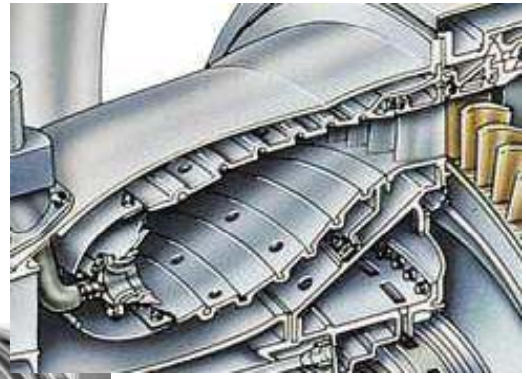
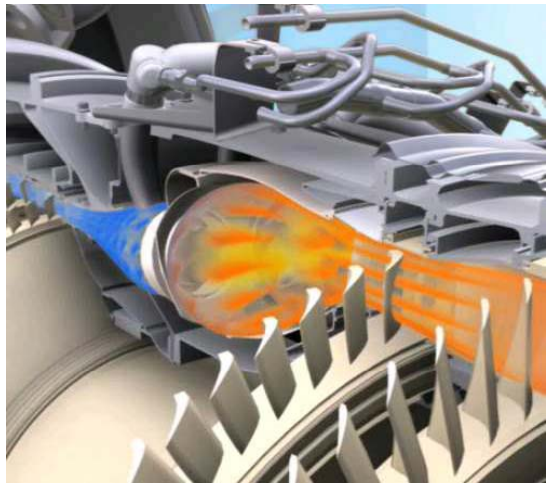
Low-Emissions Combustors Development and Testing



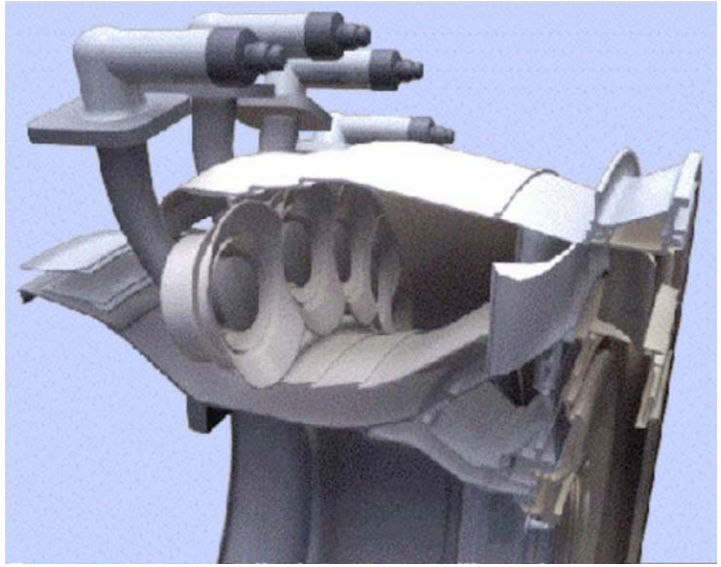


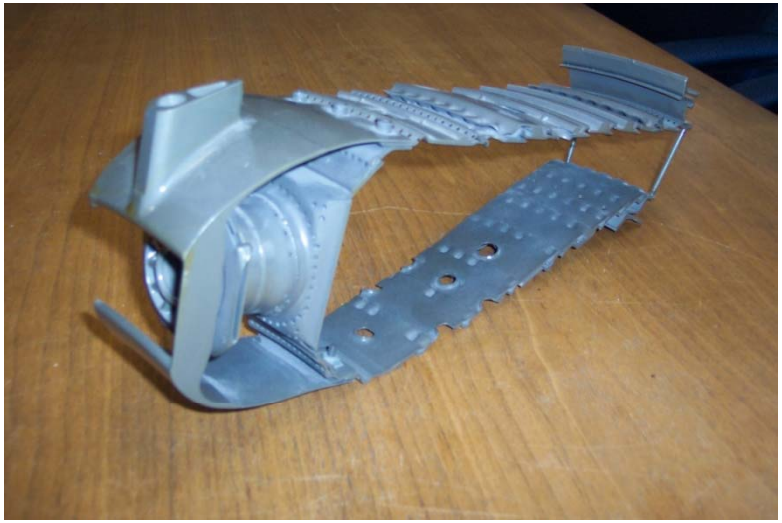
Dr. Clarence T. Chang
NASA Glenn Research Center
clarence.t.chang@nasa.gov

Pictures borrowed from GE

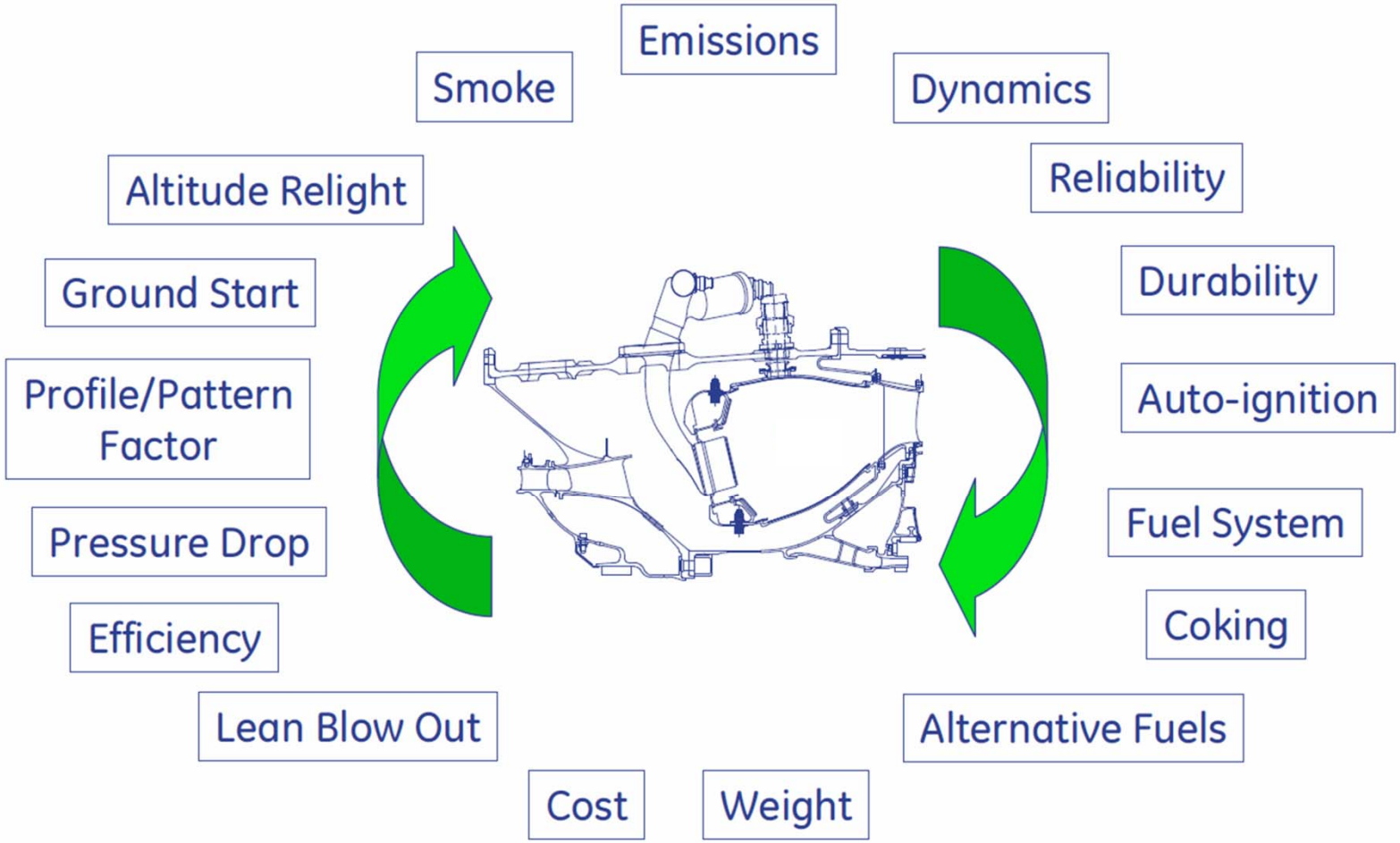
Outline

- Aeroengine combustor design process is tough ("optimum compromise")
- What's optimized
- How to test/validate
- The emissions challenge
- The resulting dynamics challenge
- Active Control as a response to the dynamics challenge





Balanced Combustor Design



Viewgraph borrowed from GE

Some Typical Operating Parameters

Parameters	Take-Off	Cruise
$PR_{OverAll}$	30-45	30
P_3	450-675 psia	150 psia
T_3	1000 - 1300 °F	800 °F
T_4	2400 - 3000 °F	1800 °F
$\Phi_{OverAll}$	0.30 - 0.5	0.25

How do we assess performance?

