Marshall Space Flight Center CFD Overview

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Computational Fluid Dynamics (CFD) activities at Marshall Space Flight Center (MSFC) have been focused on hardware specific and research applications with strong emphasis upon benchmark validation. The purpose of this overview is to provide insight into the MSFC CFD related goals, objectives, current hardware related CFD activities, propulsion CFD research efforts and validation program, future near-term CFD hardware related programs, and CFD expectations. The current hardware programs where CFD has been successfully applied are the Space Shuttle Main Engines (SSME), Alternate Turbopump Development (ATD), and Aeroassist Flight Experiment (AFE). For the future near-term CFD hardware related activities, plans are being developed that address the implementation of CFD into the early design stages of the Space Transportation Main Engine (STME), Space Transportation Booster Engine (STBE), and the Environmental Control And Life Support System (ECLSS) for the Space Station. Finally, CFD expectations in the design environment will be delineated.
MARSHALL SPACE FLIGHT CENTER CFD OVERVIEW

• COMPUTATIONAL FLUID DYNAMICS BRANCH ACTIVITIES
  • OBJECTIVES
  • INTERACTION
  • APPROACH TOWARD SOLUTIONS OF COMPLEX FLOWS

• MSFC HARDWARE RELATED ACTIVITIES
  • INHOUSE
  • ROCKETDYNE - SSME
  • PRATT AND WHITNEY - ATD

• NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM
  • PROGRAM DEFINITION
  • WORK ELEMENT SUMMARY; CFD EMPHASIS
  • EXPERIMENTAL APPARATUS
  • CONSORTIUM

• NEW NEAR TERM CFD ACTIVITIES
  • ADVANCED LAUNCH SYSTEM, ALS
  • ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM, ECLSS

• CFD EXPECTATIONS
COMPUTATIONAL FLUID DYNAMICS BRANCH ACTIVITIES

OBJECTIVES

● SUPPORT PROGRAM OFFICES
  — "QUICK TURNAROUND" APPLICATIONS
  — INTERACT WITH HARDWARE CONTRACTORS IN DEVELOPMENT OF DESIGN ENVIRONMENTS
  — PROVIDE "SMART BUYER" CAPABILITY FOR LONG-TERM APPLICATIONS
  — DEVELOP SUBSYSTEMS CFD MODELS
  — FOCUS MSFC CFD ACTIVITIES/PROVIDE CENTERWIDE CFD SUPPORT

● FOCUS DEVELOPMENT OF CFD METHODOLOGY
  — INTERACT WITH ARC, LeRC, LaRC, AND OTHER RESEARCH ORGANIZATIONS TO FOCUS TECHNOLOGY DEVELOPMENT TOWARDS MSFC HARDWARE RELATED PROBLEMS
  — DEVELOP REQUIREMENTS FOR CFD CODE VERIFICATION
  — VERIFY CODES THROUGH BENCHMARK COMPARISONS
  — ADVANCE CFD TECHNOLOGY FOR APPLICATIONS

● DEVELOP ADVANCED HARDWARE TECHNOLOGY CONCEPTS
  — TURBINE STAGE
  — IMPELLER STAGE
  — NOZZLES, PREBURNERS, ETC.
COMPUTATIONAL FLUID DYNAMICS BRANCH ACTIVITIES

ORGANIZATIONAL INTERACTIONS AND UNIQUE
CFD RESOURCES CAPABILITY

- SUBSYSTEMS MODELS FOR APPLICATIONS
  - "QUICK TURNAROUND" APPLICATIONS
  - "SMART BUYER" CAPABILITY
  - INTERACT WITH HARDWARE CONTRACTORS

- BENCHMARKED CODES AND SUPPORT
  - FOCUS NATIONAL CFD ACTIVITIES
  - FOCUS MSFC CFD ACTIVITIES
  - REQUIREMENTS FOR CODE VERIFICATION
  - BENCHMARK COMPARISONS
  - TECHNOLOGY TRANSFER IN MSFC
  - ADVANCED CFD TECHNOLOGY

