Liquefied Bleed

for Stability and Efficiency of High Speed Inlets

Phase 1 final presentation, February 27th, 2014

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Outline / summary

- Liquid Bleed innovation: Liquefying or dramatic cooling of inlet 'bleed' flow can improve propulsion efficiency and vehicle 'packaging'.
- Technical approach: Identify tools and team, conduct simple mission analyses, plan proof-of-concept tests.
- Impact: enables high-speed aircraft missions
- Results of ph. 1: milestones completed, no show-stoppers. Take-off gross weight of a TSTO vehicle could be reduced 30+%
- Distribution/Dissemination: initial contact with AFRL/NASA hypersonics coordinator and other government/industry partners.
- Next Steps: Phase 2, Assemble costs and propose P-O-C testing.

Liquefied Bleed: an innovation

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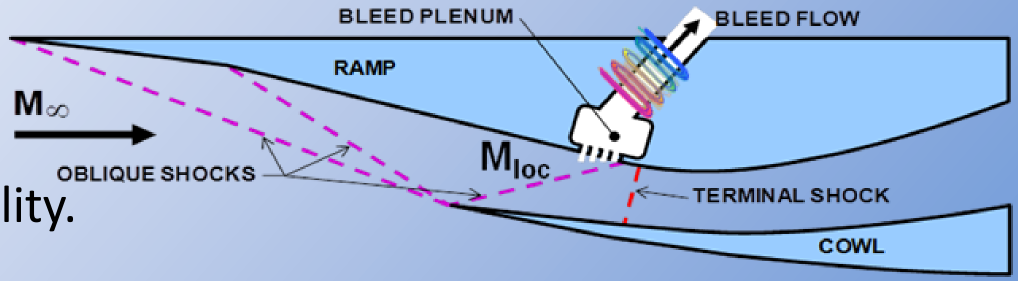
- Liquefying or dramatic cooling of inlet ‘bleed’ flow can improve propulsion efficiency and vehicle ‘packaging’.

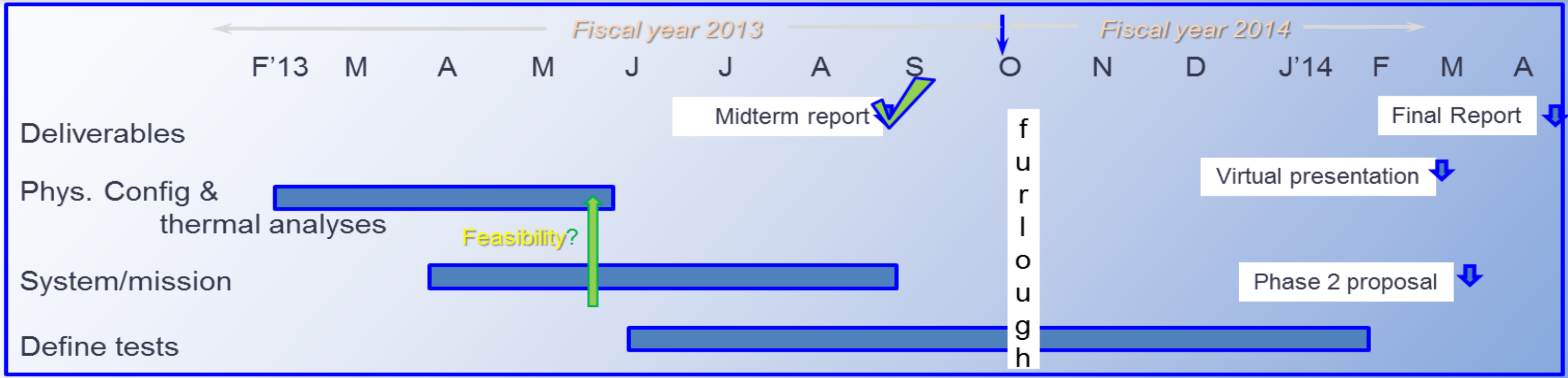
- Bleed is used by a high speed aircraft’s inlets to improve efficiency and stability.



- At hypersonic speed, the temperature increases and the bleed pressures decrease. Generally, bleed was not thought to be helpful beyond flight Mach numbers of 5 due to the resulting large and hot bleed ducting and overboard bleed air dump drag.

- Using cooling from a cryogenic fuel and a bleed air heat exchanger, the volume of the cooled or liquefied bleed air is reduced dramatically thereby reducing bleed drag, improving propulsion integration and enabling high speed bleed to improve propulsion efficiency.

