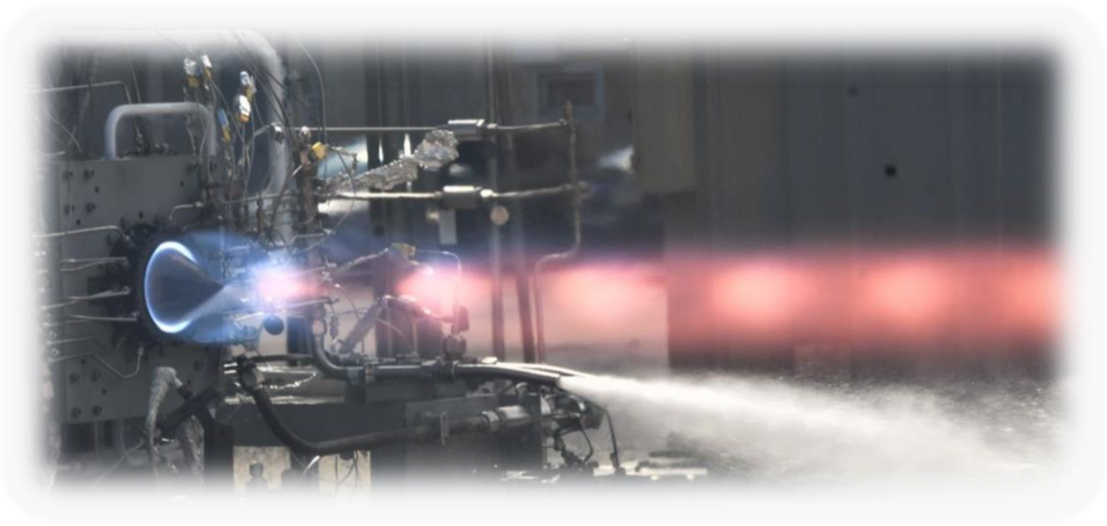
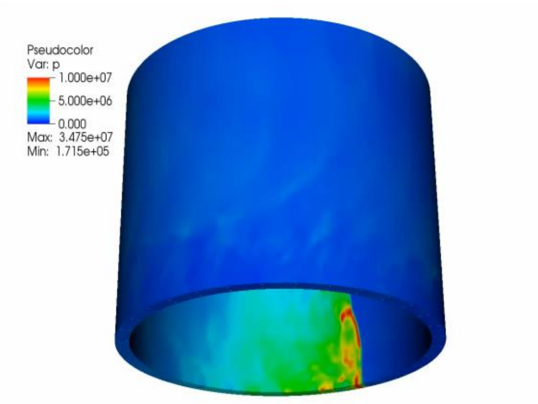
Rotating Detonation Research at NASA

Doug Perkins, PhD
Dan Paxson, PhD
NASA Glenn Research Center
June 2023





A Little Context…

- NASA has been studying various types of unsteady flow pressure gain combustion (PGC) systems since the early 1990's
  - Wave rotors (with and without on-rotor combustion) for gas turbines
  - Pulse detonation engines
    - Gas turbines
    - Rockets
    - Combined Cycles for launch vehicles and missiles
  - Pulsed resonant combustors (pulsejet derivatives) for gas turbines
  - Rotating Detonation Engines
    - Airbreathing RDE for Gas Turbines since c. 2015
    - Rockets, primarily for in-space applications, since c. 2019
- For reference, see "Summary of Pressure Gain Combustion Research at NASA", NASA TM-2018-219874.
  - 25 years of research up through 2017
  - Covers NASA performed, NASA partnered, and NASA contracted work.
  - Provides 170 references for NASA PGC work
  - Dozens of publications since 2017, however

Motivation for Airbreathing Rotating Detonation Research
Potential Impact of PGC on CFM56-7B27

<u>Baseline Engine Parameters (Take Off)</u>

- OPR=27.7
- Bypass Ratio = 5.1
- Thrust = 27300 lbs
- Combustor Exit Temperature = 2960 R
- Fan, Compressor and Turbine Efficiencies (Polytropic) of 90%, 93% and 89%, respectively
- Combustor pressure drop = 4%

<u>Comparative Engine Improvements</u>

A 5 % Combustor Pressure Rise is equivalent to:

- Increasing Fan Efficiency to 96.9%
- Increasing Compressor Efficiency to 97.0%
- Increasing Turbine Efficiency to 91.6%
- Increasing OPR to 36.6

A 10% Combustor Pressure Rise is equivalent to:

