HIFIRE: AN INTERNATIONAL COLLABORATION TO ADVANCE THE SCIENCE AND TECHNOLOGY OF HYPERSONIC FLIGHT

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Australian Government
Department of Defence
Defence Science and Technology Organisation

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Motivation For Hypersonic Flight Testing

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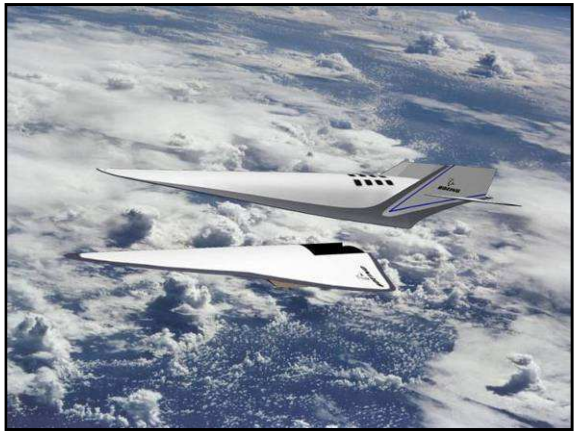
- Efficient hypersonic flight would dramatically reduce time required for global travel and could make deployment of orbital payloads significantly more routine and affordable
- Successful development of hypersonic vehicles requires generation of an extensive high-fidelity design database
- Creating a database requires collecting fundamental and system-level performance data that cannot be gathered completely in existing ground test facilities – **Flight Testing Required!**



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Hypersonic International Flight Research Experimentation (HIFiRE) Program

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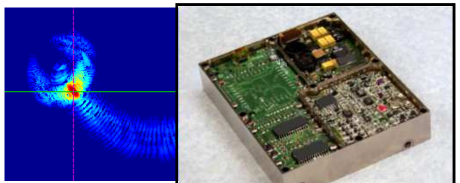
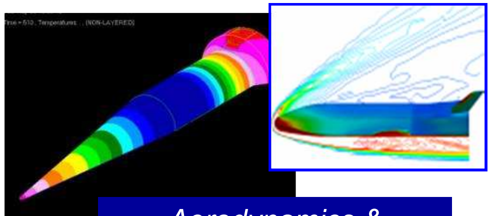
International collaboration investigating <u>fundamental</u> vehicle and propulsion phenomena and technologies critical to practical and efficient hypersonic flight

Advanced Flight Control & GNC

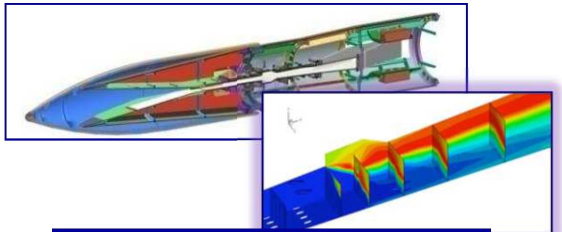


Sensors and Instrumentation

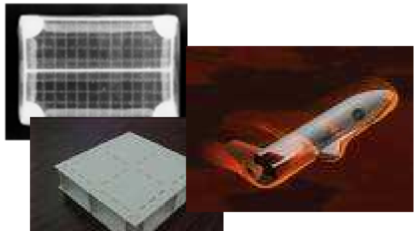
- *Conduct basic and applied research*
- *Conduct flight experiments*
- *Accelerate maturation of key technologies*
- *Develop analytical methods & data correlations*
- *Validate design methods*
- *Enhance hypersonic design database*



Aerodynamics & Aerothermodynamics



Propulsion and Aero-Propulsion Integration



Thermal Protection Systems & Thermal Management

Hot Leading Edges & Structures

Program Goal: Flight test in <u>less time</u> and at <u>lower cost</u> than traditionally possible

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Why HIFiRE Program Approach?

- **Current computational models have limited accuracy and validation**
  - Limited relevant data to gain physical insights, generate better models, and validate tools
- **Ground test facilities have limited capabilities**
  - Limited size and enthalpy conditions
  - Limited steady-state run times
- **Conventional hypersonic flight test efforts are expensive**
  - Emphasis is on demonstration rather than experimentation
    - Limits extent of scientific investigations
  - Risk intolerant
  - Driven by cost and schedule constraints
    - Higher cost, longer time, fewer flights

Roots of the HIFiRE Program

- 1995: Bowcutt and Paull first meet at an AIAA conference
- 2002: Paull contacts Bowcutt after HyShot flights in 2000-2001 to explore flight test collaboration
  - Paull also contacts Dolvin to explore collaboration with AFRL
- 2005: UQ, Boeing, and DSTO submit proposal to Queensland State Government for a Smart State Initiative grant
  - Agreement signed by all 4 parties to contribute equally to a program of 3 hypersonic flight experiments
  - Allan Paull and HyShot team hired into DSTO and Michael Smart becomes a UQ professor to lead UQ effort
- 2006: Project Arrangement signed between US and AU governments for AFRL and DSTO to execute HIFiRE program
  - Subsumes UQ, Boeing, DSTO, and Queensland Government program
  - Boeing and UQ become de facto members of program by association
- 2007: Technical Assistance Agreement between Boeing, DSTO, and UQ authorized by US State Department

HIFiRE Program Enabled By International Collaboration and Diverse Contributions

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Execution Strategy:

- Executed under authority of a bi-lateral Project Arrangement: USAF (AFRL) and AU DoD (DSTO)
- Space Act Agreement: NASA Hypersonics Program
- Third Party Agreements: Boeing, The University of Queensland (UQ), BAE Systems Australia, and DLR
- Launch Services: US Navy at WSMR and the German Aerospace Center (DLR)

Program Resources:

- Budget: US$58M CY07 (50/50 US/AU cost share)
  - Boeing, Queensland State Government, and UQ contributed cash
  - Industry in-kind contributions provide additional support
- Primarily government in-house development and integration with industry and university support
- Significant leverage of existing research programs and facilities

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International HIFiRE Research Team Includes Government, Industry & Academia

US Air Force:
- *AFRL: 4 Directorates , including AFOSR*
- *OSD TRMC (T&E/S&T)*

Australian Defence Force:
- *DSTO: Air Vehicles Division, Weapons Systems Division*
- *AOSG, RANRAU*