Technical Approach



- Small team (~6) of researchers in high-speed inlets and cryogenic propellants met 2x/month to share tools, progress, and plan proof-of-concept testing.
- Mid-term report showed merit of concept.
- How difficult is it to liquefy bleed air? > POC tests
- Recent work is to develop requirements for POC testing
  - Two tests facilities identified at GRC:
    - Small Multipurpose Research Facility, SMiRF
    - 1x1 Supersonic Wind Tunnel
  - Requirements Documents have been developed
  - Costing estimates are being used for a phase 2 proposal

Impact

- Impact: enables high-speed aircraft missions.
- Top level impact assessed through mission analysis.
  - Built on analysis of heat balance between available cryogenic hydrogen fuel and bleed air.
  - Data from FAP/Hypersonic mode transition experiment and other inlet and vehicle integration efforts were factored into mission analysis.
- Liquefied bleed is feasible, based on analysis-to-date. Even cooled bleed could be significant to a hypersonic vehicle design.
- Mission margin is increased, risks reduced if bleed air is added throughout a hypersonic vehicle mission.

Phase 1 results

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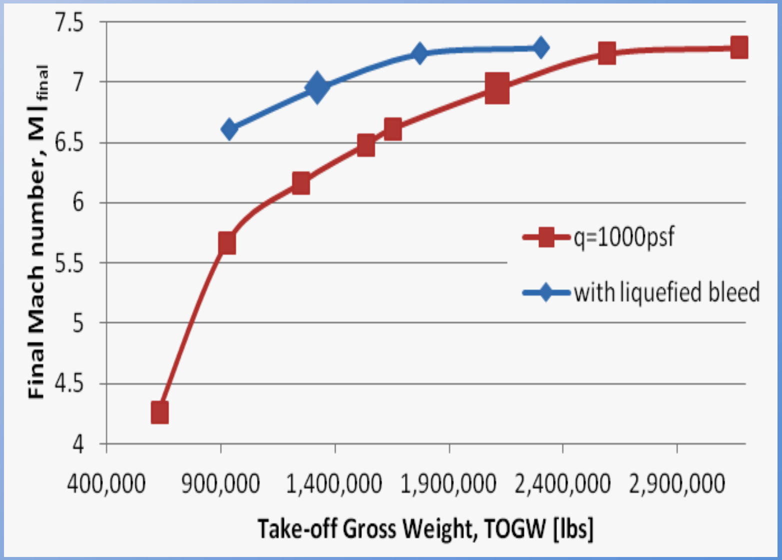
- Results of ph. 1: milestones completed, no technical show-stoppers. Cost is high.
- Thermal analysis shows liquefying bleed is feasible from available LH2 cooling capacity. With less aggressive cooling, the bleed air volume can be reduced by a factor of six.
- Take-off gross weight of a Two-Stage-To-Orbit (TSTO) airbreathing vehicle* could be reduced 30+%
- A Proof-of-Concept test is technically feasible for a follow-on phase 2 effort.



* Assumption of M7 staging, Hydrogen fueled, 2M lb TOGW baseline

Thermal analysis results

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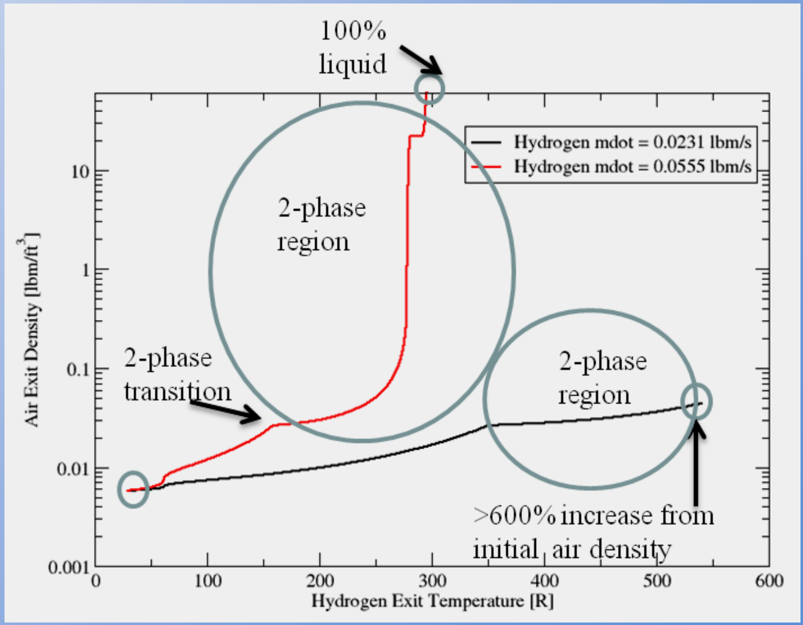
- Aggressive cooling scenario assumes 100% of stoichiometrically required hydrogen is available to cool the bleed air.

