Hybrid Wave-Rotor Electric Aero-Propulsion (HyWREAP)

NASA Aeronautics Research Institute (NARI)
FY12 LEARN Phase I Technical Seminar
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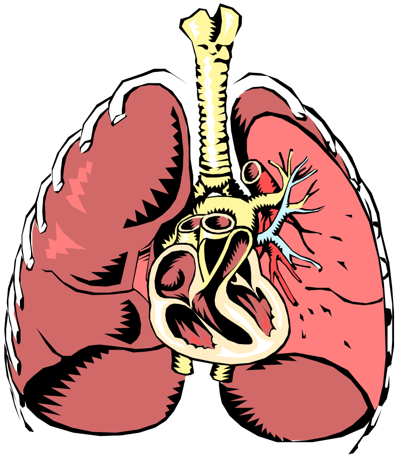
Outline

- Innovation: Non-steady flow, confined combustion, hybrid-electric synergy
- Approach: HyWREAP, wave-rotor concepts
- Impact: aviation, power gen, drones
- LEARN Phase I progress:
  - HyWREAP system model development
  - SUGAR baseline validation
  - N+4 battery, electric technology assessment
  - Airplane/propulsion architecture proposals
- Dissemination, plan for Phase II and beyond

Multiple Integrated Innovations

- Synergize, integrate three innovations:
  - Non-steady flow compression and turning expansion in a wave rotor, shrinks engine size and weight
  - Pressure-gain combustion greatly reduces fuel consumption
  - Electric drive avoids partial-power inefficient fuel use (idling, taxi, cruise, descent)
- Retain high propulsive efficiency of ducted or unducted fan propulsor
- Research focus on first two innovations where our team can contribute most

Nature: Oscillatory Flow, Waves, Flapping, Pulsing



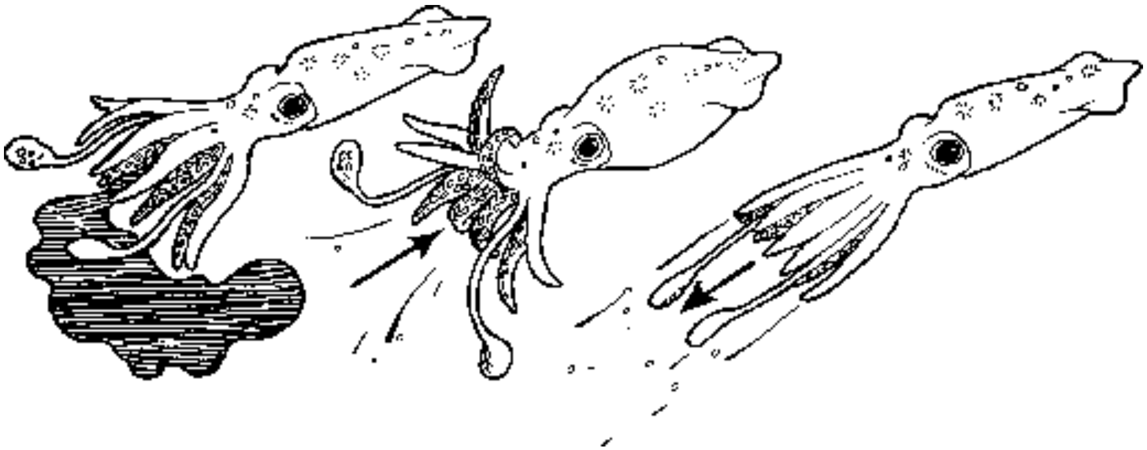
Oscillatory & pulsatile flow are ubiquitous in Nature

Engineers mostly design for steady flows and semi-static cycles, mathematically simpler to analyze.

<u>Need to design with waves and dynamically non-steady flows</u>

Flapping flight, pulse jets, wave rotors can mimic the rhythms and effectiveness of living systems.

Pulsed propulsion and confined combustion



WW II German V-1 ‘Buzz Bomb’

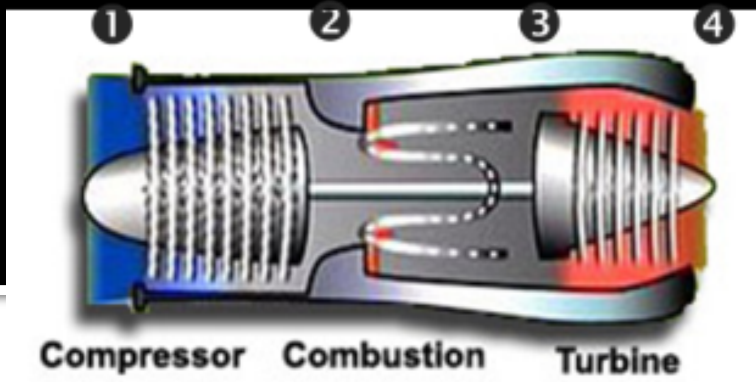
US ‘Project Squid’ research, response to the buzz bomb, known for its noise.

Inspiration from Nature – not simply bio-mimicry, but new approaches and solutions

Wave rotor utilizes non-steady flow, without adding noise

AFRL pulsed-detonation engine (PDE) flight test

How to Improve Gas Turbine Fuel Efficiency?



- ***Turbine engines -*** light, compact, durable, reliable, clean, …. **but Brayton-cycle efficiency is inherently limited, especially in smaller units**
- *Pressure-gain combustion → **a new thermodynamic cycle**.*
- Dramatic cycle efficiency improvement, together with specific power increase
- Internal wave processes compress, burn, turn 'on a dime'
- Potential low-rpm wave turbine output for aircraft fan drive
- Can diminish compressor surge/stall, eliminate combustor instability, reduce NOx emissions

Combustion: free expansion vs. pressure gain

- ‘Constant-pressure’ free-expansion combustion wastes energy pushing away the surrounding gas

- ‘Constant-volume’ confined combustion fully captures the work potential of chemical energy release

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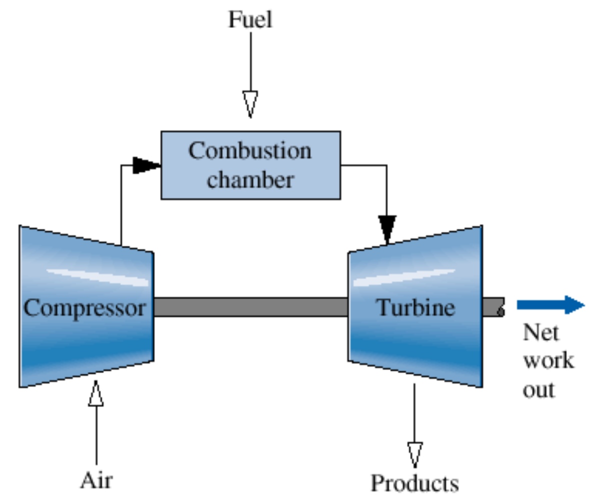

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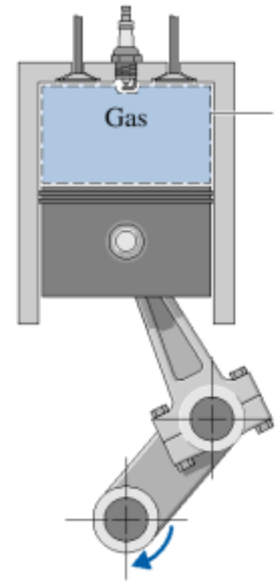

