	3.4	3.0	2.7	**2.4**
COE - Variable O&M	mills/kWh	9.3	7.7	1.8	1.6	1.4	**1.7**
COE - Fuel	mills/kWh	25.8	25.5	40.4	39.0	37.0	**33.8**
COE - Capital Recovery	mills/kWh	52.5	38.2	11.7	10.7	9.6	**9.2**
LCOE- Total	mills/kWh	128.3	102.6	72.4	68.7	64.3	**54.8**

Cost Estimation Methodology taken from: DOE/NETL-2011/1455, QGESS, Cost Estimating methodology for NETL Assessments of Power Plant Performance, QUALITY GUIDELINES FOR ENERGY SYSTEM STUDIES, 2012

Baseline Cycle Data taken from: (a) Walter Shelton, DOE/NETL-341/061013, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants & (b) James Black, DOE/NETL-341/082312, Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases, August 2012

Plant Performance Analysis Summary

- **Mass and energy balance was successfully modelled using combination of AspenPlus (V8.6) and Fortran performance codes**
- **Capital cost was estimated using QGESS and found to be 3% lower than commercial J Class turbine.**
- **Cost of Energy was estimated using QGESS and found to be 7% lower than commercial J Class turbine.**
- **CO_2 emitted was found to be lower (on lb/MWe basis) by 9%**
- **Steam bottoming cycle, although less efficient than RDE cycle, reduces sensitivity to component inefficiencies**
- **Net plant efficiency of the RDE plant is 68.3% (LHV) as compared to 62.6% baseline commercial J class offering from MHI**
- **Operating at lower equivalence ratios (0.7) in combustor benefits the plant efficiency but hurts the operability**

Technology Gaps – Phase II Program

Technology Gap ID	Title	Discussion
1	Isolator Requirements	Using measurements from coupled Isolator/Combustor testing, analytically define compressor loss with detonation pressure pulse feedback.
2	Isolator Performance	Limit pressure loss to the goal requirement by direct measurement or by combined test/analysis.
3	Injector Operability	Demonstrate combustor operability with multiwaves (up to 5) with air and natural gas over equivalence ratio range from 0.71 to 1.2
4	Injector Performance	Achieve target 95% efficiency in test or analytically define the path to 95% efficiency based on analysis and combustion diagnostics
5	Combustor Geometry	Experimentally quantify turning limits and length requirements for the annulus downstream of the combustion zone.
6	Combustion System Scaling	Develop combustor scaling laws and demonstrate by scaling and testing an air-breathing combustor.
7	Emissions	Using measurements from coupled Isolator/Combustor testing, analytically quantify the expected emissions from a rotating detonation combustor at the scale typical of gas turbine operation
8	Heat Load	Quantify effects of stratified fuel charges on detonation strength, performance, and operability and quantify potential reductions in heat load to wall.
9	Diffuser Flow Angle	Demonstrate flow angle control +/- 20^o
10	Diffuser Performance	Demonstrate goal performance pressure recovery in coupled Isolator/Combustor/Diffuser tests
11	Bypass Mixer Performance	Demonstrate uniformity of flow to turbine requirements.