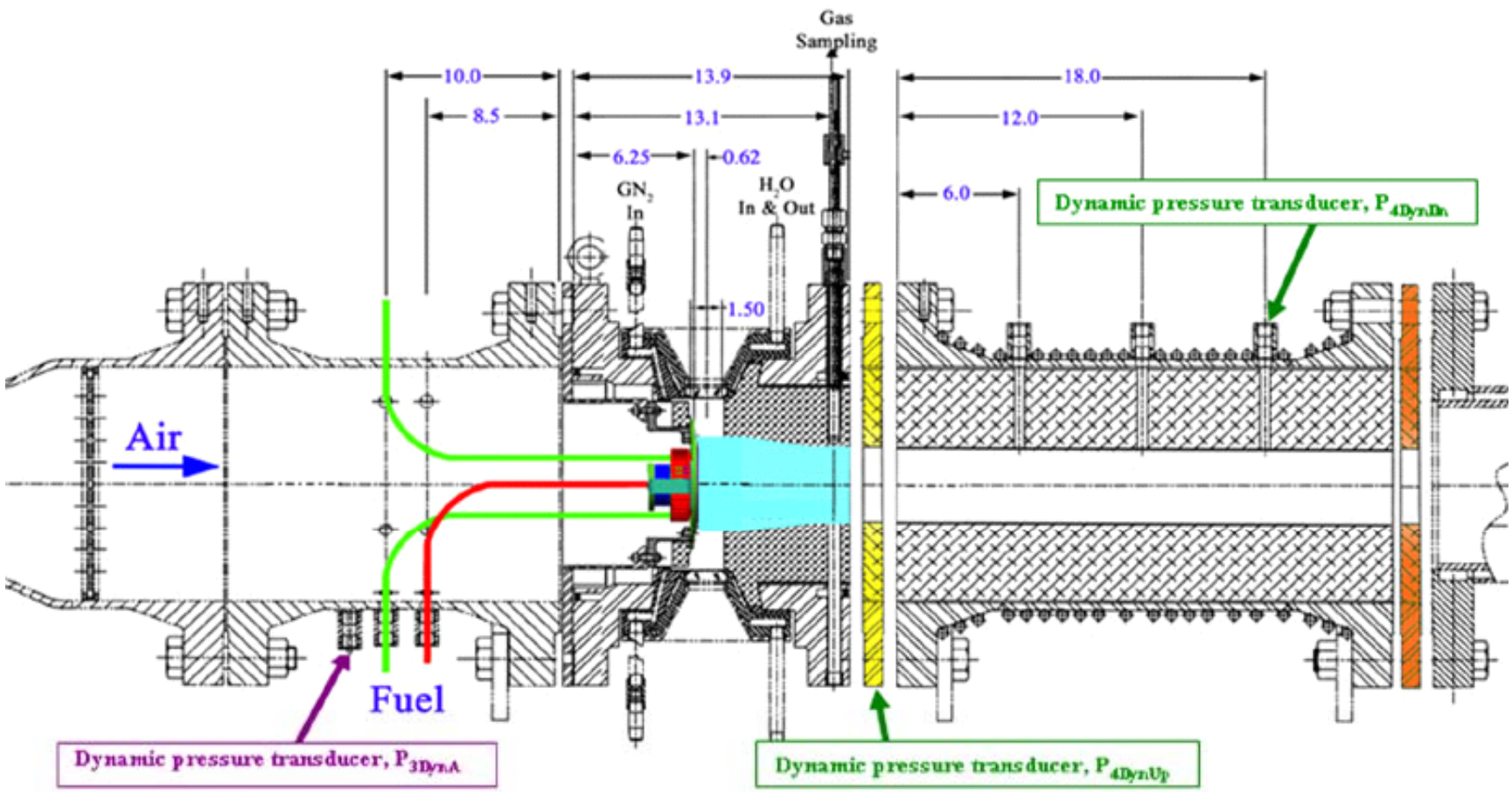
NASA Glenn Combustor Facilities
Flametube => Sector => Annular

Facility	Config.	Pres. range, psig	Max. airflow, lb/sec	Non-vitiated heated air, ˚F	Max. exhaust temp., ˚F
CE–5B-1	Sector	60 to 275	2 to 12	500 to 1350	3200
CE–5B–2	Flametube	60 to 400	0.6 to 5	500 to 1350	3200
ASCR Leg 1	Sector / annular	50 to 900	3 to 50	500 to 1200	3400
ASCR Leg 2	Flametube	50 to 900	1 to 10	500 to 1200	3400
CE-13C	Flametube	0-60	0.8	1000	3550

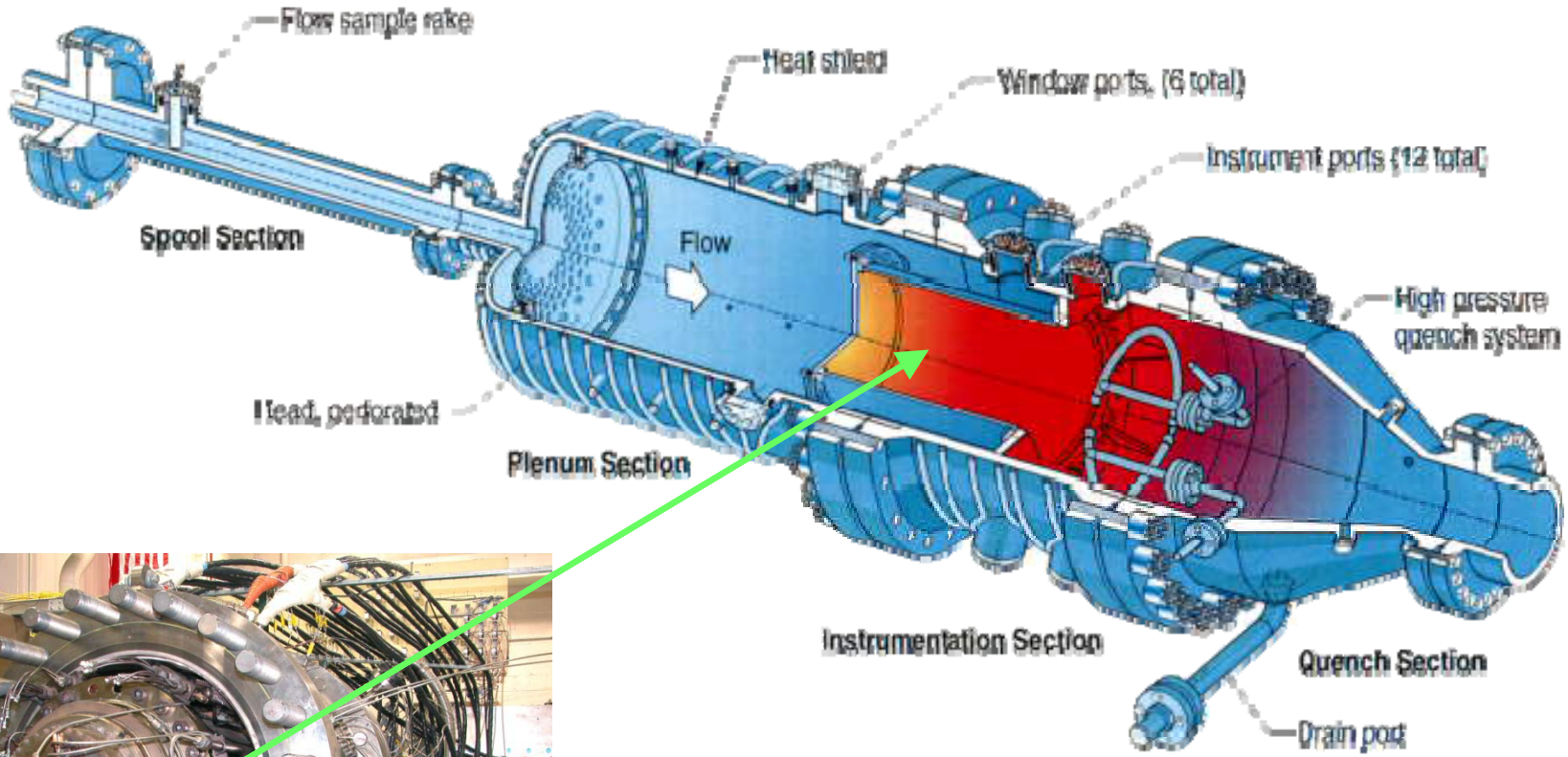
CE5B Stand 1 Flametube / sector (1200 °F, 450 psi, 30 lbm/s air flow)