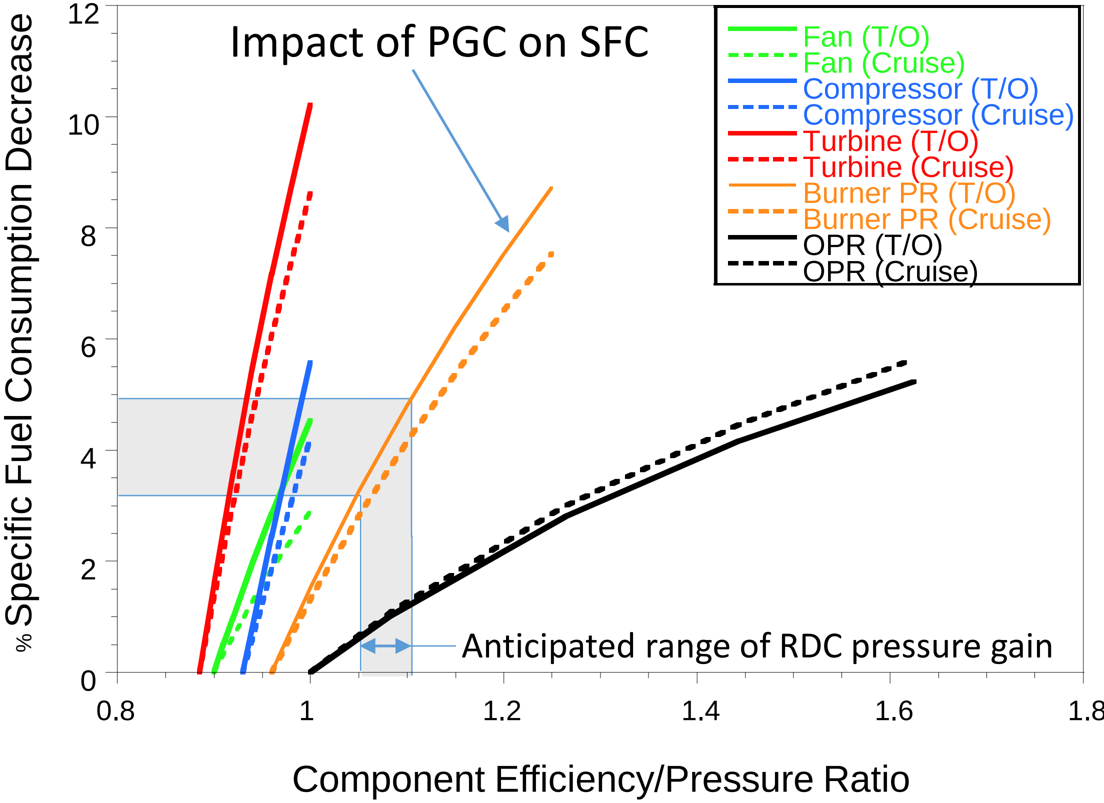
- Increasing Fan Efficiency to 100.6%!
- Increasing Compressor Efficiency to 99.0%
- Increasing Turbine Efficiency to 93.3%
- Increasing OPR to 43.0

Turbomachinery technology relatively mature

- Offers limited range of efficiency improvement

Turbomachinery improvements limited by scale

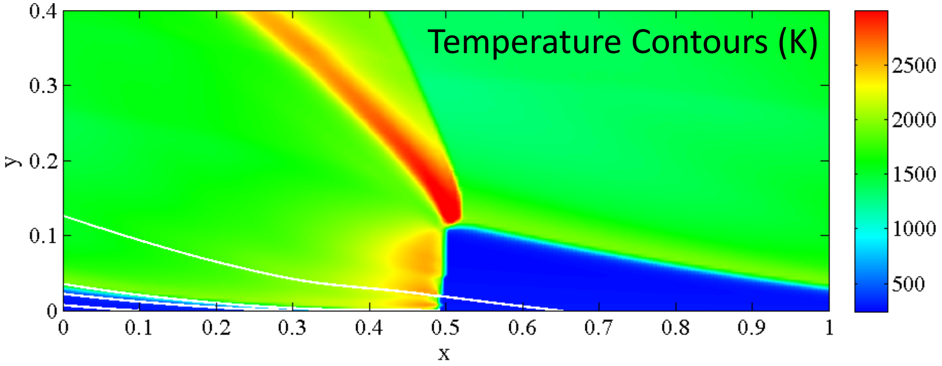
- Larger machines needed for higher efficiency
- OPR increase also increases turbine inlet temperature



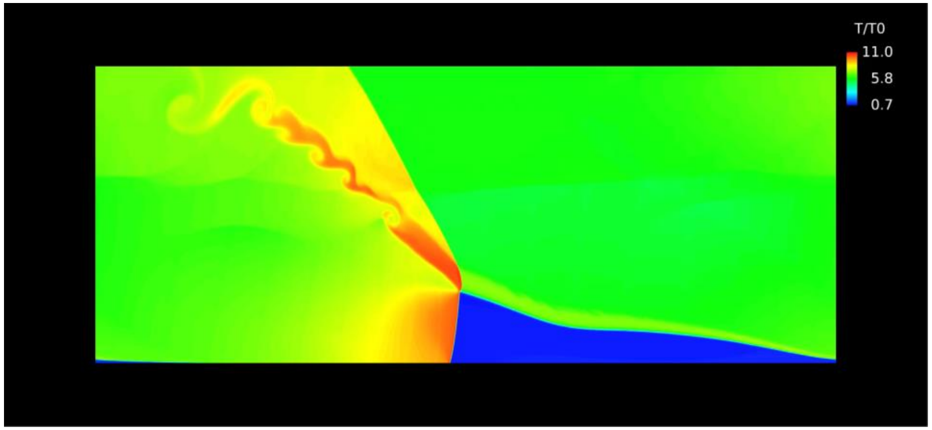
CFD-based Design Studies of Airbreathing RDC’s

RDC Requirements

- Pressure Gain!
  - Low inlet total pressure loss
  - Low inflow Mach number
  - Backflow resistant inlet
  - Rapid fuel/air mixing
  - Minimized parasitic deflagration
- Low NOx
  - Rapid combustion followed by rapid expansion
- Short Length to minimize weight
- Turbomachinery Compatibility
  - Inlet manifold shock wave isolation
  - Efficient mixing of cooling air at RDC exit to condition flow for turbine
    - Minimize pressure fluctuations
    - Acceptable turbine inlet temperature
- Wide Throttling Range
  - Ground idle to take-off



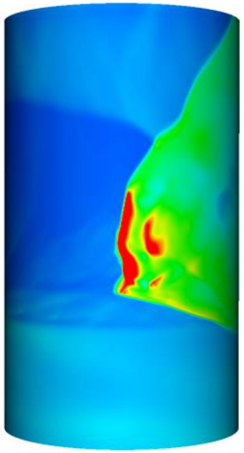
Lower fidelity quasi-2D simulation run on a 200x80 grid took ~3 minutes on a laptop to achieve a limit cycle. Typical of simulations used for concept development.