- Initial feasibility study was performed using a simple energy balance:

$$\dot{m}_{air}\Delta h_{air} = \dot{m}_{H2}\Delta h_{H2}$$

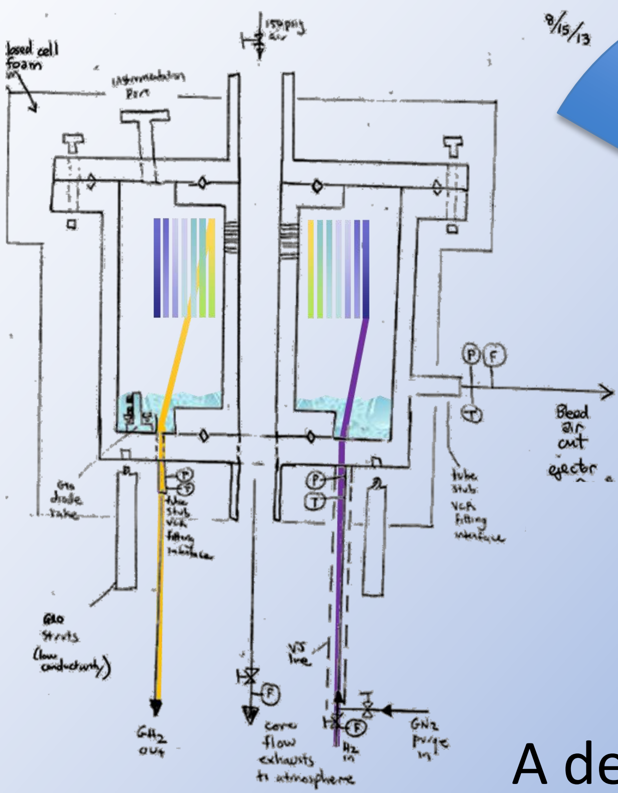
- Additional analysis required to estimated inefficiencies (i.e. due to frost formation on the heat exchanger surfaces)
  - Testing results may provide insight into these effects

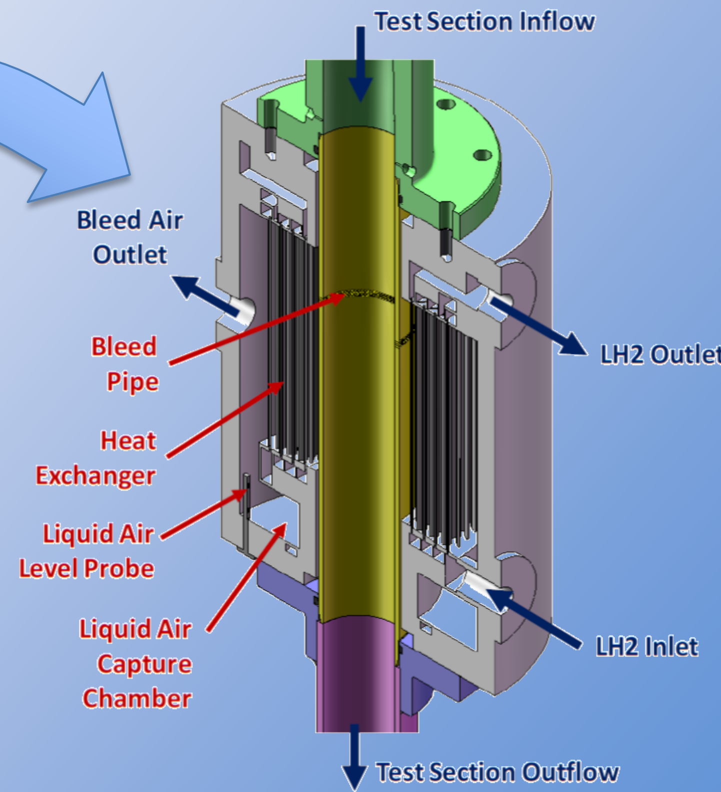
- Based on the cooling requirements, a heat exchanger concept was developed:
  - LH2 flows in high aspect ratio rectangular channels packaged radially from the core flow.



Physical configuration results

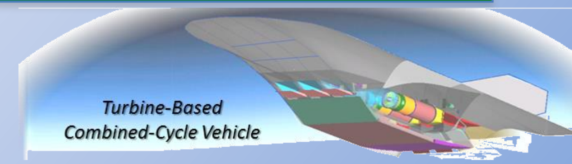
- A heat exchanger conceptual design was developed based on heat balance results.