Queensland Government:
- *Smart State Initiative*

NASA Hypersonics Project Office:
- *Langley Research Center*

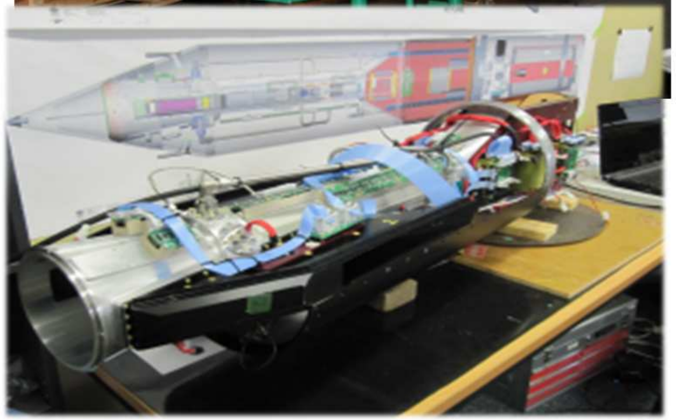
Industry
- *US: Boeing, ATK GASL, CUBRC, Ascent Labs, Kratos, GoHypersonic*
- *AU: Boeing, BAE Systems*

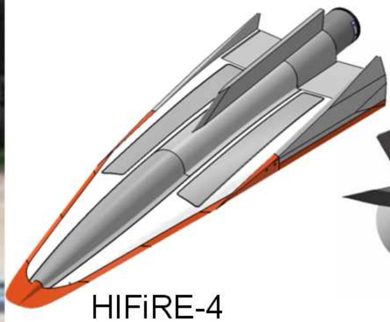
Academia:
- *US: Purdue, Univ. of Minnesota, Ohio State*
- *AU: University of Queensland, ADFA at UNSW, USQ*

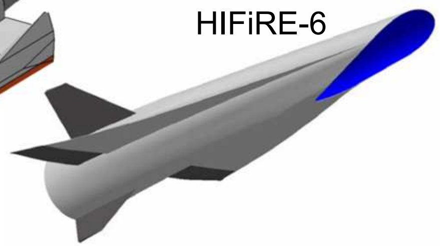
Launch Systems:
- *US: NAVSEA at White Sands Missile Range*
- *FRG: DLR MORABA*

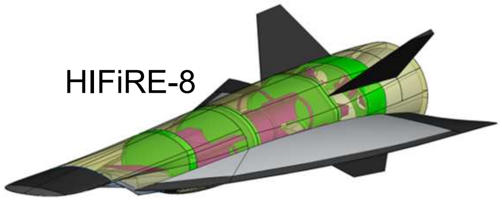
Test Ranges:
- *AU: Woomera Test Range*
- *US: Pacific Missile Range Facility*
- *Norway Andøya Rocket Range*

Nine Flight Experiments Will Investigate Critical Hypersonic Phenomena









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Various Trajectories Employed By HIFiRE to Satisfy Flight Experiment Requirements

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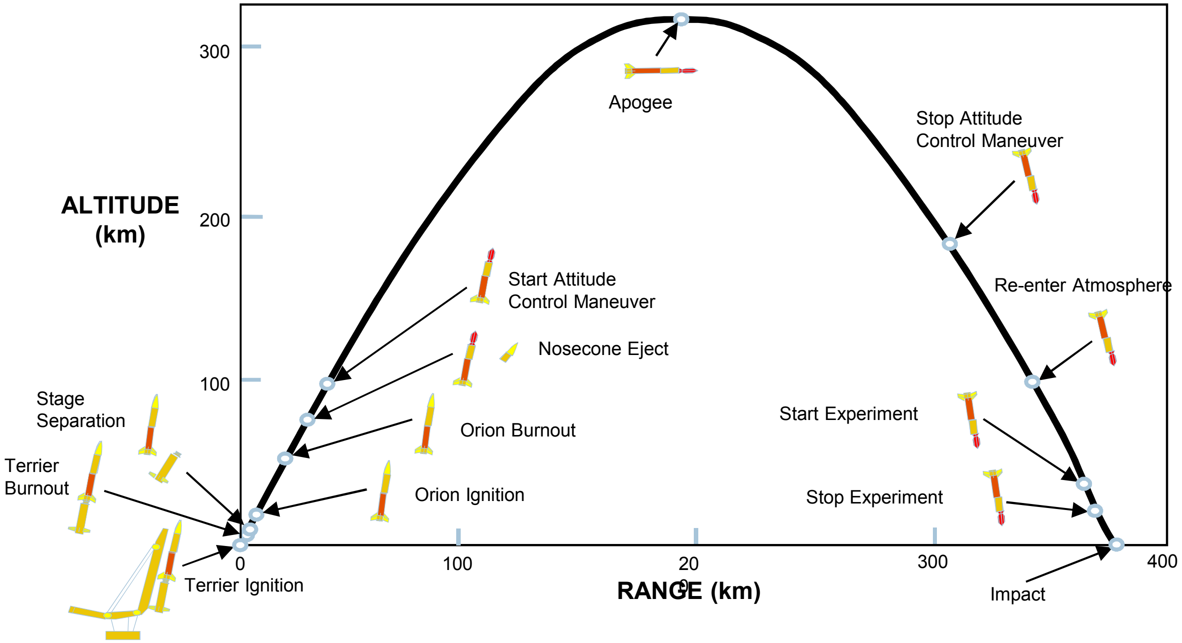

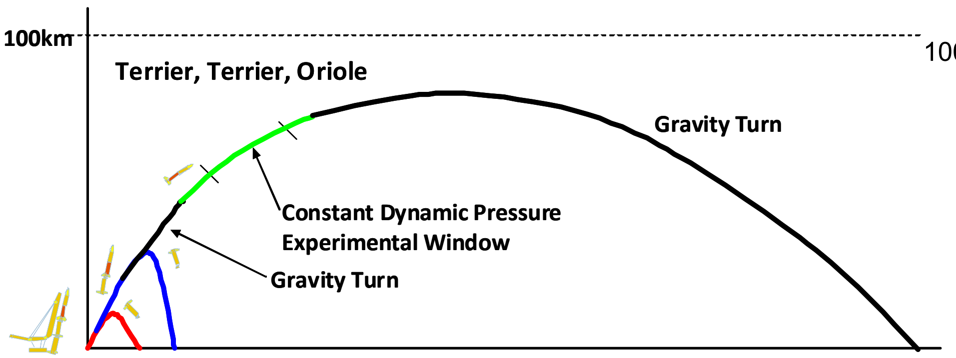

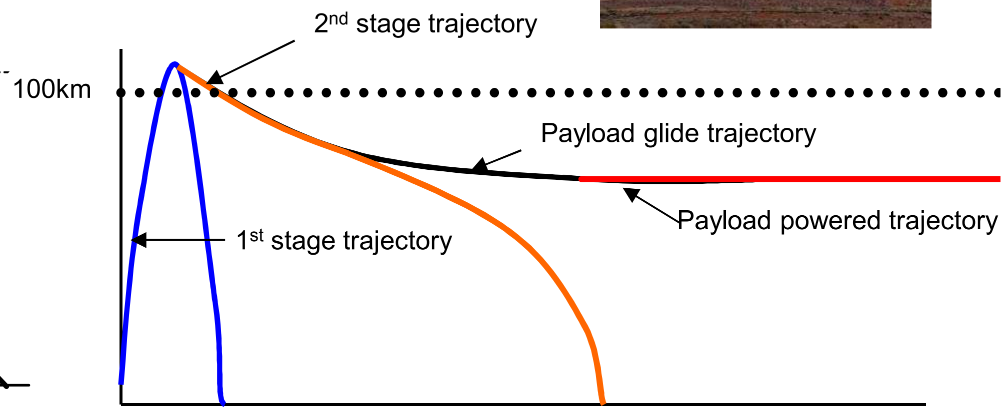

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Various Test Ranges Employed by HIFiRE as Program Needs Dictate