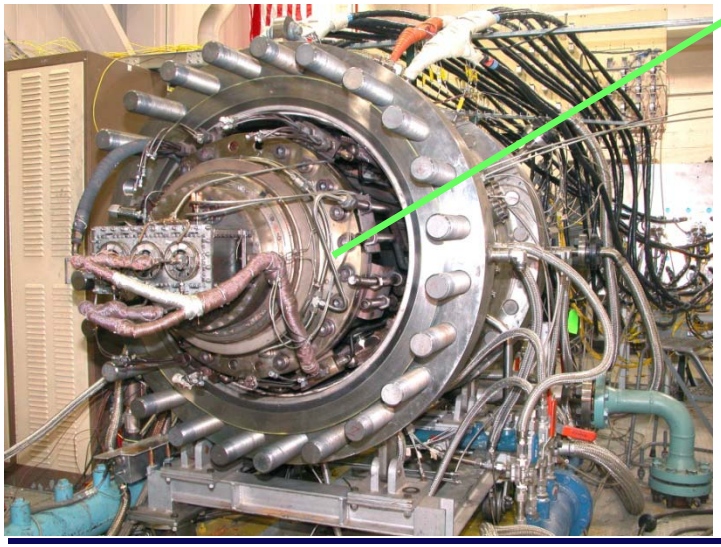
Newer – Dynamics testing

Newest – Alternate Fuels

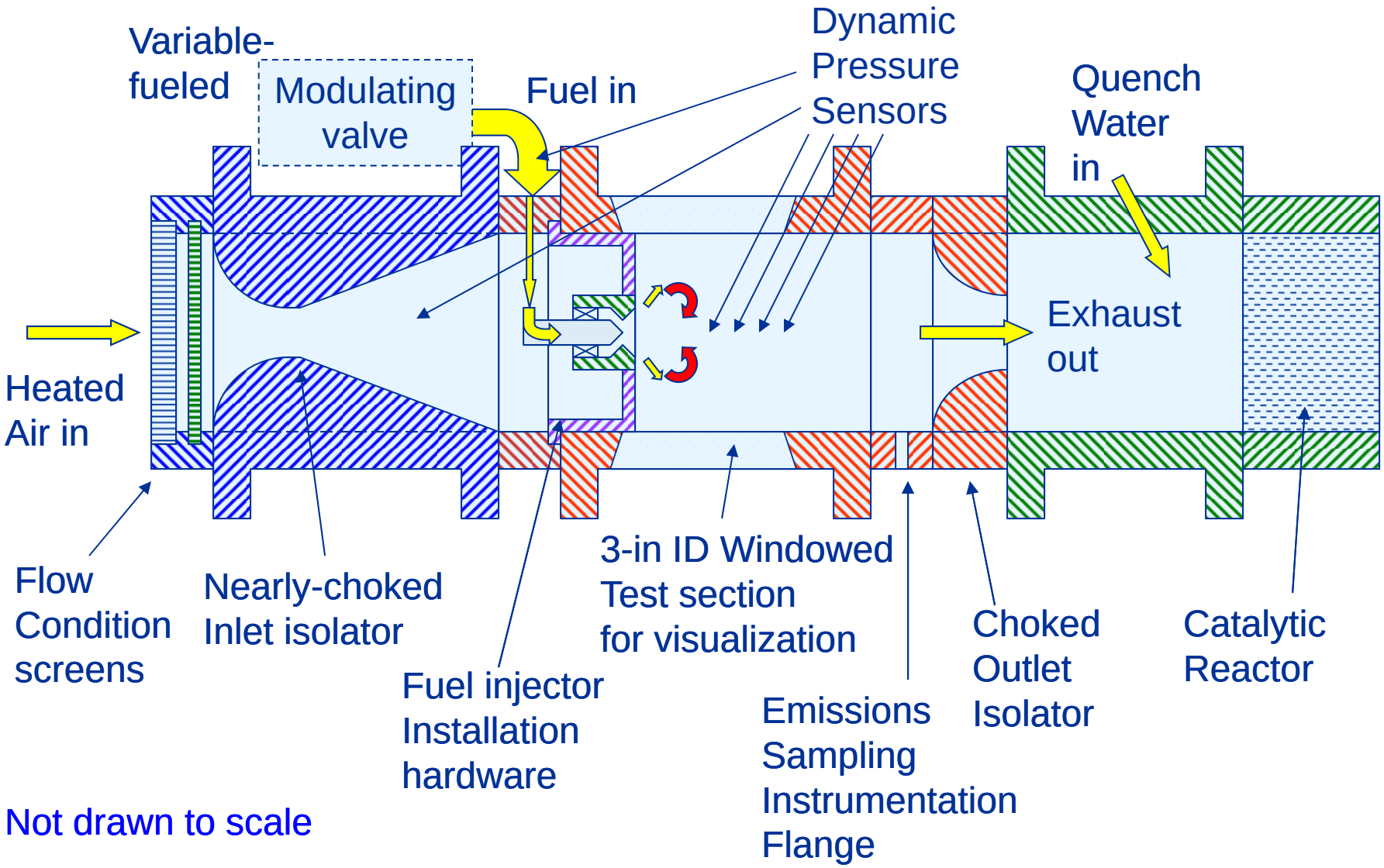


ASCR Stand -1 60 atm Sector Testing Rig.
1300 °F, 900 psi, 50 lbm/s airflow





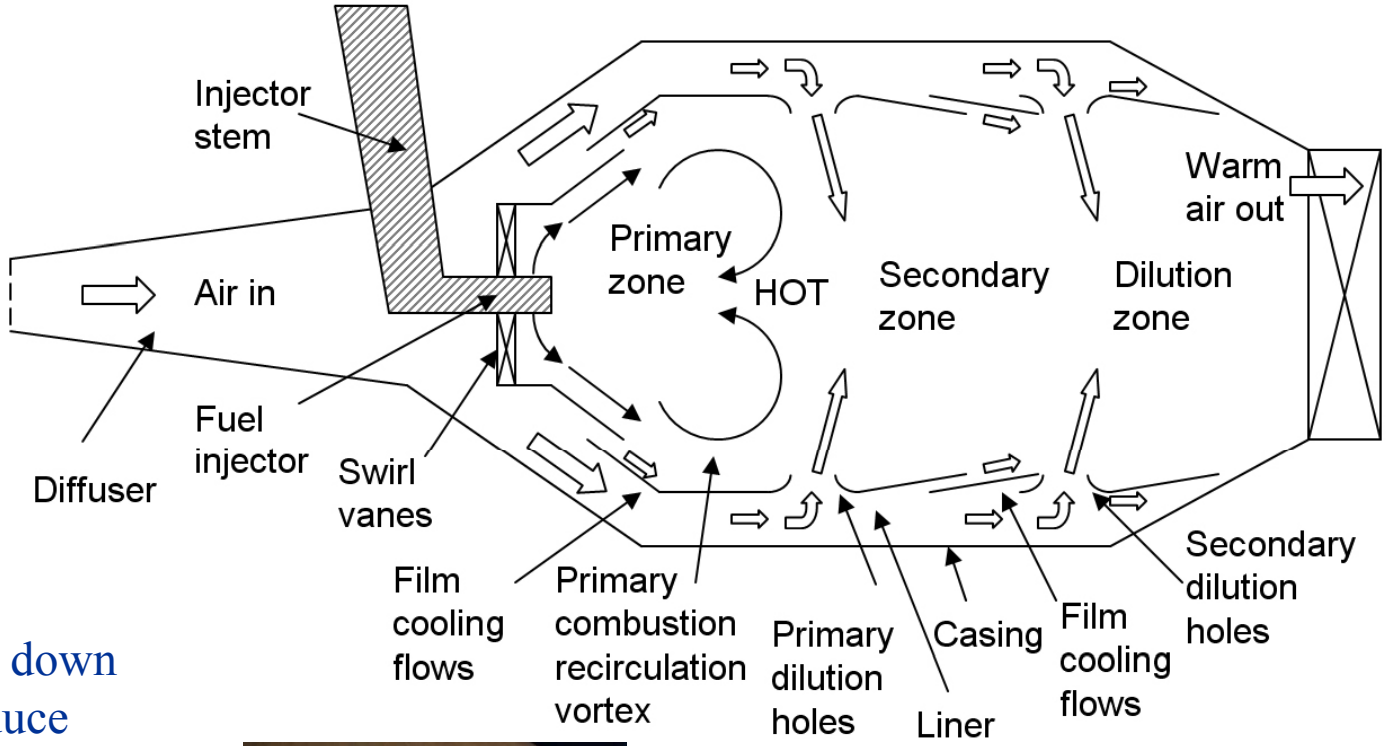
CE-13C LDI Injector Screening Rig Functional Layout (laying on its side)
1000 °F, 60 psig, 0.8 lbm/s airflow



Not drawn to scale

How does a combustor work?

Legacy Combustor Features



1. Diffuser slows down flow speed to reduce Rayleigh loss

2. Fuel-nozzle turbulence speeds up atomization by break up liquid into droplets

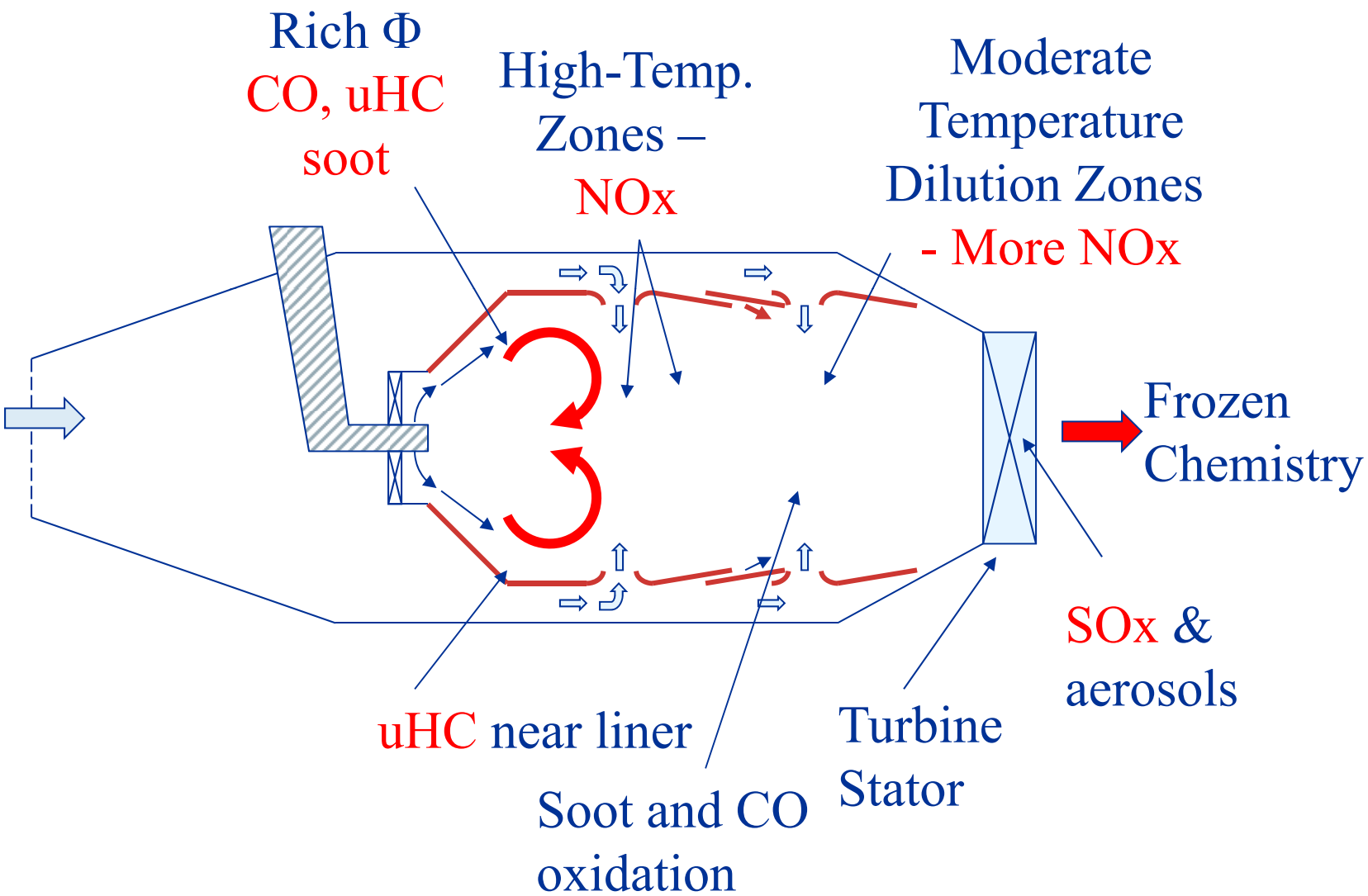
3. Liner film-cooling decouples thermal loading from pressure casing

