A research plan is being implemented at NASA to investigate inlet mode transition for turbine-based combined-cycle (TBCC) propulsion for the hypersonic community. Unresolved issues have remained on how to design an inlet system to supply both a turbine engine and a ram/scramjet flowpath that operate with both high performance and stability. The current plan is aimed at characterizing the design, performance and operability of TBCC inlets through a series of experiments and analyses. A TBCC inlet has been designed that is capable of high performance (near MIL-E-5008B recovery) with smooth transitioning characteristics. Traditional design techniques were used in an innovative approach to balance the aerodynamic and mechanical constraints to create a new TBCC inlet concept. The inlet was designed for top-end Mach 7 scramjet speeds with an over/under turbine that becomes cocooned beyond its Mach 4 peak design point. Conceptually, this propulsion system was picked to meet the needs of the first stage of a two-stage to orbit vehicle. A series of increasing fidelity CFD-based tools are being used throughout this effort. A small-scale inlet experiment is on-going in the GRC 1’x1’ Supersonic Wind Tunnel (SWT). Initial results from both the CFD analyses and test are discussed showing that high performance and smooth mode transitions are possible. The effort validates the design and is contributing to a large-scale inlet/propulsion test being planned for the GRC 10’x10’ SWT. This large-scale effort provide the basis for a Combined Cycle Engine Testbed, (CCET), that will be able to address integrated propulsion system and controls objectives.
TBCC Inlet Experiments and Analysis

(Initial Screening Results of a Small-Scale Inlet Mode Transition Experiment and progress toward a Large-scale IMX testbed)

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Overview

Background, (definition, history & objectives )

TBCC Inlet Design, (dual flow path, constraints & CFD)

CFD Results, (validation, performance & test guidance)

1x1 SWT screening results (configurations, M4, & off-design)

Conclusions and 10x10 Large-scale tests
Background: *(TBCC=Turbine Based Combined Cycle)*

- Mode-transition: definitions (*IMX*= Inlet Mode *X*, transition)
- Previous/related programs:
  - M5, X43b
  - HiSTED, Robust Scramjet, RATTLRS, FALCON
- Over-under concept and TBCC
- Current effort: Two-pronged testing
  - IMX = small-scale
  - Large-scale Combined Cycle Engine (inlet/controls/engines)
    Collaborative effort with ATK/Boeing/Williams
- TBCC IMX Objectives
TBCC Inlet Research Objectives

- Research over/under split flow inlet for TBCC.
  - Demonstrate mode transition at small and large-scales.
  - Develop a integrated database of performance & operability.
    - Low-speed inlet (sized for Mach 4 turbine engine).
    - High-speed inlet (DMRJ for Mach 7 cruise)

- Validate CFD predictions for each inlet’s design approach, and performance and operability prediction.

- Measure distortion characteristics throughout the mode transition Mach number range.

- Operability database for future mode transition controls research

- Testbed for integrated inlet/engine propulsion system tests

*Inlet mode transition addressed by small & large-scale experiments*
Inlet model requirements for CCET (Combined-Cycle Engine Testbed)

- Used 2D aerodynamic design and mechanical concept from small-scale IMX effort.
  - IMX, ‘Inlet Mode Transition’ is a small screening inlet model to qualitatively understand operability.
  - Key follow-on test is to get large scale data for quantifying performance, operability, controls development

- Forebody required roughly based on Mach 7 X43-b vision vehicles

- Facility selection: Turbine engine sizing requires large facility
  - GRC 10’x10’ propulsion supersonic wind tunnel selected

- Remotely variable ramp and rotating HS&LS inlet cowls

- Over-travel LS cowl to allow M3 to M4 mode transitions

- Variable bleeds, bypasses to allow test flexibility and controls work

- Flow metering on both turbine flowpath & DMRSJ flowpaths

- Engines diameter of ~12” chosen.
  - Mid-sized 12” engine being developed towards M4 in HiSTED, RATTLS

*Inlet model provides ‘strongback’ for propulsion integration*
TBCC Inlet Design

- High-speed: (ref. Albertson/Emami/Trexler)
- Low-speed: supersonics / mixed comp. / bleed / visc.effect / YF-12 / XB-70 / SST>HSCT
- Integration: vehicle, turbofan, high-speed flowpath
- Mach 7 Hydrocarbon fueled Scramjet with Mach 4 transition from Turbine
- Historical recoveries / Flow splits / engine demand / mission
- Impact of CFD:
  - Visualize, Instrument, Test plan,
  - Design, Controls

*Inlet design driven by TBCC studies, CFD tools, and physical constraints*
Inlet Pressure Recoveries for TBCC, ?s

Realm of uncertainty

Mil-spec recovery

Normal shock

IMX Low Speed Flowpath design

IMX Mach 4 Transition Goal

Simple var. geo./bleed

Fixed, no bleed

Recovery, Pt2/Pt0

Flight Mach Number

0.16 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1

0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6

Inlet performance can vary by 4x depending on inlet design

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FAP Annual Meeting - Hypersonic Project
Mode transition sequences: *Mach 4 shock scenarios*

- **Mach 4 shock scenarios**
  - **AOA = 4°**
  - **Inlet Transition issues**
  - **LS external shock, Start-ability**
  - **Bleed modulation?**
  - **LS internal shock control**
  - **LS distortion**
  - **Buzz limits?**
  - **HS normal shock, start-ability?**
  - **HS shock train management**
  - **Turbine spool down transient**
  - **LS & HS Cowl position, Schedule or control**
  - **HS flame stability**

*Mode transition design at Mach 4 has complex interactions*
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks
M = 2.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks
TBCC Inlet Experiments and Analysis

M = 3.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

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M = 4.