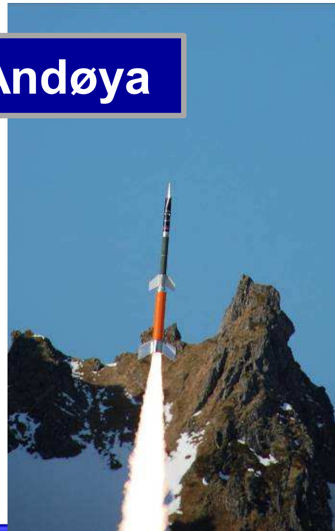
Employ launch service provider and range support from multiple sources to increase program flexibility and reduce program risk

Launch Services Providers

- **WSMR: Flights 0,1,2,6**
- **DLR Moraba: Flights 3,4,5,7**

Woomera

Andøya



PMRF

Launch Sites:

- **Woomera Test Range: Flights 0 & 1**
- **Andoya Norway: Flights 3,4,5,7**
- **Pacific Missile Range: Flights 2 & 6**

Range Upgrades Were Made to Support the HIFiRE Program

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New Capabilities Developed to Support the HIFiRE Program

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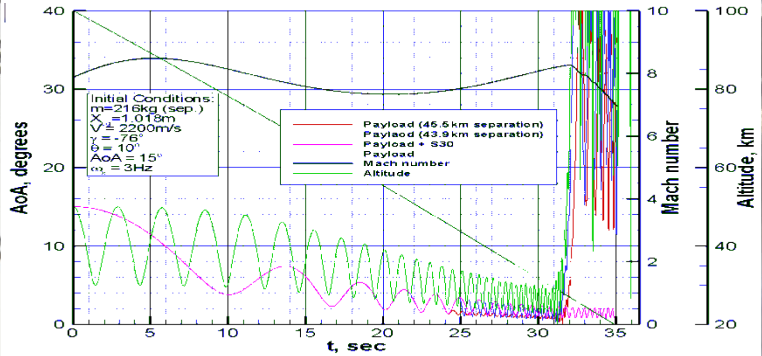