- ADVANCED DESIGN TOOLS
  - AFE
  - TURBINE/IMPELLER STAGES
  - BORE/JOINT FLOW MODELS
COMPUTATIONAL FLUID DYNAMICS BRANCH ACTIVITIES

CFD CROSS FERTILIZATION

BASIC RESEARCH
- ALGORITHM DEVELOPMENT
- NUMERICAL METHODS
- GRID GENERATION
- ADAPTIVE GRIDS
- CODE DEVELOPMENT
- FLOW PROCESS MODELING
- ADVANCED COMPUTER SYSTEMS

APPLIED CFD
- LIBRARY OF CODES
- BENCHMARK VALIDATION
- DESIGN CODES FROM VARIOUS SOURCES
- DEVELOP DESIGN CODES
- DEVELOP CRITERIA TO ASSESS CODES
- EVALUATE ADVANCED HARDWARE TECHNOLOGY CONCEPTS

ENGINEERING ANALYSIS
- PARAMETRIC STUDIES
- HARDWARE OPTIMIZATION
- PERFORMANCE OPTIMIZATION
- ANOMALY INVESTIGATION
- SYSTEM DESIGN
- DESIGN ASSESSMENT

ARC, LeRC, LaRC  MSFC  MSFC

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COMPUTATIONAL FLUID DYNAMICS BRANCH ACTIVITIES

APPROACH TOWARD SOLUTIONS OF COMPLEX FLOWS

● DEVELOP DATA BASE
  — LITERATURE SEARCH
  — COLLATE RELEVANT EXPERIMENTAL RESULTS
  — IDENTIFY SIGNIFICANT PARAMETERS, SCALING LAWS
  — DEFINE REQUIREMENTS FOR BENCHMARK EXPERIMENTS

● PERFORM FUNDAMENTAL ENGINEERING ANALYSIS
  — SIMPLIFIED 1-D OR 2-D ANALYSES
  — ELEMENTARY SENSITIVITY ANALYSIS

● PERFORM CFD CALCULATIONS
  — EXERCISE BENCHMARKED STATE-OF-THE-ART CODES
  — IMPLEMENT STATE-OF-THE-ART FLOW PROCESS MODELS
PREDICTION OF SECONDARY FLOW IN CURVED DUCTS OF SQUARE CROSS-SECTION

OBJECTIVE: TO VERIFY NAVIER-STOKES CODES FOR THE ACCURATE PREDICTION OF SECONDARY FLOW IN CURVED DUCTS

APPROACH: APPLICATIONS OF A 3-D INCOMPRESSIBLE NAVIER-STOKES CODE (INS3D) TO FLOW IN A 90° AND 180° BEND AND A 22.5° S-DUCT OF SQUARE CROSS-SECTION (25000, 50000, 100000, AND 175000 GRID POINTS); COMPARE PREDICTIONS TO LDV MEASUREMENTS

COMPUTER RESOURCES REQUIRED: 2 TO 6 MW STORAGE ON A CRAY X-MP; 3/4 HOUR RUN TIME ON CRAY X-MP FOR THE 10^5 GRID POINT CASES

IMPACT: VERIFICATION OF INCOMPRESSIBLE NAVIER-STOKES CODE FOR THE PREDICTION OF SECONDARY FLOWS IN COMPLEX INTERNAL FLOW FIELDS
Prediction of Secondary Flow in Curved Ducts of Square Cross-Section

Re = 750
M = 0.0

Outer Wall

Experiment

Inner Wall

Computation

Axial Flow at 90 Degree Bend Exit

Radial Flow at 90 Degree Bend Exit
TURBOPUMP DESIGN EQUATIONS

\[
P_{02} - P_{01} = \eta_\text{TP} \frac{\dot{m}_p}{\dot{m}_p} (T_{01} - T_{02}) \cdot c_p
\]
MSFC HARDWARE RELATED ACTIVITIES
INHOUSE PROGRAM SUPPORTING ACTIVITIES