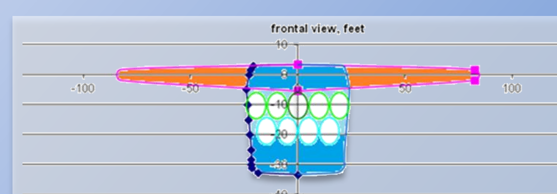


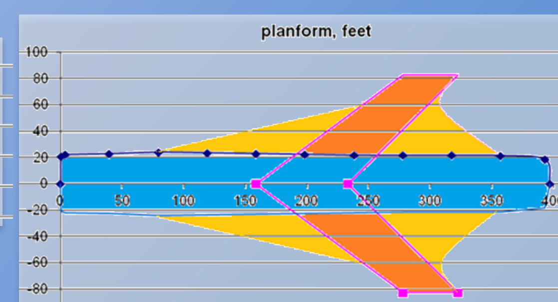
A detailed mechanical design followed, additive laser sintering fabrication is planned.

Mission analysis results



- Assumptions
  - Two-stage To Orbit mission, Staging at Mach 7
  - Trajectory analysis in which Mach and Angle of attack are variable
  - Baselined large vehicle to avoid mission closure non-linearities
    - – Take-off Gross Weight, ToGW, of 2 million pounds
    - – Dry Weight fraction of 50% + scaling laws to get DWF = f(ToGW)
  - Simple low fidelity vehicle aerodynamics with f(Mach, angle)
  - Propulsion based on Turbine-Based Combined-Cycle Engine for first stage and recent wind tunnel test of a mode transitioning inlet
  - Bleed effect: -17% DWF, +50% inlet recovery, -12% supersonic drag, Cd_o
  - Focus on first stage performance, (second stage not separated from dry weight fraction)





- Figure of merit
  - ➢ Take-off Gross Weight

Mission analysis results

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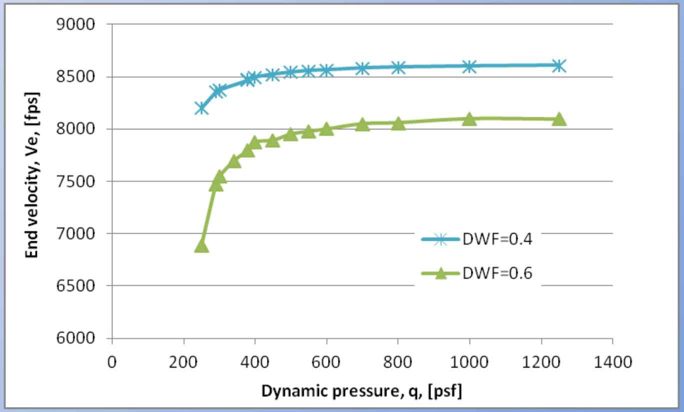
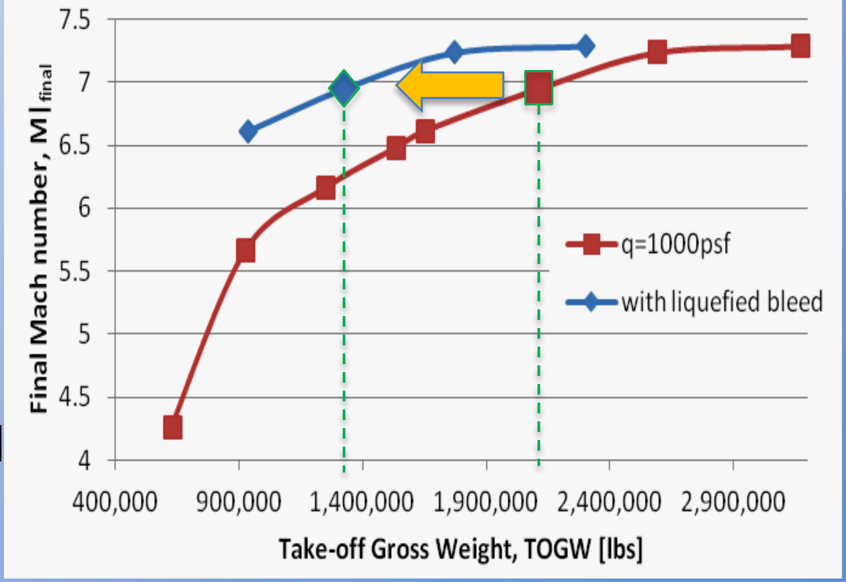
- Results
  - To 'validate' effect of Dry Weight Fraction, DWF
  - Mission/trajectory simulation has correct trends



- Effect of Liquefied bleed:
  - Figure of merit: Take-off Gross Weight (as a function of staging Mach number)
  - At M_{stage} = 7, a 30^{+}% reduction in ToGW is possible due to liquefied bleed. (From 2Mlbs, baseline to 1.3 Mlbs with liq. bleed)