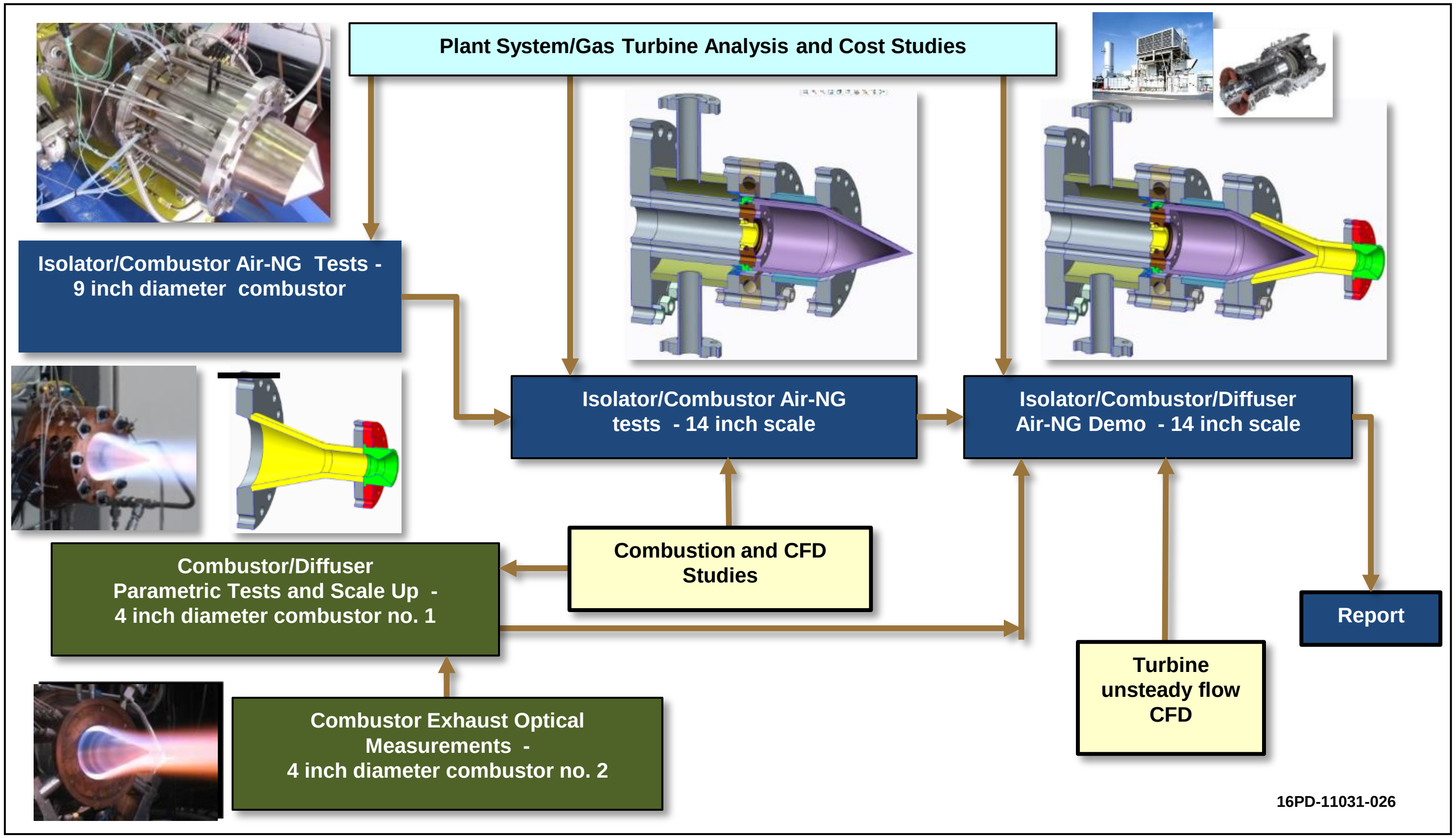
RDE Phase II Program Plan

RDE Phase II Program Overview

Advance Pressure Gain Combustion Technology for Turbine Applications

Component Design, Test, Performance Data → **Integrated Component Design And Test** → **Power Plant Study**