4. Swirling flow forms recirculation vortex to provide flame-holding

5. Primary dilution holes provides dilution and vortex anchor

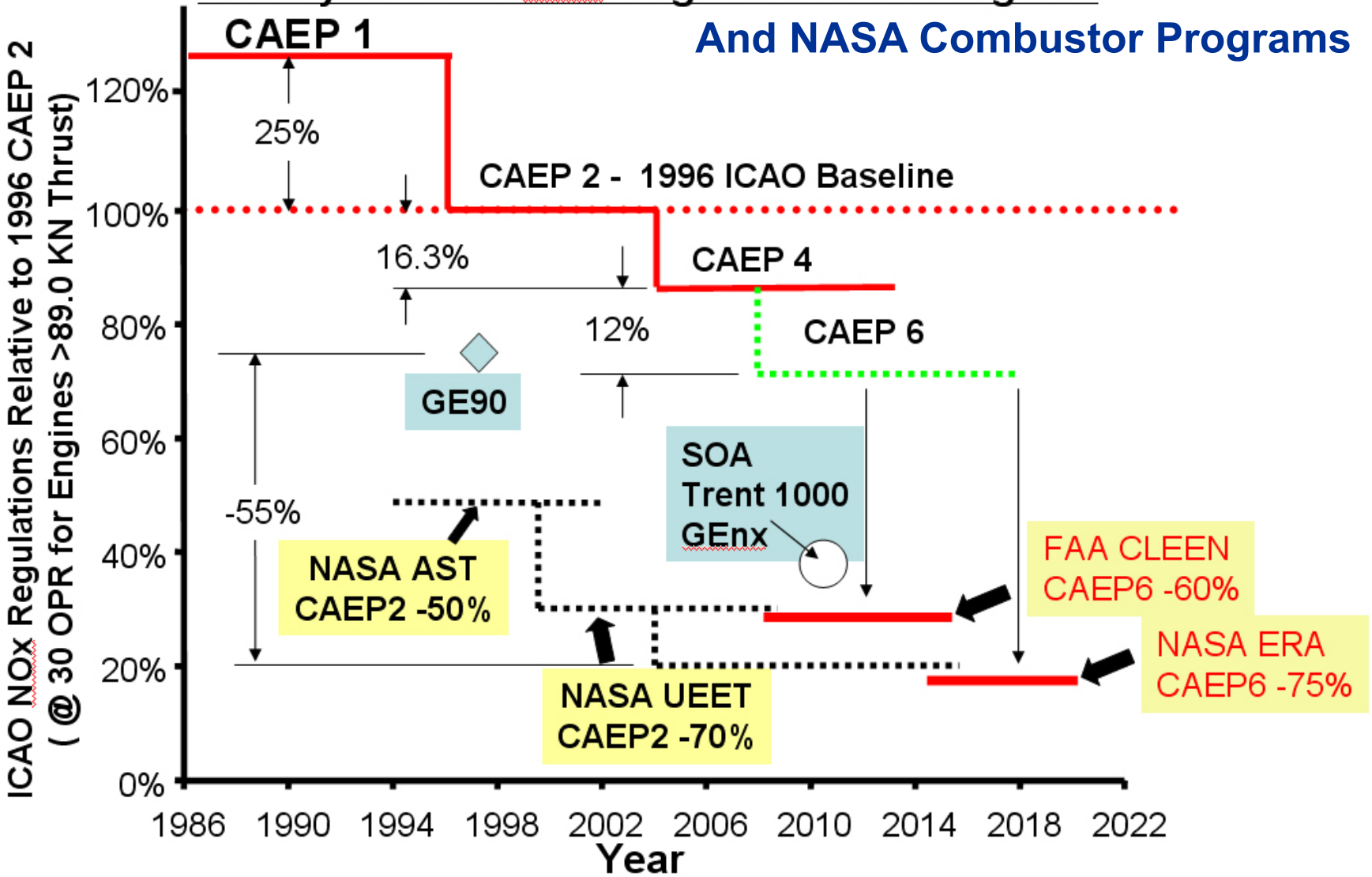
6. Secondary dilution holes add more air to bring T4 down and shape T4 profile

Where Does Pollution Come From?

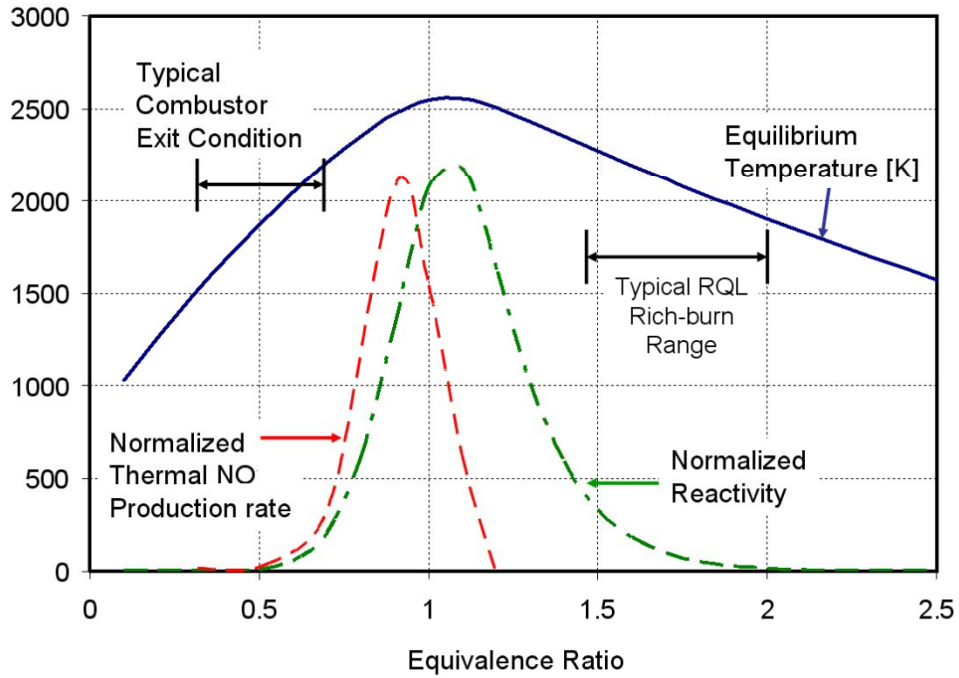


History of ICAO NOx Regulations for Engines

And NASA Combustor Programs



NOx Formation Concept and Avoidance Strategy

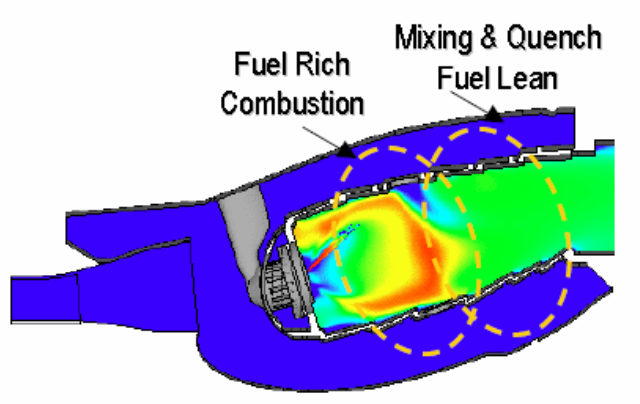


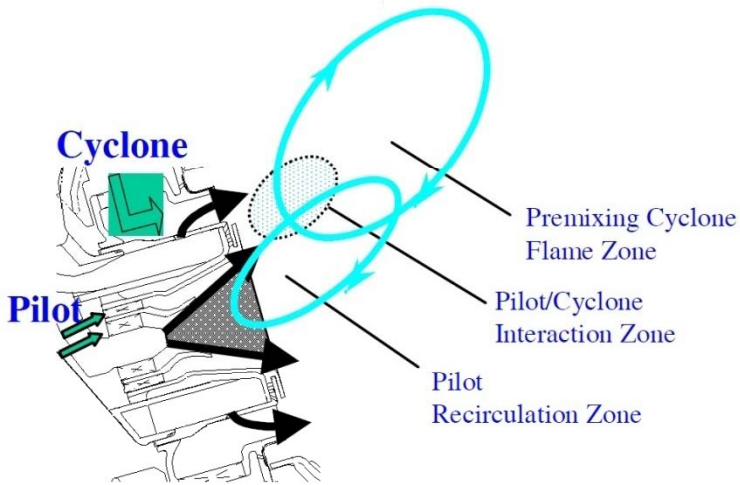
NOx Formation Rate (Highly Temperature Dependent) x Residence time = ObNOxious output