Test planning results

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- Heat exchanger sized for the Small Multi-purpose Reseach Facility, SMiRF
- Design of key facility hardware complete
- Two facilities could provide complimentary data
  - SSLB (Small-Scale Liquid-Bleed) Test @ SMiRF
    - For proof-of-concept of bleed air liquefication
  - BCT (Bleed Cooling Test) @ 1x1 SWT
    - For build bleed database to higher Mach numbers and effect bleed air cooling
- Three requirements packages released to gather cost estimates: (2 tests + LN_2 system for 1x1 SWT)
- Meetings / feedback
  - 12/31 met with 1x1 SWT facility engineer
  - 2/3 met with SMiRF facility engineers
  - 2/4 met with one vendor on the LN_2 system for 1x1 SWT
  - 2/21, Cost ROMs are underway – exceed available phase 2 funds.

SMiRF, 1st of 2 Test facilities

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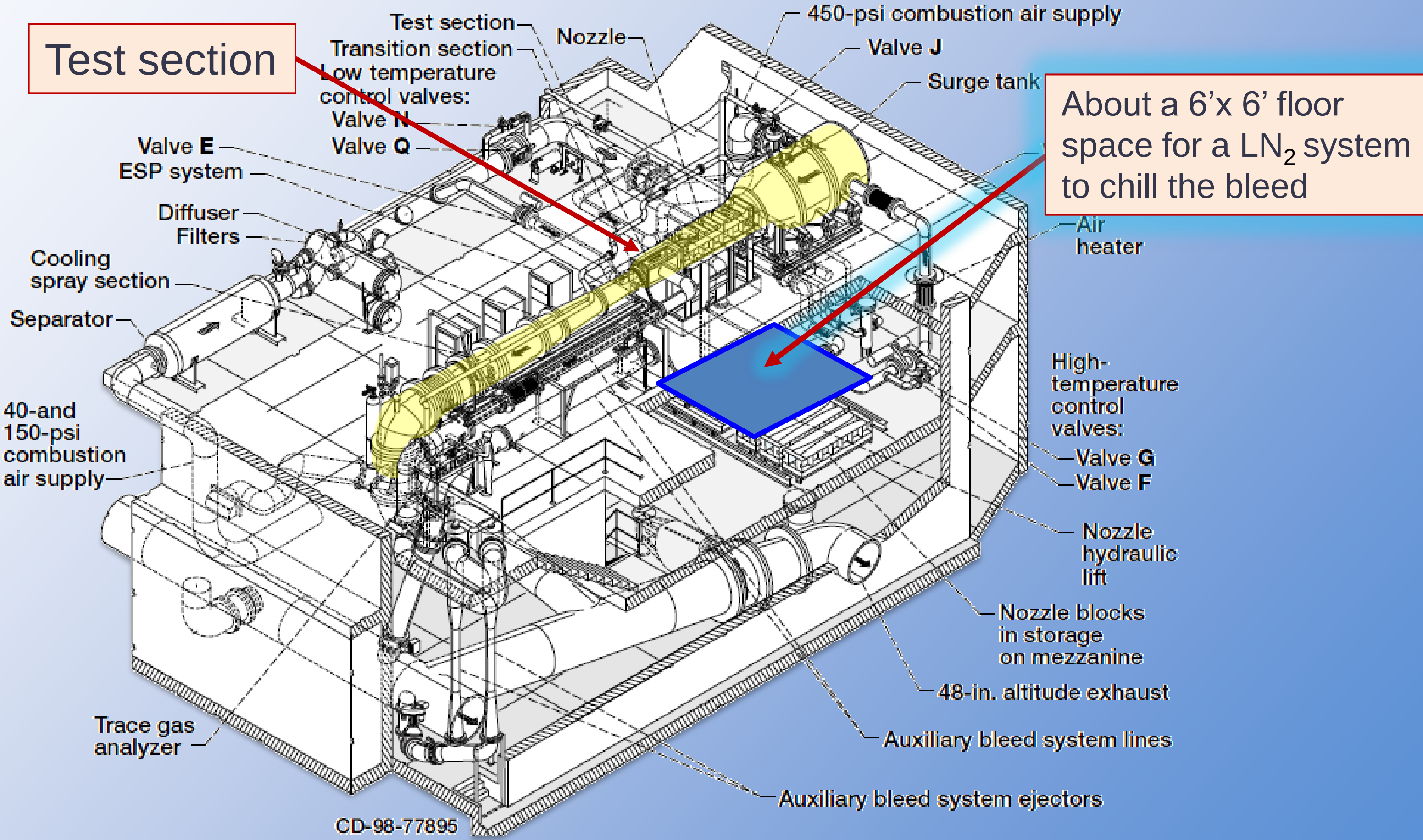
- Small Multipurpose Test Facility
- Capable of fully liquefying air with existing LH2 infrastructure
- Air supply limited

