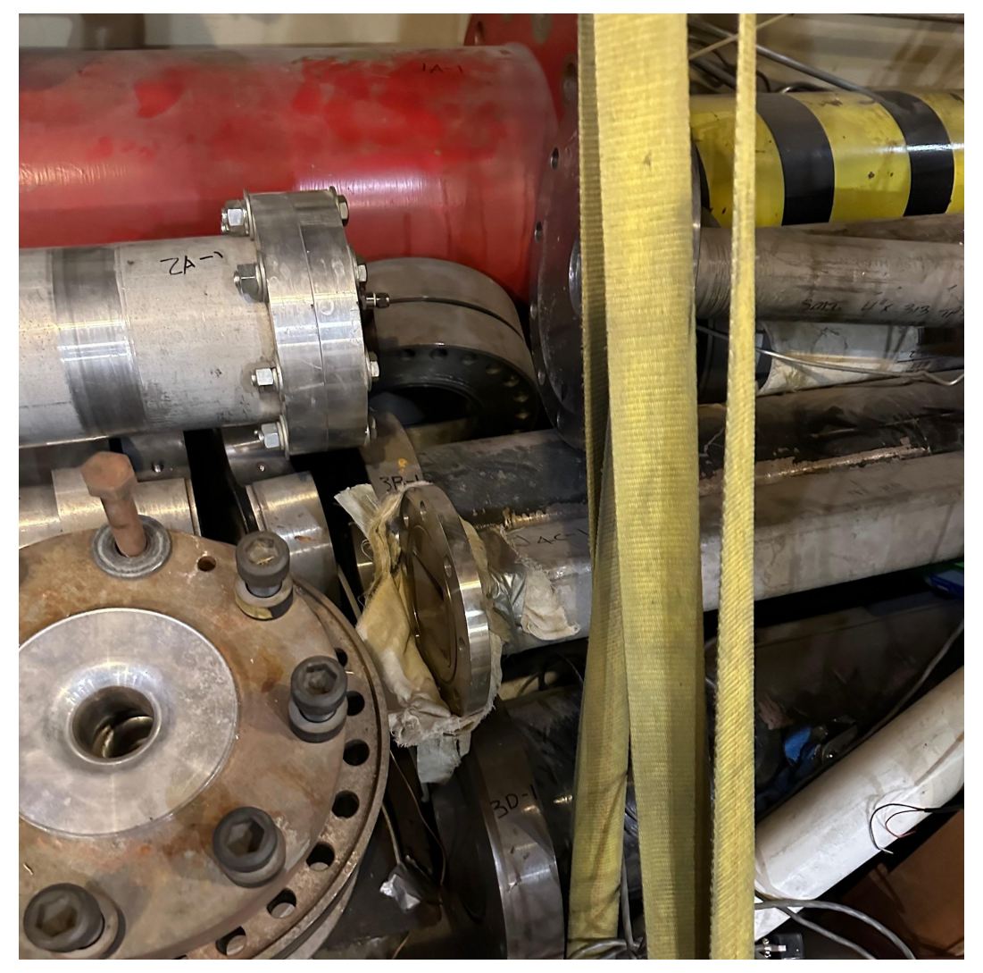
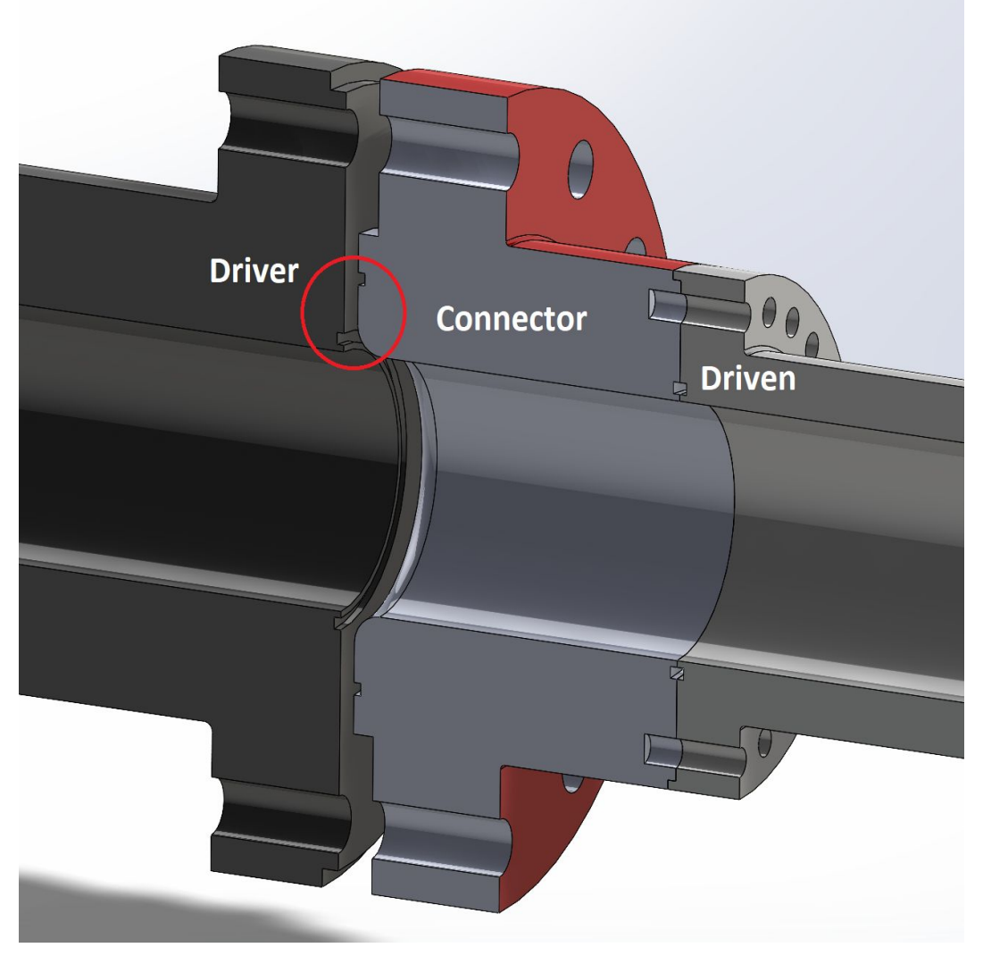
Designing a Hypersonic Ludwieg Tube for UW