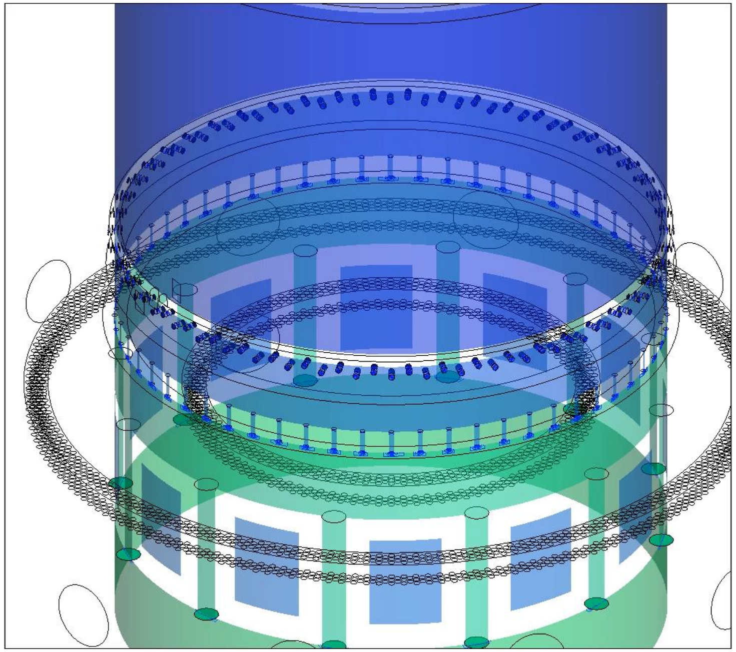
Temperature contours from a moderate fidelity quasi-2D simulation run on a 1600x600 grid took 2 days on the NASA HPC cluster to achieve a limit cycle.

Some Additional Calculations of Airbreathing Rotating Detonation Configurations


Geometry


Pressure

Moderate fidelity 3D simulation run on NASA HPC cluster for ~2 days to reach limit cycle (~6M grid points). Typical of simulations used for concept refinement.


Blue- Fuel, Green-Pressure

Initial Start-up Transient for NPGS rig simulation using a high fidelity code with 40M grid points. Takes ~1 week to calculate a single wave rotation

An Example of Low Fidelity, Under-Resolved Quasi-2D CFD used for Basic Concept Evaluation

- Gas-gas 2-gamma model (reactants/products)
- 1 Step heat release with pressure switch
- Coarse grid (200 x 200)
- “Magic” inlet valve

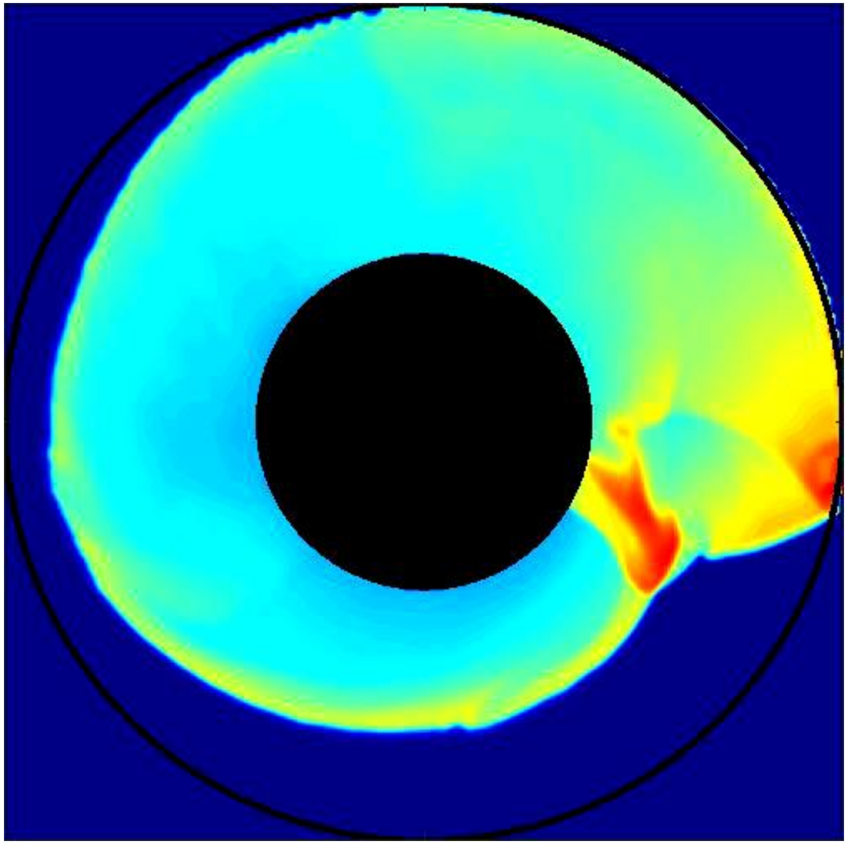
Annular RDE

T_{tout}=7.22 (theory=7.22)
EAP_{ent} = 5.90 (entropy flux avg.)
PRESSURE $GAIN_{ent}$ = 48%
PRESSURE $GAIN_{EAPi}$ = 17%

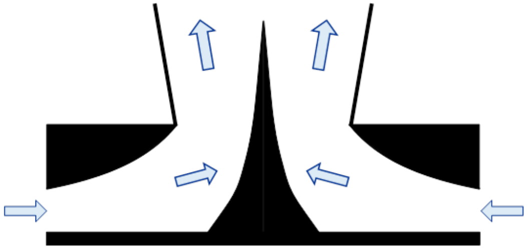
Disk RDE

T_{tout} = 7.22 (theory=7.22)
EAP_{ent} = 9.01 (entropy flux avg.)
PRESSURE $GAIN_{ent}$ = 125%!!
IMPLIED PRESSURE $GAIN_{EAPi}$ = 78%!!

