Appendix 8

Reentry Research Tools

Hypersonic Wind Tunnels

While the history of the military use of ballistic missiles rightly starts with the development of the A-4 (V-2) missile, perhaps just as important was the discovery by Allied troops of two highly advanced wind tunnel facilities at Peenemünde in the summer of 1945. Apparently one had been in operation, a small diameter (1.2 foot) super-supersonic wind tunnel for intermittent use up to Mach 5 and a larger diameter (3.3 foot) continuous flow super-supersonic wind tunnel designed for speeds up to Mach 10.

In 1945, the first hypersonic wind tunnel in the United States was proposed by John Becker at Langley. Design difficulties and a perceived lack of urgency by NACA and Langley administrators delayed the construction for over a year but in 26 November 1947, the first tests were successfully run at Mach 6.9.[1] Eggers at Ames, proposed a continuous flow hypersonic tunnel and it was completed in 1950. Between these two facilities, hypersonic research began in earnest, mainly focusing on aerodynamic issues directed towards supersonic aircraft research.

By 1955, the three major ballistic missile programs, the Air Force Thor (IRBM) and Atlas (ICBM) and the Army Jupiter (IRBM), made reentry vehicle research a high national priority. Two flight regimes required detailed study. The 1,500 nautical mile IRBM Thor and Jupiter warhead reentry speed would be nearly 15,000 feet per second while the 5,000 nautical mile range ICBM would be nearly 25,000 feet per second.[2] Basic ballistic shapes, along the lines suggested by Allen and Eggers were tested up to the Mach 7-10 capabilities of the early hypersonic wind tunnels, confirming their theoretical results. However, the limitations in run times and temperatures, as well as atmospheric densities, soon illustrated the need for additional testing facilities.

Shock Tubes

The first shock tube was built in France in 1899 by Vielle to study flame fronts and propagation speeds resulting from explosions.[3] The concept languished until 1946 when Payman and Shepard in Britain published a thorough description of the design and use of shock tubes in studying explosions in mines.[4]

There are many variations of shock tube design but all share a basic two chamber concept. The first chamber is separated from the second with a burst diaphragm calculated to burst when the gas in the first chamber is compressed to a predetermined value. Since 1949, shock tubes have been used to augment aerodynamic studies using hypersonic wind tunnels, in particular the use, by the mid-1950s, was focused on reentry vehicle design and material selection since speeds greater than Mach 10 could easily be achieved, as well as much higher temperatures. The major drawback was the limited duration of test conditions.[5,6] Both Ames and Langley utilized shock tubes for reentry vehicle research.[7,8]

Avco Corporation learned of the shock tube work of Arthur Kantrowitz at Cornell University=s School of Aeronautical Engineering funded by the Naval Ordnance Laboratory. Kantrowitz ran test models of the Mark 4 reentry vehicle that Avco was developing as a backup for the General Electric Mark 3 for Atlas, as well as the primary reentry vehicle for the Titan I. In 1956, he left Cornell to head up the Avco Everett Research Laboratory, where he led development of the ablative materials for the final Mark 4 design as well as for the Minuteman Mark 5 and Mark 11 reentry vehicles.[9]

Light-Gas Gun

The two-stage light-gas gun was invented in 1948, by E.J. Workman at the New Mexico Institute of Mining, as a method to dramatically increase projectile velocity. Despite the impressive German and Russian developments in artillery during World War II, perhaps the most famous of which was the German Tiger Tank 88 mm gun, projectile velocities remained at an upper limit of 9,000 feet/second.

The basic concept of the light-gas gun was to replace the gaseous byproducts of conventional gun powders which propelled the projectile, with a column of hydrogen or helium. A standard gunpowder cartridge was used to fire a plug down a barrel filled with helium or hydrogen (hence the term light-gas) which would compress to the bursting point, a diaphragm immediately behind the actual test projectile. When the diaphragm burst, compressed light-gas would propel the projectile down a second barrel allowing far greater velocities to be achieved, since the molecular weight of the propellant gas would now be approximately 1/8th that of the water, carbon dioxide and nitrogen byproducts of gunpowder combustion (4 g/mole for helium versus approximately 30 g/mole.)