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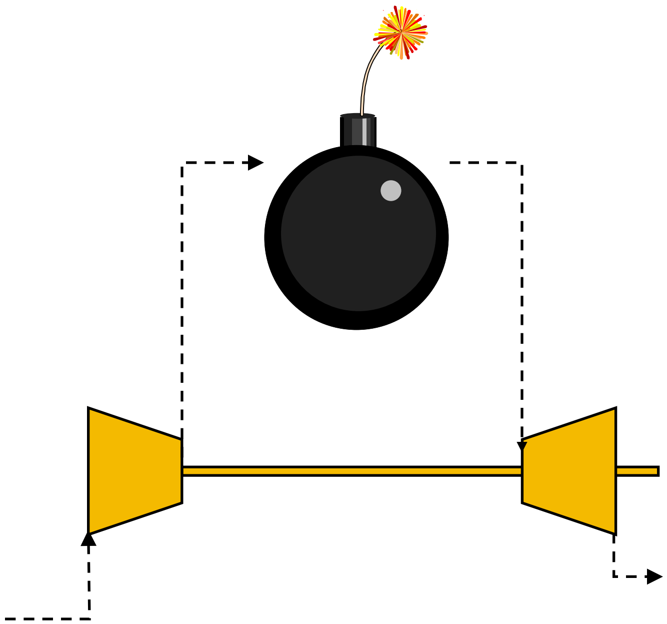
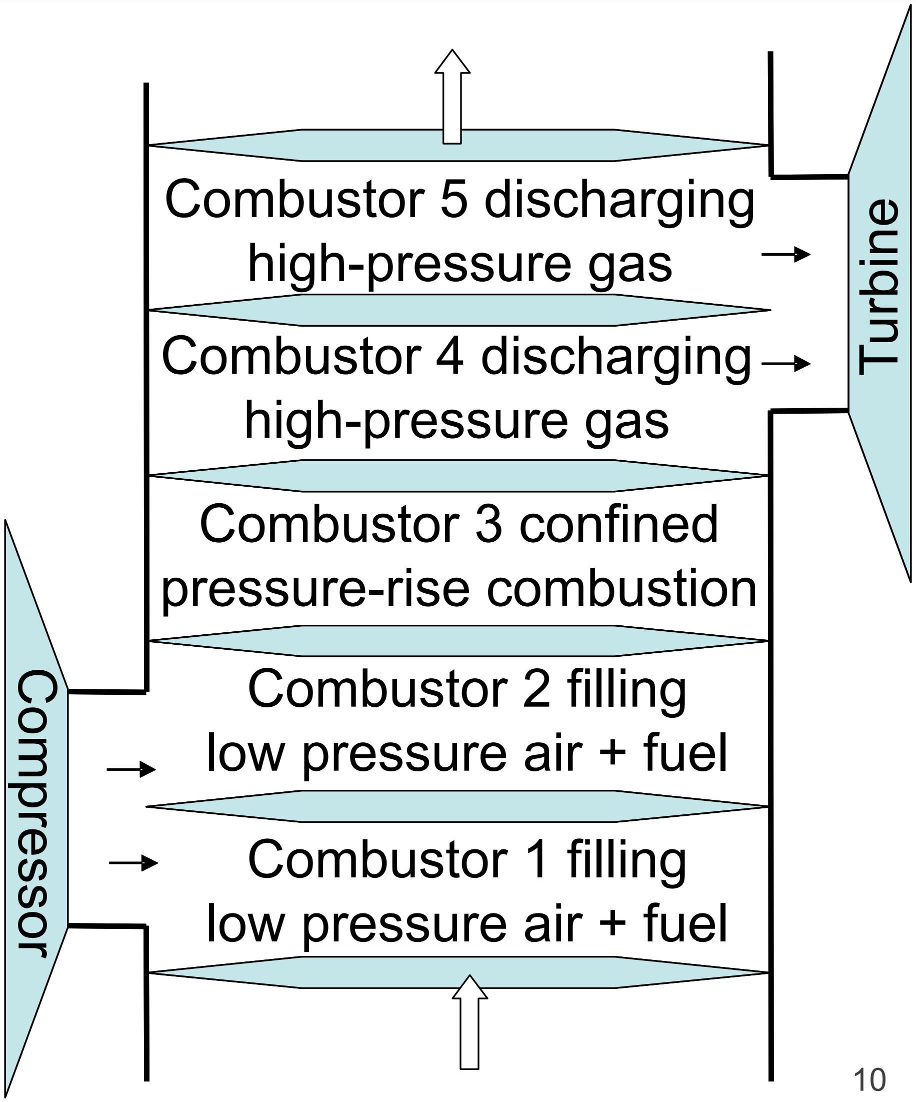


Wave-Rotor Constant-Volume Combustor (WRC)

•Confined, constant-volume deflagration for high pressure gain, low delivered pulsations, limited stresses

•Multiple combustors, synchronized
→ essentially steady inflow and outflow,



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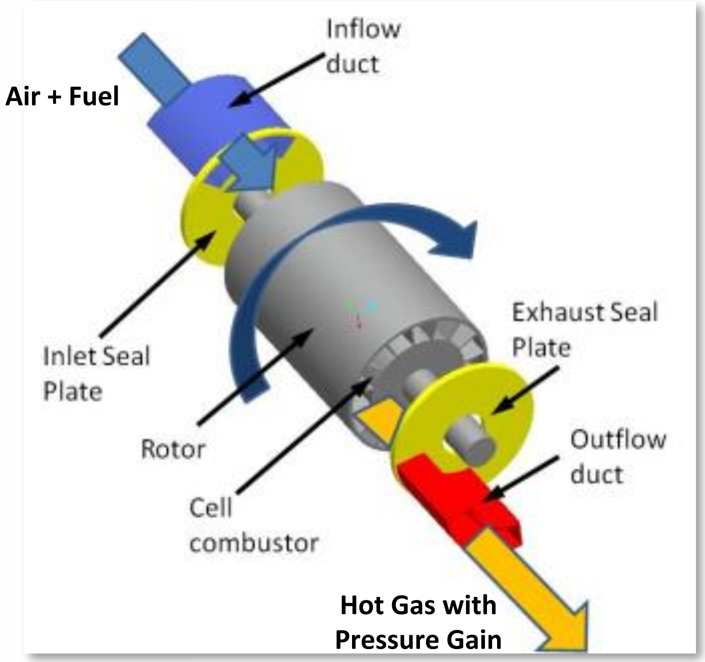
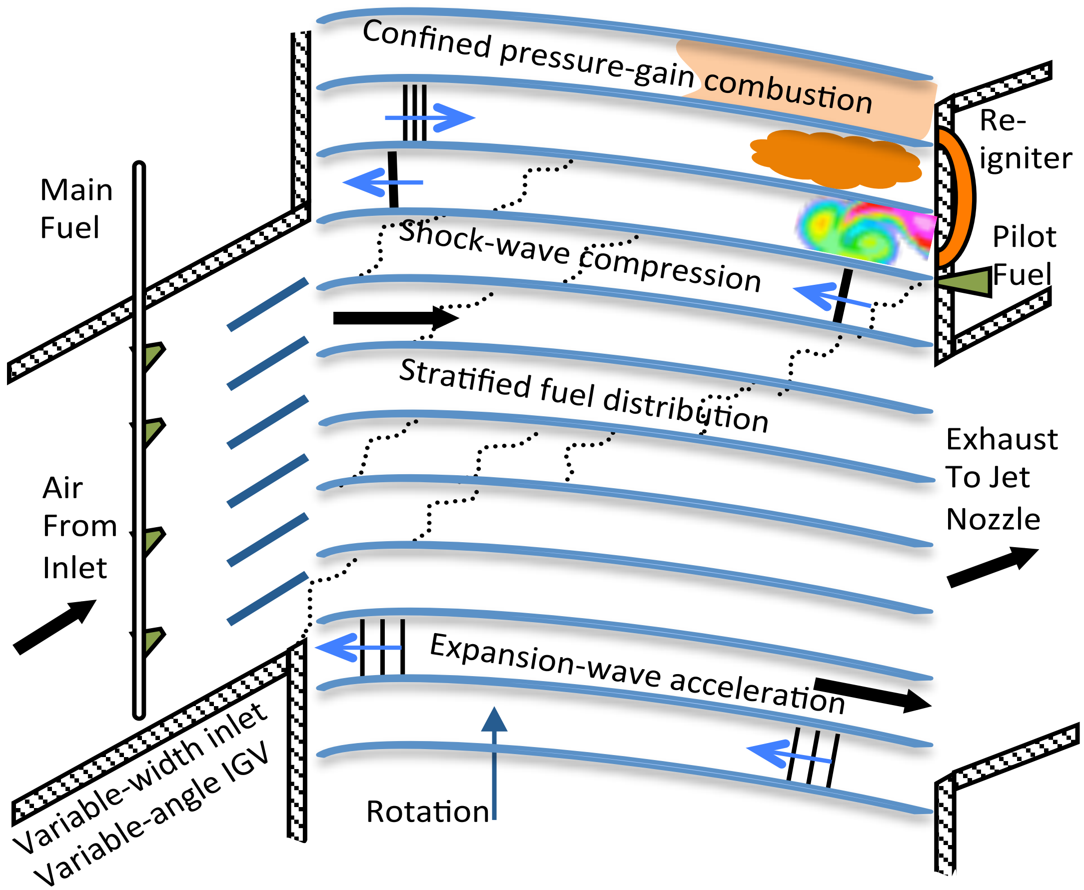