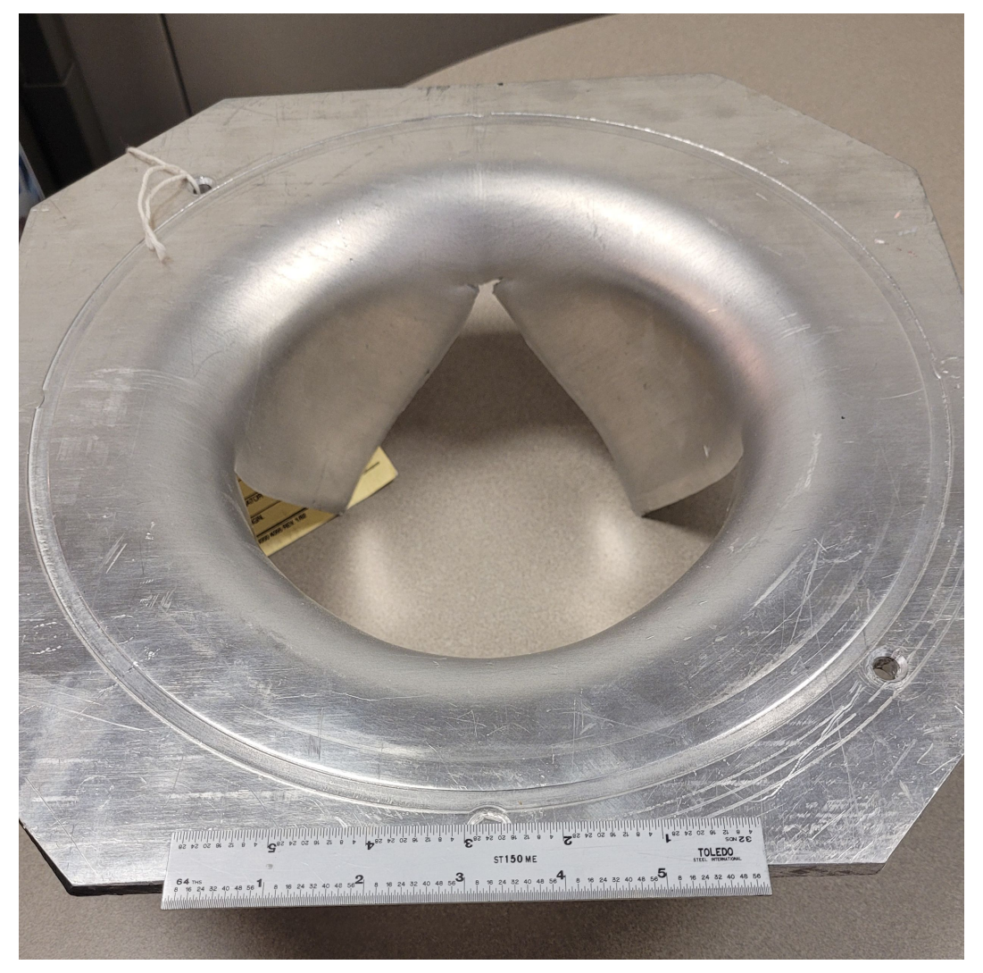
STUDENT: YEONGJUN “MARVIN” BOK

Motivation / Investigation of Existing Pipes

- Preliminary design of an interchangeable shock tunnel (shock tube + Ludwieg tube) for future hypersonic tests has been conducted, focusing on cases for **Mach 5-10** using a Ludwieg tube configuration (driven tubes only).
- Pipes and connectors from the previous hypersonic shock tunnel facility used in the 80s in the AERB basement are investigated.
- Pipes are made of moly steel (potentially 4340), pressurized up to 5000 psi for the driver section and 3000 psi for the driven section, and integrated with scored aluminum diaphragms. (Scott O’Brian, '93 UW A&A Ph.D)