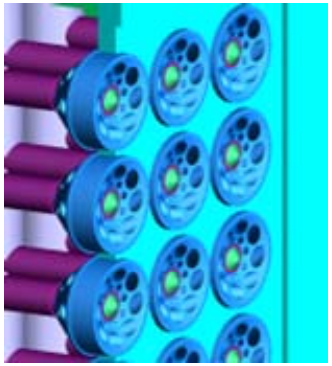
Key to Low-NOx:

1. Avoid high temperature burning
2. Keep the exposure time short

NOx Reduction Combustor Concepts







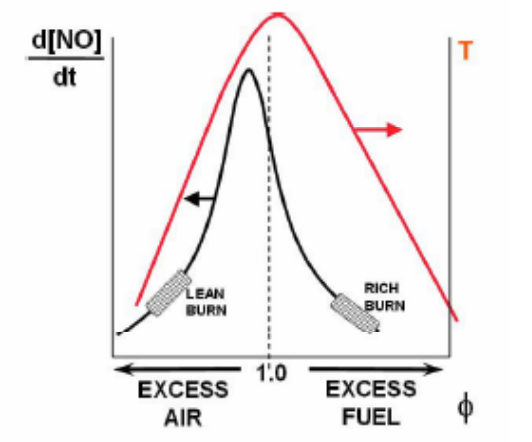
RQL**

Rich-burn

Partial-Pre-Mixed*

LDI

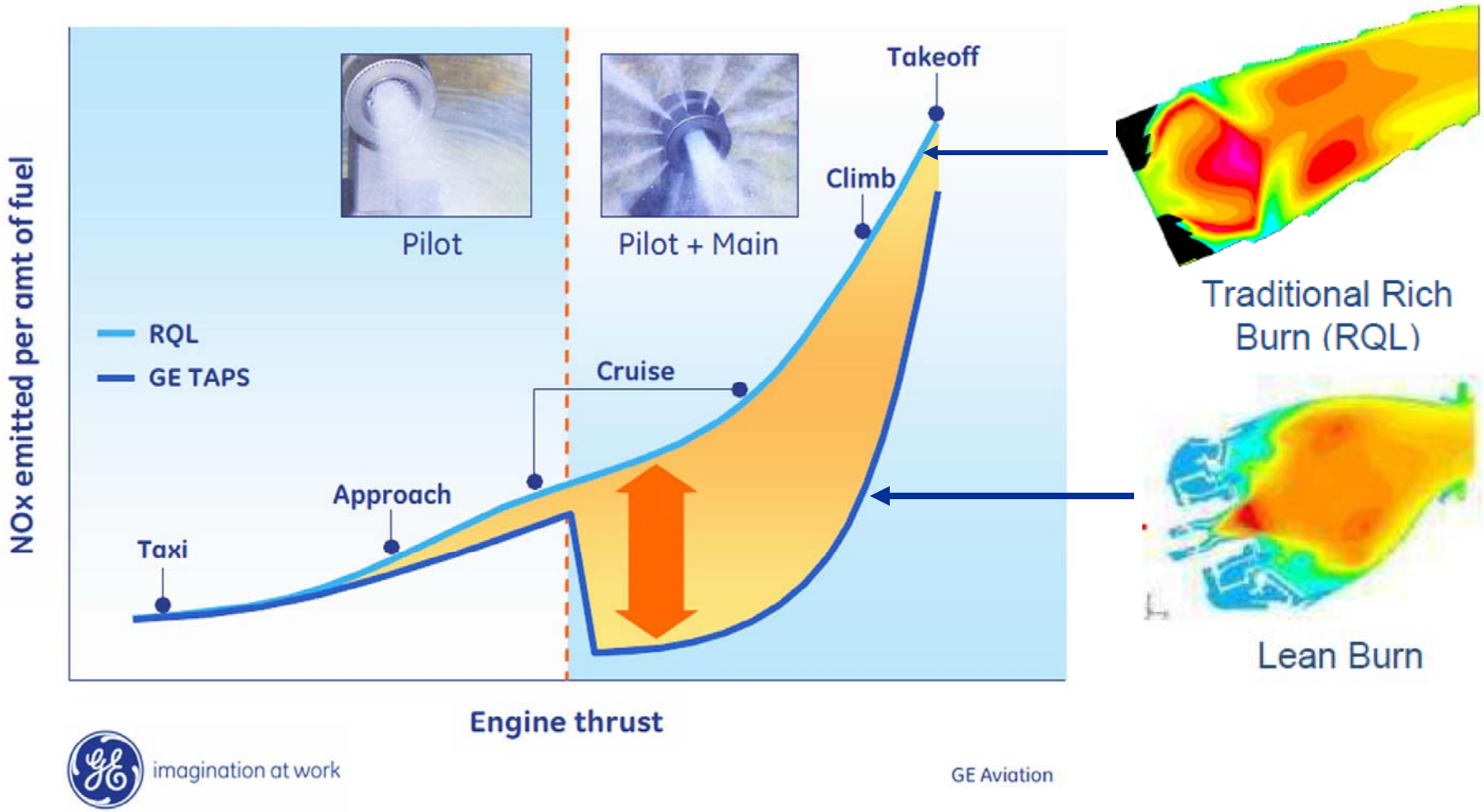
Lean-burn



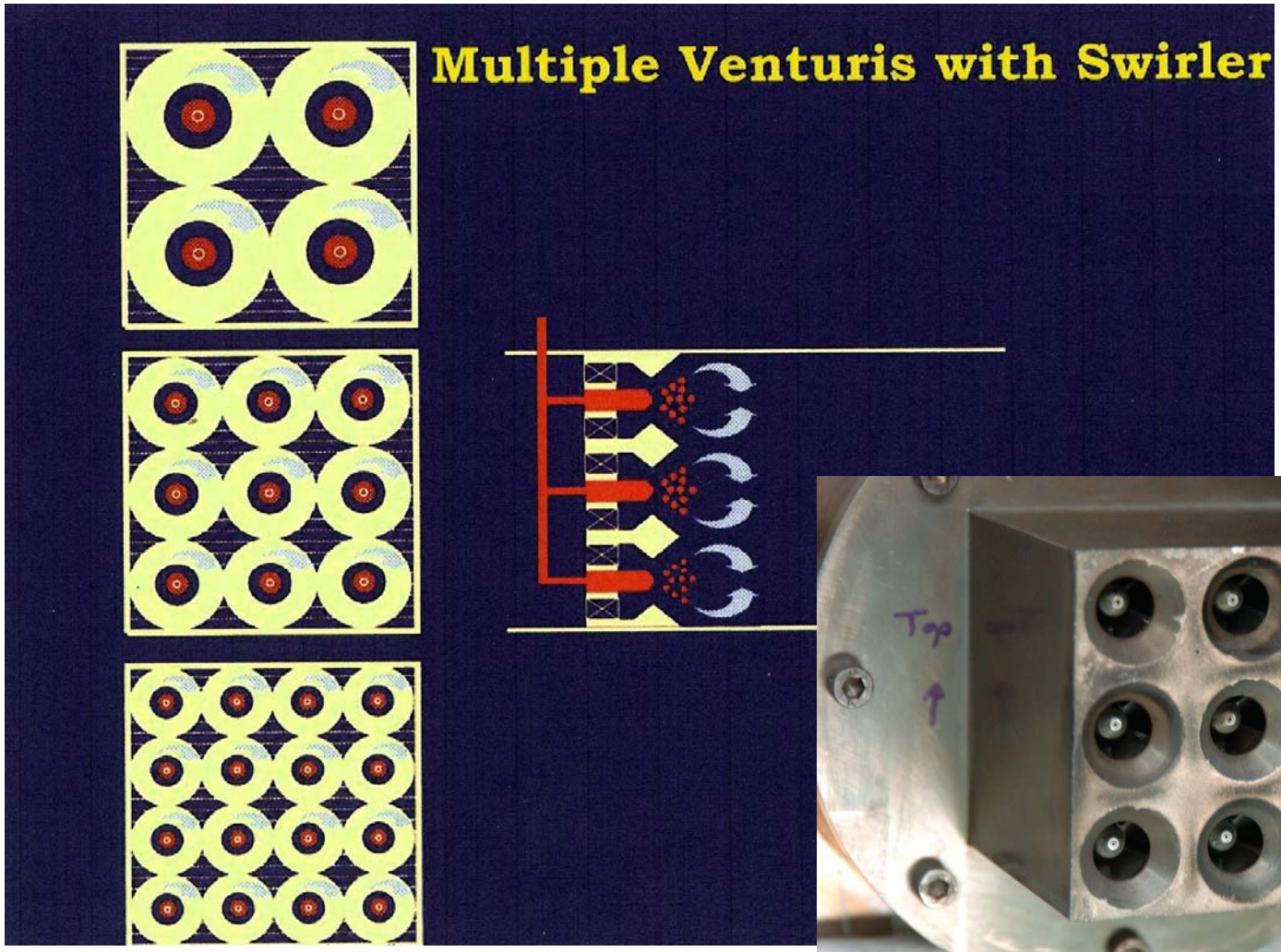
**McKinney, 2007
*Dodds, 2008

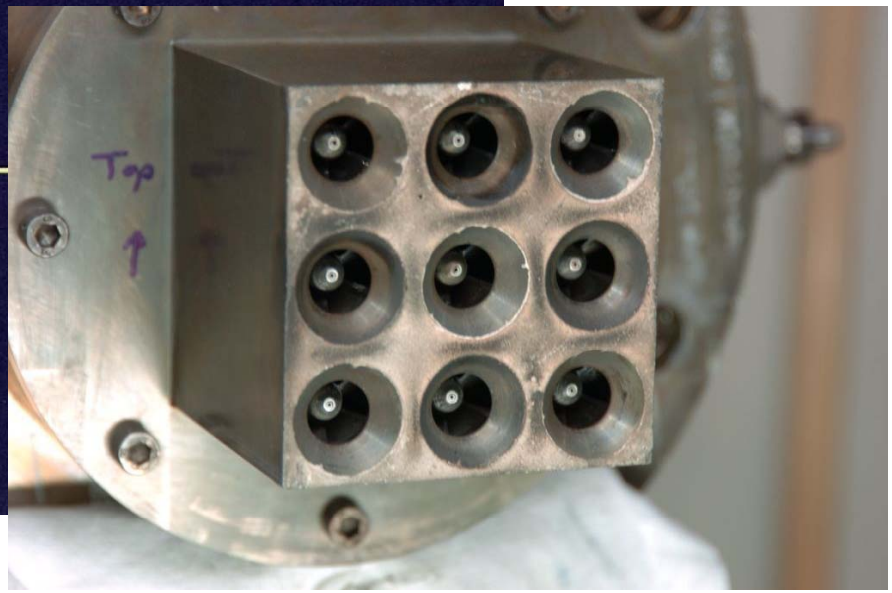
Lean-burn Fuel Staging Enables Low NOx at Cruise