- Existing Hardware
- Separate Test Sites

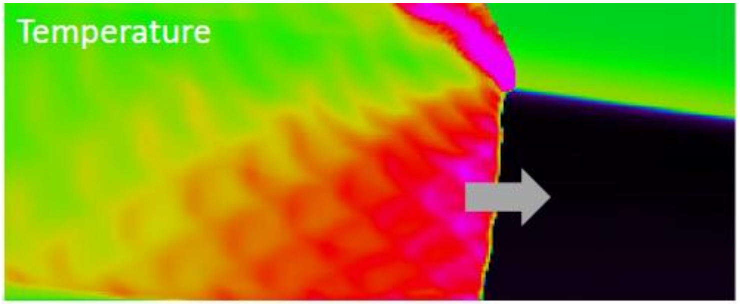


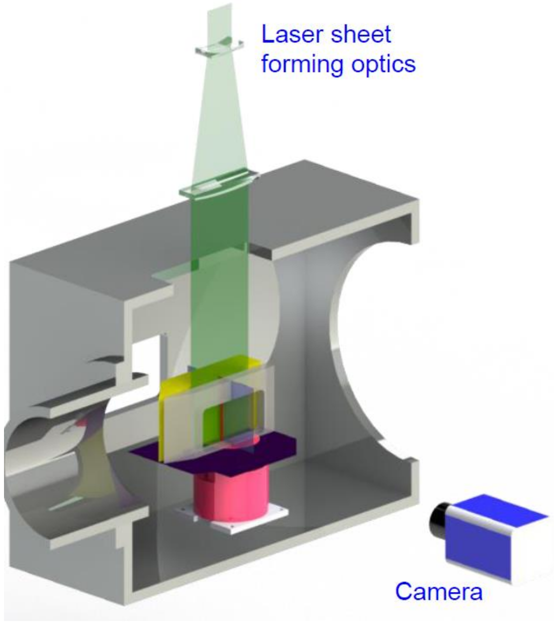
Phase II Partners

- Aerojet Rocketdyne
  - Project Lead & RDE technology
  - CFD & Model Development
  - Risk Mitigation & Testing Program
  - NGCC Integrated Plant Study
- University of Michigan
  - CFD modeling of RDE for injector & combustion physics
  - Investigate injector and combustion dynamics
  - Test diagnostics
- University of Alabama
  - Test facility with 10 cm RDE2 and various diffuser geometries.
  - Optical diagnostics for combustor & diffuser exhaust flow characterization.
  - Test Operations
- Purdue University
  - Flow Effects on Turbine Efficiency
  - Turbine Blade Unsteady Flow Analysis
  - NG/Air test facility with 9.4 inch RDE
  - NG/Air test facility with 14 in RDE
  - Test Operations
- Southwest Research Institute
  - Test facility with 10 cm RDE1 and various diffuser geometries
  - Test Operations
- University of Central Florida
  - High fidelity optics diagnostic for composition & unsteady flow analysis
- Duke Energy
  - NGCC integrated plant study support and review
  - Funding Partner

University of Michigan

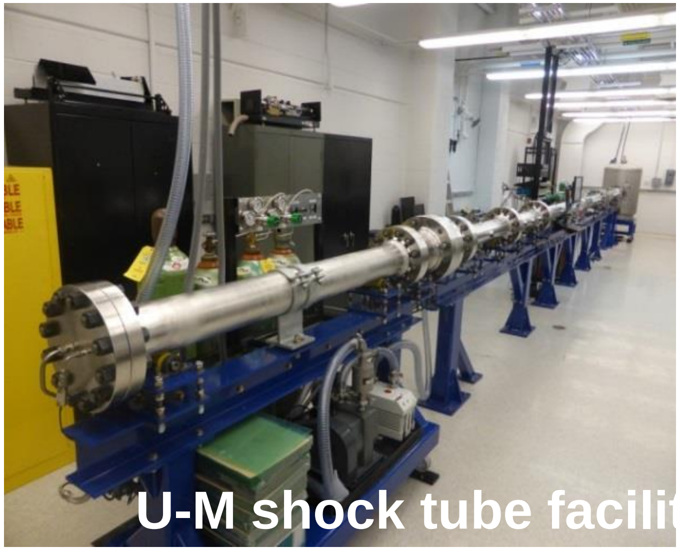
- **Dr. Mirko Gamba (Subscale Testing) and Dr. Venkat Raman (RDE CFD)**
- **Leverage developments on Michigan’s current UTSR contract**
- **Use visualization diagnostics on a realistic injector configuration**
- **Use FENICS CFD code to quantify inlet and turbine interface losses, including non-equilibrium effects on detonation.**