CFD Video Showing Contours of Temperature in Injection Plane



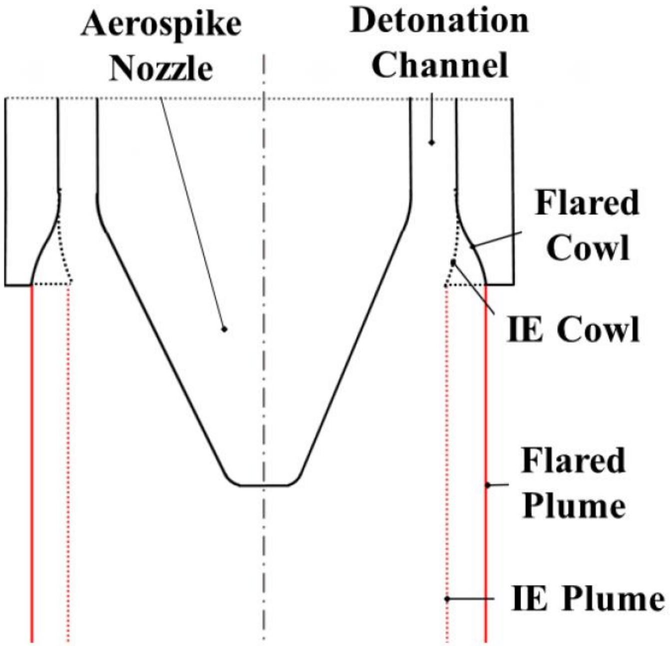
Standard RDE Geometry



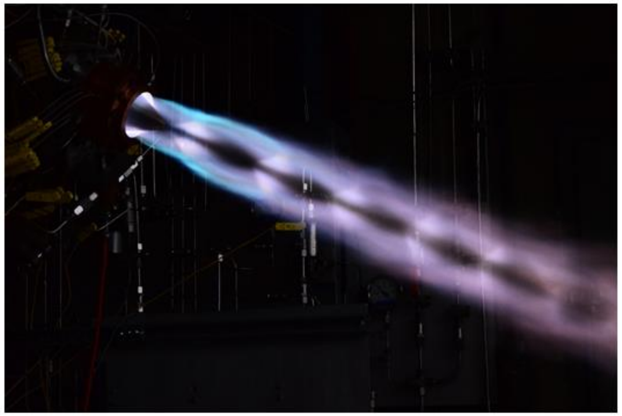
Cross Section of Radial Concept

NASA Has Been Creeping Into RDRE Research The Last ~5 years

- Started with 2 NASA Space Technology Research Fellowships at Purdue starting between 2017-2018 (Nozzles, Liquid Hydrocarbon Fuel/Heat Transfer)

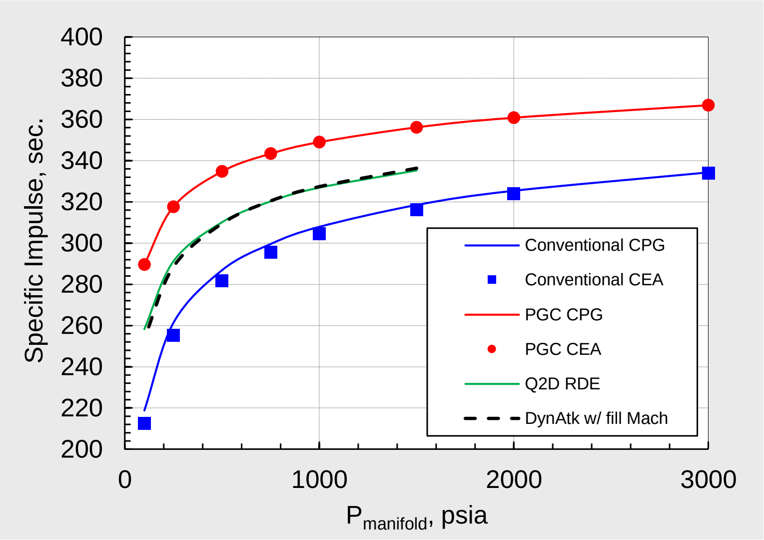


RDRE Nozzle Concept (Harroun/Heister)



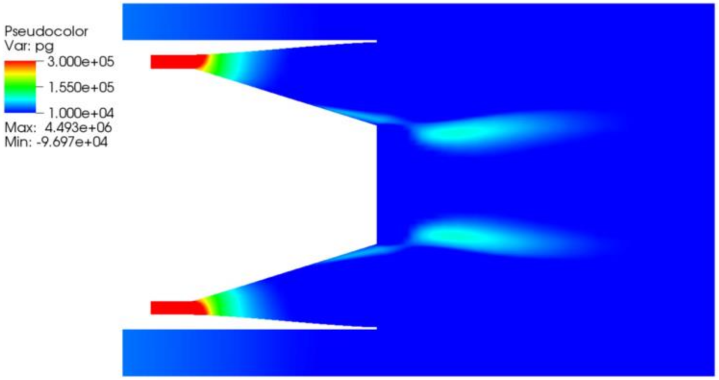
Hydrocarbon RDRE Fuel Testing (Humble/Heister)

…Added 2 small 1-year NASA GRC IR&D efforts in FY19 (Cycle Code, Nozzle Design Methodology)

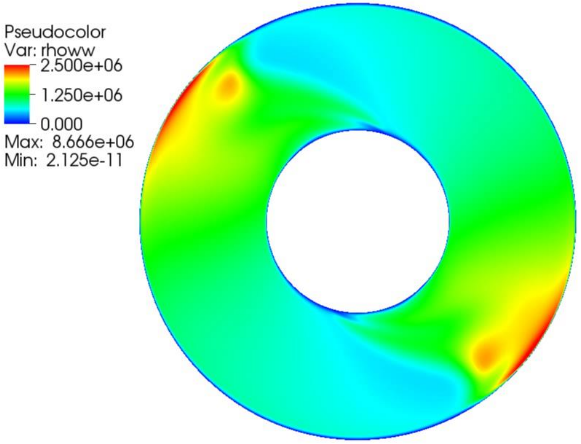


- Spreadsheet integrated performance model using lumped parameter analysis, runs in seconds
- RDRE modeled as an infinite number of PDE tubes. Ignores non-axial flows, but this is a small effect in RDRE’s
- CEA code embedded to provide detonation parameters and fluid properties
- Validated combustor model against NPGS experimental data and In-house CFD (see Fig. – compare green line (CFD) to black dashed line (spreadsheet model))
- Shows performance potential of an RP-1/GOx RDRE (with losses) compared to an equivalent conventional rocket. (Sea Level, O/F=2.62)