NOx flight cycle comparison (GE TAPS vs. traditional RQL combustor)

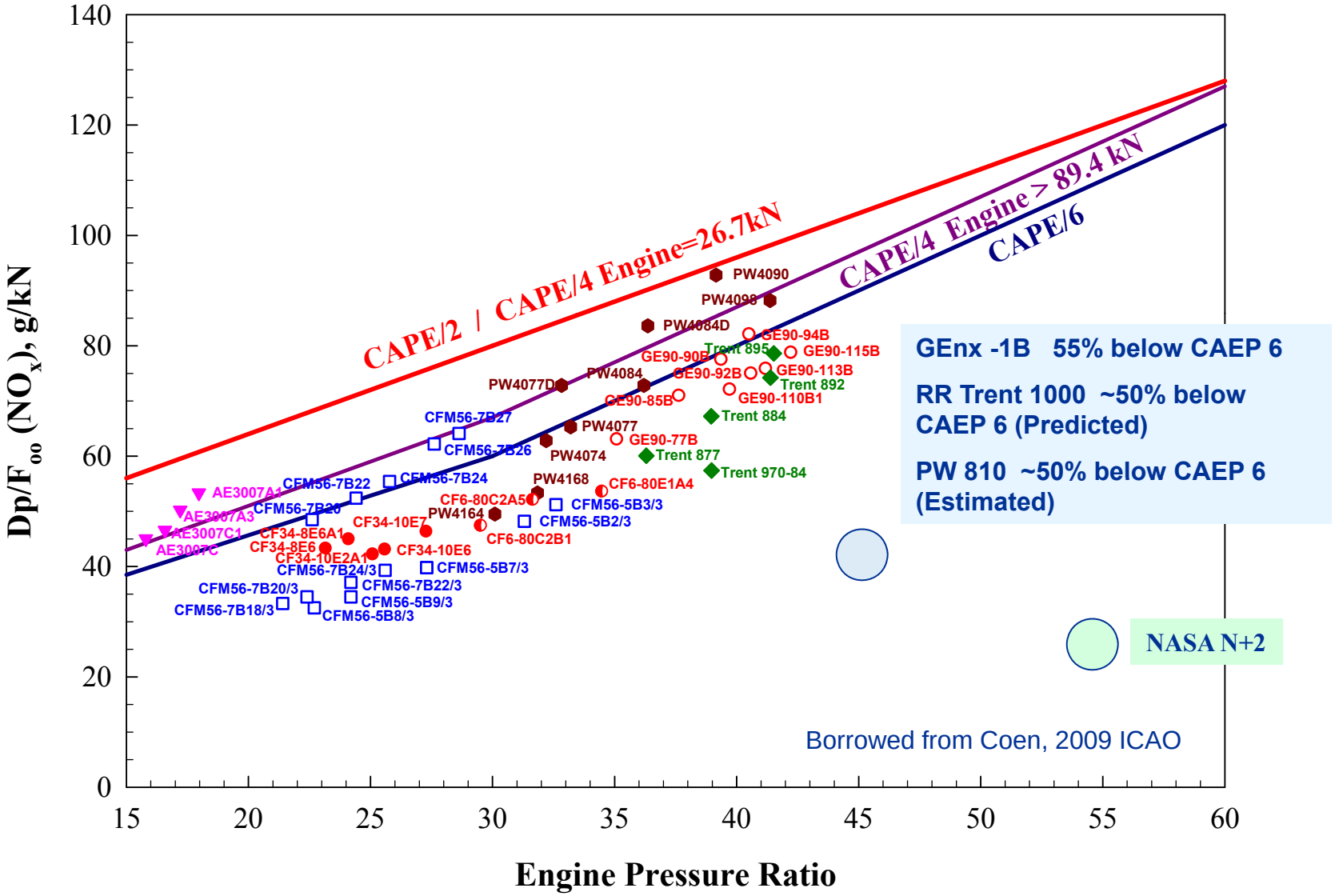


Lean Direct Injection – Low NOx Concept

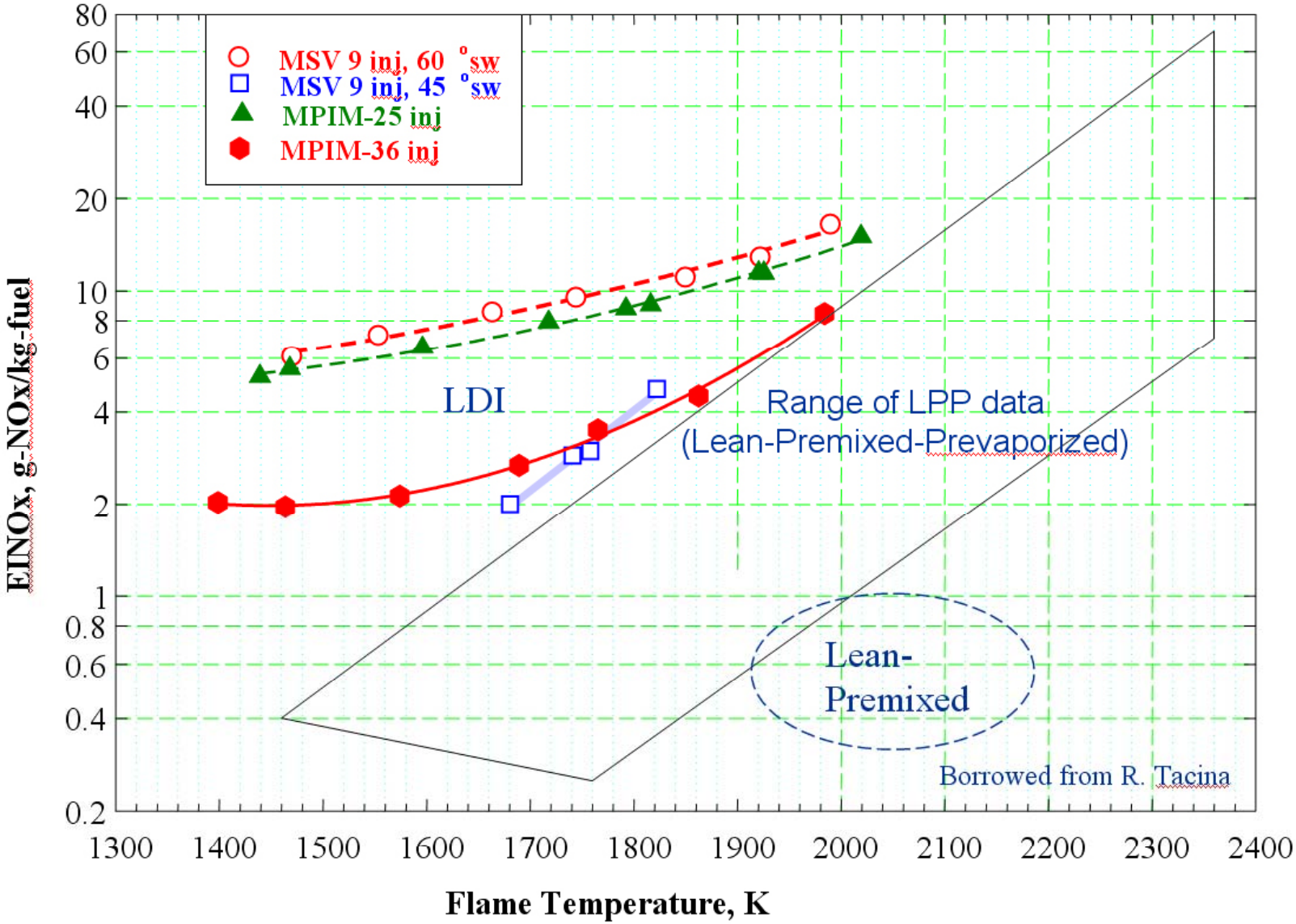




Current LTO NOx Emissions

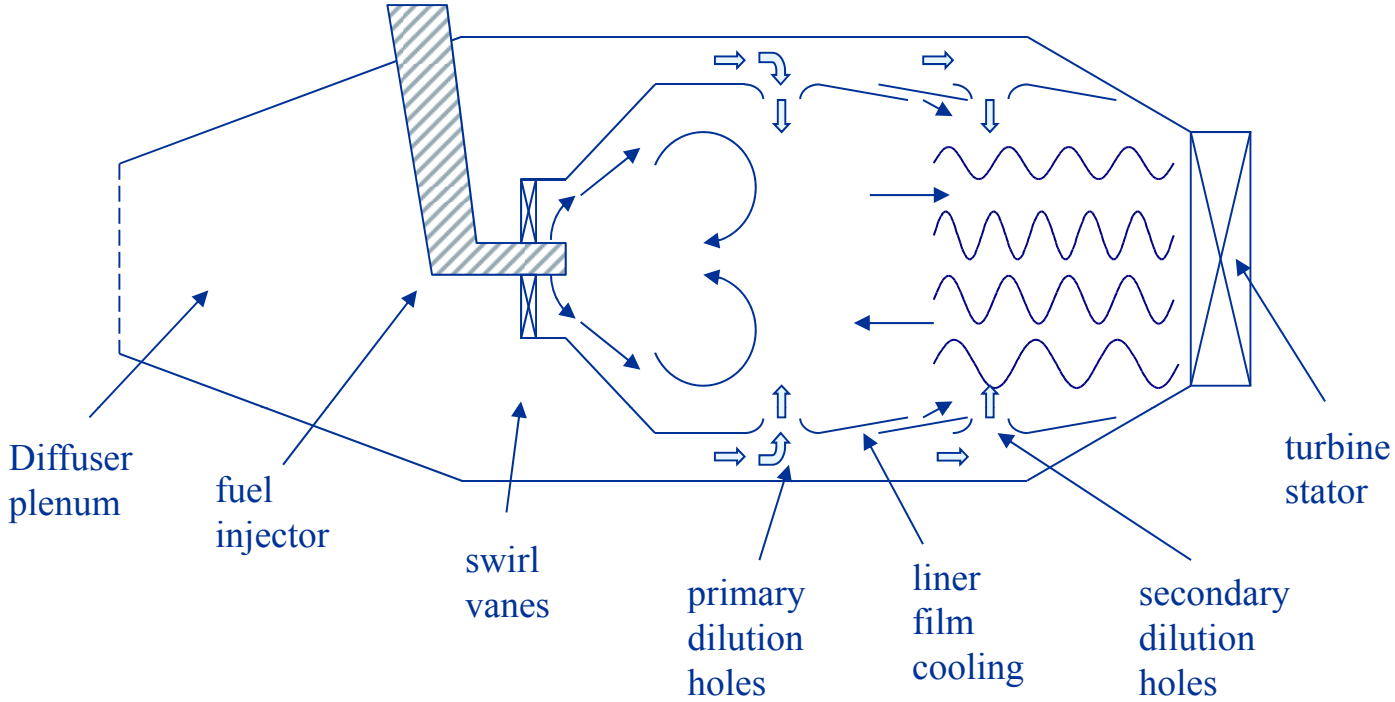


Effect of Fuel Injection Schemes on NOx Emission



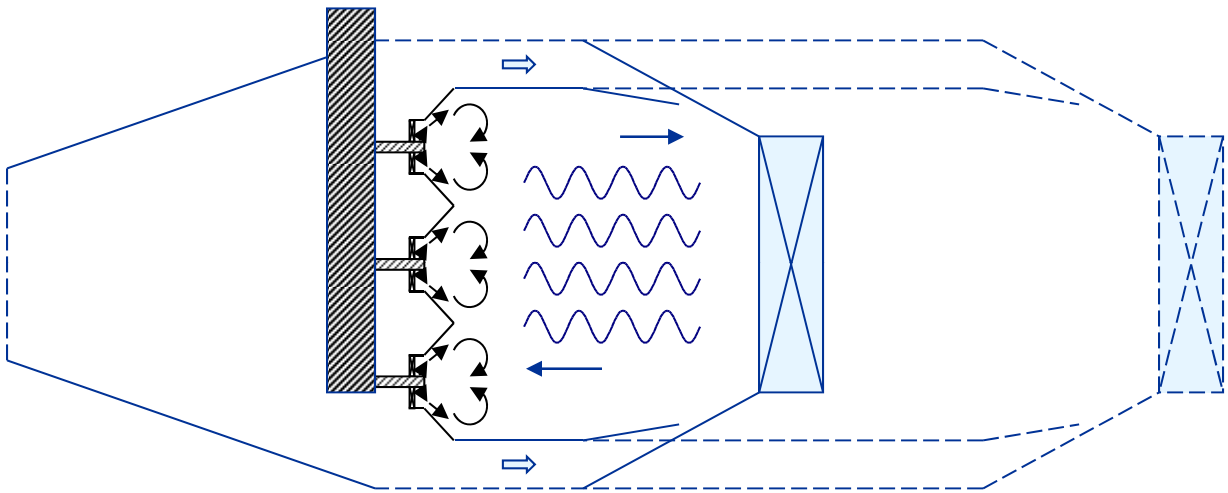
Why do we need combustor control?

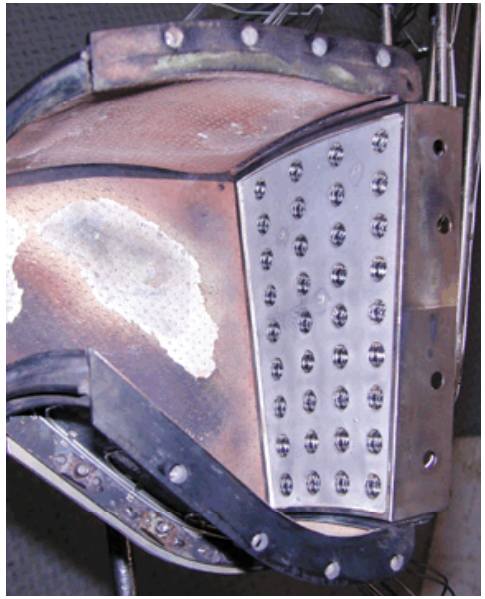
Issues that Affect Combustor Instability / Acoustics



1. **Well-defined acoustic boundary conditions**
2. **Perturbations from fuel-nozzle turbulence**
3. **Recirculation vortex provides flame-holding**
4. **Liner film-cooling provides damping**
