Applied Aeroscience and CFD Branch Overview

Gerald J. LeBeau
Dr. Benjamin S. Kirk
Applied Aeroscience and CFD Branch
Engineering Directorate
Houston, Texas USA
Lyndon B. Johnson Space Center
Principal Mission: Human Spaceflight

International Space Station
MPCV Orion
Commercial Crew

Mission Control
Astronauts
The Future of Human Space Exploration

NASA’s Building Blocks to Mars

Earth Reliant

- Proving Ground
- Missions: 6 to 12 months
- Return: hours

Earth Independent

- U.S. companies provide affordable access to low Earth orbit
- Missions: 1 month up to 12 months
- Return: days
- Missions: 2 to 3 years
- Return: months

Exploring Mars and other deep space destinations

- Learning the fundamentals aboard the International Space Station
- Traveling beyond low Earth orbit with the Space Launch System rocket and Orion crew capsule
- Expanding capabilities by visiting an asteroid in a Lunar distant retrograde orbit

U.S. companies provide affordable access to low Earth orbit

Traveling beyond low Earth orbit with the Space Launch System rocket and Orion crew capsule

Expanding capabilities by visiting an asteroid in a Lunar distant retrograde orbit

Exploring Mars and other deep space destinations

Learning the fundamentals aboard the International Space Station

Missions: 6 to 12 months
Return: hours

Missions: 1 month up to 12 months
Return: days

Missions: 2 to 3 years
Return: months
Aeroscience Technical Competencies

(1) Aerodynamic Characterization  (2) Aerothermodynamic Heating
(3) Rarefied Gas Dynamics  (4) Decelerator (Parachute) Systems

Ground Testing  Modeling and Simulation  Flight Testing
Principal JSC Initiatives & Aeroscience Support

1. Operate the International Space Station
   - Aerodynamic & aerothermodynamic response for rarefied flows
   - Plume modeling for visiting vehicles
   - ISS end-of-life disposal

2. Develop the Multipurpose Crew Vehicle *Orion*
   - Develop aerodynamic & aeroheating databases
   - Support development of the parachute recovery system

3. Enable Commercial Access to Space
   - Develop system requirements and assess design compliance
   - Perform IV&V of partner aerosciences products
   - Support reimbursable activities to commercial partners
International Space Station Operations
NASA’s Exploration Architecture

ORION | SPACE LAUNCH SYSTEM
Capability Comparison

<table>
<thead>
<tr>
<th>Rocket Type</th>
<th>Payload Volume (m³)</th>
<th>Payload Mass (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas V 551</td>
<td>100</td>
<td>70 t</td>
</tr>
<tr>
<td>Falcon 9</td>
<td>200</td>
<td>105 t</td>
</tr>
<tr>
<td>Delta IV H</td>
<td>300</td>
<td>130 t</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>400</td>
<td>70 t</td>
</tr>
<tr>
<td>Saturn V</td>
<td>600</td>
<td>105 t</td>
</tr>
<tr>
<td>NASA 70 t</td>
<td>800</td>
<td>130 t</td>
</tr>
<tr>
<td>NASA 105 t</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>NASA 130 t</td>
<td>1200</td>
<td></td>
</tr>
</tbody>
</table>

As of November 8, 2012
Orion Aerosciences
JSC Responsible Flight Regimes

Direct Entry
- Mach 25
- Entry Heating Phase

Skip Entry
- Hypersonic Abort

Atmospheric Entry Environment
- 2nd Stage Abort
- LAT Sep

1st Stage Abort
- 2nd Stage Abort
- LAT Sep

Ascent Abort Separation Environment
- Pad Abort

Ascent Abort
- Separation

Environment
- Atmospheric
- Entry
- Plumes
The Orion Spacecraft

**Crew Module**
Human habitat from launch through landing and recovery.

**Launch Abort System**
Provides crew escape during launch pad and ascent emergencies.

**Service Module**
Power, propulsion and environmental control support to the Crew Module. Provided by the European Space Agency.
Entry Aerothermodynamic Modeling
Parachute Recovery System Development

Extraction from a C-17

Smart Separation & PTV Programmer Static Line Deployment.