Side view of two-wave solution



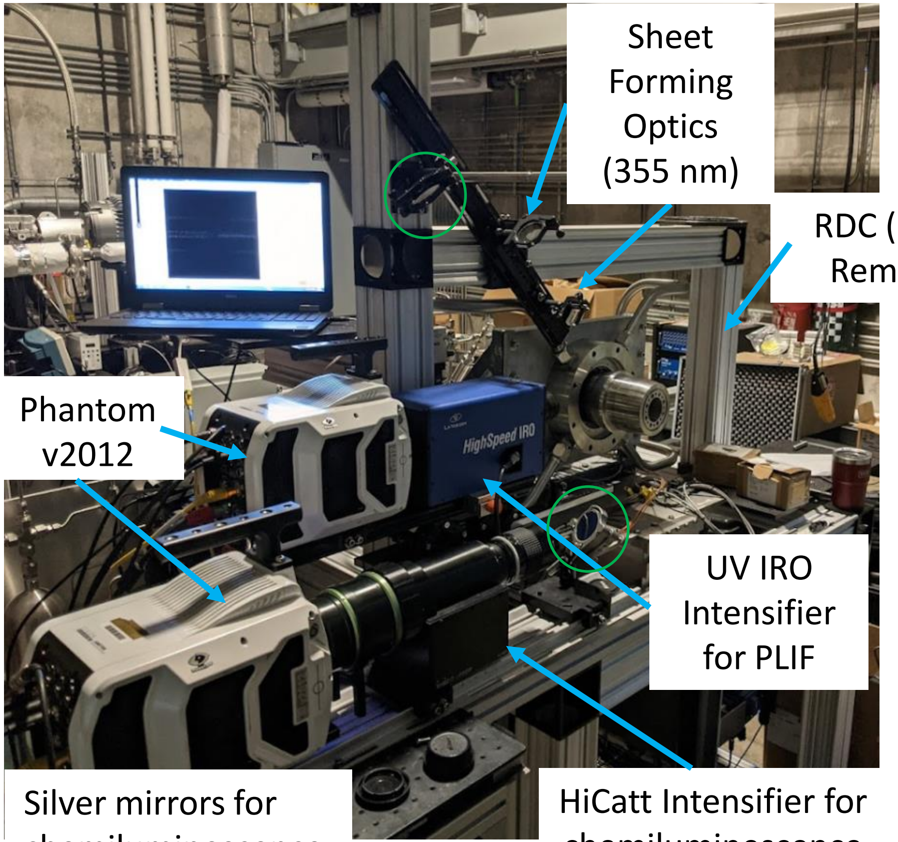
Aft end view of two-wave solution



Coupled 2-D combustor/3-D nozzle design
Study results for MSFC ACO project

…Added STTR Phase I/II Award – Spectral Energies/Purdue starting in August 2019. Laser diagnostics for liquid fuel at high pressure, publically available code validation data. Completed January 2023.

200 kHz Imaging Setup:



Sheet Forming Optics (355 nm)

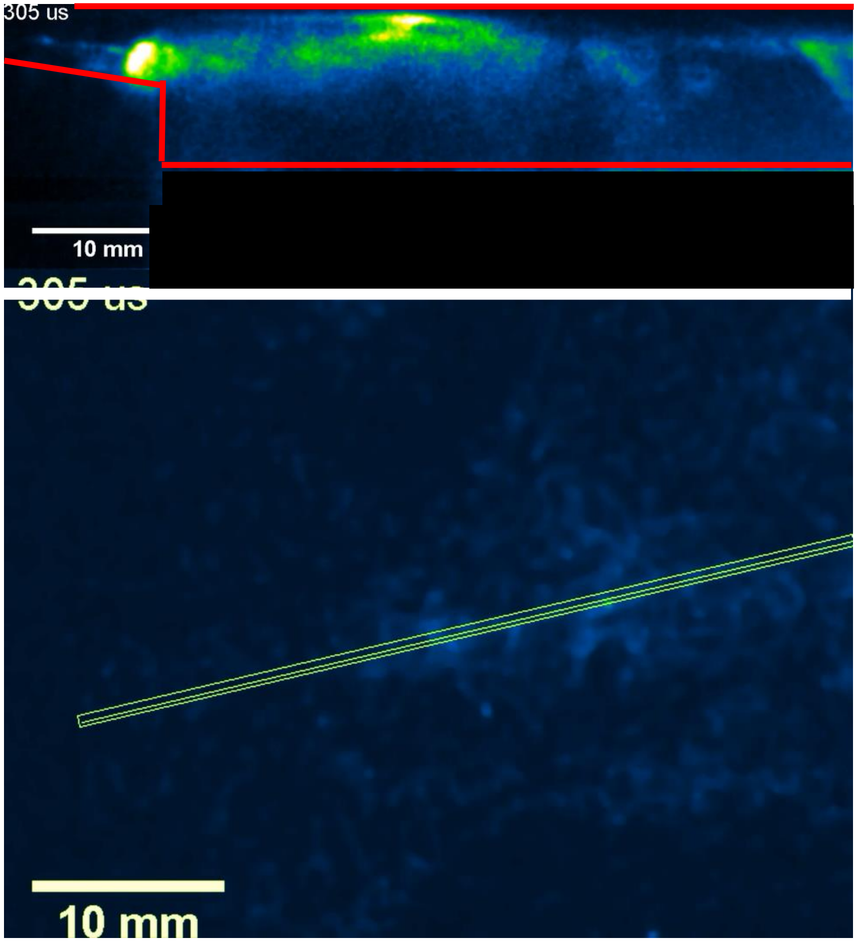
RDC (Quartz Removed)