SSME

- HPFTP TURBINE BLADES
- SINGLE CRYSTAL HOLLOW CORE TURBINE BLADES
- TURBINE DISK CAVITIES
- LOX PUMP BEARING INLET CAVITY
- LOX PUMP BEARINGS
- FUEL PREBURNER
- LOX PREBURNER
- LOX MANIFOLD TEE (4000 Hz)
- HOT GAS MANIFOLD/MANIFOLD STRUTS
- PUMP COOLANT FLOW PATHS
- NOZZLE/MCC MISMATCH
- HPOTP NOZZLE PLUG TRAJECTORIES
- TRANSIENT BEHAVIOR OF FUEL PREBURNER MANIFOLD
- UTRC HPFTP COOLANT FLOW EXPERIMENT
- BEARING DEFLECTOMETER (TTBE)

ATD

- TURBINE INLET TEMP. REDISTRIBUTION
- TURBINE TEMP. PROFILE REDISTRIBUTION
- ROTOR-STATOR INTERACTION
- TURNAROUND DUCT AND HOT GAS MANIFOLD
- BEARING ANALYSIS
- LOX PUMP INLET SCROLL
- FUEL PUMP INTERSTAGE CROSSOVER DUCTS
- FUEL PUMP INLET SCROLL
- LOX PUMP DISCHARGE VOLUTE
- SEALS

SRB

- BORE FLOW
  - CANTED NOZZLE
  - BROKEN INHIBITOR
- FIELD JOINT
  - FLOW AND THERMAL TRANSIENT
  - PRESSURIZATION TRANSIENT
- NOZZLE-TO-CASE JOINT
  - FLOW AND THERMAL TRANSIENT
  - PRESSURIZATION TRANSIENT

INHOUSE | CONT.
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X | X
X | X
X | X
X | X
X | X
X | X
X | X
X | X
X | X
X | X
X | X

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MSFC HARDWARE RELATED ACTIVITIES  
INHOUSE PROGRAM SUPPORTING ACTIVITIES (CONTINUED)

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MSFC HARDWARE RELATED ACTIVITIES
ROCKETDyne APPLICATION OF CFD TO SSME

TURBOMACHINERY

HPFTP IMPELLER CAVITY
HPOTP P/B BEARING DISCH CAVITY
HPOTP TURBINE END BRG DISCH CAVITY
HPOTP 2ND STG TURBINE NOZZLE
HPFTP 1ST STG TURBINE DISK CAVITY
HPOTP TURBINE END BRG FLOOD COOL
HPOTP R/S INTERACTION
HPFTP TURBINE DISK CAVITIES
HPFTP 2ND STG TURBINE DISK CAVITY/DIVERTER
SC/HC 2ND STG TURBINE DISK CAVITY DIVERTER
ROUGH SURFACE SEAL FLOW
SC/HC 1ST STG TURBINE
HPFTP 1ST STG TURBINE
SC/HC 1ST STG TURBINE
HPFTP 1ST STG TURBINE
SC/HC 1ST STG TURBINE R/S
HPFTP 1ST STG TURBINE R/S
HPOTP 1ST STG TURBINE R/S
LPOTP 4TH STG TURBINE R/S
HPOTP IMPELLER-DIFFUSER UNSTEADY
HPOTP BRG FLOWFIELD
HPFTP 1ST STG TURBINE W/STRUTS
HPOTP IMPELLER
HPOTP 1ST STAGE TURBINE W/STRUTS
HPOTP P/B DIFFUSER
T/P HARDWARE DEVIATION SENSITIVITIES
TO REDUCE MR'S

CODE
STEP
STEP
STEP
REACT 2D
STEP
STEP
REACT 2D
STEP
STEP
REACT 2D
STEP
REACT 2D
REACT 2D
REACT 2D
REACT 3D
REACT 3D
REACT 3D
REACT 3D
REACT 3D
REACT 3D
REACT 3D
REACT 3D
2D/3D
2D/3D