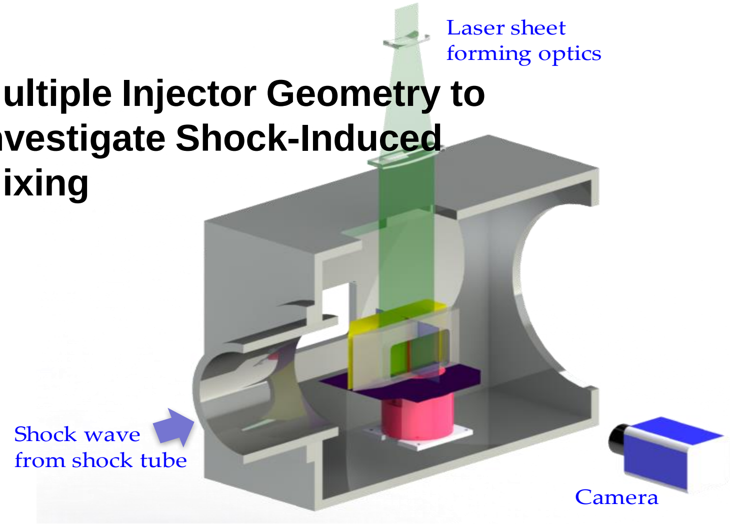


University of Michigan Capabilities

- Computational
  - UTCOMP: Massively Parallel, Multiblock, Compressible High-Speed Flow Solver for Simpler Geometries
  - OpenFOAM: Open Source Software Modified Substantially for Reacting Flow LES
  - FENICS: Finite-Element Open Source Software Linked to Detailed Chemistry Tools such as CANTERA using Python Framework
  - Allows Rapid Adjoint Calculations, for Optimization of Geometries.
- Experimental
  - U-M Shock Tube Facility
  - U-M Linearized RDE Analogue and Reduced-Scale (6”) RDE
  - Low-acquisition rate (10 Hz) Stereoscopic PIV Systems
  - Multi-Component Analyzer (Non-Dispersive Infrared Detectors) for CO, CO2, CH4, NOX Measurements
  - OH, CH, Kr, and NO PLIF systems Composed of a High-Energy, Pulsed Nd:YAG Laser
  - Kilohertz-rate, High Power 532 nm Nd:YAG PIV laser (Quantronix Hawk-Duo) for PIV Measurements