Deploy 2 programmer chutes after separation

Release programmers and mortar fire 3 FBCPs

FBC Jettison and drogue mortar fire

3 Pilot chutes are mortar deployed. These deploy the main parachutes.

CPSS falls under two Extraction Parachutes and then 2 main

Crewed flight-like
Technical Competencies

Aerodynamics
Aerothermodynamics
Rarefied Gas Dynamics
Decelerator Systems
Aerodynamics Discipline Overview

• Provide comprehensive aerodynamic induced environments from ascent through entry and landing to Trajectory and Structural analysts.

• Products include
  – Ascent, entry and abort aerodynamics, external pressure distributions, protuberance air loads, stability derivatives, acoustics/overpressure, venting, plume effects, prelaunch wind effects and wake environments for parachute analysis.

• Tools
  – Computational Fluid Dynamics codes
  – Wind tunnels from subsonic through hypersonic regimes.
  – Flight tests
Aerodynamics Discipline Overview
Aerodynamics Challenge: Launch Acoustics

- Accurate, efficient prediction of unsteady transonic environments. CFD requires small time steps to accurately capture physics. Wind tunnel testing requires ≈ 5 seconds of physical time to achieve statistical convergence.
Aerodynamics Challenge: Dynamic Stability

- Prediction of dynamic stability characteristics using CFD on a bluff body with jets in cross flow.
Aerothermodynamics Discipline Overview

• Goal is to provide **heating environments to all external spacecraft components for all flight regimes**
  – Components: acreage, steps/gaps, seals, penetrations, protuberances, reaction control systems
  – Flight regimes: ascent, exo-atmospheric, entry

• Current customers include Orion, Commercial Crew, and technology development projects
  – Orion: Leads agency wide team that develops aerothermodynamic environment database, provides technical authority oversight, provides mission support (historically provided mission support and damage assessment for Orbiter)
  – Commercial Crew: Supports all commercial partners with both inline product development and technical authority oversight
  – Technology development: Leads development of high fidelity computational fluid dynamics (CFD) and ablator and thermal analysis (ATA) tools
  – Discipline level customers include thermal protection and guidance, navigation, and control communities: trajectory-based heating indicators, arcjet characterization and flight traceability assessment, coupled aerothermal-TPS simulations

• Product development utilizes multi-faceted approach including ground and flight testing, computational methods, historical data, and engineering-level analysis
  – Ground testing: Experience testing in every high quality aerothermal facility in nation. Orion work has included ~30 ground tests in over 10 facilities
  – Flight testing: Orion PA-1 and EFT-1, Orbiter flight tests for boundary layer transition, catalysis, and protuberance heating
  – Computational methods: CFD is the workhorse for acreage heating database development (DPLR, Loci-CHEM, OVERFLOW, US3D, FIN-S, DAC). ATA is primarily used for wind tunnel and flight environment reconstruction (CHAR). Boundary layer transition (STABL)

• Emphasis is placed on overcoming technical challenges to improve product quality
  – Environments on geometrically complex components: ascent vehicles, cavities and protuberances, steps/gaps
  – Jet interaction environments: launch abort systems, RCS
  – Boundary layer transition: physics based and empirical methods
  – Fluid-surface interactions: ablation, shape change, catalysis
Aerothermodynamics Discipline Overview

Technical Challenges:

Database Development

Ascent Environment Testing and CFD

Mission Support, Damage Assessment, and Flight Testing

Ground Testing

Flight Testing

Analysis

Inputs:

Product Integration:

= Product
Aerothermodynamics Challenge: Orion RCS Jet Interaction Heating

Predicting heating induced from 12 RCS jets on Orion Crew Module is a primary technical challenge due to unsteady flow interactions over a broad range of freestream conditions.

Orion has conducted 6 tests to develop RCS environments.

CUBRC RCS model with 400+ gages

PLIF flow visualization of roll jet

LaRC RCS model with TSP

Investigation of RCS jet interaction with parachute riser lines

Initially reliant on empirical models alone, Orion team has been developing a validated CFD capability.
Aerothermodynamics Challenge: STS-118 Deep Tile Damage

Location of tile damage due to ET ice impact on ascent

Photograph during focused inspection

Laser Doppler Range Imaging used to get 3D details of damage geometry

In-mission CFD result

Pre-test

Assessment of ground-to-flight traceability effects indicated that damage would not propagate during re-entry

Arcjet test showed the potential for damage propagation

Post-test

Post-flight photograph showed no damage propagation.