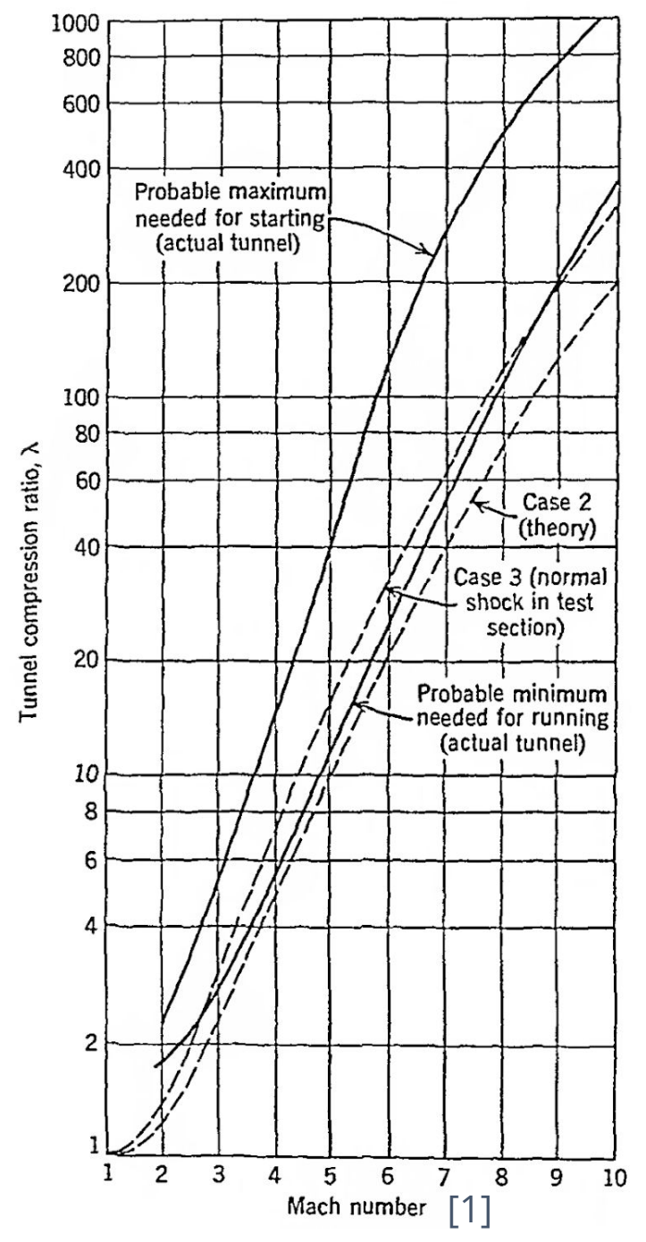






Tube Fill Pressure

- The maximum pressure of the tubes is calculated using Lame’s equation with the Tresca criterion:
  Driver tube yield point = 19600 psi
  Driven tube yield point = 13300 psi
- The reasonable maximum operating pressure for the driven tube is set to be **2500 psi** (FoS = 5.32).
- The minimum pressure required to start the tube is determined based on Pope and Goin’s experimental values of the tunnel starting compression ratio (λ) [1].
- λ: The ratio of test section total pressure to the dump tank (diffuser exit) pressure.

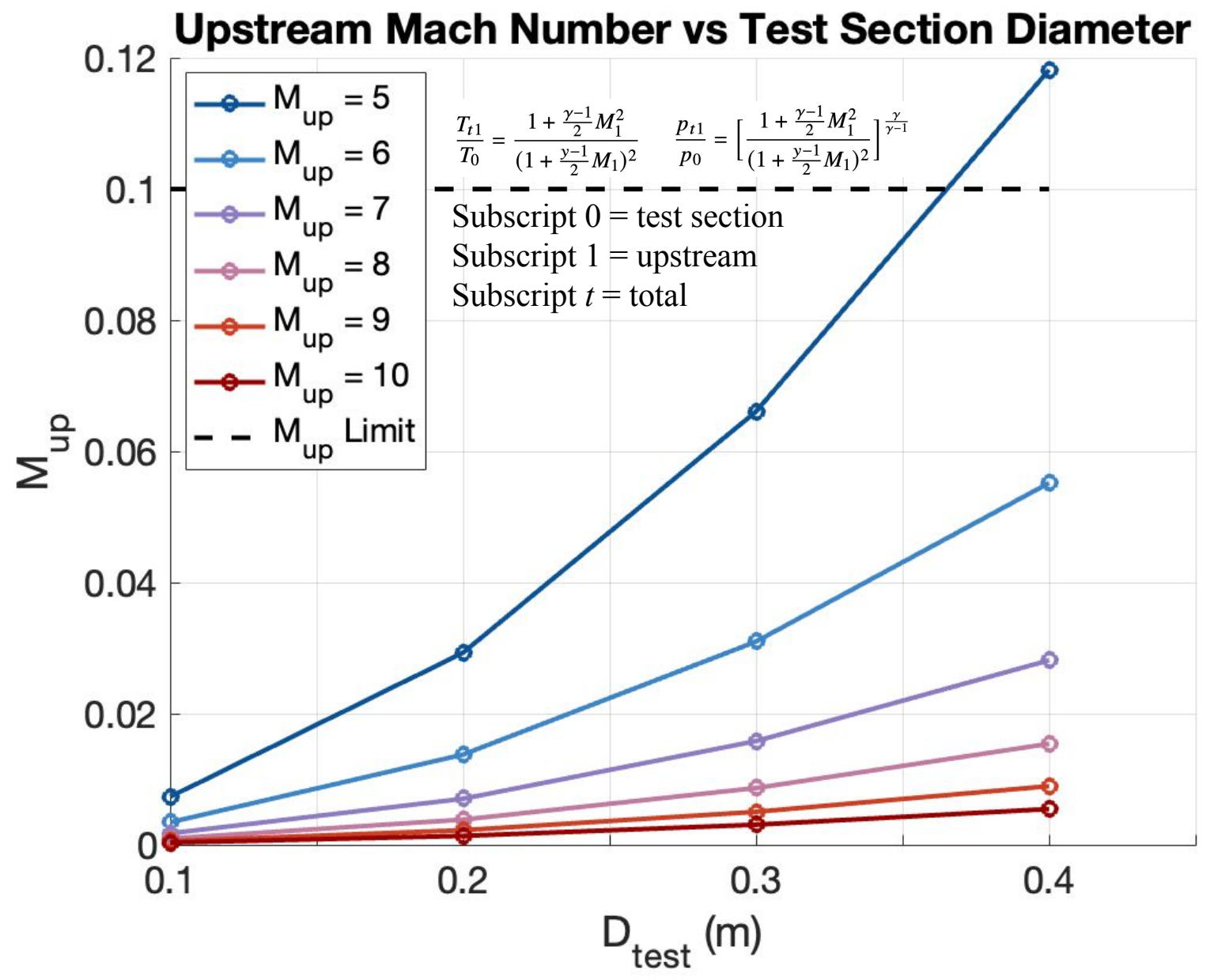


[1]