NON TURBOMACHINERY

HOT GAS MANIFOLD
FUEL-SIDE
2-DUCT TURBULENT
3-DUCT TURBULENT
OXIDIZER-SIDE
AXISYMMETRIC
3D
COMBINED HGM

CODE
INS3D
INS3D

MAIN INJECTOR
FLUCTUATING PRESSURE &
DYNAMIC LOADING

NOZZLE
MCC/NOZZLE MISMATCH

4KHZ RESONANCE

TEST BED LOX FLOWMETER

CODE
USA
USA
USA
STEP
MSFC HARDWARE RELATED ACTIVITIES
PRATT AND WHITNEY APPLICATION OF CFD TO ATD

● MOTIVATION
  — DESIGN VERIFICATION
    ● CFD ANALYSIS OF CRITICAL FLOWPATHS IN SSME TURBOPUMPS
    ● IDENTIFY POTENTIAL FLOWFIELD NONUNIFORMITIES, REGIONS OF SEPARATED FLOWS
    ● PROVIDE DETAILED FLOW DATA TO MECHANICAL DESIGN GROUPS FOR ADDITIONAL STRUCTURAL, THERMAL ANALYSES
  — ANALYTICAL SUPPORT
    ● WHERE NECESSARY, PERFORM FUNDAMENTAL CFD RESEARCH TO SUPPORT THE DESIGN VERIFICATION PROCESS
    ● INCORPORATE THESE IMPROVEMENTS INTO THE DESIGN DECKS
MSFC HARDWARE RELATED ACTIVITIES
PRATT AND WHITNEY APPLICATION OF CFD TO ATD

• ACCOMPLISHMENTS

  – ANALYZED COMPLETE HOT GAS FLOW PATH
  
  – PROVIDED TURBINE INLET CONDITIONS
  
  – PROVIDED STRUT PRESSURE LOADS FOR MECH DESIGN
  
  – TAD CALCULATIONS RESULTED IN SUBSTANTIAL REDUCTION IN INSTRUMENTATION
  
  – CFD MODELS OF TAD-HGM, LOX PUMP INLET, PREBURNER AND FUEL PUMP CROSSOVER DUCTS READY FOR HOT TEST SUPPORT
  
  – TURBULENCE MODEL SELECTED FOR COMPLEX DUCT FLOWS
  
  – ARICC SUBSTANTIALLY UPGRADED
  
  – CAD TO CFD CAPABILITY IMPLEMENTED
  
  – 2D INVISCID ROTOR-STATOR INTERACTION CAPABILITY DEVELOPED AND DEMONSTRATED
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM

PROGRAM DEFINITION

TECHNOLOGY ACQUISITION PHASE

SEEKS IMPROVED UNDERSTANDING OF THE BASIC CHEMICAL AND PHYSICAL PROCESSES OF PROPULSION

DEVELOPS ANALYSIS METHODS, DESIGN MODELS, AND CODES USING ANALYTICAL TECHNIQUES SUPPORTED BY EMPIRICAL LABORATORY DATA AS REQUIRED

RESULTS ARE OBTAINED THROUGH TEN DISCIPLINE WORKING GROUPS

- BEARINGS
- STRUCTURAL DYNAMICS
- TURBOMACHINERY
- FATIGUE/FRACTURE/LIFE
- IGNITION/COMBUSTION
- FLUID & GAS DYNAMICS
- INSTRUMENTATION
- CONTROLS
- MANUFACTURING/PRODUCIBILITY/INSPECTION
- MATERIALS
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM
PROGRAM DEFINITION

● LARGE SCALE SUBSYSTEM TECHNOLOGY VALIDATION
  — VALIDATES TECHNOLOGY EMANATING FROM THE ACQUISITION
    PHASE AT THE LARGE SCALE COMPONENT OR SUBSYSTEM LEVEL
  — THREE CATEGORIES OF EFFORT
    • LARGE SCALE COMBUSTORS ✓
    • LARGE SCALE TURBOMACHINERY ✓
    • CONTROLS AND HEALTH MONITORING