•Light-weight rotor within common pressure casing

WRC turbine with work extraction by flow turning in curved channels

Efficiently flowing, mechanically elegant, tightly integrable component

- Flow Features
  - Precisely timed waves
  - Wave compression, dead stop
  - Wave expansion, turn in place
  - Self-cooling, transient heat
  - Stratified fuel distribution
- Combustion Features
  - Pressure-gain
  - Quick jet ignition
  - Fast deflagration, helped by
    - initial turbulence
    - hot-jet penetration
    - wave-flame interaction
    - centrifuging



‘Unwrapped’ section view

Electric propulsion benefits

- Minimal energy loss at all load
- Avoids inefficient fuel burn at low-load: taxi, idle, Avoids energy dumping: regeneration descent
- High energy density storage, e.g. Li-air battery using atmospheric O2
- Could use lower cost, carbon-free, and renewable energy sources
- Note: battery weight remains as energy is used, unlike fuel-burning systems
- Hybrid strategy depends on airport charge economics

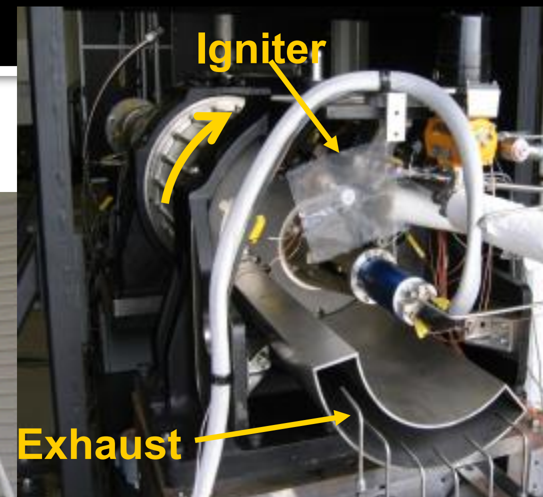
WRC Impact

- Gas turbines dominate in aviation fuel and power-gen natural gas consumption
- WRC can cut SFC and CO_2 emissions by 20-30%, while dropping weight and cost/MW
- Retrofit repowering is feasible
- Full market penetration can save fuel worth ~ $100 billion and 500M tons CO_2 emissions per year globally

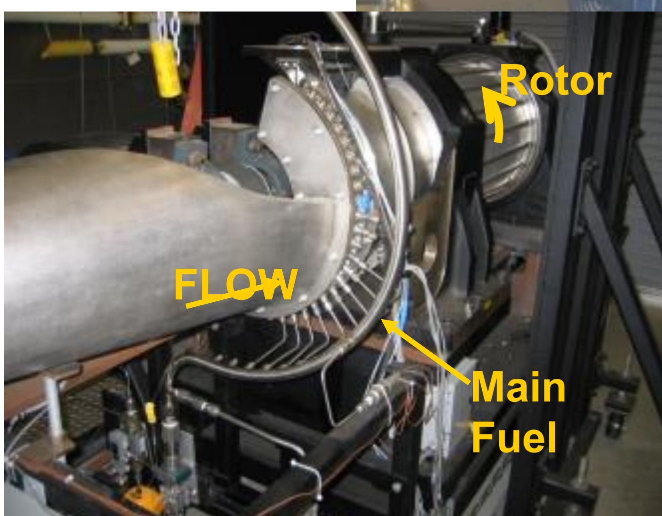
HyWREAP Impact

- Aviation: 90% reduction in fuel-burn and greenhouse gas emissions
  - Strategy: minimize fuel use, airport charging
- UAV: multiply time aloft, irregular power
  - Strategy: recharge in flight with super-efficient small WRC turbine engine
- Ground power gen: 20-30% reduction in fuel use and greenhouse gas emissions
  - Strategy: smaller, distributed WRC gas turbine engines backing up variable renewable power

Wave-Rotor Constant-Volume Combustor Test Rig & Facility



Air tank: 2,200 psi/2,000 ft^3
-Mass flow controlled
-up to 20 lb/sec
Fuel flow: up to 1.0 lb/sec propane
Motor driven system