Test Section Sizing

- Since the test section diameter significantly impacts the size of the test article [1], a larger test section diameter is preferable.
- Considering the heating requirements in the test section, minor decreases in test section P_0, T_0, H_0, Re, and t_{test} for larger D_{test}, and the need to avoid exceeding an upstream Mach number of 0.1 [5], the optimal test section diameter is set at **0.3 m** for the UW Ludwieg tube.

Upstream Mach Number vs Test Section Diameter

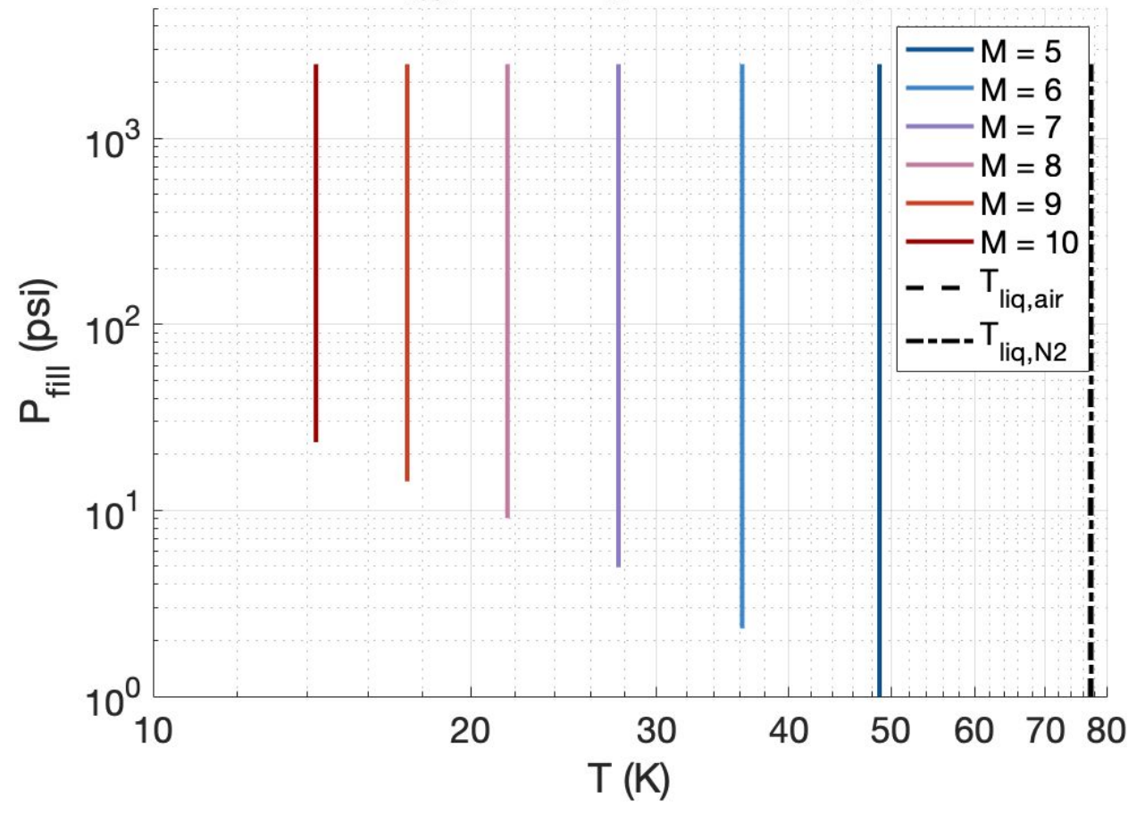


Tube Fill Temperature

- Minimum required temperatures are calculated based on a target Mach number and a test section total pressure using Wegener and Mack’s experimental values for air and nitrogen condensation [2].