1x1 SWT, 2nd of 2 Test facilities

- Existing tunnel proven to gather quality inlet bleed data



Test planning (SSLB @ SMiRF)

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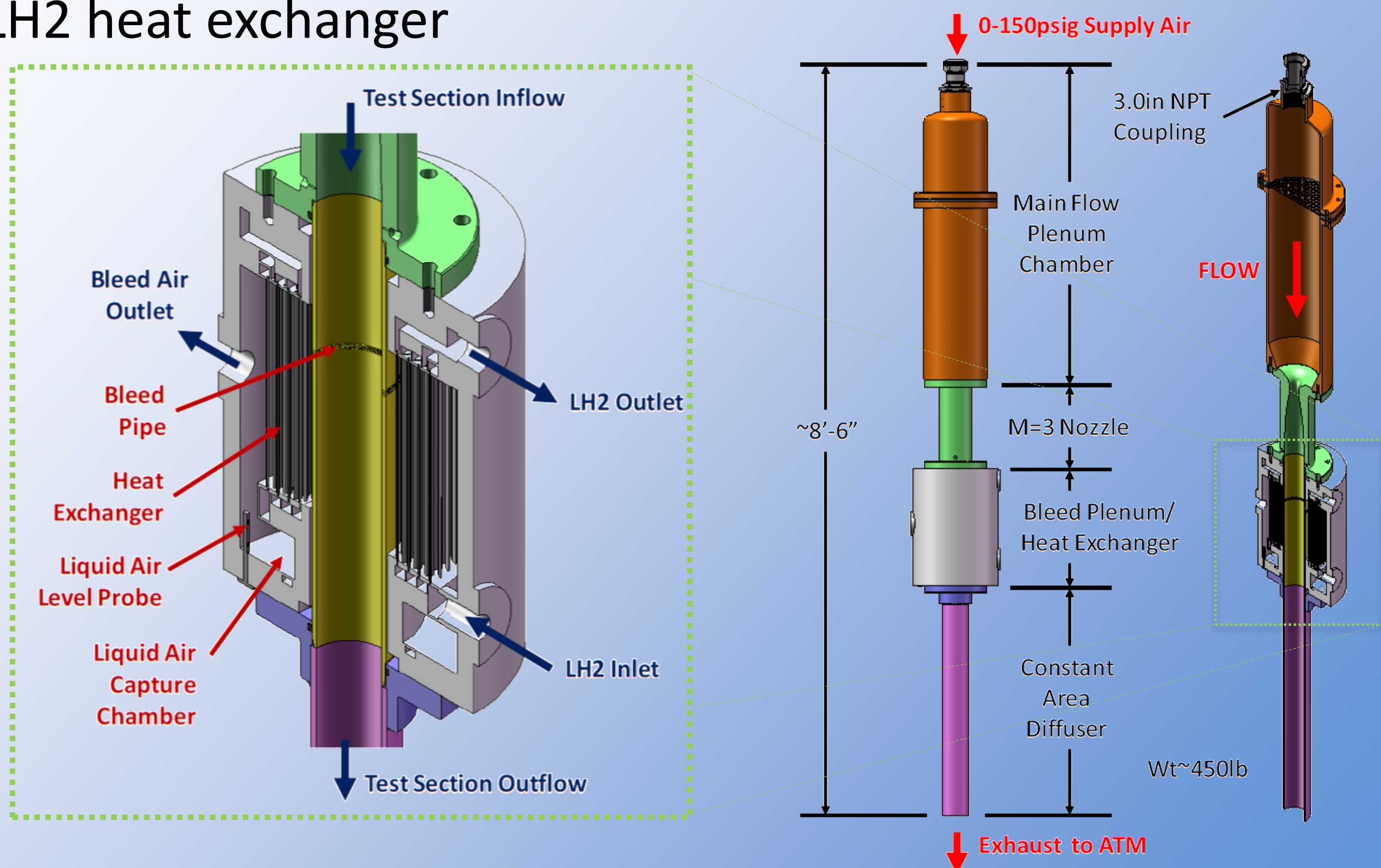
- Small-Scale Liquid-Bleed Test Article with inset showing LH2 heat exchanger



Test planning (1x1 SWT)