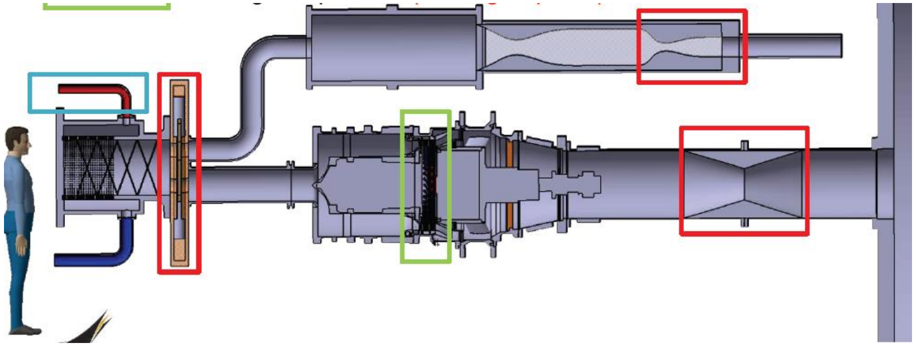


Multiple Injector Geometry to Investigate Shock-Induced Mixing

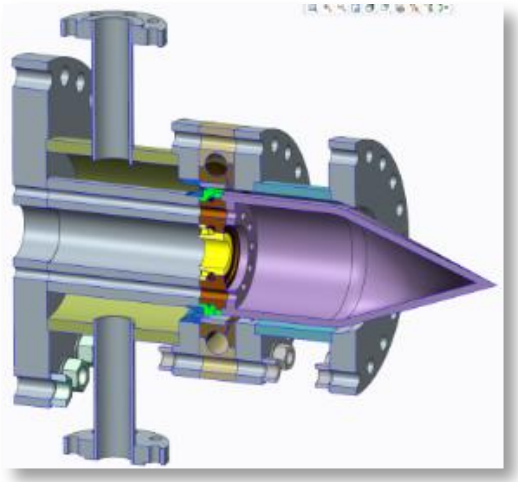


Purdue University

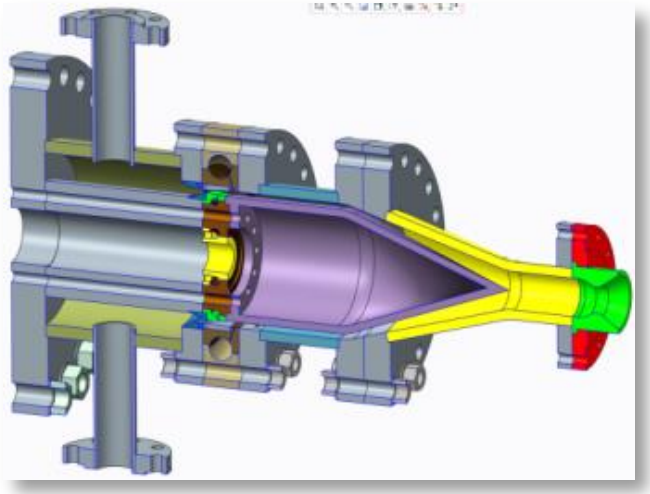
- Purdue University – Dr. Guillermo Paniagua (unsteady turbines) and Dr. Carson Slabaugh (RDE testing)
- Leverage developments on Purdue's current UTSR contract
- Numerically investigate unsteady turbine performance in static and rotating cascades
- Hot-fire test an RDE at 40 lb/sec of air flow with natural gas
- Hot-fire test an integrated Inlet/Combustor/Diffuser at 40 lbs/sec of air flow



Engineering Scale Test Data from Purdue



Engineering Scale IC-RDE Assembly

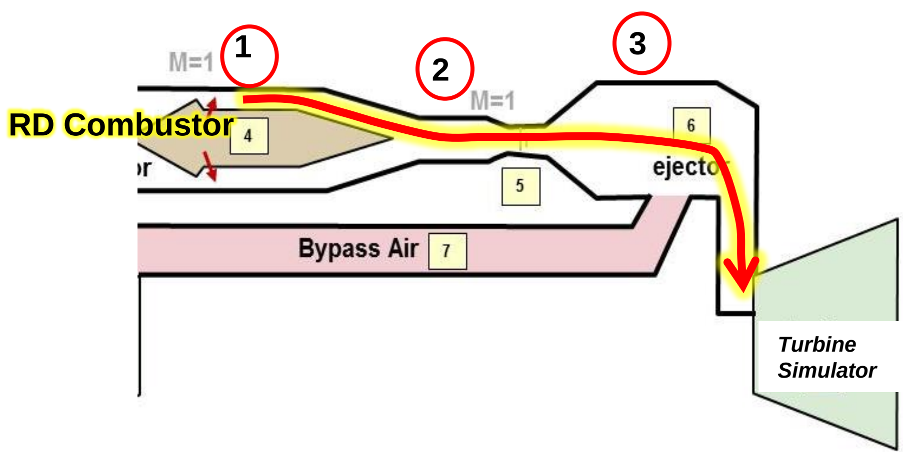


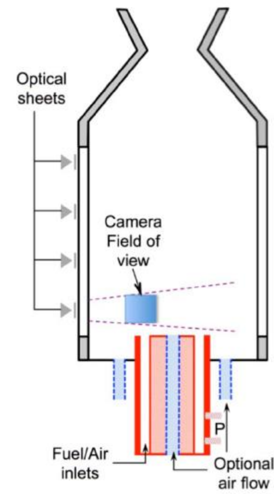
Engineering Scale ICD-RDE Assembly

- Engineering Scale RDE
  - Air/NG firing
    - Oxygen enriched air capability
    - C2 olefin enriched NG capability
  - 250 psia average combustor exit stagnation pressures
  - IC-RDE diagnostics measurements
    - Wave speed
    - Number of waves
    - Combustor exit static pressures at 10 micro-second resolution
  - ICD-RDE diagnostics measurements
    - Wave speed
    - Number of waves
    - Combustor exit static pressures and gas velocities at 10 micro-second resolution
    - Exit stagnation gas pressure
- Task Objectives for Closing Program GAPs
  - Measure pressure gain/loss at diffusor exit
  - Anchor RDE performance models with diagnostic measurements
    - Calculate pressure gain/loss from anchored performance models

University of Alabama

- **University of Alabama, Tuscaloosa – Dr. Ajay Agrawal**
- **PIV, Chemiluminescence and PLIF at 20 KHz to characterize unsteady flow at the exit of the RDE.**
- **Set up existing AR 10 cm RDE at UA and operate on enriched air and methane**
- **Test AR 10cm RDE with representative diffuser and mixer geometries**