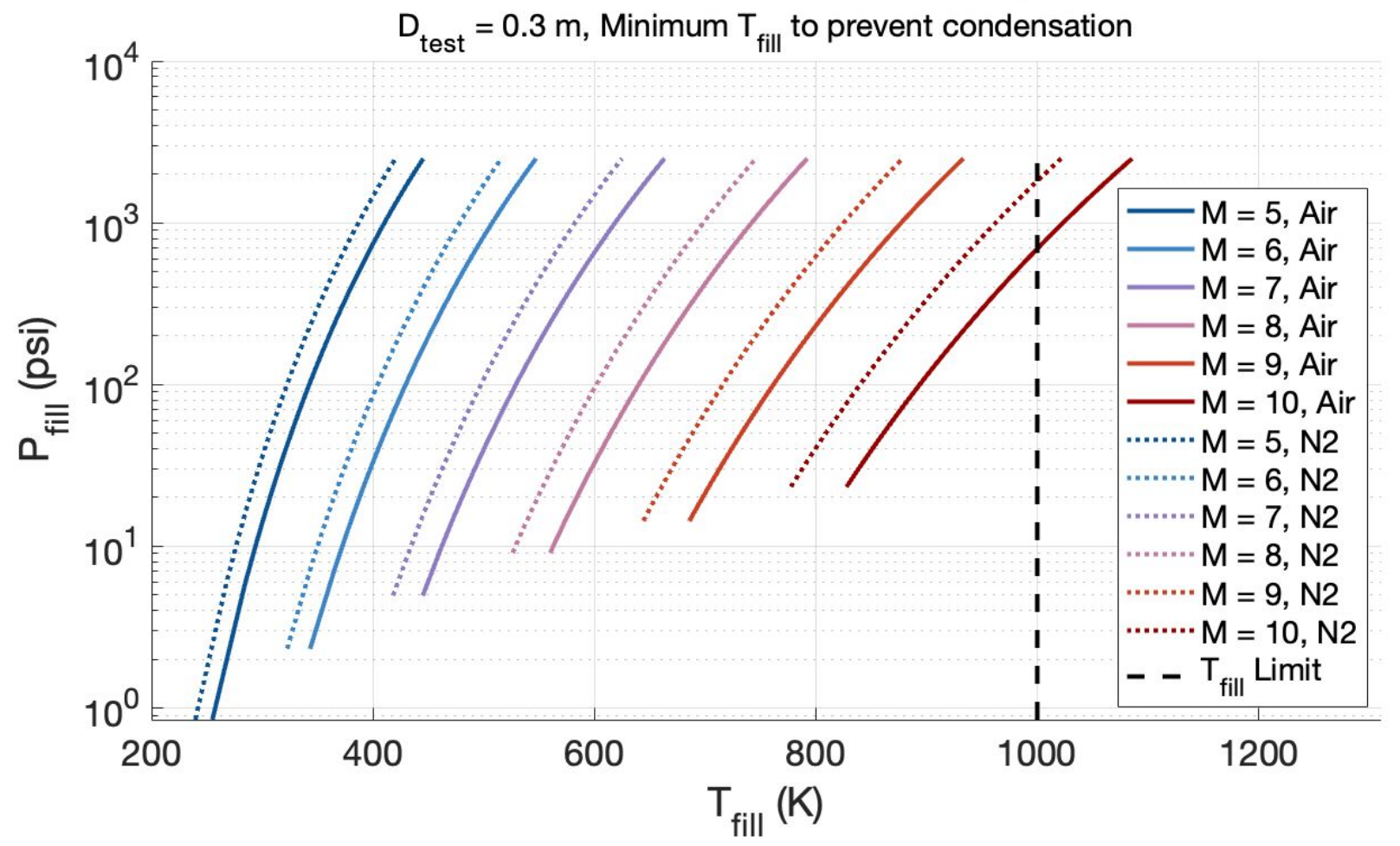
Tube Fill Pressure vs Test Section Static Temperature

Air and N2, D_{test} = 0.3 m, T_{fill} = 300 K, Min P_{fill} to 2500 psi



Tube Fill Pressure vs Tube Fill Temperature

D_{test} = 0.3 m, Minimum T_{fill} to prevent condensation



Comparison with Other Ludwieg Tubes

- UTSI M4LT:

P_0 = up to 150 Psi, T_0 = 300K,
Re = $1.0 \times 10^6 - 1.65 \times 10^7$ /ft,
t_{test} = 105 – 125 ms

- UTSI M7LT:

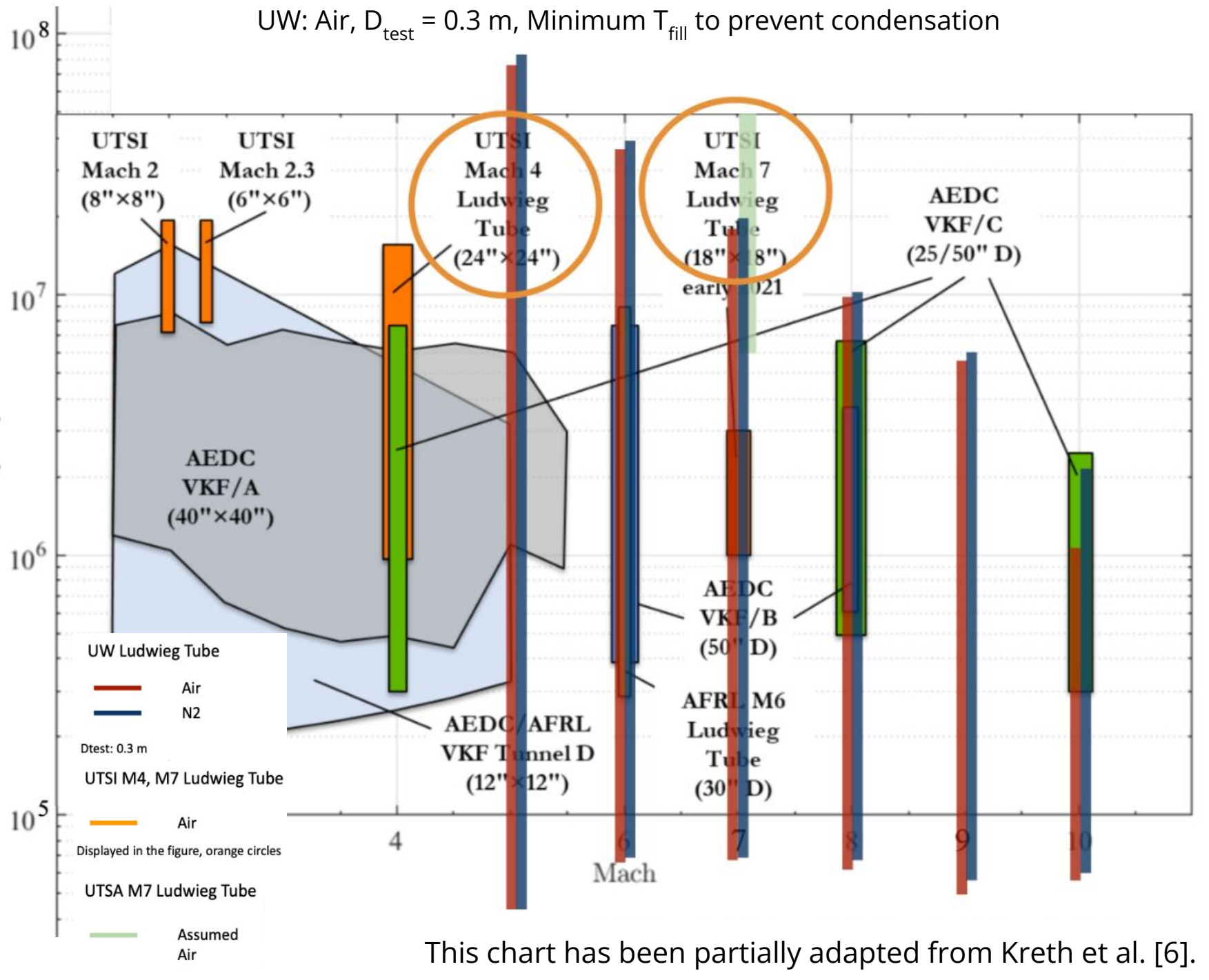
P_0 = 150-300 Psi, T_0 = up to 560K,
Re = $1.0 \times 10^6 - 3.0 \times 10^6$ /ft,
t_{test} = up to 135 ms

