Agenda

- Honeywell Aero Gas Turbine Product Lines
- Design-by-Analysis
- CEDS Motivation
- CEDS Approach
- Key Modeling Technologies
- Combustion Technology Enablers
- Conclusions
Honeywell Turbine Engine Products

APUs
- 100 to 1400 hp for commercial and military aircraft

Turbofan Engines
- 3,000 to 10,000 lb thrust for commercial and military aircraft

Turboprop Engines
- 575 to 1,600 shp for commercial and military aircraft

Turboshaft Engines
- 500 to 5,000 shp for tanks, commercial and military rotorcraft

All Benefit from Robust Design by Analysis
Design-by-Analysis

Focused on physics based modeling for fidelity and reduced development time and cost

Strategy:
• Multi-year dedicated team efforts
• High-fidelity analysis methods
• Streamlined design processes
• High-performance computing clusters
• Rapid-prototype hardware development

Benefits:
• Get design right the first time
• Reduce development cost
• Increase efficiency
• Meet environmental requirements
• Address warranty cost

<table>
<thead>
<tr>
<th>Fan &amp; Compressor Design System</th>
<th>Combustion &amp; Emissions Design System</th>
<th>Turbine Design System</th>
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</thead>
</table>
Combustion and Emissions Design System

**Technology Description**
Improve the capabilities of combustor design system and enhance analysis tools fidelity for robust design-by-analysis.
Reduce combustor development time and cost so that a successful design is attained with significantly fewer hardware iterations.

**Goals**
- Reduce number of rig/engine tests to 3 for TRL 6 design
- Eliminate redesign cycles
- Meet stringent emissions goals and longer service life.
- Reduce warranty costs
Key RQL Low Emissions Technology Trades

CFD is a Key Enabler for Managing Combustor Design Trades

- Fielded -25% NOx 2010 Certification
- SABER-1
- SABER-2
- SABER-3
- SABER-X
- Demonstration -40% NOx
- SABER-1
- SABER-2
- SABER-3
- SABER-X
- Demonstration -60% NOx
- SABER-1
- SABER-2
- SABER-3
- SABER-X

State-of-the-art combustor technology at 7%, 30%, 85%, 100% rated thrust
Plotted from Engine Emissions Databank
Combustor System Failure Modes Examples

**TBC Spalling**
- Loss of TBC due to temperature exposure, material strain

**Oxidation & Burn-thru**
- Material Loss due to temperature exposure

**Thermo-Mechanical Fatigue**
- Material Cracking under cyclic thermal stress
- Initiation & Propagation

**Plasticity/Creep**
- Material Distortion under sustained loads at high temp.

Creep Deformation

**Burn-thru**

Robust Lifing Methodology is a Must
# Simulation Scorecard
(Consensus of OEMs presented at the 2011 MACCCR Workshop)

<table>
<thead>
<tr>
<th>Quantity of interest</th>
<th>Status</th>
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<tbody>
<tr>
<td>Cold-flow aerodynamics/pressure drops</td>
<td><img src="#" alt="Green" /></td>
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<tr>
<td>Exit temperature profile/contours</td>
<td><img src="#" alt="Green" /></td>
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<tr>
<td>NOx Trends (op cond, geom., rich, lean burn)</td>
<td><img src="#" alt="Green" /> <img src="#" alt="Yellow" /></td>
</tr>
<tr>
<td>CO Trends (rich and lean burn)</td>
<td><img src="#" alt="Yellow" /></td>
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<tr>
<td>Unburned hydrocarbons trends</td>
<td><img src="#" alt="Yellow" /></td>
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<tr>
<td>Radiation/liner wall temperatures</td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Soot trends</td>
<td><img src="#" alt="Red" /></td>
</tr>
<tr>
<td>Ignition, Lean-blowout</td>
<td><img src="#" alt="Red" /> <img src="#" alt="Yellow" /></td>
</tr>
<tr>
<td>Combustion dynamics</td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Augmentors</td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Constant volume combustion</td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>Liquid rockets</td>
<td><img src="#" alt="Red" /></td>
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<tr>
<td>High speed ram/scram jets</td>
<td><img src="#" alt="Red" /> <img src="#" alt="Yellow" /></td>
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</tbody>
</table>

**Key**
- **Green**: Adequate (can get by)
- **Yellow**: Inadequate (low/some confidence)
- **Red**: Hopeless! (very low confidence, or methods not well developed)