● TECHNOLOGY TEST BED VALIDATION
  — VALIDATES TECHNOLOGY EMANATING FROM THE ACQUISITION
    PHASE AT THE ENGINE SYSTEM LEVEL
  — THREE CATEGORIES OF EFFORT
    • COMBUSTORS ✓
    • TURBOMACHINERY ✓
    • CONTROLS AND HEALTH MONITORING
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM
WORK ELEMENT SUMMARY

- TECHNOLOGY ACQUISITION

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<tbody>
<tr>
<td>G2</td>
<td>TURBINE DRIVE COMBUSTOR DESIGN</td>
</tr>
<tr>
<td>G29</td>
<td>TTB COMBUSTION MODELS</td>
</tr>
<tr>
<td>G31</td>
<td>COMBUSTION CODE ENHANCEMENTS</td>
</tr>
<tr>
<td>G32</td>
<td>COMBUSTION STABILITY CODE</td>
</tr>
<tr>
<td>G33</td>
<td>TURBULENCE MODELS FOR COMB. ANALYSIS</td>
</tr>
<tr>
<td>G39</td>
<td>ERE PREDICTION METHODS</td>
</tr>
<tr>
<td>H6</td>
<td>FLUID STRUCTURE INTERACTION</td>
</tr>
<tr>
<td>H16</td>
<td>VERIFICATION OF INTERNAL FLOW ANALYSIS IN 3D GEOMETRIES</td>
</tr>
<tr>
<td>H19</td>
<td>EVALUATION CRITERIA FOR INTERNAL FLOW CFD NUMERICAL MODELING</td>
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<tr>
<td>H22</td>
<td>ADAPTIVE COMPUTATIONAL METHOD FOR HIGH REYNOLDS NUMBER INTERNAL FLOWS IN ADVANCED PROPULSION SYSTEMS</td>
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<tr>
<td>H23</td>
<td>DEVELOPMENT OF CONVERGENCE ACCELERATION TECHNIQUES FOR ALGORITHMS APPLIED TO COMPLEX 3D INTERNAL FLOWS</td>
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<tr>
<td>H35</td>
<td>ADVANCED INS3D CFD CODE</td>
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<td>H36</td>
<td>CFD CONSORTIUM</td>
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- LARGE SCALE SUBSYSTEM TECHNOLOGY VALIDATION

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<td>EXP. VER. OF CFD TURB. STAGE DESIGN</td>
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<td>LSVT4</td>
<td>HI PRESS TURBOMACHINERY SYS. VALIDATION</td>
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<tr>
<td>LSVT5</td>
<td>3D TURBOPUMP FLOWFIELD</td>
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<tr>
<td>LSVT6</td>
<td>EXP. VER. OF IMPELLER STAGE DESIGN</td>
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<td>LSVT10</td>
<td>MEASUREMENTS IN MULTI ELEMENT INJECTOR</td>
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<td>LSVT12</td>
<td>CFD TURNAROUND DUCT DESIGN VALIDATION</td>
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TECHNOLOGY TEST BED VALIDATION

- TBVC4  INJECTOR DIAGNOSTICS
- TBVC1  IMPROVED HPOTP PREBURNER PUMP
- TBVT2  ENHANCED ROTOR CODES
- TBVT3  IMPROVED BEARING COOLANT PATH
- TBVT5  WATER FLOW MODELS
- TBVT8  HGM FUEL SIDE ANALYSIS
- TBVT9  CFD DATA REDUCTION HARDWARE
- TBVT10 HPOTP JET COOLANT RING
- TBVT13 PREBURNER DOME FILLING FLOW ANALYSIS
- TBVT24 TURBINE STAGE CFD ANALYSIS AND DATA BASE FOR
  UNSTEADY AERO/HEAT TRANSFER
- TBVT25 DEV. OF UNSTEADY AERO HEAT/TRANSFER EXPERIMENTS
  DATA BASE FOR AXIAL TURBINE STAGES
- TBVT26 ADVANCED AXIAL TURBINE STAGE DESIGN METHODS
- TBVT27 ADVANCED IMPELLER DESIGN METHODS
- TBVT28 CFD ANALYSIS OF BSMT
- TBVT29 UTRC ROTOR/STATOR HEAT/TRANSFER
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM