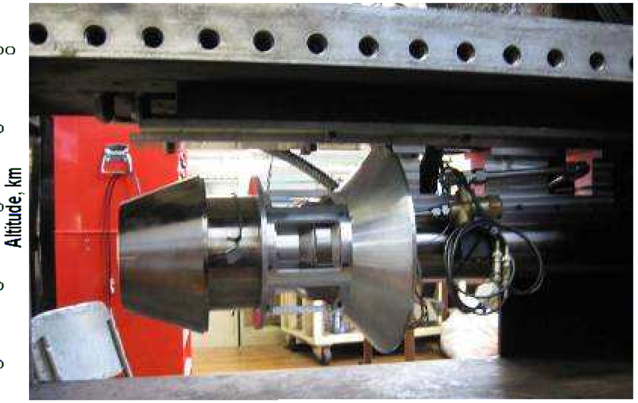

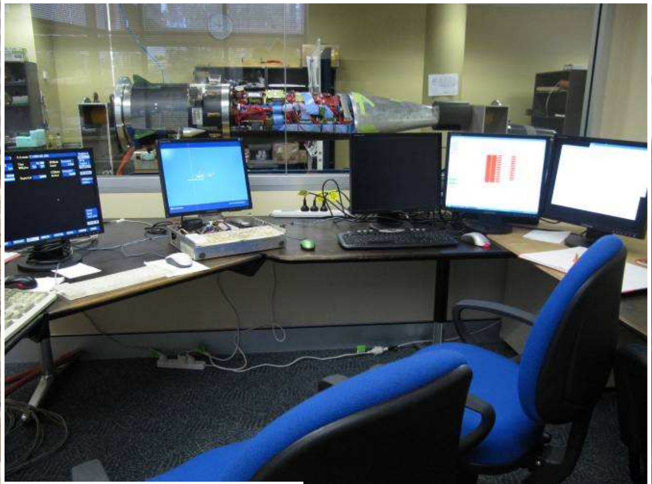

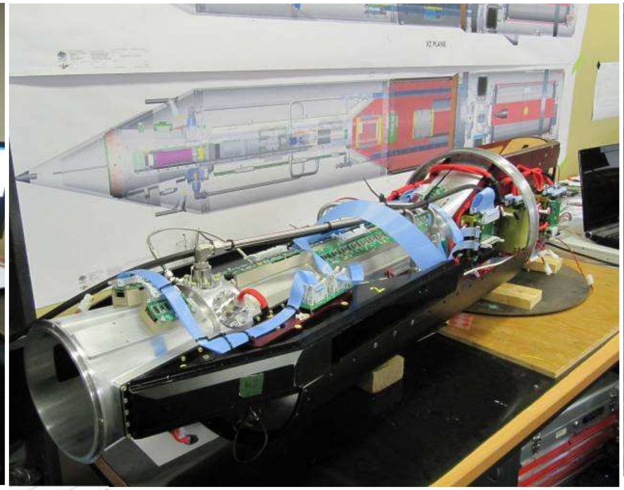

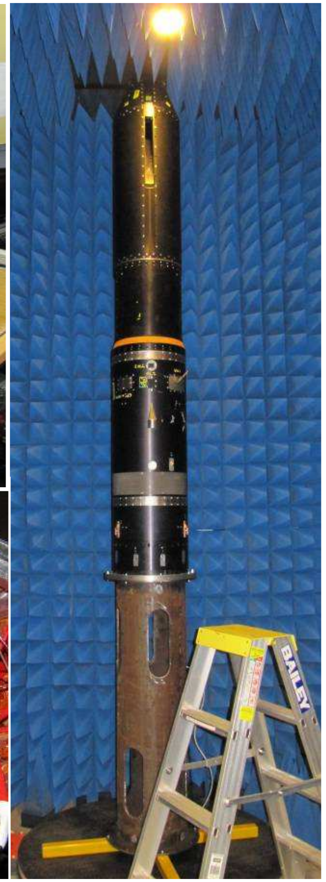

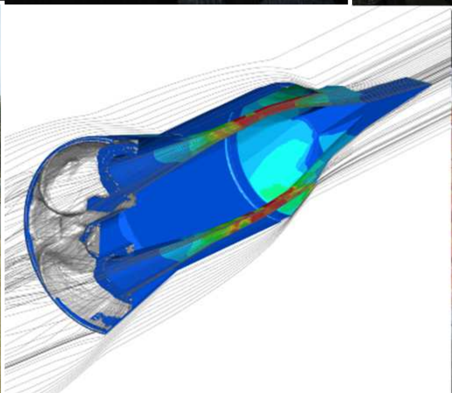

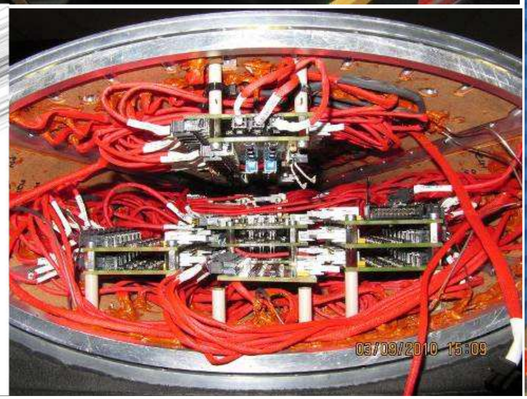

HIFiRE Payload Certification is Comprehensive

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HIFiRE-0 Verified Critical Flight Systems

Experimental Objectives:

- Demonstrate exo-atmospher
  re-orientation
- Demonstrate survivability

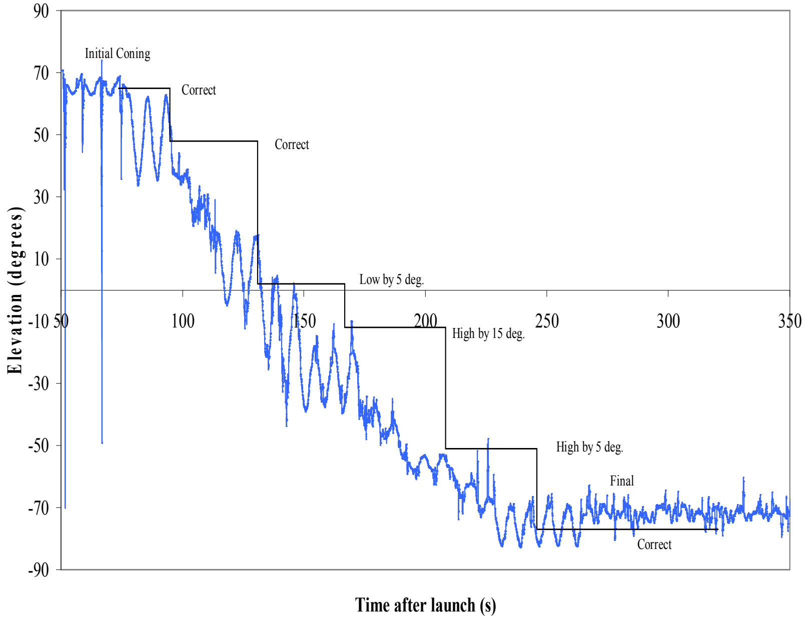
Trajectory:

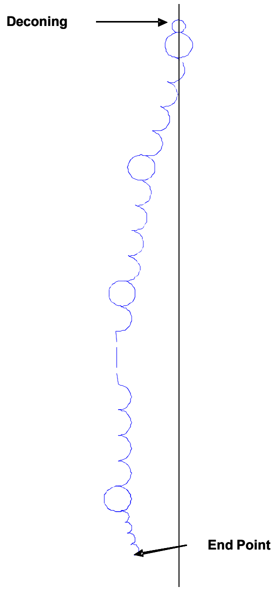
- Ballistic with Mach 8 entry
- Test Window: T=0-dest
- Launch Vehicle: Terrier-Orion

Flight (

Milestones:

- Successfully flown from Woomera on 7 May 2009
- Re-orientation 100% successful
- Flight hardware 80% successful
- Flight Software 95% successful
- Recovery 100% successful
- RMS 50% successful (prematurely failed)





HIFiRE-1 Measured Hypersonic Boundary Layer Transition on an Axisymmetric Cone

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Defence Science and Technology Organisation

Experimental Objectives:

- Measure boundary layer transition on an axisymmetric cone
- Gather data on shock/shock boundary layer interaction
- Measure air mass flux via Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Validate ground test measurements and computational predictions

Trajectory:

- Ballistic with Mach 7.2 entry
- Launch Vehicle: 2-stage Terrier-Orion

Milestones:

- Successfully flown from Woomera on 23 March 2010
- Collected unique boundary layer transition data that expanded the knowledge base for this critical physical phenomenon

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HIFiRE-1 Boundary Layer Transition Data
Increased Knowledge of Critical Physics

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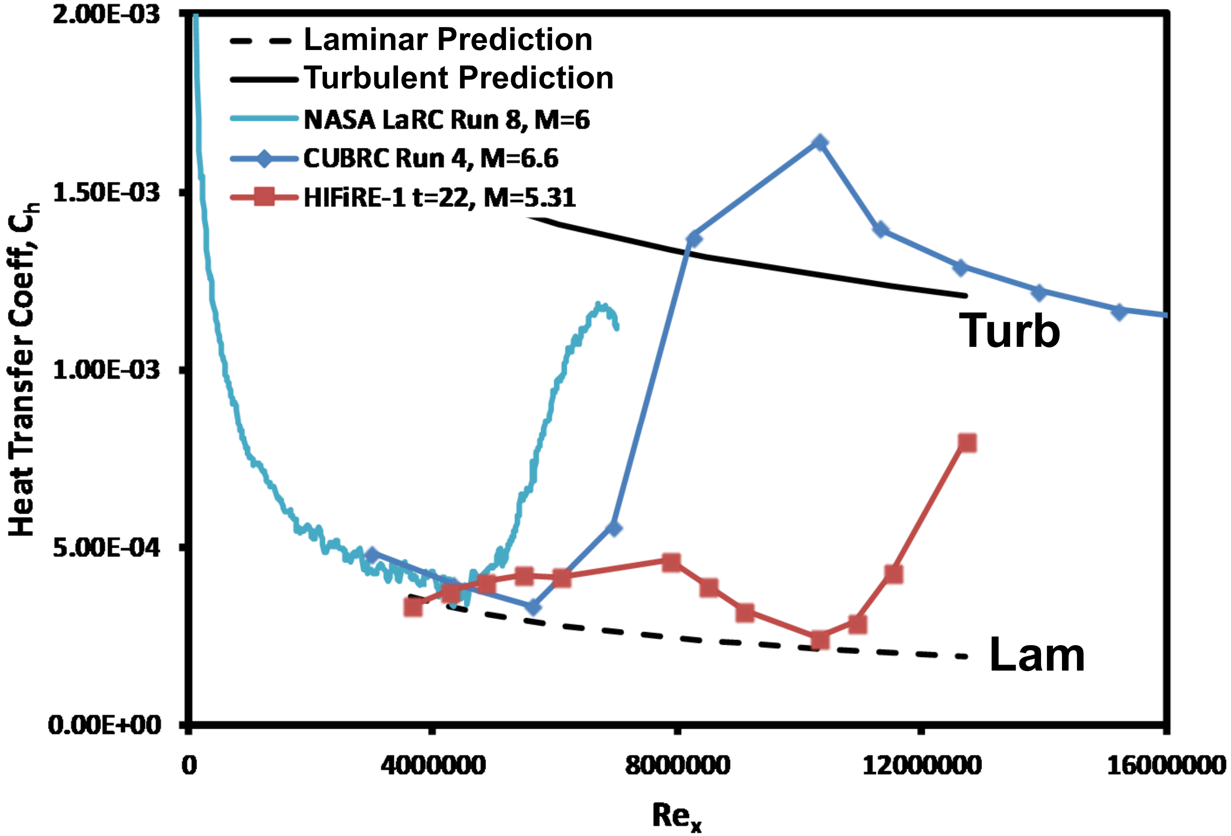