- UTSA M7LT:

P_0 = up to 2000 Psi, T_0 = up to 700K,
Re = up to 6.0×10^8 /ft,
t_{test} = 70 – 100 ms

Reynolds Number vs Mach Number Comparison

UW: Air, D_{test} = 0.3 m, Minimum T_{fill} to prevent condensation



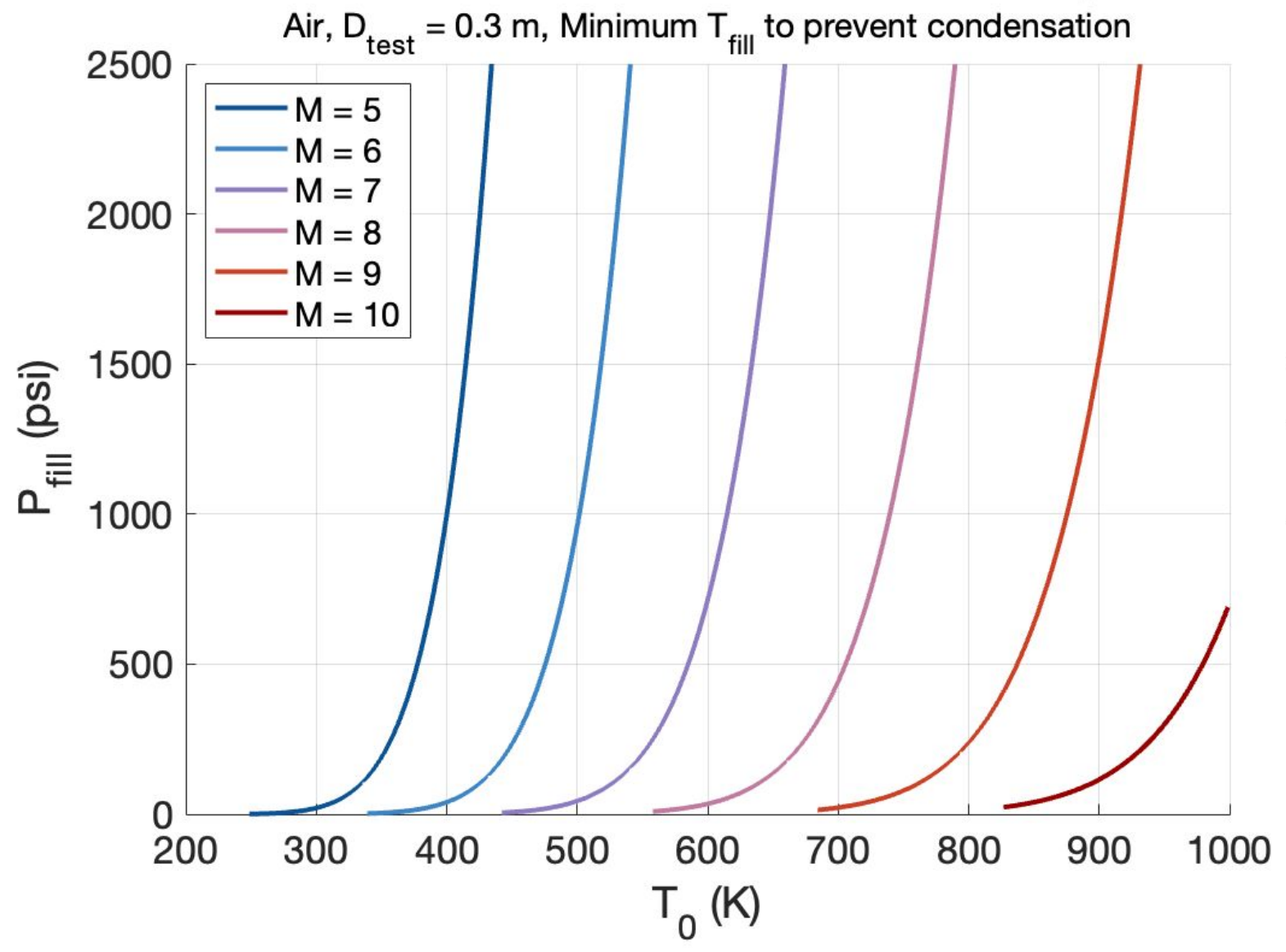
This chart has been partially adapted from Kreth et al. [6].