5. **Multiple temperature zones**
6. **Φ' interaction with P'**

Lean-Burning, Ultra-Low-Emissions Combustors Are More Susceptible to Thermoacoustic Instabilities





1. Higher performance fuel injectors => more turbulence
2. No dilution air => reduced flame holding
3. Reduced film cooling => reduced damping
4. More uniform temperature distribution => acoustically homogeneous
5. Shorter combustor => higher frequency instabilities

How do we deal with combustor instabilities?

1. Smart design
2. Modulate air to get out-of-phase cancellation
3. Fuel-modulation to get out-of-phase cancellation

However…

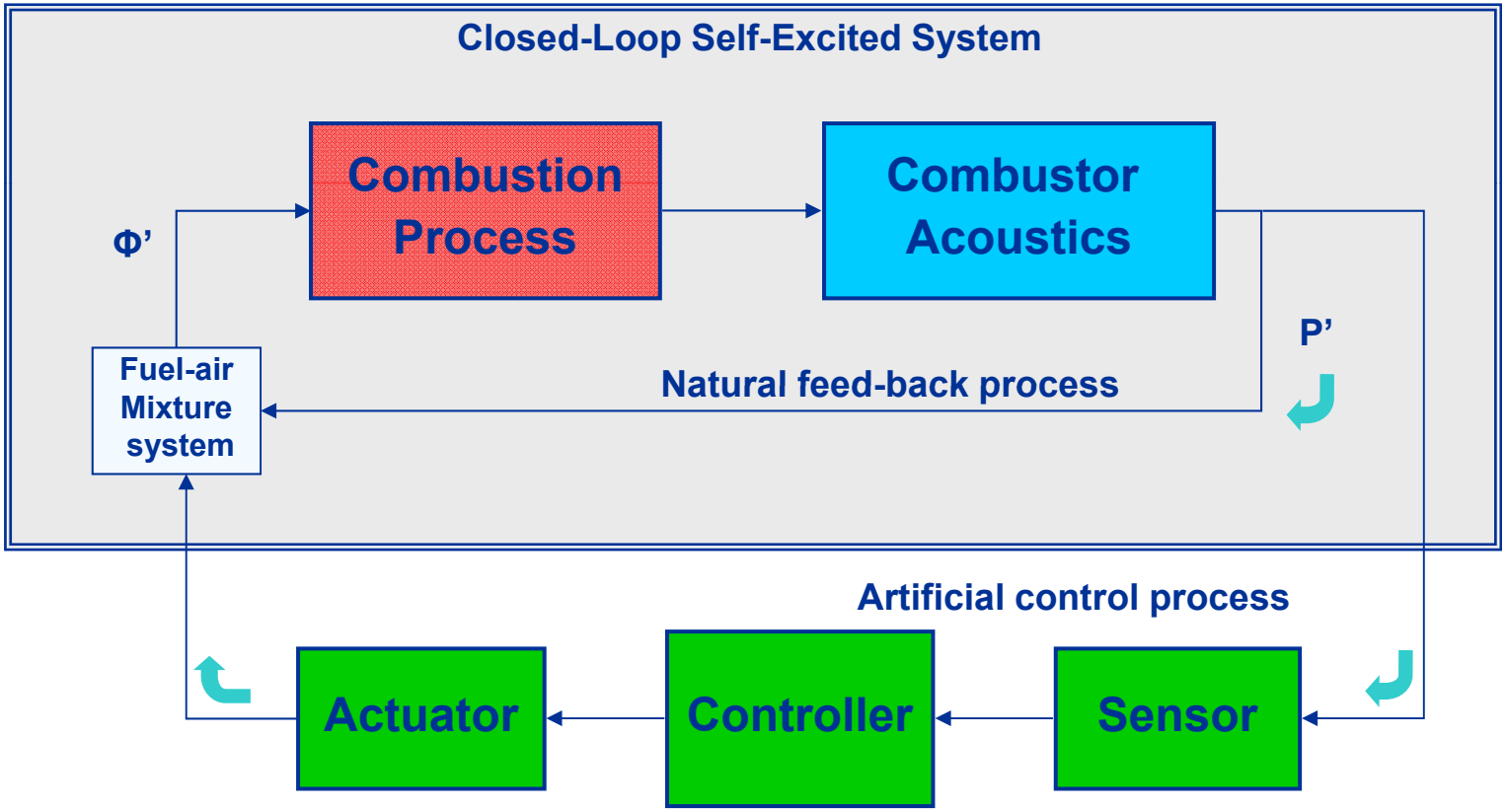
Method 1 is preferred, but we're not sure it's enough.