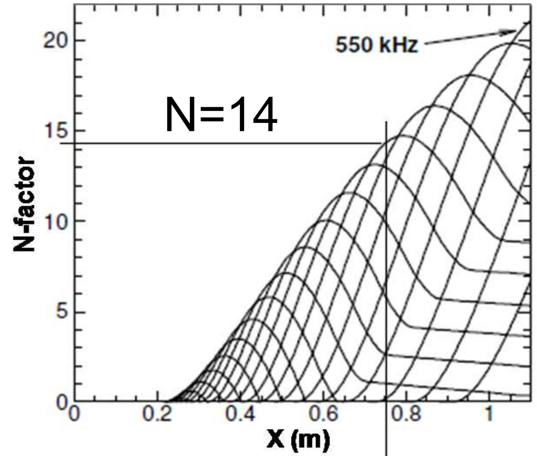

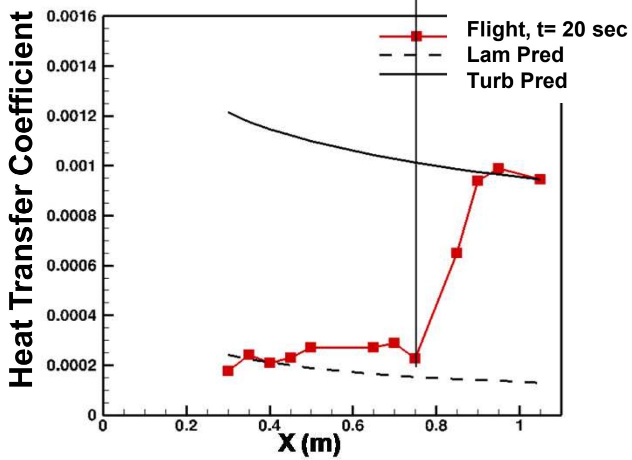

Flight transition Reynolds number 2X wind tunnel
Stability N-factor 40% higher than expected

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HIFiRE-5 and 5B Will Measure Boundary Layer Transition With 3-D Flow Effects

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Experimental Objectives:

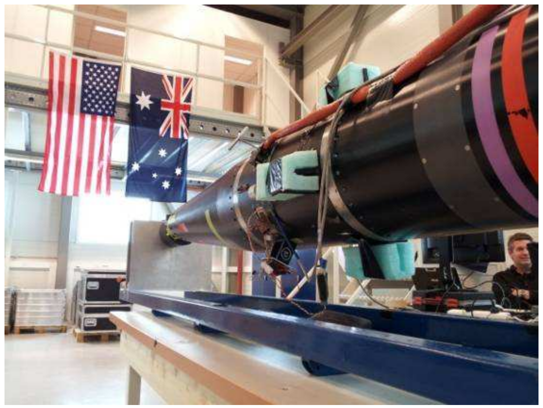
- Measure boundary layer transition with 3-D flow effects
- Evaluate C/SiC material performance
- Demonstrate high-rate temperature instrumentation

Trajectory:

- Ballistic with Mach 7+ entry
- Test Window: Mach 7+ at high Reynolds number
- Launch Vehicle: 2-stage S30-Improved Orion

Milestones:

- Launched from Andøya Rocket Range in Norway on 25 April 2012 (HIFiRE 5B launch scheduled Septemeber 2013)
- Second stage rocket motor failed to ignite
- Collected aerodynamic data up to failure – some experimental objectives met
- All Technical Objectives meet



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HIFiRE-2 Demonstrated Scramjet Mode Transition

Australian Government
Department of Defence
Defence Science and Technology Organisation

Experimental Objectives:

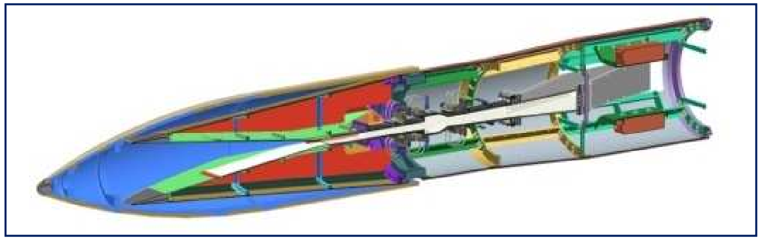
- Hydrocarbon scramjet mode transition and operability
- Scramjet lean blow out at Mach 8+
- TDLAS measurement of combustion species concentrations

Trajectory:

- Suppressed via delayed stage ignition and gravity turn
- Test window: accelerate under rocket boost from Mach 5.4 to 8+ at 72 kPa dynamic pressure
- Launch Vehicle: 3-stage Terrier-Terrier-Oriole

Milestones:

- Fully successful mission from PMRF on 01 May 2012
- Preliminary data review indicates all objectives met
- First time scramjet mode transition from subsonic to supersonic combustion demonstrated via acceleration



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HIFiRE-3 Demonstrated Radical Farming Scramjet Combustion

Australian Government
Department of Defence
Defence Science and Technology Organisation

Experimental Objectives:

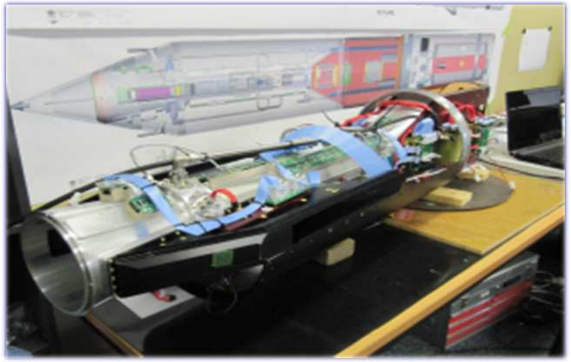
- Demonstrate the combustor performance of an axisymmetric hydrogen-fueled scramjet that employs "radical farming"
- Start an axisymmetric high contraction ratio inlet
- Validate ground test measurements and computational predictions