Phantom v2012

UV IRO Intensifier for PLIF

Silver mirrors for chemiluminescence are circled in green

HiCatt Intensifier for chemiluminescence

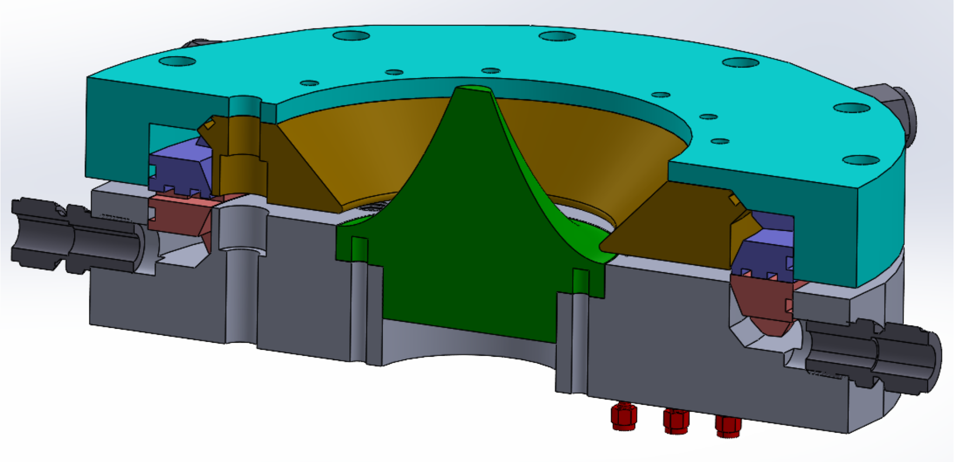


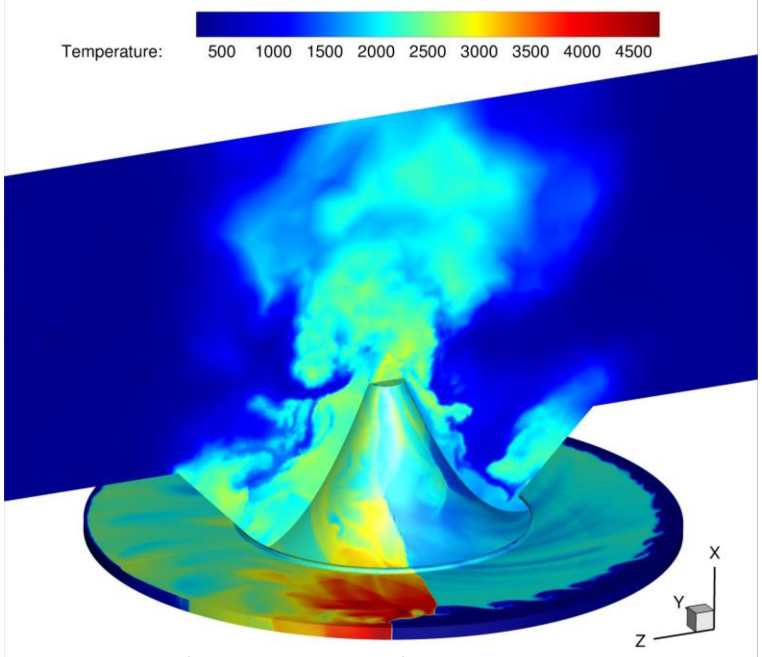
[redacted]

Simultaneous 200 KHz diesel PLIF and broadband chemiluminescence imaging

Liquid fuel spray and detonation interaction study (355 nm Diesel PLIF)

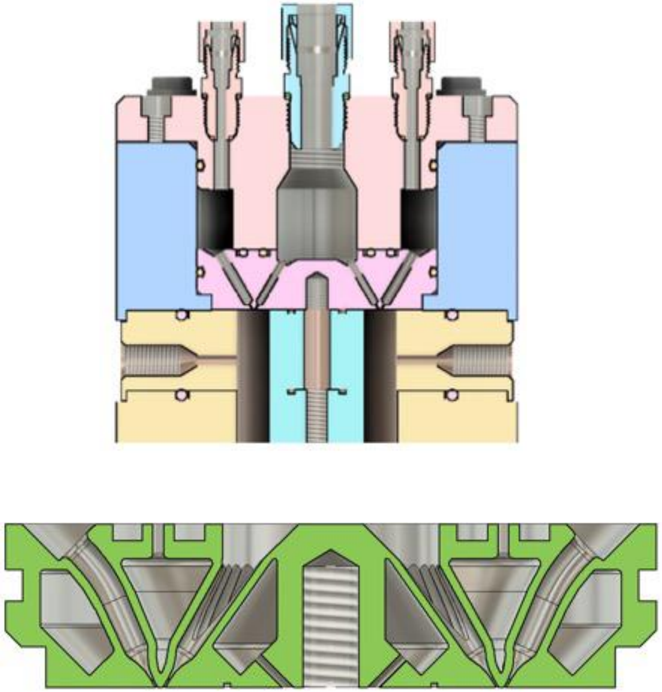
…Added U of Alabama Disk RDRE Design and Testing 3-year grant in 2020 – CH4/O2 (gas-gas) - Dr. Ajay Agrawal