CONSORTIUM OBJECTIVES

- FOCUS CFD APPLICATIONS IN PROPULSION
  - TECHNOLOGY ACQUISITION PHASE
    - DIRECT BASELINE PROGRAM TOWARDS IMPROVED ACCURACY, STABILITY, AND EFFICIENCY
  - LARGE SCALE SUBSYSTEM TECHNOLOGY VALIDATION
    - STIMULATE CFD VALIDATION TOWARDS PROPULSION FLOWS
    - DIRECT APPLICATIONS CODES TOWARD DESIGN TOOLS AND ADVANCED HARDWARE TECHNOLOGY CONCEPTS
- IDENTIFY NATIONAL CFD PROPULSION REQUIREMENTS
- STIMULATE A FORUM FOR GOVERNMENT, INDUSTRY, AND UNIVERSITY INTERACTIONS
- ENCOURAGE INDUSTRY TO PARTICIPATE IN CFD DEVELOPMENT WITH IRAD FUNDS
- PROVIDE SYNERGISM IN THE CFD COMMUNITY
- PROVIDE PEER REVIEW OF CFD PROGRAMS
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM

CONSORTIUM TASKS

- Develop a plan to apply CFD to current and future propulsion systems
- Identify and rank critical flow problems related to propulsion systems
- Identify national CFD related resources
- Define high performance computing requirements to accomplish CFD for propulsion applications
- Direct CFD technology development to propulsion applications
- Assess and validate CFD applications in propulsion systems
- Develop evaluation criteria
- Define and implement benchmark validation tests
- Direct the application of CFD design tools towards advanced hardware technology concepts
- Accelerate the transfer of CFD technology from universities and research centers to industry and hardware development centers
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAM

CONSORTIUM TEAMING

FOCUS DEVELOPMENT OF CFD METHODOLOGY
AND
DEVELOP ADVANCED HARDWARE TECHNOLOGY CONCEPTS

* TURBOMACHINERY

* DUCTS, COOLANT FLOWS, DRIVEN CAVITIES

RARIFIED GAS FLOWS

* COMBUSTION DRIVEN FLOWS

SOLID ROCKET MOTORS

* ACTIVITIES SUPPORTED BY ETO RESOURCES
NASA EARTH-TO-ORBIT PROPULSION R&T PROGRAMS
DELIVERABLE PRODUCTS/MILESTONES
TURBINE STAGES

● THREE-DIMENSIONAL MULTISTAGE CFD CODES
  ● RESEARCH CODE
    ○ 3-D MULTISTAGE CFD CODE TO PREDICT STEADY AND
      UNSTEADY FLOW FIELD CHARACTERISTICS, PERFORMANCE,
      LOADS AND HEAT TRANSFER
  ● PRODUCTION CODE
    ○ MODIFICATION TO RESEARCH CODE TO ENHANCE ENGINEERING
      APPLICATION
      ● UPGRADED EFFICIENCIES
      ● STREAMLINE PRE/POST PROCESSING ETC.