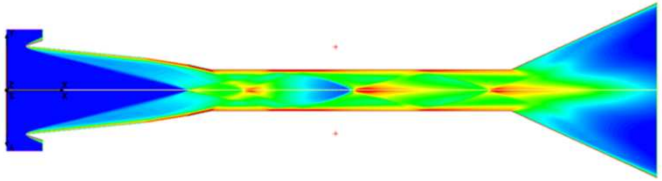
Trajectory:

- Ballistic with Mach 8 re-entry
- Captive-carry by 2nd stage booster
- Launch Vehicle: 2-stage S30-Improved Orion

Milestones:

- Flown successfully on 13 September 2012 at Andøya
- Preliminary data review indicates all objectives met





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HIFiRE-7 Will Flight Test an Ethylene Scramjet Employing a REST Inlet

Australian Government
Department of Defence
Defence Science and Technology Organisation

Experimental Objectives:

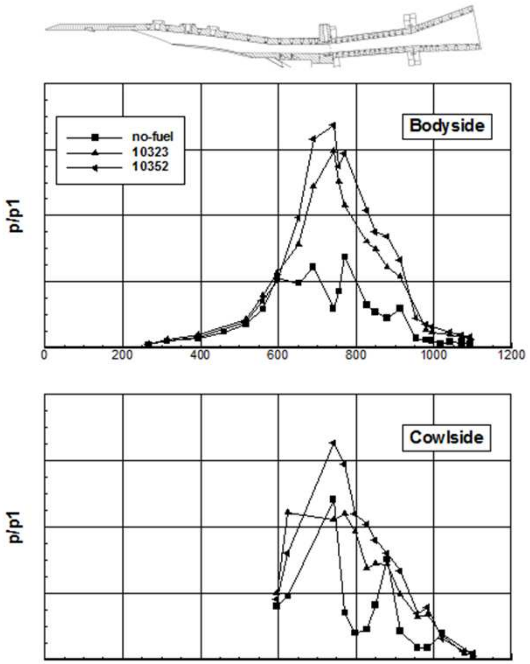
- Measure thrust production of a REST inlet Scramjet
- Compare thrust measurements with CFD predictions

Trajectory:

- Ballistic with Mach 7.8 entry
- Test Window: 32-26km
- Launch Vehicle: VSB-30

Milestones:

- Manufacture completed
- Launch planned from Andøya in June 2013



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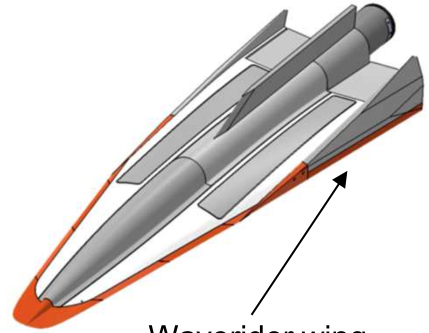
HIFiRE-4 Will Test Flight Control and Aero Performance of a Hypersonic Waverider

Australian Government
Department of Defence
Defence Science and Technology Organisation

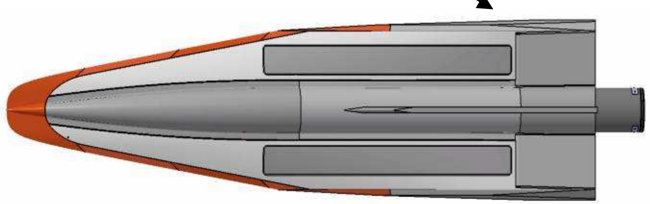
Experimental Objectives:

- Control hypersonic waverider through a pull-up maneuver
- Reduce risk of free-flying hypersonic experiments boosted by sounding rockets
- Validate exo-atmospheric payload separation and attitude control strategies for hypersonic entry vehicles
- Validate hypersonic vehicle design and analysis tools



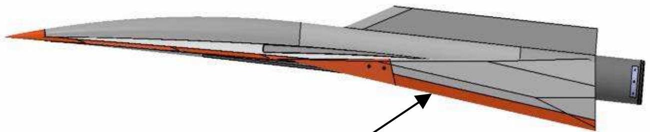
Trajectory:

- Two back-to-back flyers in shroud flown ballistic with exo-atmospheric separation and Mach 6 entry
- Test: One flyer executes a 25-deg pull-up and the other pulls up to horizontal and flies to a water “landing”
- Launch Vehicle: VSB-30



Milestones:

- Critical design review complete
- Manufacturing ongoing
- Launch planned from Andøya in April 2014