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CEDS Approach

• Geometric fidelity
• Improve fuel-air mixing predictions
• Develop primary and secondary fuel spray atomization models
• Chemistry sub-models to improve performance, thermal, and emissions predictions
• Perform advanced material characterization and improve thermal and stress analyses
• Develop advanced constitutive and lifing models
• Streamline analysis process for both preliminary and detailed design phases

Reliable spray, F/A mixing, and reaction kinetics models are prerequisites to accurate CFD predictions
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Reliable plasticity, creep, and heat transfer models are prerequisites to accurate thermo-structural predictions.
Key Modeling Technologies: Fuel-Air Mixing

- LES established as standard design method
  - Energy containing scales are directly resolved with adequate mesh resolution
  - Suitable combustion and spray models used
  - Better insight to combustion dynamics
  - Accurate prediction of flame shape and exit profile
- Leveraging HPC for massive parallel computing
  - 14000 cores cluster
  - Solution obtained in days
  - Pre-processing time <1 day

From RANS to LES
Key Technologies: Spray

• Emissions predictions highly dependent on spray atomization modeling and evaporation.
• Low-power behavior of combustors quite sensitive to droplet atomization and transport.
• Secondary breakup model (Wave, Taylor Analogy, and SSD) calibrated for HON atomizers.
• Major progress in developing VOF models for primary atomization in collaboration with Academia.
Key Technologies: Kinetics and Emissions

- Developed in-house Jet-A mechanisms tailored to NOx and Smoke predictions
  - NOx prediction accuracy improved by 50%
  - Soot trends and smoke number predicted using customized soot model
- Excellent progress toward predicting CO trends
  - On the ICAO LTO cycle, CO is highest at Idle
  - Combustor features that impact CO
    - Residence time
    - Fuel spray atomization and mixing
    - Quenching of CO by liner cooling air
  - Proprietary global Jet-A mechanism developed to predict CO trends with LES
Key Technologies: Lifting Methods

- Completed comprehensive material properties database with extensive characterization
- Established hysteresis curves for modeling plasticity and creep
- Reduced uncertainty in wall temperature prediction
- Developed constitutive models in collaboration with Academia (fatigue, creep, oxidation, crack propagation)
- Improved lifting predictions from 6X to within 2X
CEDS Accomplishments

• More accurate analysis process (CFD and thermo-mechanical)
  - Pattern factor, Exit temperature profile, flame shape
  - Emissions (NOx, CO and Soot)
  - Heat transfer, Lifing
• Faster design and analysis cycles
  - Robust CFD analysis process relying on COTS and in-house tools
  - Massive parallel processing
• Rig test reduction
  - Multi-million dollars savings in test reduction since 2009
  - Examples:
    ▪ Case 1: All combustor performance parameters achieved within 1 rig test
    ▪ Case 2: NOx target achieved with 50% less rig tests
    ▪ Case 3: Demonstrated 50% NOx reduction within 1 rig test

On-Track to Meet Established Program Goals & Metrics
Honeywell Combustion Technology Enablers

- Advanced CFD based on Large Eddy Simulation
- High performance computing capability
- Flame visualization
- Combustor Materials Specimen test facility
- State-of-the-art spray diagnostic facility
- Combustor rig testing facility
- 757 flying test bed
Conclusions

- Combustion and emissions design system program to standardize design by analysis and enhance predictive capabilities.
- Conflicting trades in the design of low-emissions combustor technology complicate CEDS mission.
- LES is the new paradigm for designing advanced combustion systems.
- LES, advanced spray models, and detailed kinetics offer benefits for predicting flame structure, temperature field, and emissions.
- NOx, CO, and Smoke are reasonably well predicted for trend and absolute values.
- Lifing models established to improve service life.
- Rig and engine tests reduction on track for CEDS goal.
THANK YOU
LES Benefits: Flame Structure

LES Results agree Well with Flame Camera Images
LES Benefits: Flame Structure

LES and RANS Produce Different Flame Structure
LES Benefits: Exit Temperatures

Exit Temperature Reasonably Predicted by LES
LES Mesh Requirements

- Resolution of 80% of the turbulent kinetic energy is desirable

\[ ER = \frac{E_{res}}{E_{res} + \langle E_{sgs} \rangle} \]