First US Demonstration

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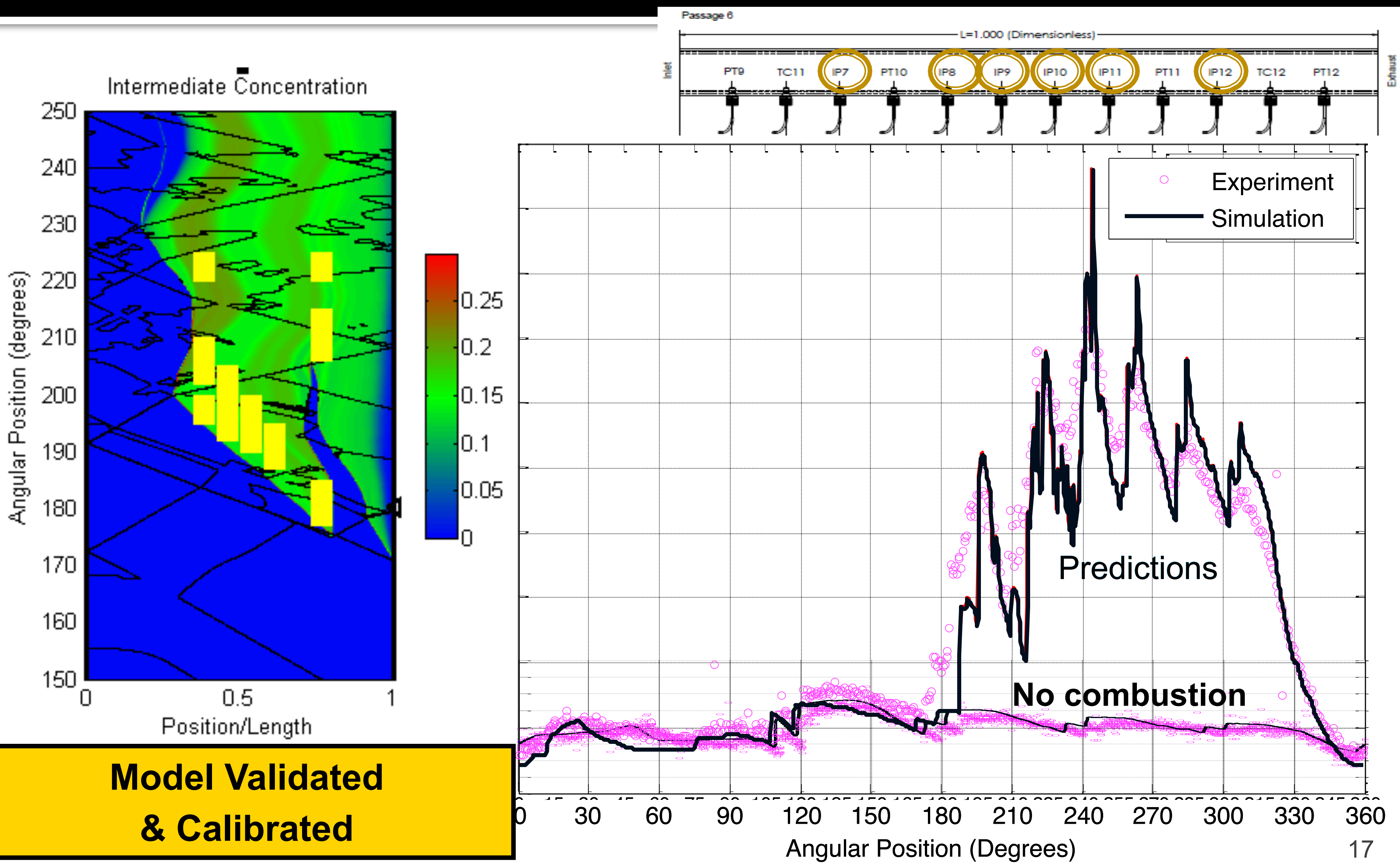
Sponsored by Rolls Royce
Highly instrumented & flexible
Runs at Purdue University Zucrow Labs
Designed using modeling tools originally developed at NASA Glenn

Flame and pressure sensor measurements agree with predictions



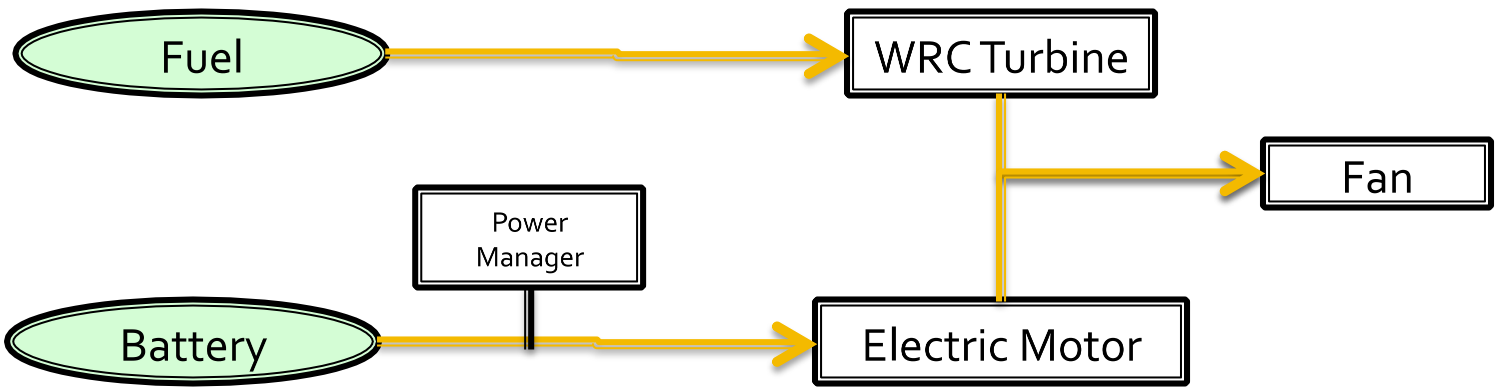
Model Validated & Calibrated

LEARN Phase I progress

- HyWREAP system model development
  - Computational fluid dynamics (CFD) & combustion in WRC turbine channels
  - Thermodynamic model of WRC turbine engine
  - HyWREAP flight fuel burn model
- SUGAR baseline validation
- N+4 battery, electric technology assessment
- Airplane/propulsion architecture proposals
- Phase II plan, technology roadmap

HyWREAP architecture and operation

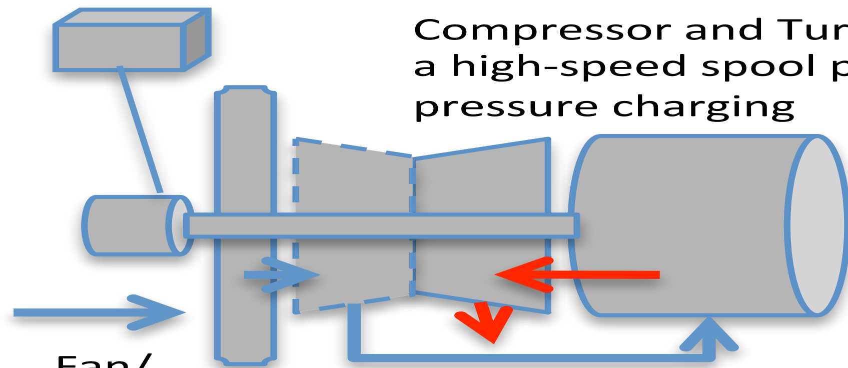
- Parallel hybrid



- Take-off and climb using fuel via WRC turbine
- Cruise optimized for efficient hybrid operation
- Taxi, descend on electric power

Hybrid Wave-Rotor Electric Aero-Propulsion (HyWREAP)