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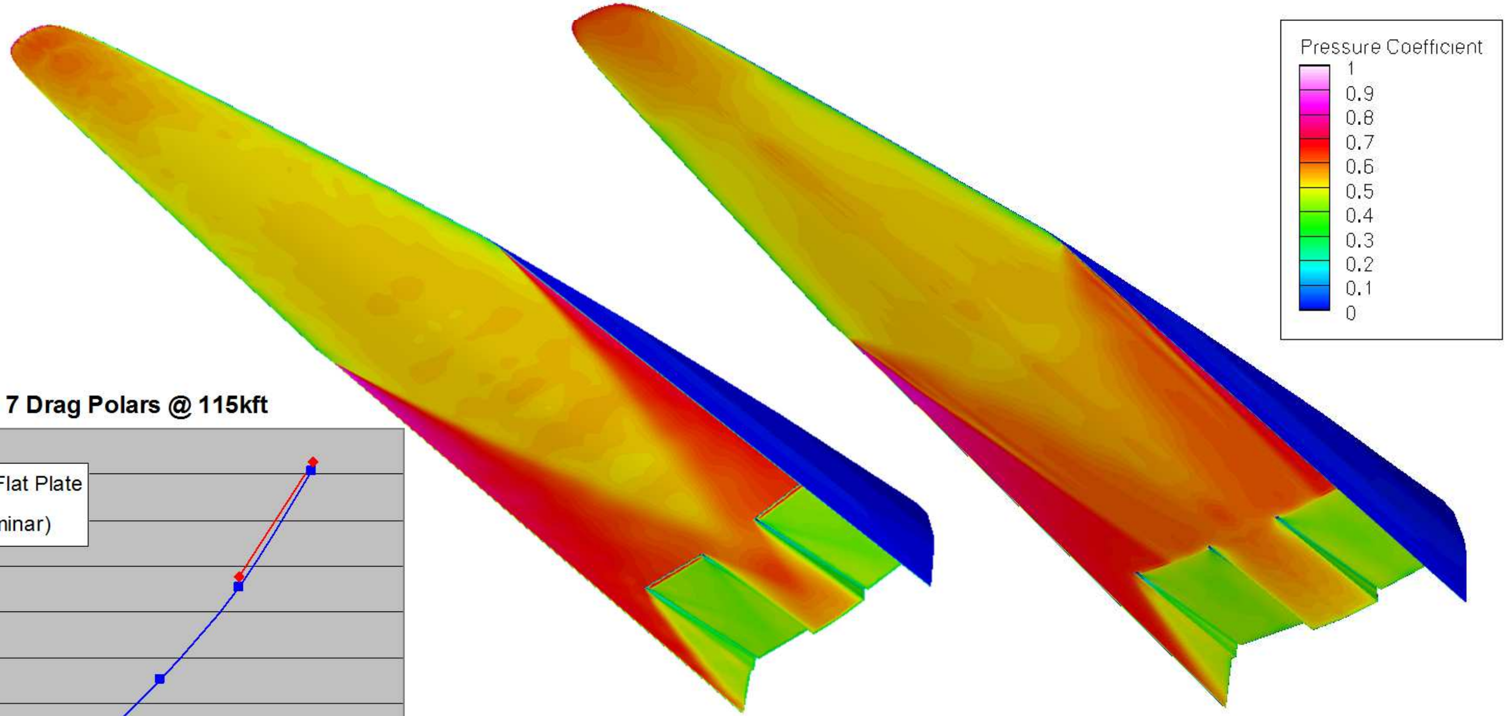
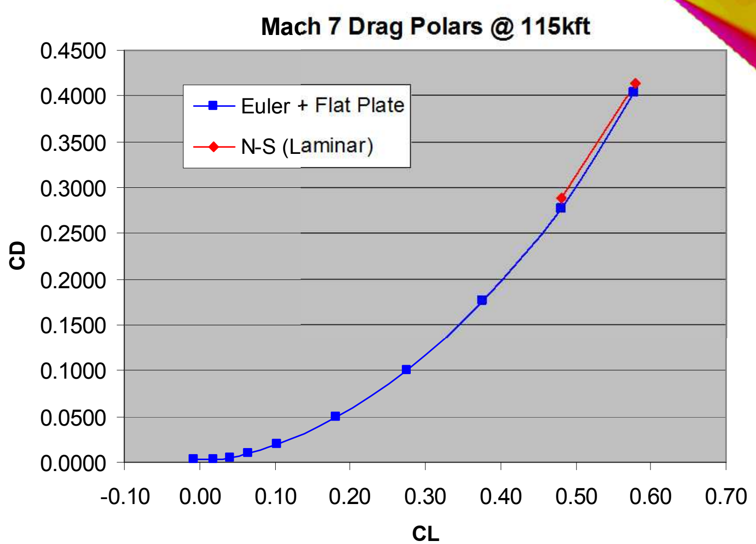
Navier-Stokes CFD Verifies Euler Plus Friction Drag Aero Analysis Approach

Mach = 7, Altitude = 115kft, AoA = 25 deg, beta = 0, delta = -5 deg





Cart3D Euler

OVERFLOW Laminar Navier-Stokes

HIFiRE-6 Will Test The Performance of An Adaptive Flight Control System

Australian Government
Department of Defence
Defence Science and Technology Organisation

Experimental Objectives:

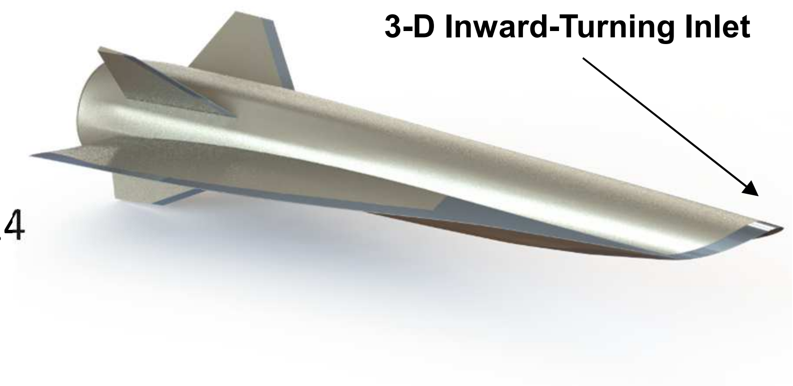
- Evaluate hypersonic vehicle adaptive flight control system (AFCS) tracking performance in maneuvering flight
- Maintain controlled flight through test window and collect sufficient data to validate AFCS performance

Trajectory:

- Suppressed trajectory with direct insertion to test window
- Test Window: Mach 7 at 48 kPa dynamic pressure
- Launch Vehicle: 3-stage Talos-Terrier-Oriole

Milestones:

- Concept design review complete
- Preliminary design ongoing
- Launch planned from PMRF in November 2014



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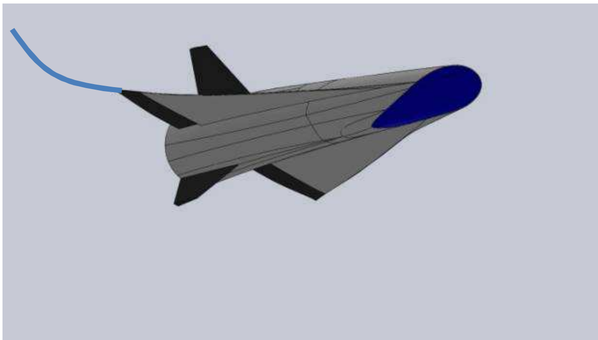
HIFiRE-6 Approach For Testing Adaptive Flight Control System

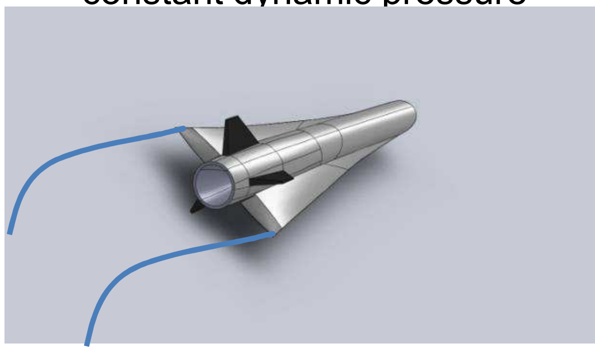
Objective: Assess adaptive control law tracking performance by executing a series of relevant maneuvers at Mach 6-7