EG3 supported DAT with arcjet test support, aerothermal assessment of re-entering with damage, and explored environments on potential repair options.
Flight Vehicle Boundary Layer Transition Prediction

Figure 3: Thermal image of Endeavour during STS-134 re-entry near the point of closest approach, Mach 5.8, AOA = 28.8 deg, Slant Range ~32 nautical miles.

Figure 6: Transition patterns on Port wing. Turbulent wedges appear aligned with RCC panel T-seals. Mach = 5.8, AOA = 28.8 deg.
Flight Vehicle Boundary Layer Transition Prediction
Rarefied Gas Dynamics Discipline Overview

• Objective:
  – Provide state-of-the-art capabilities and tools for analysis of a variety of low density, non-continuum flows (from transitional to free molecular)

• Customers:
  – International Space Station
  – Orion

• Products:
  – Thruster plume modeling and plume impingement analyses
  – Spacecraft aerodynamics and aeroheating (reentry, aerocapture, aerobraking, orbital decay)
  – Application, development, maintenance of several computational tools (RPM3D and DAC (which is also distributed))

• Methods:
  – Mainly computational modeling

• Tools:
  – DAC (DSMC code)
  – RPM3D (Engineering tool for plume impingement analyses)
  – FREEMO (Free molecular code)
  – Other computational tools (RAMP, BLIMP, DPLR, …)
Rarefied Gas Dynamics Discipline Overview

Aeroheating

Plume modeling

Aerodynamics

Free Molecular

Continuum

Transitional
International Space Station Proximity Operations
Rarefied Gas Dynamics Challenge: Plume impingement effect analyses

- **HTV3 Main engine abort**
  - Flow expands from continuum in the nozzle to free molecular in the far field
  - Complex flow fields must be properly modelled at each stage

---

**Step 1:**
Near field modeling
(Continuum -> CFD)

**Step 2:**
Far field modeling
(Transitional -> DSMC)

**Step 3:**
Surface interaction modeling
(Transitional -> DSMC or
Free molecular -> Engineering tool)
Rarefied Gas Dynamics Challenge: Bridging the gap between CFD and DSMC

- The DSMC method can be used to model continuum flows but is generally too expensive to use for real-life problems.
- For re-entry databases, a bridging function is used between the highest CFD solution and the lowest DSMC solution → not as accurate a model in that region as everywhere else.

Challenges:
- Match gas parameters and chemistry models between codes.
- Improve the DSMC code efficiency.
- Incorporate advanced models in the CFD code to better model the rarefaction effects.

Surface properties on a capsule heat shield at 80 km and at zero angle of attack and sideslip angle with out-of-the-box codes.
Decelerator Systems Discipline Overview

• The Decelerator Systems Discipline has significant experience in guided and ballistic parachute system development
  – Design, development, performance evaluation, and certification
• The team currently provides expertise to several high-visibility NASA projects & programs:
  – Orion capsule development (Chief Engineer and hardware design support)
  – Commercial Crew (Design reviews and expert consultation)
• Methods and tools include:
  – Testing: Air drop testing, ground testing
  – Analysis: State-of-the art parachute system modeling published at technical conferences
  – Measurements: Innovative instrumentation and avionics
  – Partnerships with academia to develop Fluid Structure Interaction models of parachutes
Decelerator Systems Team Overview

Parachute Deployment Testing

Air Drop Testing

Sub-Scale Wind Tunnel Tests

Riser Abrasion Testing
Wide Operation Space & Fault-Tolerance

- Parachute design is complicated due to a wide range of operating conditions
  1. Pad abort ➔ get the parachutes out fast
  2. Nominal reentry ➔ staged deployment to manage loads
  3. Final design is a compromise, which is the essence of engineering

- Fault tolerance is also a design requirement

Apollo 15 approaching splashdown
Decelerator Systems Challenge: Pendulum Motion Under Two Main Parachutes