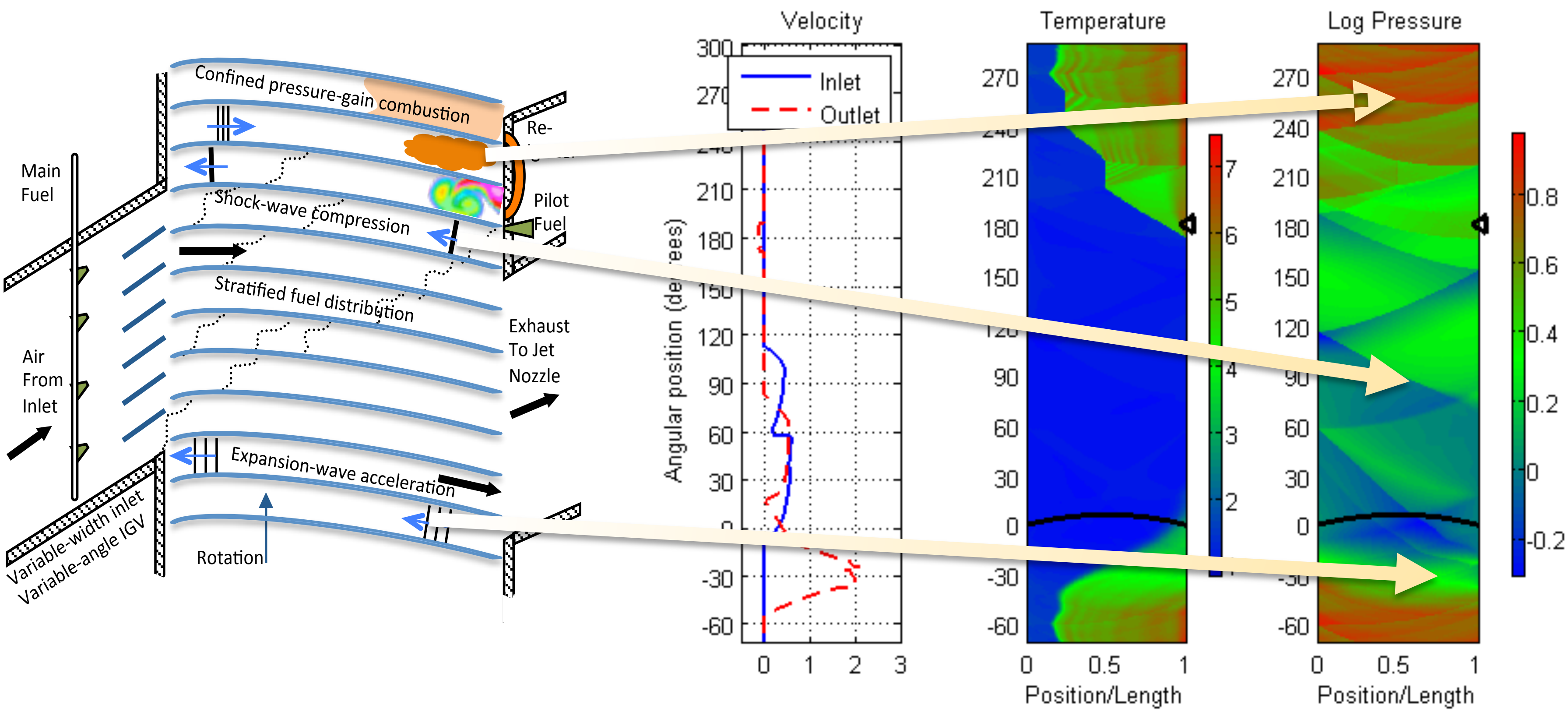
- WRC engine drives propulsor in parallel with electric motor



- WRC has compressor, combustor, and turbine functions in one low-speed rotating component, with curved channels
- Combines heat release and work output
- Retains a compressor-turbine spool for pressurization
- Materials limits still set turbine inlet temperature

WRC Turbine CFD simulation

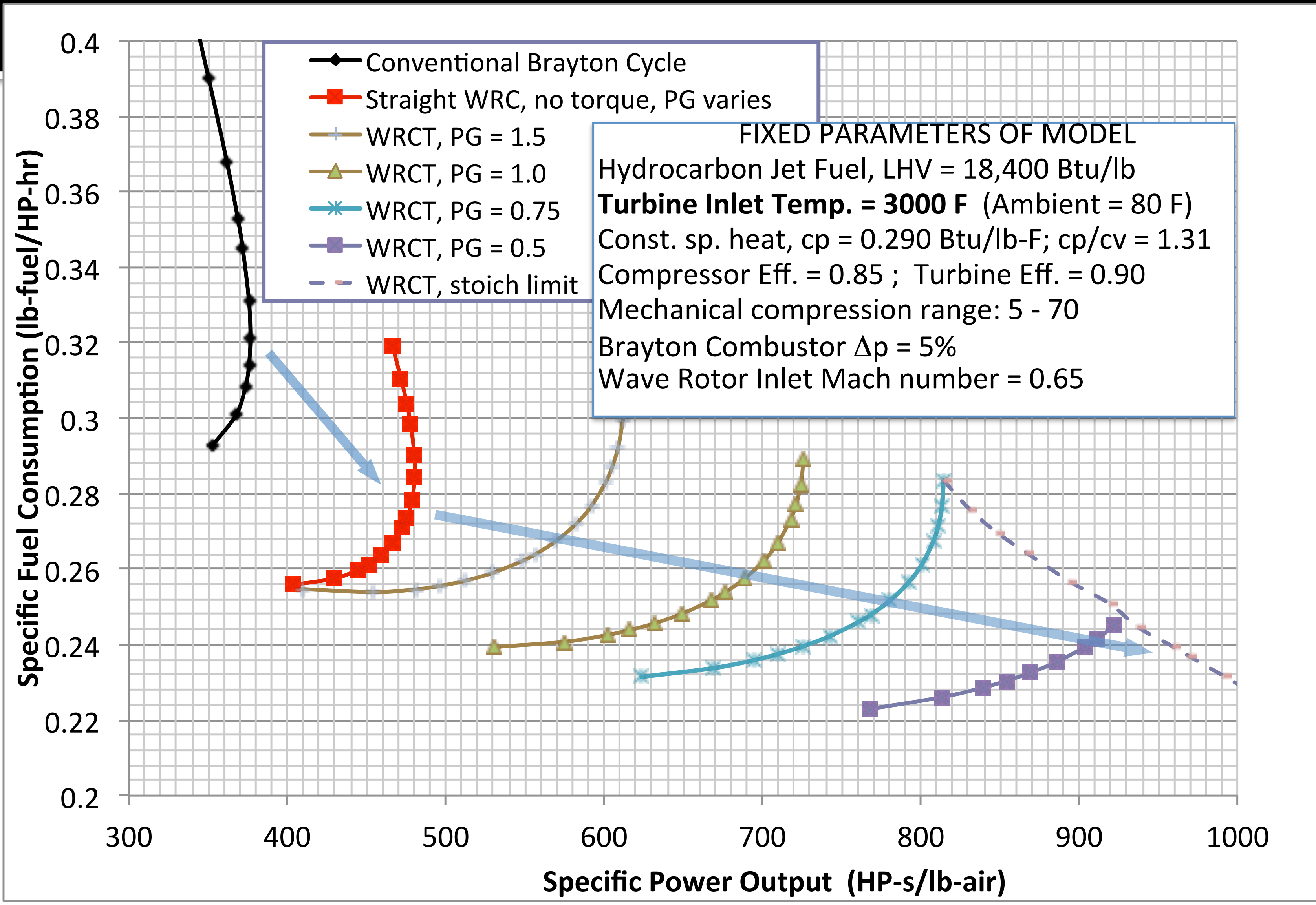
Blade: parabolic profile, +20° to -20°



CFD model adopts the transient one-dimensional approach originally developed at NASA Glenn Research Center for pressure-exchange wave rotor flows.