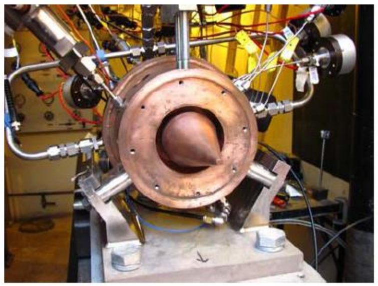
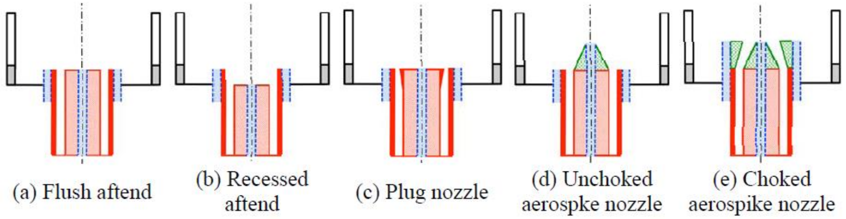
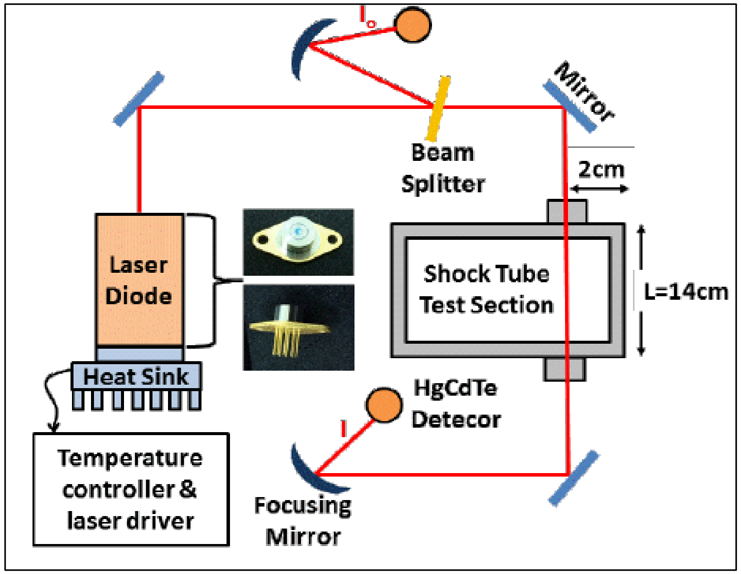


Fig. 3: (a) Schematic diagram illustrating RDE integrated with the mixing chamber, (b) photograph of the high-pressure combustion test rig to be modified for the proposed study, and (c) Example of RDE hardware at Aerojet Rocketdyne that will be utilized in this study.



University of Central Florida

- **University of Central Florida – Dr. Subith Vasu**
- **Conduct diagnostics on RDE exhaust at UA and SwRI to determine chemical species concentrations.**

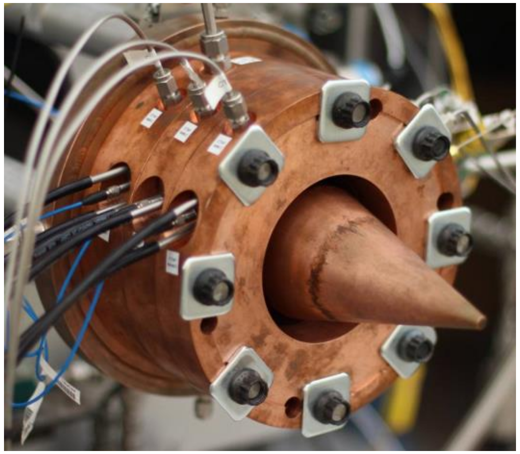


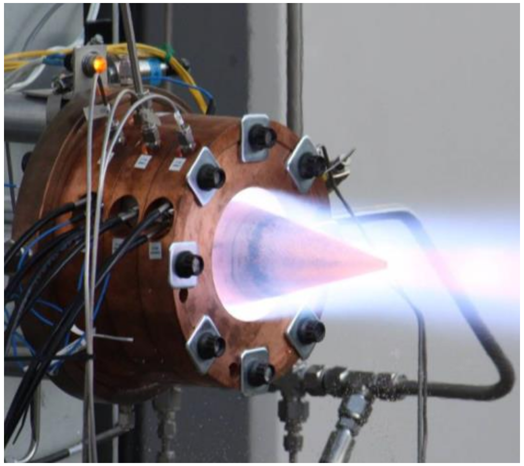
UCF setup for high-speed unsteady measurements of pressure, temperature, species, density and axial/tangential velocities