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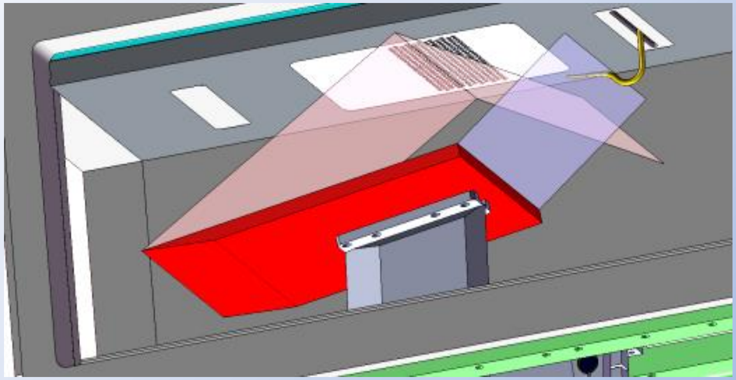
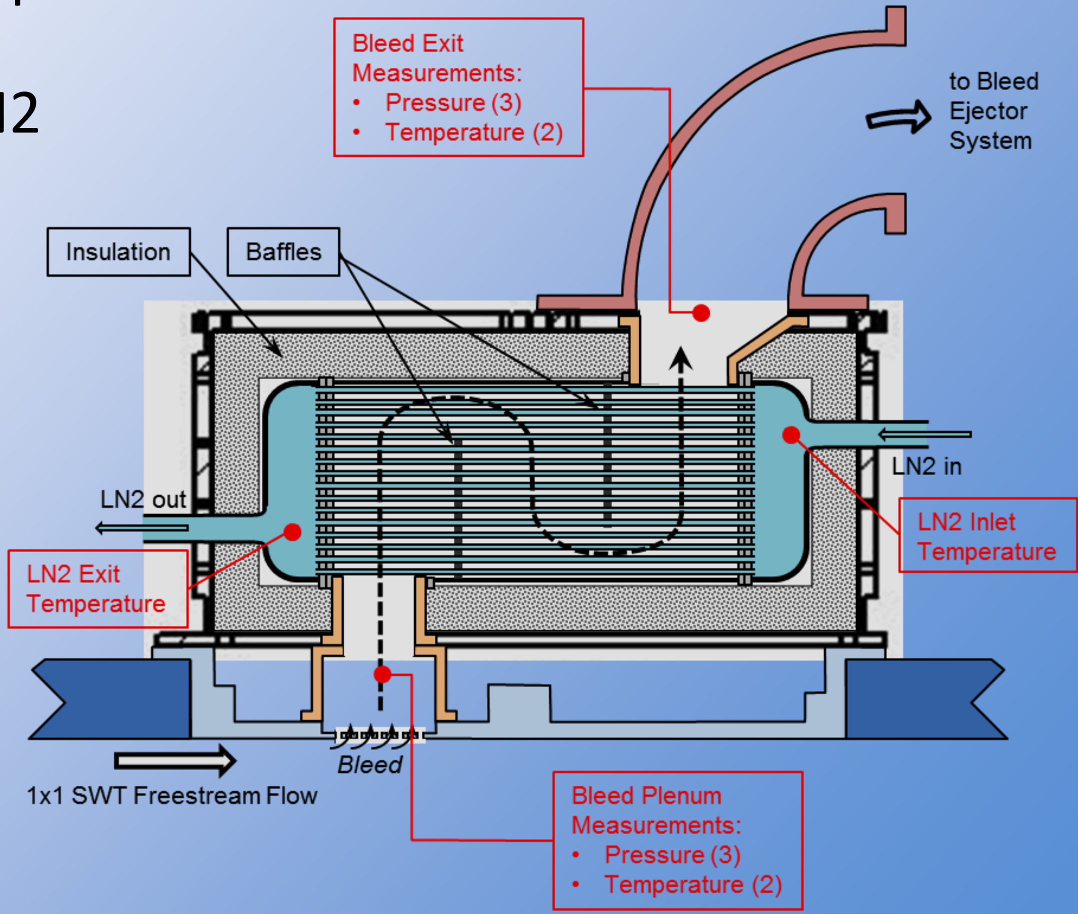
- Initial data at Mach 3 useful to anchor bleed modeling tools and eliminate extrapolation.

- Heat exchanger and a LN2 system (CCS_1nw) are needed to gather cooled bleed data.





Test planning (1x1 SWT)