Present model combines blade force, combustion, all needed submodels for losses

SFC and power for HyWREAP and WRC engines



SUGAR Volt hybrid-electric passenger airplane

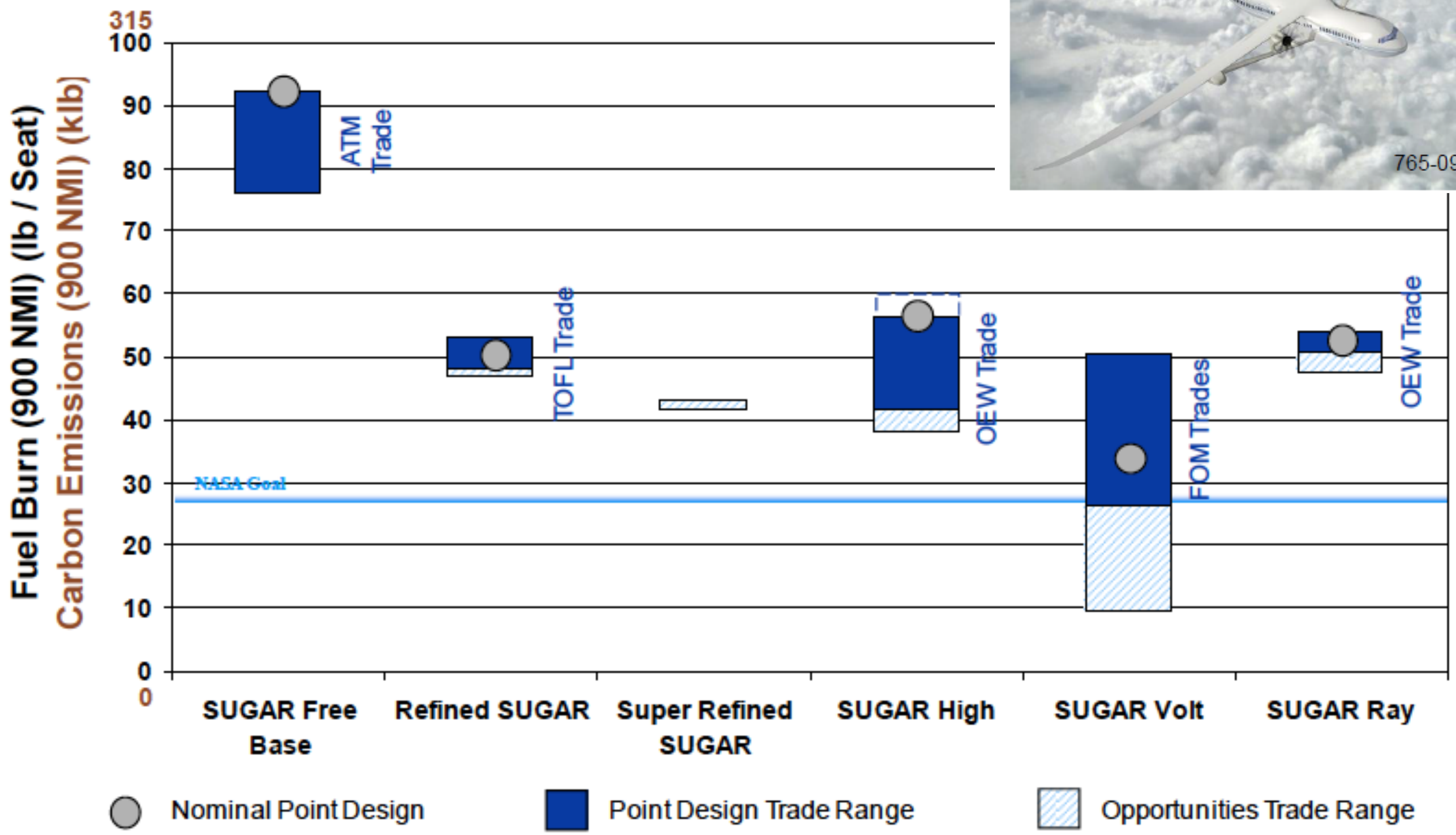
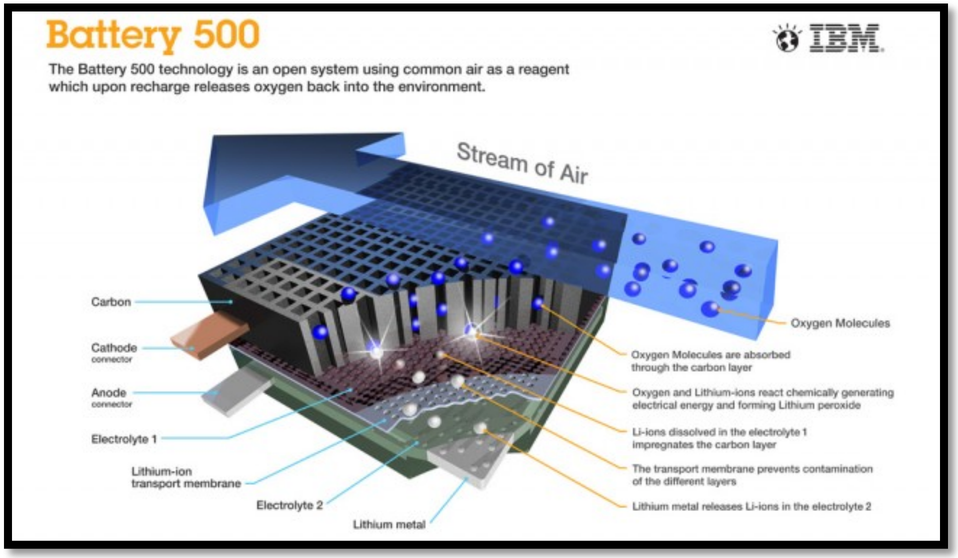


Figure 6.13 – Fuel Burn and Carbon Emissions

SUGAR: Hybrid-electric also the best for NOx and other emissions reduction

N+4 battery & electric motor technology



- Li-Air battery, uses O_2 from air
- High energy density
- IBM design showed promise

- Superconducting motors will need circulating liquid N_2 (~70 K), using cryo-cooler
- Liquid natural gas (LNG, ~100 K) fuel can help cryo-cooler efficiency; likely not eliminate it