● UNSTEADY THREE-DIMENSIONAL DATA BASE FOR MULTISTAGE TURBINE
  ● INITIAL UNSTEADY AERO DATA BASE
  ● ENHANCED UNSTEADY AERO DATA BASE
  ● HEAT TRANSFER DATA BASE

● IMPROVED FLOW PROCESS MODELING
  ● TURBULENCE MODEL FOR PROTEUS
  ● TURBULENCE MODEL FOR AXIAL TURBOMACHINERY

● ADVANCED CONCEPTS AND DEMONSTRATION OF DESIGN TOOLS
  ● PRELIMINARY CONCEPT DEFINITION
  ● TESTS
  ● ADVANCED CONCEPT DEFINITION
  ● FINAL RIG TEST VERIFICATION
  ● HOT FIRE TEST (TTVF)

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NEW NEAR TERM CFD ACTIVITIES

STBE/STME DESIGN APPROACH FOR LOW COST

THE ALS FAMILY

PAYLOAD (w/o MARGIN)
- ALS-S: 108 (116) KLB
- ALS-L: 150 (160) KLB
- ALS-L2: 226 (236) KLB

BOOSTER PROPELLANT
- SOLID (12)
- O₂/H₂

TITANIUM VAC
- 4 x 612 KLB
- 3 x 612 KLB
- 3 x 612 KLB

- 12 x 716 KLB
- 7 x 612 KLB
- 12 x 612 KLB

FT

• DESIGN PRIORITIES
  - RELIABILITY
  - COST
  - PERFORMANCE/WEIGHT
  - COMMONALITY

• DESIGN BENEFITS
  - REDUCED INTERNAL ENVIRONMENTS
  - ROBUSTNESS
  - REDUCED DEVELOPMENT TIME
  - REDUCED INVENTORIES/INTERCHANGEABILITY
NEW NEAR TERM CFD ACTIVITIES

STME BASELINE DESIGN REQUIREMENTS

- GAS GENERATOR CYCLE, SERIES TURBINE DRIVE,
- LOX/LH2 PROPELLANTS
  CHAMBER PRESSURE = 2250 psi
- FIXED THRUST OF 580K (VAC)
- DUAL THRUST: 580K AND 435K (VAC)
- RELIABILITY = .99, 90% CONFIDENCE LEVEL (DEMONSTRATED)
- EXPENDABLE OR REUSABLE (15 CYCLES)
- GIMBAL CAPABILITY FOR TVC, +/-6 DEGREES
- FIXED NOZZLE, AR = 62:1
- USABLE IN SINGLE OR MULTI-ENGINE ARRANGEMENT
- HIGH RELIABILITY, LOW COST
NEW NEAR TERM CFD ACTIVITIES

CFD ACTIVITIES TO SUPPORT STBE/STME DESIGN

● THRUST CHAMBER
  — INJECTOR
  — MAIN COMBUSTION CHAMBER
  — NOZZLE
  — COOLING CHANNELS

● TURBINE
  — INLET FLANGE
  — INLET MANIFOLD
  — ROTOR-STATOR INTERACTION
  — MULTISTAGE ANALYSIS
  — AIRFAILS/GUIDE VANES
  — TURBINE EXHAUST — TURN AROUND DUCT

● GAS GENERATOR
  — INJECTOR
  — COMBUSTION CHAMBER

● SYSTEM ANALYSIS
  — DUCTS
  — MANIFOLDS
  — VALVES
  — CAVITIES

● PUMPS
  — INLET FLANGE
  — VOLUTE/INDUCER/IMPELLER
  — DIFFUSER/CROSSOVER DUCTS
  — DISCHARGE COLLECTOR/DUCTS
  — BEARINGS
  — SEALS

● ENGINE AIRFRAME INTERACTION
  — PLUME
  — AEROTHERMAL/LOADS
# New Near Term CFD Activities