- Orion parachute development testing has included 4 tests with 2 main parachutes (nominally 3) to understand rate of descent characteristics with a failed main parachute
- During 2 of the 4 tests, the parachute & test vehicle system experienced an unexplained pendulum motion
  - Could effect touchdown incidence angle
- The main parachutes have a high drag coefficient and tend to “glide”
  - Both parachutes have glided together instead of exhibiting the somewhat random motion observed in most parachute cluster testing
- This phenomenon has not been reported previously and is currently under investigation
  - Complex interaction between the aerodynamics, system mass properties, and contact modeling
- Tools and methods being used to understand the complex phenomenon include:
  - Detailed trajectory reconstructions
  - Fluid Structure Interaction (FSI) modeling
  - Parachute aerodynamic sensitivity studies

FSI of 2-cluster System at Non-zero Angle of Attack
The Orion parachute team has observed large (~50%) variations in riser loads during drop testing when the risers twist up. This phenomenon has not previously been one of the design considerations for cluster parachute systems. Twist is induced by vehicle motion below the parachutes & random parachute motions. The changes in load are in phase with vehicle dynamics once the risers are twisted. Monte Carlo trajectory simulations are being used to understand the likelihood of this phenomenon taking place when the parachutes are highly loaded. A detailed ground test program is underway to understand the potential magnitude of the variations.
Tools & Capabilities
### Computational Tools

<table>
<thead>
<tr>
<th></th>
<th>Aerodynamics</th>
<th>Aerothermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td>Cart3D</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>Chimera Grid Tools</td>
<td>X X</td>
</tr>
<tr>
<td>ARC</td>
<td>CBaero</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>DPLR</td>
<td>X X</td>
</tr>
<tr>
<td>ARC</td>
<td>NEQAIR</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>Pegasus</td>
<td>X X</td>
</tr>
<tr>
<td>JSC</td>
<td>CHAR</td>
<td>X</td>
</tr>
<tr>
<td>JSC</td>
<td>DAC</td>
<td>X X</td>
</tr>
<tr>
<td>JSC</td>
<td>Debris</td>
<td>X</td>
</tr>
<tr>
<td>JSC</td>
<td>Orion Aero API</td>
<td>X</td>
</tr>
<tr>
<td>JSC</td>
<td>RPM 3D</td>
<td>X X</td>
</tr>
<tr>
<td>JSC</td>
<td>SNEWT</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>OVERFLOW</td>
<td>X X</td>
</tr>
<tr>
<td>MSFC</td>
<td>ARTIF</td>
<td>X</td>
</tr>
<tr>
<td>MSFC</td>
<td>Loci-CHEM</td>
<td>X X</td>
</tr>
<tr>
<td>U of M</td>
<td>STABL</td>
<td>X X</td>
</tr>
<tr>
<td>Sandia</td>
<td>DAKOTA</td>
<td>X</td>
</tr>
</tbody>
</table>