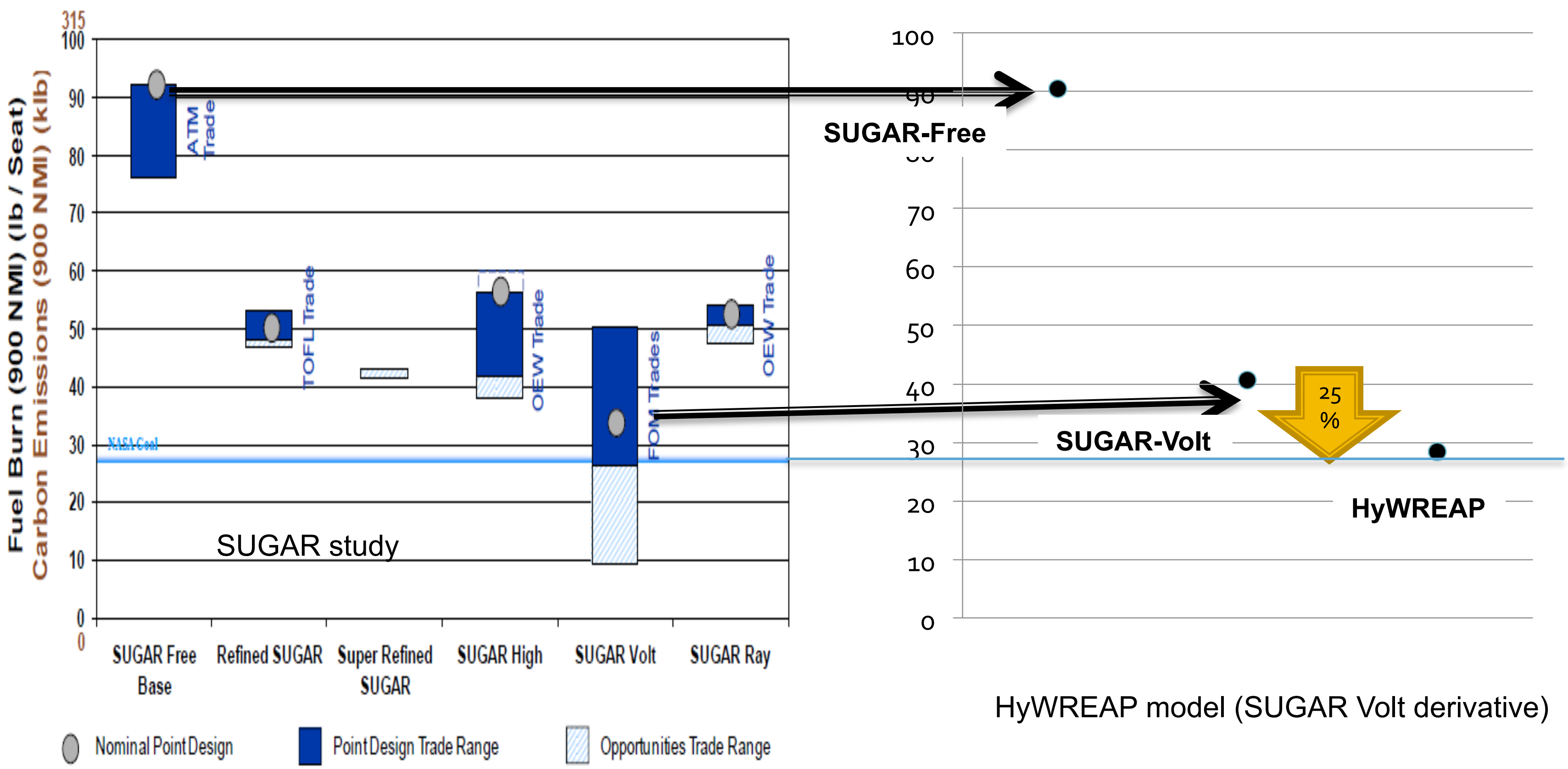
B737 class airplane

- SUGAR-Volt derivative
- Mission: B737 equivalent, pax: ~150, 3000 nm max range, 900 nm typical flight,
- Parallel hybrid fan drive
- Fuel: liquid LNG or Jet-A.

System Design and Operational Design

- Select power source(s) at each flight phase
- Size combustion engine and battery/motor systems to meet power output
- Select economic sequence of operation of the two sources through flight regimes: takeoff, climb, cruise, descent/loiter, landing, taxi
- Retain normal safety margins for takeoff engine failure, landing go around

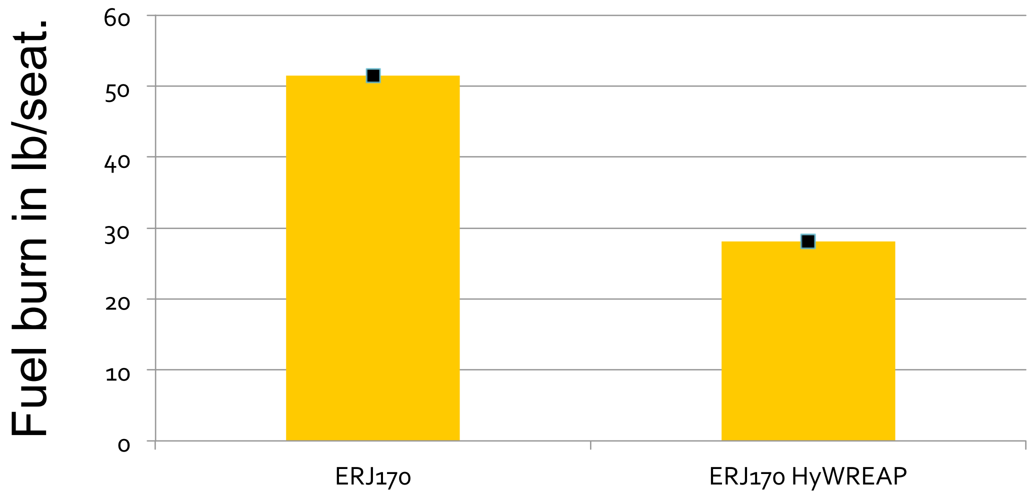
B737-class propulsion system fuel burn



HyWREAP model (SUGAR Volt derivative)