Test Section Calculation: Shock Propagation

- For the in-house code,
  known variables are: gas type, tube fill pressure, tube fill temperature, target Mach number, fill tube diameter, and test section diameter
  to calculate: upstream (fill tube) Mach number, test section total pressure, test section total temperature, test section total enthalpy, test section velocity, test section Reynolds number, and test time,
  based on Ludwieg tube shock loss, the isentropic relationship in the nozzle area ratio, Davis and Gwin’s test time theory [3], and losses due to the normal shock [4].

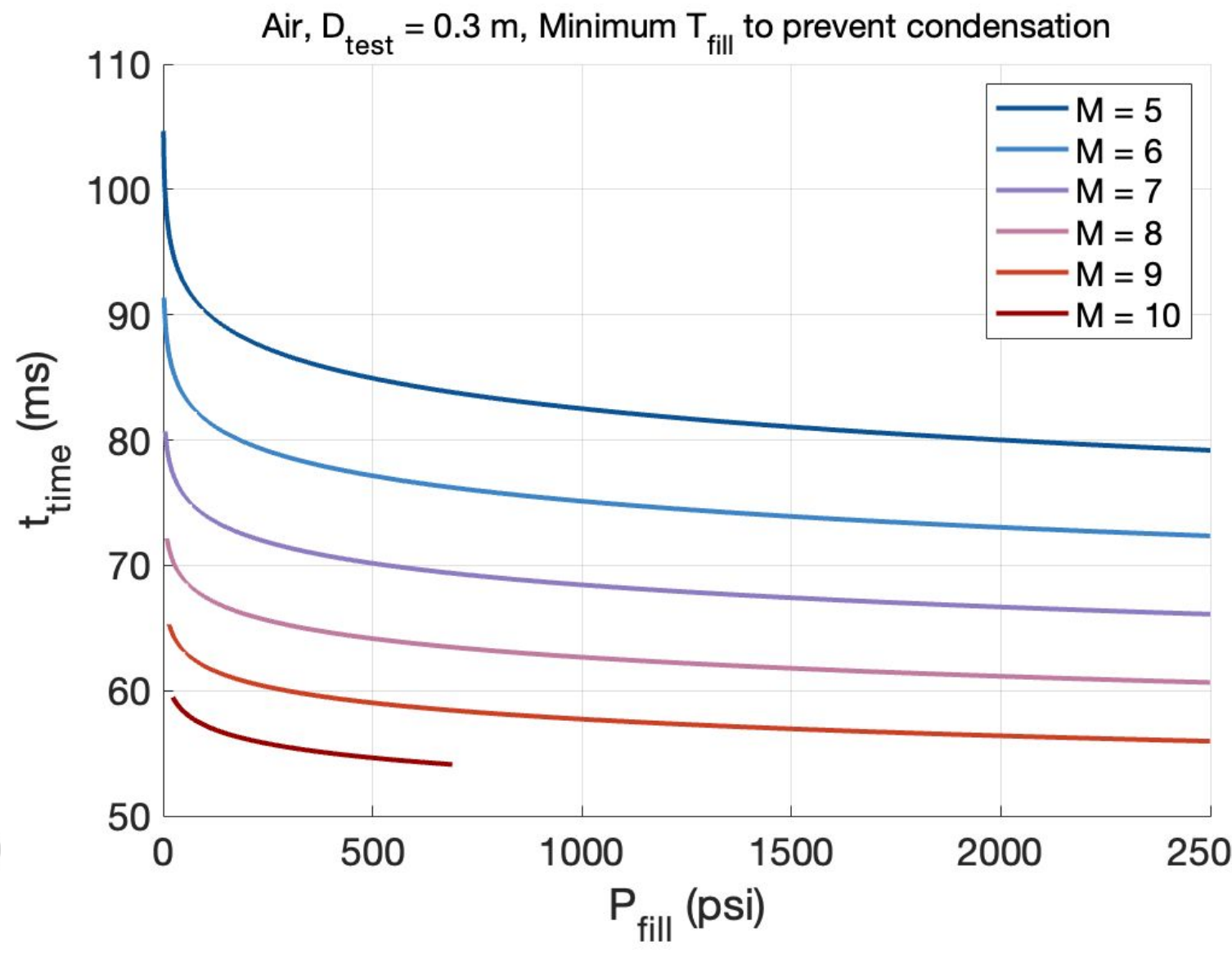
Tube Fill Pressure vs Test Section Total Temperature