**Environmental Control and Life Support System (ECLSS)**

## Space Station Configuration

### Respirable Atmosphere and Water Requirements

<table>
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<th>Degraded</th>
<th>Emergency</th>
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<td>CO₂ Partial Pressure</td>
<td>N/m³ (mmHg)</td>
<td>400 MAX</td>
<td>1013 MAX</td>
<td>1600 MAX</td>
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<td>O₂ Partial Pressure</td>
<td>N/m³ x 10³ (Oea)</td>
<td>19.5 - 23.1 (2.83 - 3.35)</td>
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<td>15.8 - 23.7 (2.3 - 3.45)</td>
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<td>Total Pressure</td>
<td>N/m³ x 10³ (Oea)</td>
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<td>99.9 - 102.7 (14.5 - 14.9)</td>
<td>99.9 - 102.7 (14.5 - 14.9)</td>
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<td>Temperature</td>
<td>°K (°F)</td>
<td>201.5 - 209.8 (65 - 80)</td>
<td>201.5 - 209.8 (65 - 80)</td>
<td>286.8 - 302.6 (60 - 89)</td>
</tr>
<tr>
<td>Dewpoint</td>
<td>°K (°F)</td>
<td>273.9 - 294.3 (55 - 70)</td>
<td>273.9 - 294.3 (55 - 70)</td>
<td>273.9 - 294.3 (55 - 70)</td>
</tr>
<tr>
<td>Ventilation</td>
<td>m/s (ft/min)</td>
<td>.076 - .203 (15 - 40)</td>
<td>.051 - .500 (10 - 100)</td>
<td>.051 - 1.016 (10 - 200)</td>
</tr>
<tr>
<td>Trace Contaminants</td>
<td>mg/m³</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Particulates</td>
<td>PARTICLES/m³</td>
<td>3,500,000 0.5 MICRO-METERS</td>
<td>TBD &gt; 150 MICRONERES</td>
<td>TBD</td>
</tr>
<tr>
<td>Micro-Organisms</td>
<td>CFU/m³</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>
NEW NEAR TERM CFD ACTIVITIES

CFD ACTIVITIES TO SUPPORT ECLSS

● GENERIC BASELINE CFD MODELS
  ▪ PLANAR, ONE MODULE (NS)
  ▪ 3D, ONE MODULE (NS)
  ▪ 3D, INNER LOCK DUCTS (NS)
  ▪ PLANAR INTERMODULE (NS)
  ▪ 3D, INTERMODULE (NS)

● FLOW CONTROL DESIGN PARAMETRIC OPTIMIZATION
  ▪ INTERNAL CONFIGURATION VARIATIONS
  ▪ VENTILATION CONTROL
  ▪ INTRAMODULE VENTILATION (FANS)
  ▪ CONTAMINATION TRANSPORT
  ▪ CO₂/FLOW MANAGEMENT
  ▪ BODY FORCE EFFECTS

● BENCHMARK COMPARISONS
  ▪ PARAMETRIC DESIGN OF EXPERIMENTS
  ▪ CODE VALIDATION
CFD EXPECTATIONS

• DIRECT HARDWARE DESIGN UTILIZING CFD
  — PROVIDE INITIAL IMPACT IN DESIGN
  — PERFORM DESIGN OPTIMIZATION STUDIES
  — DEVELOP ADVANCED HARDWARE TECHNOLOGY CONCEPTS

• ESTABLISH EVALUATION CRITERIA FOR CODES AND CLASSES OF PROBLEMS

• BENCHMARKED/VALIDATED CODES
  — LAMINAR FLOWS
  — TURBULENT FLOWS $u$, $p$
  — ACOUSTIC PROBLEMS
  — CERTAIN CLASS OF UNSTEADY PROBLEMS

• USER FRIENDLY CODES
  — B.S. LEVEL ENGINEER 2-3 YRS EXPERIENCE
  — GUIDELINES FOR CLASSES OF PROBLEMS
  — CAD/CAM/CAE; GEOMETRY GRID GENERATION
  — GENERALIZED BOUNDARY CONDITIONS
  — ALGORITHM GRID OPTIMIZATION FOR SOLUTION EFFICIENCY
  — ARTIFICIAL INTELLIGENCE/EXPERT SYSTEMS
  — MODULAR CODES

• FLOW ADAPTIVE GRIDS FOR CURRENT CLASS OF PROBLEMS

• MULTIPLE SCALE AND/OR ZONAL TURBULENCE MODELS, MULTIPHASE, MULTISPECIES, COMBUSTION FLOW PROCESS ENGINEERING MODELS EVOLVED FROM EXPERIMENTS AND CFD ANALYSIS