Mode transition sequences
Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks
$M = 4$ mode transition.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

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$M = 4$ low-speed closed.

Mode transition sequences
Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks
M = 3 low-speed closed.

Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

$M = 7$ low-speed closed.
IMX model for 1’x1’ SWT: Mechanical Design, (2/15/07)

IMX Instrumentation: ~144 steady-state pressures, 5 dynamics, 3 positions
IMX model for 1’x1’ SWT:  
Photo of bleed exits

Low speed Inlet design dominated by nine bleed regions
CFD Analyses of IMX

- Design validation: MOC/Euler/RANS
  - Shock wave structure
  - Boundary Layers
  - Throat Mach number

- Inlet performance
  - Integrated back-pressure (cane curves)

- Testing guidance:
  - Bleeds – 9 regions: extents and flow amounts,
    - CFD derived bleed
  - Throat Mach number (or contraction ratio),
    - Cowl contour
  - Shoulder interaction,
    - Cutback cowl

*CFD has been an integral tool throughout IMX project*
Early CFD showed expected flowfields through mode transition.
Low-Speed Inlet Bleed Study

- Bleed Model
- Adjust bleed plenum static pressures
- Match design bleed rates

Values in (parentheses) are design goals
Bleed rates are at supercritical flow
3D oblique perspective view shown (1/2 plane)

```
SW1(1.4%): 1.1%  
SW2(1.0%): 0.4%  
SW3(0.4%): 0.47%  
C1(1.2%): 0.74%  
C2(1.0%): 1.7%  
R1(1.65%): 2.1%  
R2(1.2%): 1.4%  
R3(1.4%): 1.8%  
R4(1.5%): 2.7%  
Total(10.75%): 12.35%
```

**CFD able to model complexity of inlet bleed design**
Low speed Inlet Bleed Study:

Cowl shock cancellation / Shoulder interaction

Effect of cutting back cowl leading edge on static pressures near the ramp shoulder

Baseline Cowl, No cutback

Adverse shock interaction characterized at LS inlet ‘shoulder’
Mode Transition at Mach 4

Sequence of 2D steady-state solutions at 2-deg increments

LS inlet mode transition screened by 2D CFD
Back-pressured CFD Study: Performance ‘Cane’ Curves

- Low-Speed Inlet Performance
- 1x1 SWT Run 26 bleed configuration
- Constant bleed plenum pressure b.c., (non-physical stability)

CFD suggests LS recovery performance obtainable
Back-pressured CFD Study:
Distortion at M4,
- high bleed
- no v.g.s

M4 1X1 (Back Press)
- Q = 1720 psf
- Mach 4
- T_{inf} = 126 R
- P_{inf} = 1.05 psia

Distortion=\sim 8.6\% = [(\text{max}-\text{min})/\text{ave}]

CFD indicates distortion without vortex generator may be high
1x1 SWT screening results, 50+ runs to date

- Configurations / bleed

- M4 results:
  - performance,
  - popping behavior,
  - distortion,
  - Mode-x

- Off-design results: recovery and distortion

1x1 experiment underway, major objectives are complete
TBCC Inlet Experiments and Analysis

Mach 4 performance & Inlet Mode Transition Screening

- Total pressure recovery, $P_2/P_0$
- Decreasing low-speed cowl angle
- Inlet performance at fixed cowl angles (engine flow variation)
- Simulated mode transition (decreasing cowl angle, then combined cowl angle and reduced engine "simulated" flow)
- Reducing engine corrected airflow
- Mach 4 performance & Inlet Mode Transition Screening
- NASA Glenn 1X1 SWT
- $M_0 = 4.0$

Mach 4 performance is near design goal: mode transition smooth

Probable best mode transition schedule

Mass flow ratio, $m_2/m_0$

Recovery, $P_2/P_0$

Match point

Reducing engine corrected airflow

Inlet performance at fixed cowl angles (engine flow variation)

Simulated mode transition (decreasing cowl angle, then combined cowl angle and reduced engine “simulated” flow)
Conclusions

• TBCC Inlet design approach is valid
• CFD as a toolset is becoming helpful in inlet design
  ➢ and continues to be part of: Visualize, Validate, Instrument, Test plan
  ➢ fixed exit bleed boundary conditions needs further modeling

• Small-scale Test Results: 1x1 SWT
  ➢ near mil-spec recovery demonstrated
  ➢ distortion effect must be investigated further
  ➢ cowl contour / reduced throat Mach number is desirable
  ➢ smooth mode-x is possible

• TBCC Inlet design verified for large-scale 10x10 SWT entry
  ➢ Mechanical design nearly complete, hardware delivery in spring ’08
  ➢ Results to date show confidence that larger-scale will perform as designed