Air, D_{test} = 0.3 m, Minimum T_{fill} to prevent condensation



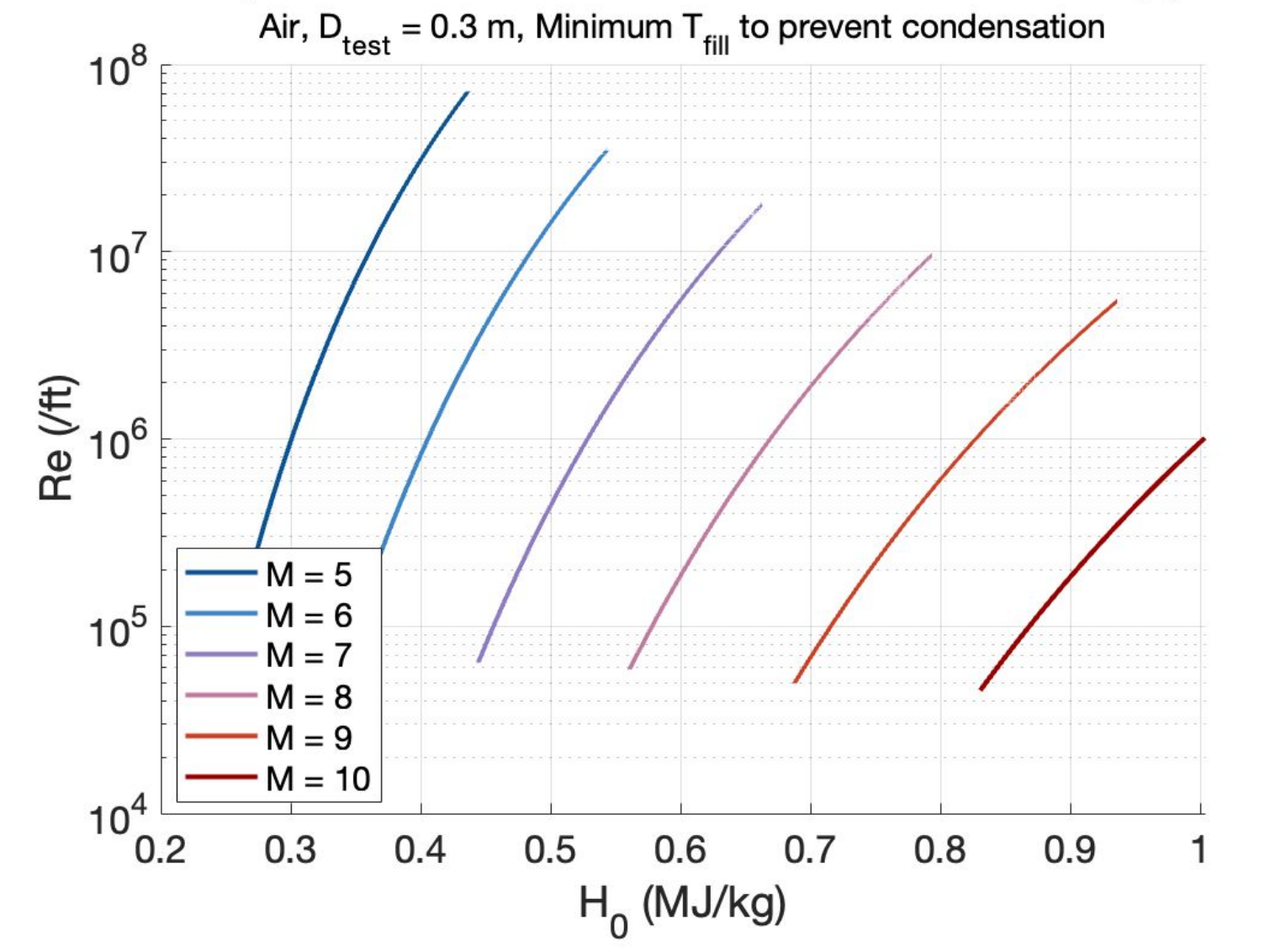
Test Time vs Tube Fill Pressure

Air, D_{test} = 0.3 m, Minimum T_{fill} to prevent condensation



Reynolds Number vs Test Section Total Enthalpy

Air, D_{test} = 0.3 m, Minimum T_{fill} to prevent condensation



Conclusion

- With D_{test} = 0.3 m, target M = 7, and the minimum T_{fill} to prevent condensation (445K - 663K), the Ludwieg tube will accommodate the flow with a range of Re from 6.40×10^4 to 1.78×10^7 /ft and t_{test} from 66.1 to 80.7 ms.

Future Work, References, and Acknowledgments

- Maximum pressure affected by tube fill temperature (structural concerns).
- Relationship between test section flow properties and flight conditions.

Faculty: Owen Williams
Graduate Student: Sumukh Peddada (Collaborator)
Undergraduate Student: Yeongjun “Marvin” Bok

[1] Pope, A. and Goin, K. L., “High-Speed Wind Tunnel Theory,” High-Speed Wind Tunnel Testing, Wiley, New York, 1965, pp. 35–38.
[2] Wegener, P. P. and Mack, L. M., “Condensation in Supersonic and Hypersonic Wind Tunnels,” Advances in Applied Mechanics, Vol. 5, 1958, pp.315-316.
[3] Davis, J. W. and Gwin, H. S., “Feasibility Studies of a Short Duration High Reynolds Number Tube Wind Tunnel,” NASA TM X-53571, January 1968.
[4] Wang, C., “Transient Flow Analysis of a Supersonic Ludwieg-Tube Wind Tunnel,” Master’s Thesis, Department of Mechanical and Aerospace Engineering, The University of Texas at Arlington, Arlington, TX, 1989.
[5] Gragston, M., Davenport, K., Siddiqui, F., Webber, N., Smith, C. D., Kreth, P. A., and Schmisseur, J. D., “Design and Initial Characterization of the UTSI Mach 7 Ludwieg Tube” AIAA Paper 2023-1457, January 2023. https://doi.org/10.2514/6.2023-1457
[6] Kreth, P., Gragston, M., Davenport, K., and Schmisseur, J., “Design and Characterization of the UTSI Mach 4 Ludwieg Tube,” AIAA Paper 2021-0384, January 2021. https://doi.org/10.2514/6.2021-0384

Rendered image of the existing pipes in AERB

Driver (6 ft x 2), will not be used for Ludwieg tube

Driven (12 ft x 2 + 6 ft x 4)

Nozzle – Test Section – Dump Tank

ADVISERS: OWEN WILLIAMS

WILLIAM E. BOEING
DEPARTMENT OF AERONAUTICS & ASTRONAUTICS