- **Design and Fab Next Generation (NG) Optical Diagnostic Measurement System**
  - **1 micro-second resolution**
  - **Adds species concentration measurements**
  - **Adds tangential velocity measurements**
  - **Adds phase angles among gas pressure, gas velocities, gas density, and temperature measurements**
  - **Measures the mass-flux averaged transient stagnation gas pressures upstream of the diffuser in-situ**
  - **Capable of Determining total pressure losses across diffuser or downstream ejector/mixer**
- **Task Objectives for Closing Program GAPs**
  - **Provide measurement confirmation of pressure gain/loss for an ICD-RDE**

Southwest Research Institute

- Southwest Research Institute – Shane Coogan
- Set up existing AR 10 cm RDE at SwRI and operate on enriched air and methane
- Test alternate diffuser configurations for design/performance data. Collect same diagnostics data as at UA





Project Task Summaries

- **Task 1 Program Support**
  - Provide overall program management for the RDE4GT project to facilitate coordination and management of technical efforts, subcontracts and suppliers, schedule and budget.
- **Task 9 System Engineering and Analysis**
  - Define RDE requirements and lead SOPO technical execution and project coordination.
  - Lead studies on turbine blade interaction with unsteady flows, and update NGCC power plant study.
- **Task 10 CFD and Model Development**
  - Upgrade and validation of AR CFD models (URANS and LES) for RDE performance
  - UM conducts LES CFD analysis of AR RDE to quantify PGC and calibrate AR CFD kinetic models
  - UM tests AR injector designs with diagnostic tools visualizing unsteady flow physics
- **Task 11 Unsteady Measurements**
  - UA will conduct tests with RDE combustor and diffuser configurations to obtain exiting flow field data to determine hardware pressure losses. CFD predictions will be reviewed and the codes updated

Project Task Summaries

- **Task 12 Isolator/Combustor Risk Reduction**
  - Purdue shall test the updated designs of the 9.4 inch RDE with NG/Air and the test data compared to CFD/model predictions, status component efficiencies and to update the analytical models
  - Based on the task 11 and 12 test data and analysis, AR will design the Engineering Scale RDE Combustor.
- **Task 13 Diffuser Risk Reduction**
  - SwRI will test diffuser concepts coupled with a 4 inch RDE provided by AR. Test data will be compared CFD/model predictions, status component efficiencies and to update the analytical models.
  - Based on the diffuser test data and analysis, AR will design the Engineering Scale RDE Diffuser
- **Task 14 Engineering Scale Integrated Testing**
  - Purdue will test the integrated Engineering Scale RDE and provide optical diagnostics to verify PGC in the larger scale RDE.
- **Task 15 RDE Test Diagnostics**
  - UCF will research, develop, and procure advanced optical diagnostic instrumentation to analyze RDE exhaust flows. Data acquired will determine mass flux averaged total gas pressures, gas velocities and combustion species.

Summary and Next Steps

- **Under Phase I of the NETL "Rotating Detonation Combustion for Gas Turbines" contract, Aerojet Rocketdyne assessed the potential of incorporating a rotating detonation engine into a Natural Gas Combined Cycle power plant.**
  - AspenPlus cycle analysis of RDE-based power plants has been completed.
    - 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 21 cm (9.4-inch) air/methane RDE at gas turbine conditions has been completed.

- **Under Phase II, a multi-faceted team of researchers will systematically characterize and optimize the fluid and mechanical interface between the RDE and a turbine cascade.**
  - Multiple test programs will be undertaken using 10 cm, 21 cm and 31 cm combustors using advanced diagnostics
  - CFD models will be developed and anchored as design tools for maximizing RDE and unsteady turbine performance.