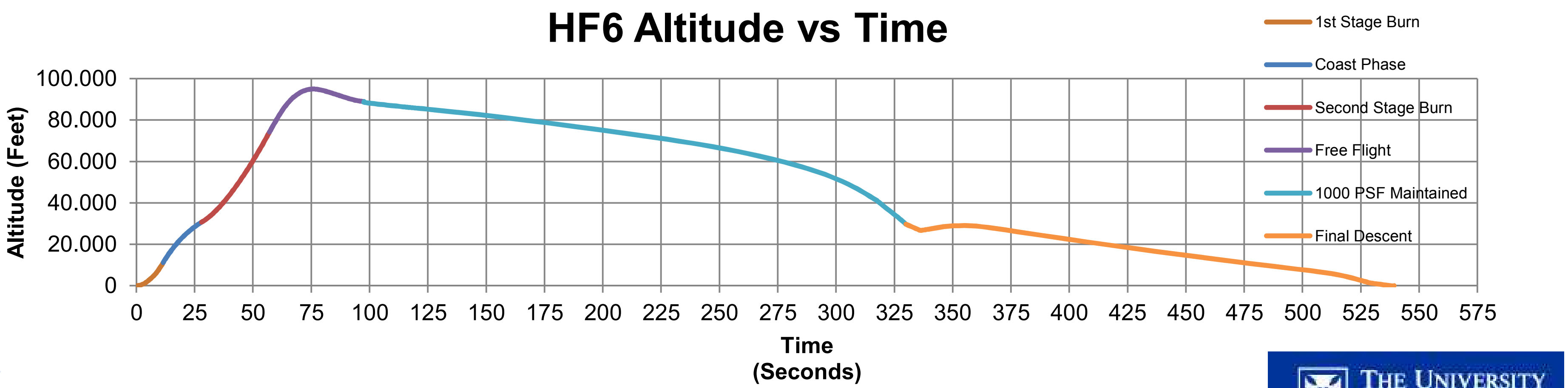
Maneuver 1:
After separation, acquire desired dynamic pressure and Mach

Maneuver 2:
Constant g turn maintaining constant dynamic pressure



Maneuver 3:
Constant g turn in opposite direction maintaining constant dynamic pressure





HIFiRE-8 Will Fly an Airframe Integrated With the HIFiRE-7 Ethylene Scramjet

Experimental Objectives:

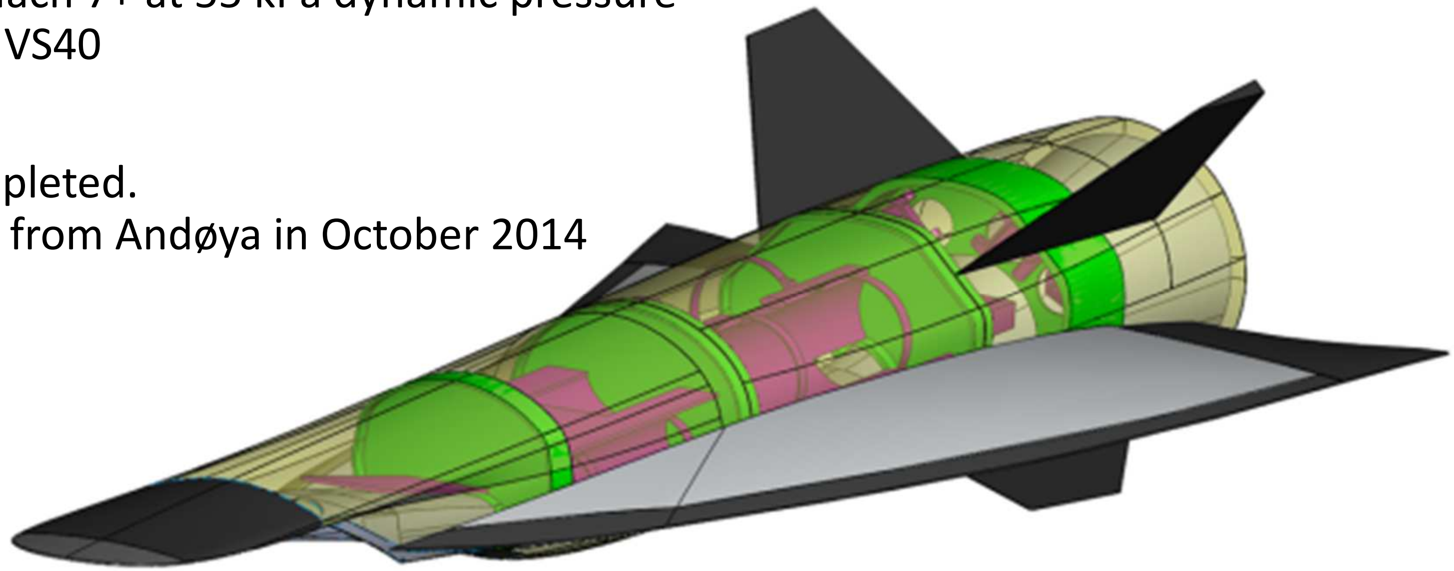
- Demonstrate 30 seconds of horizontal scramjet powered flight

Trajectory:

- Suppressed exo-atmospheric with low entry flight path angle and pull-up to test window
- Test Window: Mach 7+ at 55 kPa dynamic pressure
- Launch Vehicle: VS40

Milestones:

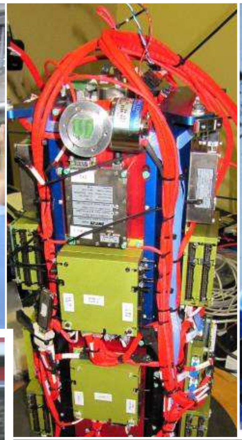
- CoDR to be completed.
- Launch planned from Andøya in October 2014



Summary

- Potential rewards of routine and efficient hypersonic flight are many, but several challenges remain before full value of hypersonic flight can be realized
- Addressing technical challenges is itself challenging due to high flow energy and extreme thermal environment of hypersonic flight
  - Hypersonic environment difficult to replicate in ground test facilities
- HIFiRE program created to increase knowledge base for critical hypersonic phenomena and mature enabling technologies
  - Nine focused research projects, each culminating in a flight experiment to address one or more scientific questions or technical challenges
- A primary objective of program is to conduct flight experiments faster and at lower cost than traditionally achievable
  - Use low-cost sounding rockets and accept greater technical risk
- To execute the HIFiRE program the resources of a diverse and capable international team were assembled and effectively employed










DLR
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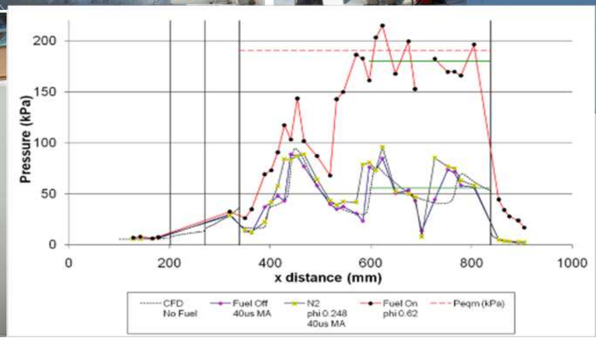
MOBILE RAKETENBASIS

Thank you


Pressure (kPa)
0
50
100
150
200
x distance (mm)
0
200
400
600
800
1000
CFD No Fuel
Fuel Off 40us MA
N2 phi 0.248 40us MA
Fuel On phi 0.62
Peqm (kPa)