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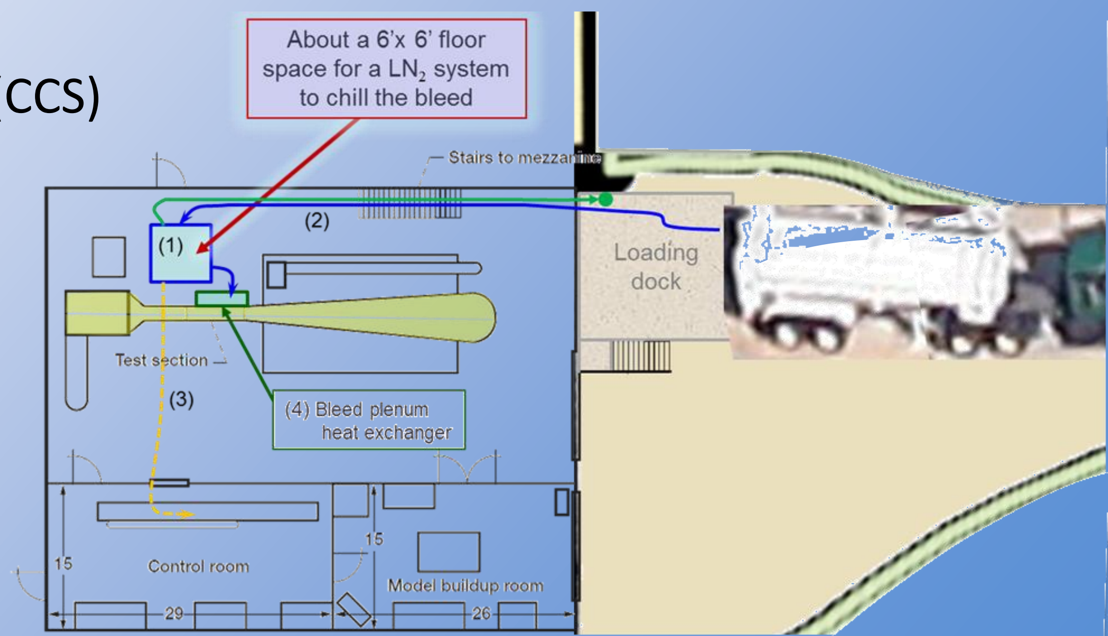
- Test plan
  1. Gather traditional bleed data (no heat exchanger) at Mach 3
  2. As budget allows (augmentation?)
     » Procure CCS* for liquefied nitrogen
     » Procure heat exchanger
     » Conduct cooled bleed tests.

- *Cryogenic Cooling System (CCS)

  A self-contained system for supplying LN2 to a heat exchanger. The system would allow wind tunnel testing of actively cooled bleed.



Test planning ROM costs

- Rough-Order-of_Magnitude (ROM) costs
- SSLB test at SMiRF
  - Compressed air supply is limited.
  - Bringing lab. air supply about 500 ft. downhill
    - Could be several $100K's
    - Facility upgrade funding?
  - Full Cost ROM unavailable as of 2/21/2014.

- BCT (Bleed Cooling Test) at 1x1 SWT
  - Cost ROM for the LN2 supply system and heat exchanger unavailable as of 2/21/2014. Update (3/17/14): just equipment might be ~$250K
  - Test entry cost ROM was ~$230K with research support.
  - Provides validation data but not through air liquefaction regime

Distribution/Dissemination

- Distribution/Dissemination—initial contact with AFRL/NASA hypersonics coordinator and other government/industry partners.

  - CCE-LIMX phase 3 received FY14 money through SAA/AFRL
    - Initiated discussion with NASA/AFRL
  - Decided that discussion with Industry for endorsement / collaboration would be too early.
  - Ongoing relationship with TechLand Research, Inc.
  - Other government partnerships?

Next Steps

- For Phase 2: Assemble costs and propose P-O-C testing.
- Maximum Phase 2 Award value ($275K + $75K option) prohibits even one of the two tests, i.e. SMiRF and 1x1 SWT.
- ➢ Need additional funding (Research facility augmentation?)
- ➢ A choice will need to be made
  - SMiRF which allows actual liquefaction of the air

    O R
  - 1x1 SWT which addresses bleed data and cooled (but not liquefied) air.
  - SMiRF seems to be best choice at this time as it has LH_2 required to liquefy the bleed air.
  - Actual Cost ROMs may impact this choice (3/17/14: ROMs >$500K)
  - Reassess Test Requirements, seek outside facility resources, continue analyses
- ➢ Postpone current phase 2 proposal, examine test costs & alternatives

Summary

- **Liquid Bleed innovation:** Liquefying or dramatic cooling of inlet 'bleed' flow can improve propulsion efficiency and vehicle 'packaging'. The propulsion improvements can enable high-speed aircraft missions.
- **Results of phase 1:**
  - Identify tools and team, conduct simple mission analyses, plan proof-of-concept tests.
  - Milestones completed, no show-stoppers. Take-off gross weight of a TSTO vehicle could be reduced 30+%
  - Conceptual design of heat exchangers underway
  - Adaptive hardware for testing is designed and procured.
  - Postpone current phase 2 proposal, examine test costs & alternatives
- **Distribution/Dissemination:** initial contact with AFRL/NASA hypersonics coordinator and other government/industry partners.
- **Next Steps: Postpone Phase 2,** refine costs for future P-O-C testing.

Thank you for the support through the ARMD/NARI Seedling Funds