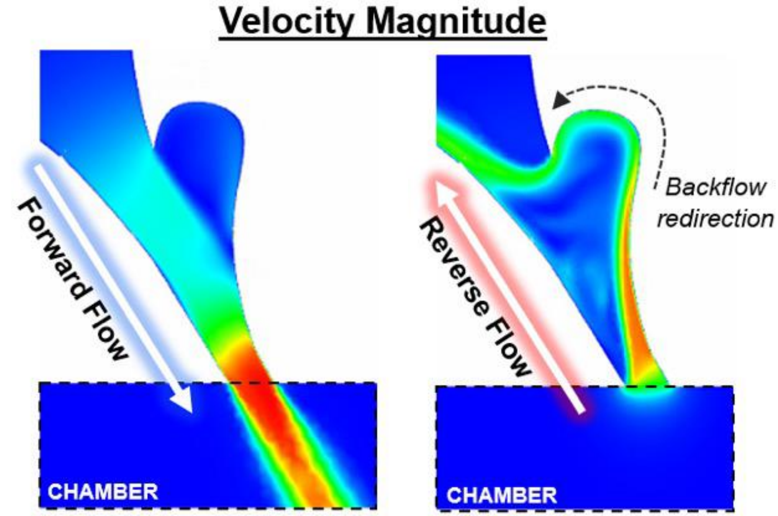


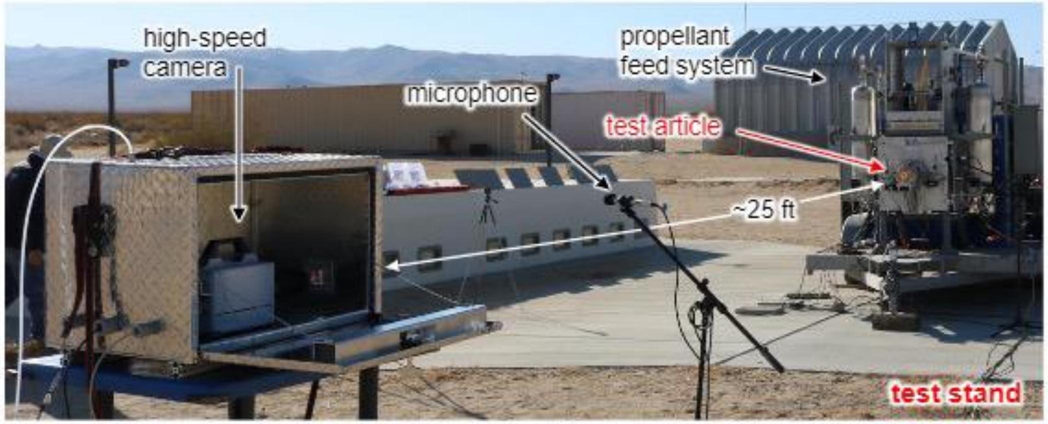


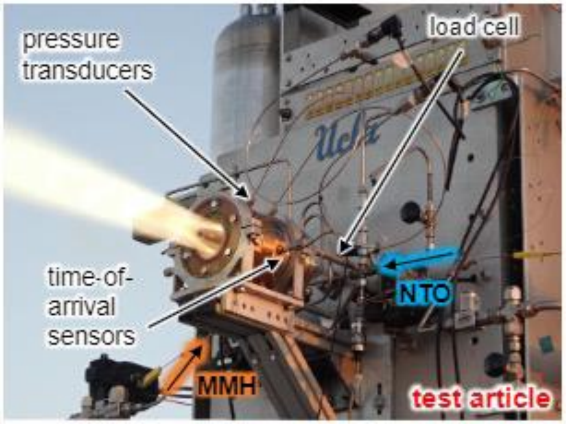
CFD by Doug Schwer at NRL

…As well as a 3-year grant to UCLA for design and testing of a MMH/NTO RDRE - Dr. Mitchell Spearrin

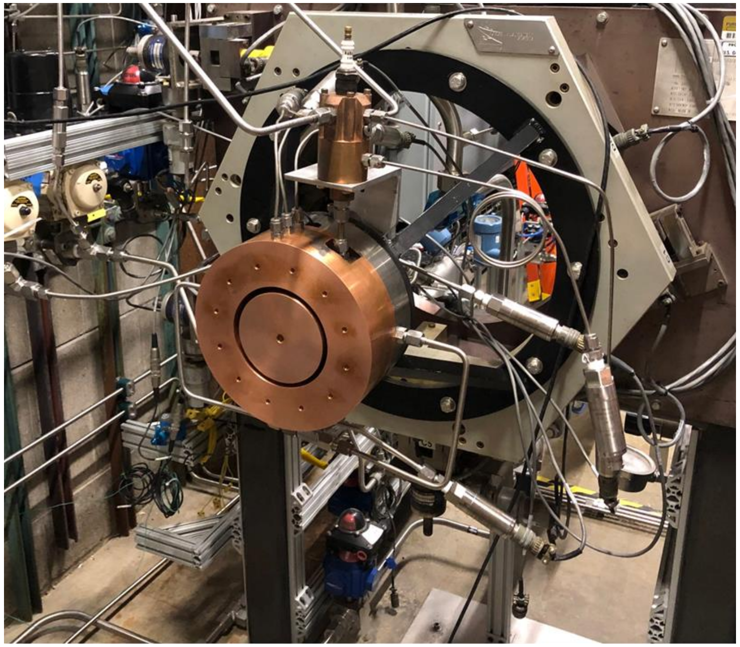


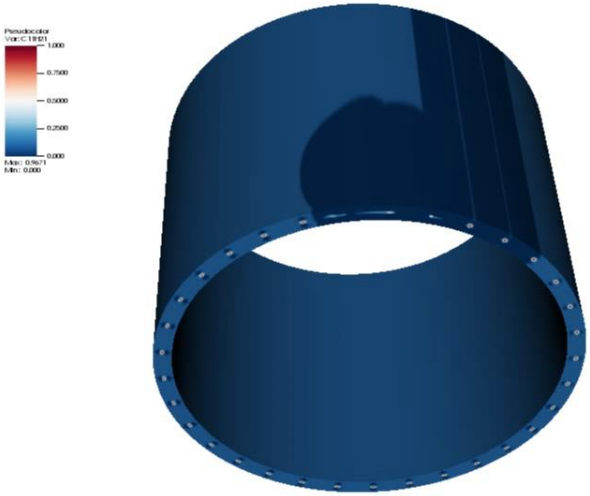






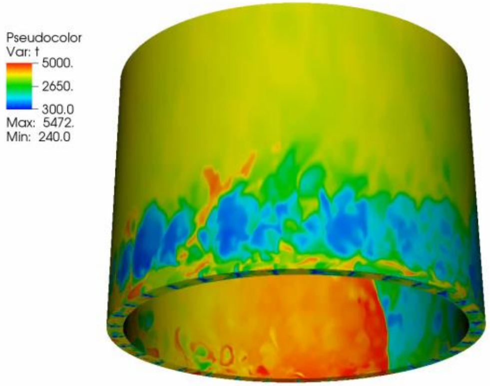
…And a 3rd 3-year grant to Purdue for a RP/H2O2 RDRE
Dr. Steve Heister