### Test Facilities

<table>
<thead>
<tr>
<th></th>
<th>Aerodynamics</th>
<th>Aerothermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td>9- by 7-Foot Supersonic Wind Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>11-Foot Transonic Unitary Plan Facility</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>Electric Arc Shock Tube</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>Flight Mechanics Lab Test Cell 2</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>Hypervelocity Free-Flight Ballistic Range</td>
<td>X</td>
</tr>
<tr>
<td>ARC</td>
<td>National Full-Scale Aerodynamics Complex</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>4-Foot Supersonic Unitary Plan Wind Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>20-Foot Vertical Spin Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>Aerothermodynamics Laboratory 31-Inch Mach 10 Air Facility</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>Aerothermodynamics Laboratory 20-Inch Mach 6 Air Facility</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>National Transonic Facility</td>
<td>X</td>
</tr>
<tr>
<td>LaRC</td>
<td>Transonic Dynamics Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>AEDC</td>
<td>16-Foot Transonic Wind Tunnel (16T)</td>
<td>X</td>
</tr>
<tr>
<td>AEDC</td>
<td>Aerodynamic 4-Foot Transonic Wind Tunnel (4T)</td>
<td>X</td>
</tr>
<tr>
<td>AEDC</td>
<td>Hypervelocity Wind Tunnel 9 (T9)</td>
<td>X X</td>
</tr>
<tr>
<td>Boeing</td>
<td>Polynsonic Wind Tunnel (PSWT)</td>
<td>X</td>
</tr>
<tr>
<td>Caltech</td>
<td>T5 Hypervelocity Shock Tunnel Facility</td>
<td>X</td>
</tr>
<tr>
<td>CUBRC</td>
<td>Cornell Aeronautical Laboratory (CAL) 48-Inch Shock Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>CUBRC</td>
<td>Large Energy National Shock Tunnel (LENS I)</td>
<td>X</td>
</tr>
<tr>
<td>CUBRC</td>
<td>Large Energy National Shock Tunnel (LENS II)</td>
<td>X</td>
</tr>
<tr>
<td>CUBRC</td>
<td>Large Energy National Shock Tunnel (LENS XX)</td>
<td>X</td>
</tr>
<tr>
<td>Eglin</td>
<td>AFB ARF Ballistic Range</td>
<td>X</td>
</tr>
<tr>
<td>Lockheed Martin</td>
<td>High Speed Wind Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>Texas A&amp;M</td>
<td>Oran W. Nicks Low-Speed Wind Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>U. of Washington</td>
<td>Aeronautical Laboratory Kirsten Wind Tunnel</td>
<td>X</td>
</tr>
<tr>
<td>U.S. Air Force Academy</td>
<td>Subsonic Wind Tunnel</td>
<td>X</td>
</tr>
</tbody>
</table>
DAC’s User Base

- NASA or DoD
- Industry
- University

Locations:
- Ball Aerospace
- Lockheed Martin Astronautics
- University of Colorado
- Perceptek, LLC
- ITT Industries
- Worcester Polytechnic Institute
- Penn State University
- Michigan Tech
- NASA Ames
- Aerotherm
- Lockheed Martin Missiles & Space
- Northrop Grumman
- Boeing - Rocketdyne
- Boeing - Downey
- Boeing - Phantom Works
- Boeing - Huntington Beach
- Phoenix Analysis & Design Technologies
- Spectrum Astro, Inc.
- Raytheon
- University of Texas at Tyler
- Boeing
- NASA JSC
- University of Houston
# CHAR - Capabilities & User Base

## CHAR’s Toolbox

<table>
<thead>
<tr>
<th>Feature</th>
<th>CHAR</th>
<th>STAB</th>
<th>TD (Thermal Desktop/Sinda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charring Ablation</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1D</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2D</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Porous Flow</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enclosure Radiation</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Inverse</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generalized mesh</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact conduction</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Adaptive Mesh</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Stress</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rigorous Verification</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid/Thermal Coupling</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CHAR: New EA Ablation Tool!
STAB: Legacy EA Ablation Tool!
TD (Thermal Desktop/Sinda): EA Thermal Analysis Tool!

JSC
ARC
LaRC
JPL

CHAR: New EA Ablation Tool!
STAB: Legacy EA Ablation Tool!
TD (Thermal Desktop/Sinda): EA Thermal Analysis Tool!

Page 13

CHAR - Capabilities & User Base

CHAR STAB TD
Charring Ablation X X
1D X X X
2D X X
3D X X
Porous Flow X
Enclosure Radiation X X X
Inverse X
Generalized mesh X
Contact conduction X X
Adaptive Mesh X
Thermal Stress X
Parallel X X
Rigorous Verification X
Fluid/Thermal Coupling X

CHAR: New EA Ablation Tool!
STAB: Legacy EA Ablation Tool!
TD (Thermal Desktop/Sinda): EA Thermal Analysis Tool!

Page 13
Aerolab – High Performance Computing Facility

300 TB Lustre File System

ICE 8200
- 64x 12-core
- Intel x5650™
- DDR IB
- 2GB/Core

ICE 8400
- 64x 12-core
- Intel x5650™
- QDR IB
- 4GB/Core

ICE-X
- 48x 16-core
- Intel E5-2670™
- FDR IB
- 4GB/Core

500 TB Lustre File System