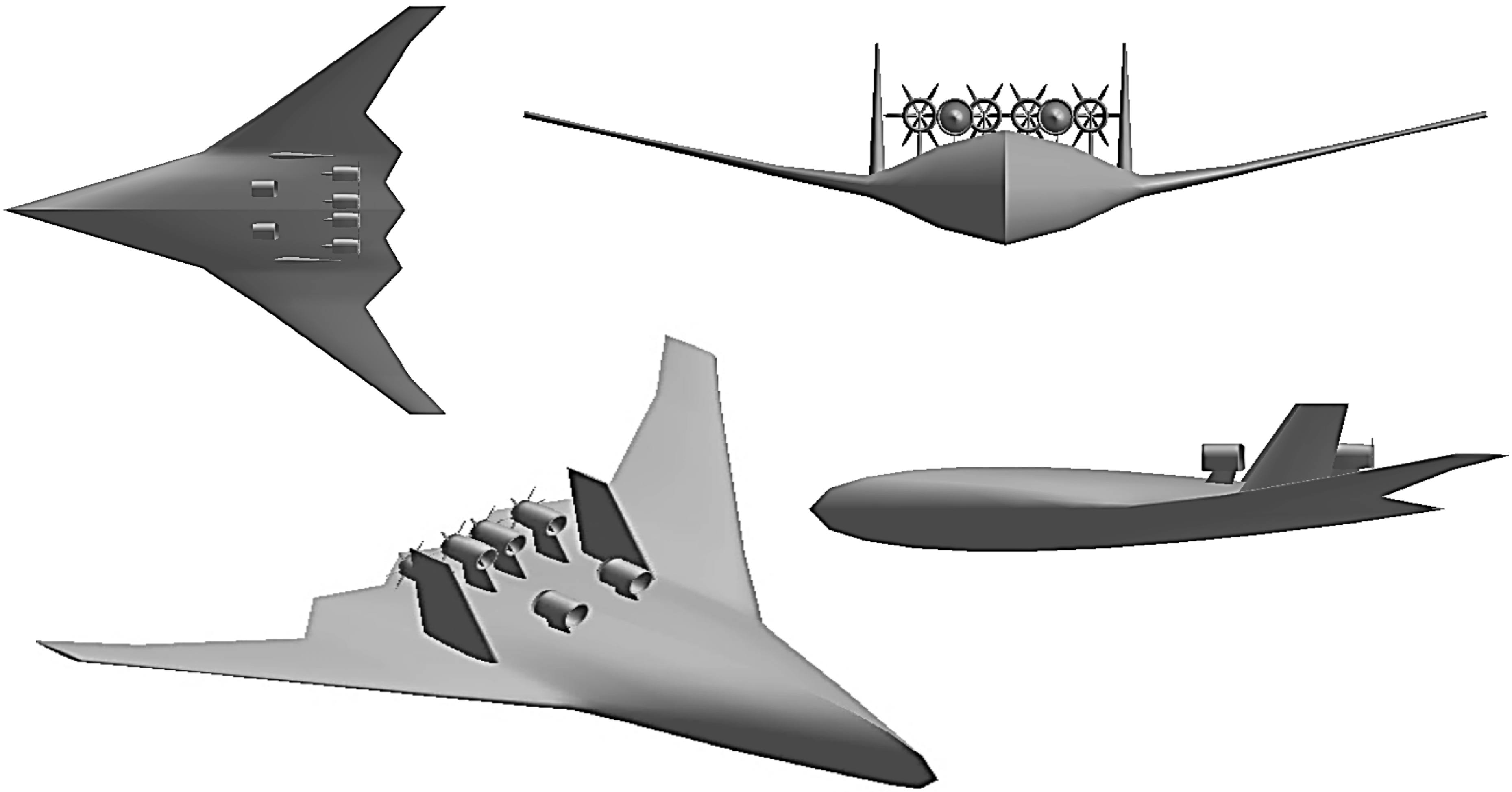
Regional jet fuel burn

- Aircraft-Embraer ERJ 170
- Range=400 nm (1800 nm maximum range on standard aircraft)
- Pax=80



Does not include improvement in airframe design or any other N+4 era technologies

Regional Jet HyWREAP Airplane Design



Aircraft design by Tuskegee University student team

Phase II Plan & Dissemination

- Use CFD tool to optimize WRC blading for a selected engines and aircraft application, evaluate stresses vs. materials limits
- Concept aircraft design to minimize fuel burn
- Refine WRC propulsion system SFC estimation at takeoff, climb, cruise
- Estimate hybrid propulsion system weight for selected aircraft
- Design N+1 technology HyWREAP for UAV
- Design, plan WRC test turbine using WRCR rig
- Assess technology issues; develop roadmap
- NASA Glenn & Rolls-Royce are good dissemination agents on Phase II team, with the 3 universities

Summary

- WRC Turbine computation model completed and being used to characterize performance
- HyWREAP system model validated with Boeing SUGAR Volt fuel-burn reduction
- HyWREAP benefits verified to reduce fuel burn 25% below SUGAR Volt for B737 class
- Additional aircraft applications evaluated
- Phase II plan developing
- Already disseminating ideas by publication plans, and via NASA Glenn & Rolls-Royce

Supplementary Slides

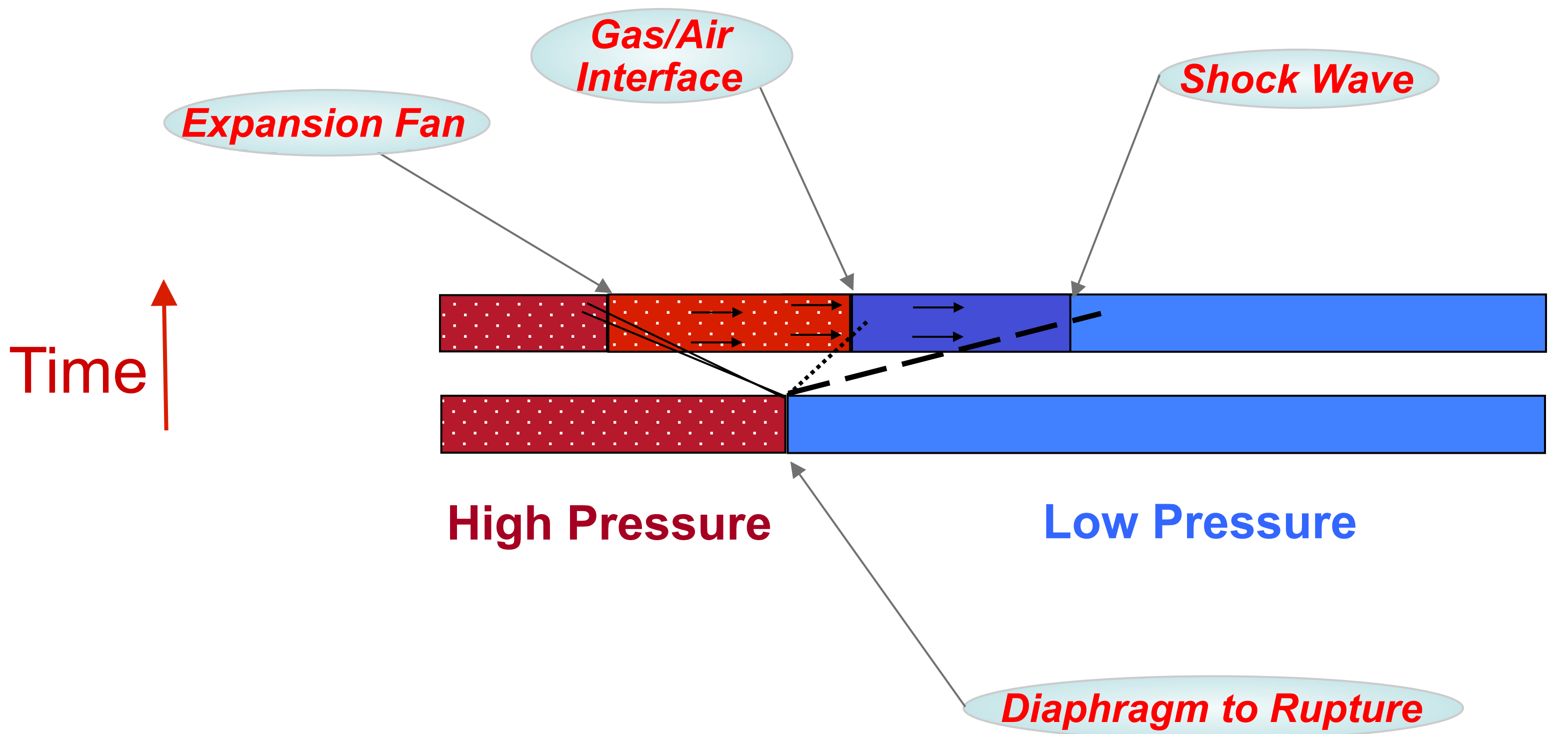
Pressure-Gain Wave Rotor Combustion Benefits for Gas Turbines

- Pressure-gain WRCVC provides substantial benefits
  - high fuel efficiency relative to conventional gas turbines
  - CO_2 emissions reduction, stable combustion of high-H_2 fuels
  - engine size, cost reduction
- Measured internal combustion in WRCVC is supported by simulation model and design tools
  - high-frequency pressure traces
  - flame ionization probes
- Self-cooled rotating combustor is easily manufactured and integrates well with turbomachinery
- GT's can retain moderate, low-cost materials and technologies for mechanical compression and turbine temperatures

IUPUI - CPRL has developed a strong knowledge base on wave rotor combustion, supported by Rolls-Royce and Purdue University

Pressure Exchange in a Shock Tube

– a basic example of unsteady flow work transfer



<u>Pressure waves</u> cause direct work action by one fluid on another – an energy exchange.

Pressure Wave Energy Exchange - Much Faster than Mixing

Pressure Exchange in a Shock Tube

– a basic example of unsteady flow work transfer

Cornell Aero Labs, ~1960
Wave Superheater

Shock-driven wind tunnel for atmosphere re-entry testing