Method 2 requires lots of actuation power input and bulk.
Method 2 also may induce diffuser flow separation due to flow perturbation.

Method 3 requires the least actuation power and bulk and produces the most energy change.

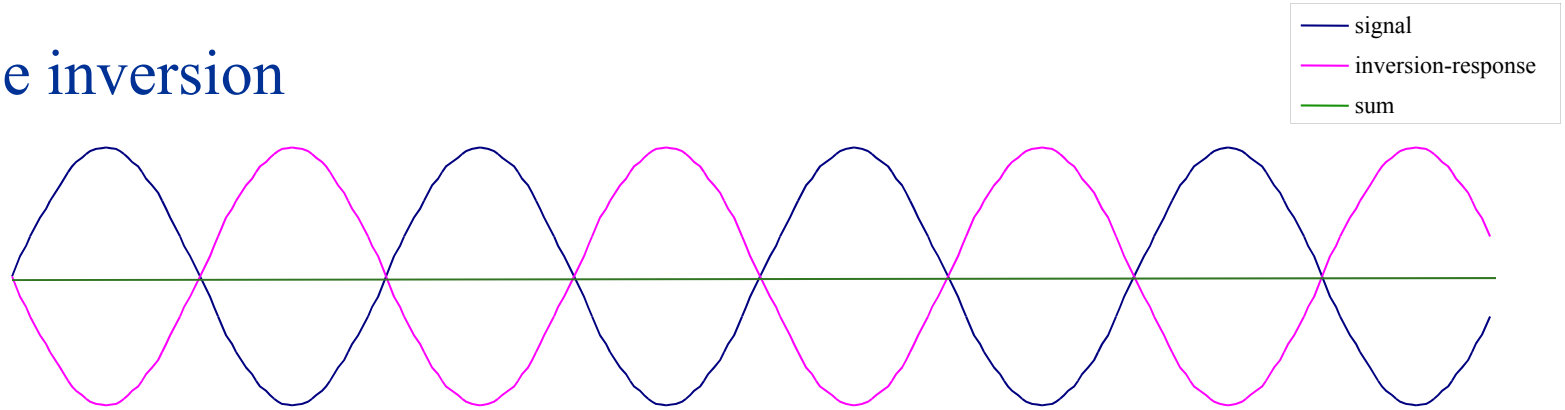
Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur

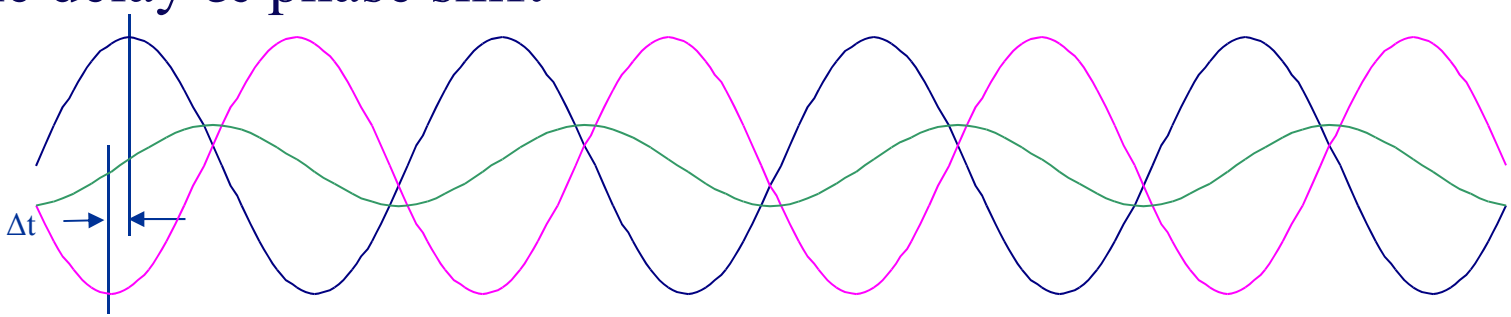


Why is instability control so difficult?

Phase inversion

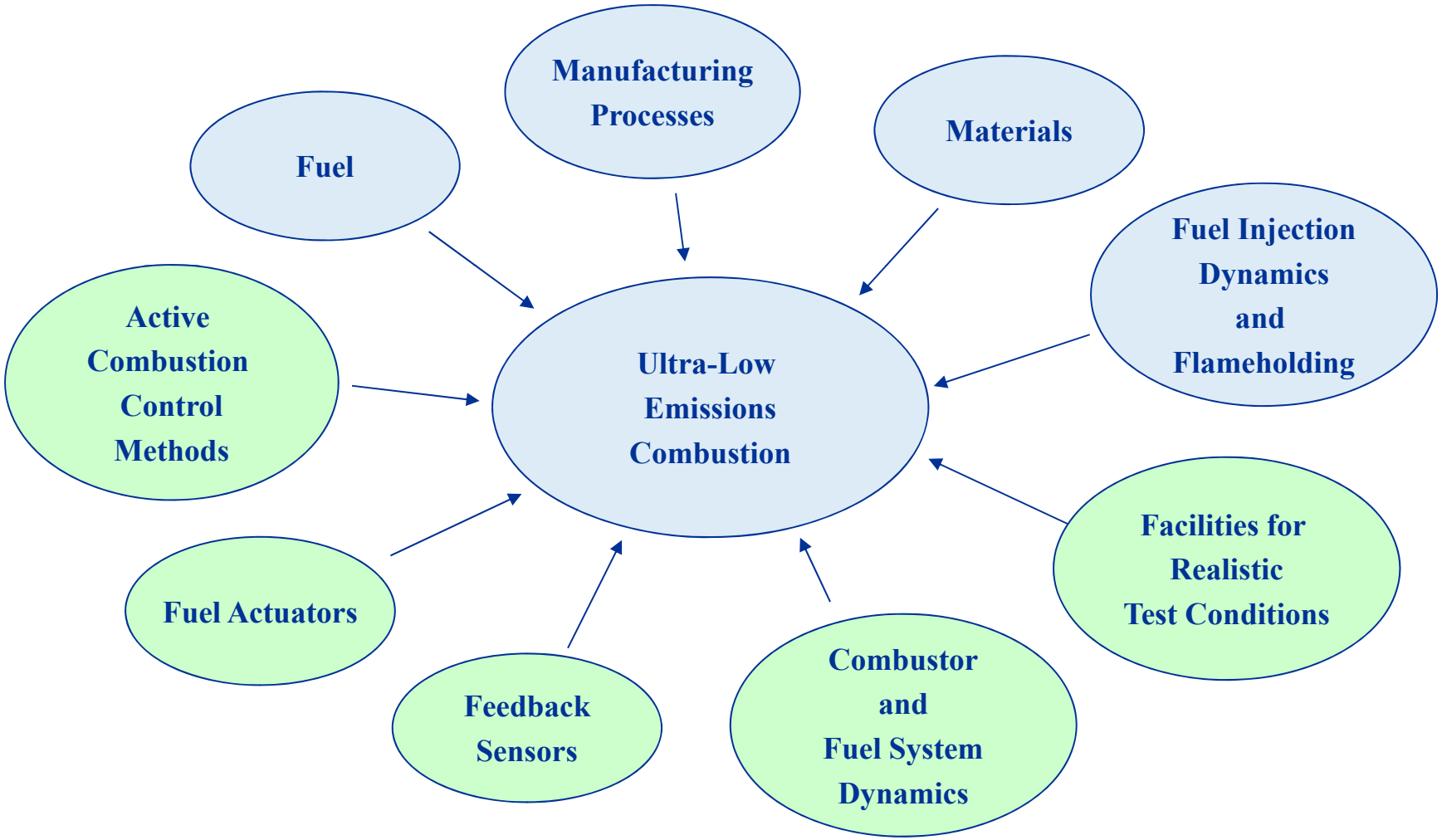


Time delay & phase shift



Low signal-to-noise ratio – What frequency? What phase?

Synergistic Technologies to Enable Ultra-Low Emissions Combustion



Observations

- Small changes can affect major behavioral change
- Combustor should not be considered one homogeneous medium

References

1. Arthur H. Lefebvre, Gas Turbine Combustion, 2nd Ed., Taylor & Francis, 1999.
2. Dodds, Will, Engine Technology Developments to Address Local Air Quality Concerns, International Coordinating Council of Aerospace Industries Associations, 2008
3. Dodds, Will, Twin Annular Premixing Swirler (TAPS) Combustor, The Roaring 20th Aviation Noise & Air Quality Symposium, 2005
4. Dodds, Will, Engine and Aircraft Technologies to Reduce Emissions, UC Technology Transfer Symposium "Dreams of Flight", March 1, 2002
5. McKinney, R.G., Sepulveda, D., Sowa, W. and Cheung, A.K. (2007) The Pratt & Whitney TALON X low emissions combustor: revolutionary results with evolutionary technology. AIAA 2007-386, The 45th AIAA Aerospace Sciences Meeting, January 2007, Reno, Nevada.
6. Collier, F.S. (2009) Progress toward aviation's environmental goals and objectives – an LTO NO*x* perspective. ICAO/CAEP Workshop, London, UK, March 30, 2009.
7. Foust, M.J, et al., "Development of the GE Aviation Low Emissions TAPS Combustor for Next Generation Aircraft Engines," AIAA-2012-0936, Nashville, TN, January 9-12, 2012.