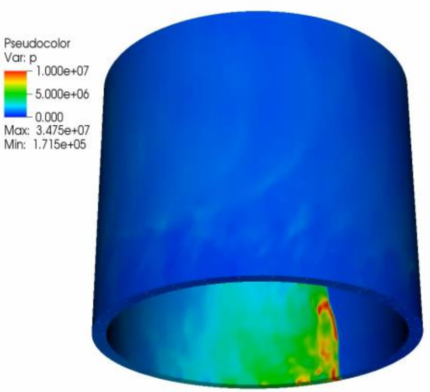


Fuel Concentration Contours of Purdue RDRE Geometry with 33 sets of Discrete Injectors Modeled Using NCC code (GRC) – Initial Combustor Startup (Non-Optimal Operation)

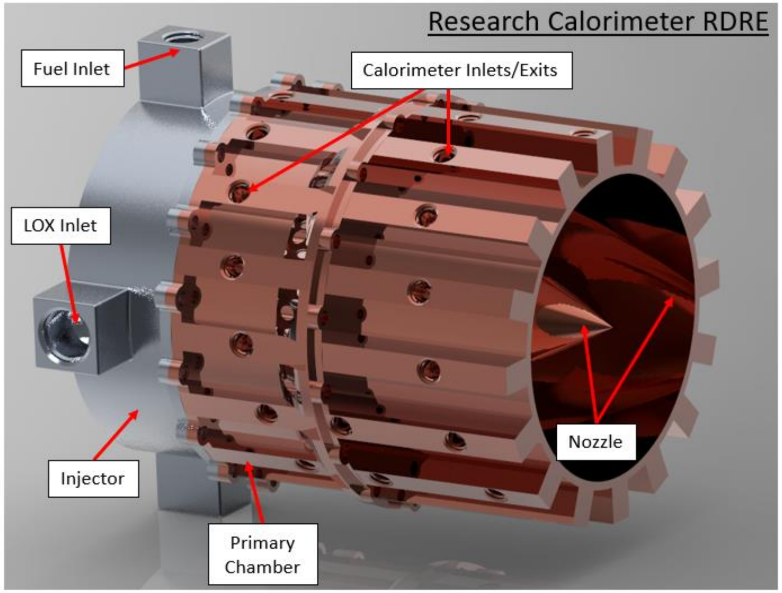
Temperature

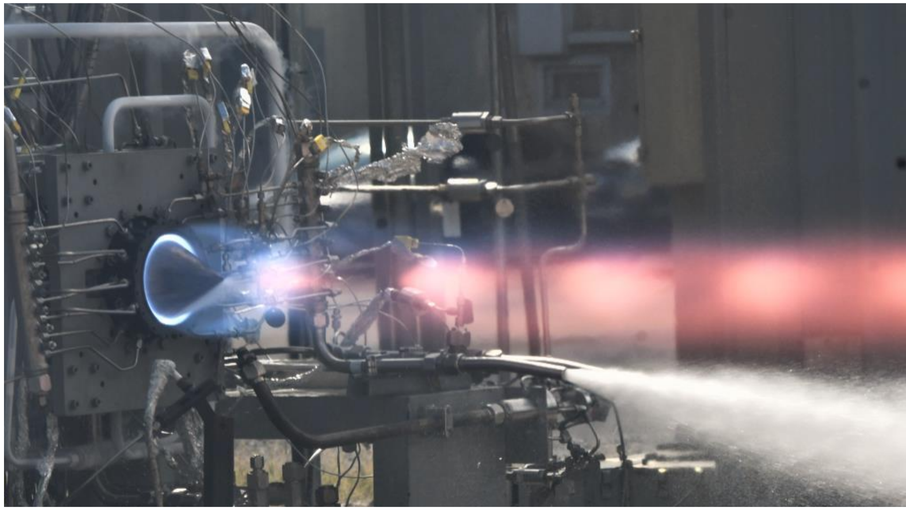


Pressure



…And then a MSFC/IN-Space, LLC collaborative effort to design, additively manufacture, and test a long duration cooled RDRE in 2021-22





- Tested with LOx/LCH4 and LOx/LH2
- Runs up to 2 minutes were achieved
- Calorimeter data taken
- Partial regenerative cooling with LCH4

Currently, NASA MSFC/GRC has partnered with Venus Aerospace in the design and testing of a higher pressure, increased thrust follow on to this original effort.

And More Recently…

- Added another NASA fellowship student at University of Alabama, Huntsville for injector design and manufacturing and another student at the University of Illinois-Champaigne for developing reduced order models from CFD simulations.
- Awarded phase I/II SBIR to Spectral Energies, LLC for development and testing of advanced injector concepts for RDRE's in April 2023.

Concluding Comments

- RDRE's represent a promising path forward for improved chemical rocket performance, applicable across the board
- Design cannot be accomplished by traditional methods. CFD is the only path due to gasdynamics.
- We really don't know what an optimized RDRE even would look like yet.
- Currently have good support up at NASA HQ for continuing and growing this work.
- Program driver within NASA is in-space applications – orbital transfer, landers. etc.
- While increased I_{sp} will always be of interest, decreased feed pressure and decreased engine length are also of significant interest for certain applications.