Workman's research group received funding from the Army Ballistic Research Laboratory (BRL) and proved the concept, reaching a velocity of 9,800 feet per second, and then quickly extending it to nearly 14,000 feet per second. The results caught the attention of the BRL managers, the device was declared classified and removed, with all of the associated equipment, to the BRL facilities. Work did not continue at BRL for reasons that are not clear.

With the need for a relatively inexpensive method to flight test small models of proposed Atlas and Thor reentry vehicles, in the mid-1950s, the light-gas gun concept was given new life via contractors and universities as well as researchers at both Langley and Ames. Velocities were soon extended beyond 25,000 feet per second (Figure 1).[10]

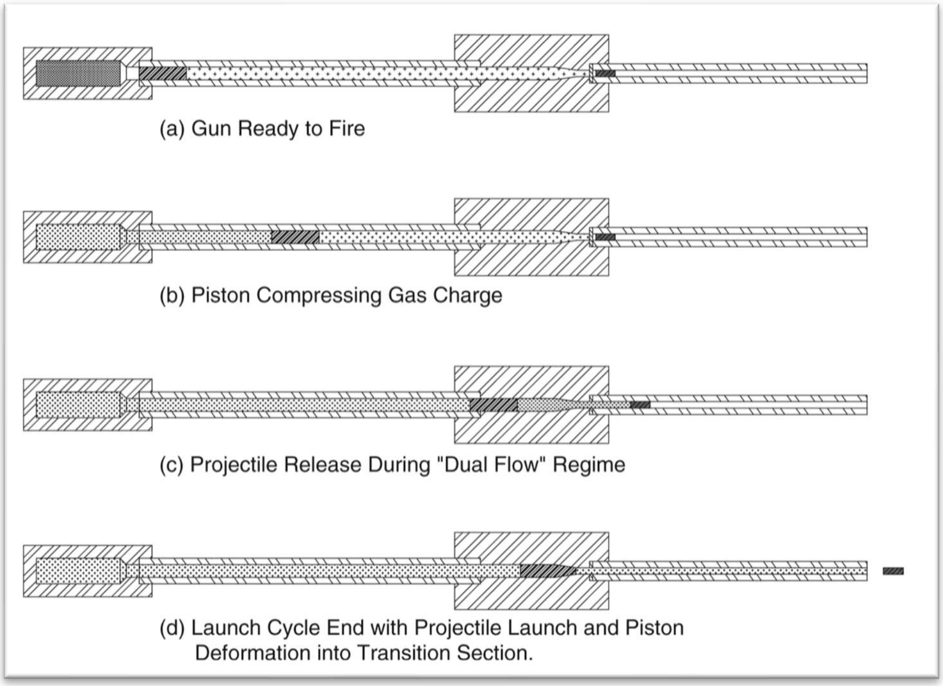

Figure 1. Stages of light gas gun operation. Used with permission, H. F. Swift, 2005.

Atmospheric Entry Simulator

At Ames in early 1955, Eggers pondered the idea of simulating reentry through the varying densities of the upper and lower atmosphere. Could a method be found for launching a test article at reentry speeds into a test chamber that could simulate the gradual increase in atmospheric density which was the most problematic for the thermal stress of reentry? A light-gas gun could be used for launching the test article as their development had progressed to provide reentry velocities but how to simulate the atmosphere at 100,000 feet where most of the aerodynamic heating takes place? The necessary 100-fold variation in atmospheric density in this part of the reentry envelope might be achieved using components of a supersonic wind tunnel, the settling chamber and the exit portion of a Mach 5 supersonic nozzle. Eggers reasoned that the light-gas gun could be used to fire a small-scale reentry vehicle model into the Mach 5 supersonic nozzle and then caught for detailed examination. The result was a small prototype Atmospheric Entry Simulator (AES) which was built in 1956, and successfully tested in 1957, evolving into a larger version in 1957.[11] This large AES was used successfully in exploratory work on blunt body copper heatsink designs meant for use on the shorter range and substantially lower heat regime IRBM missiles with reentry speeds of 15,000 feet per second (Figure 2).[12,13]

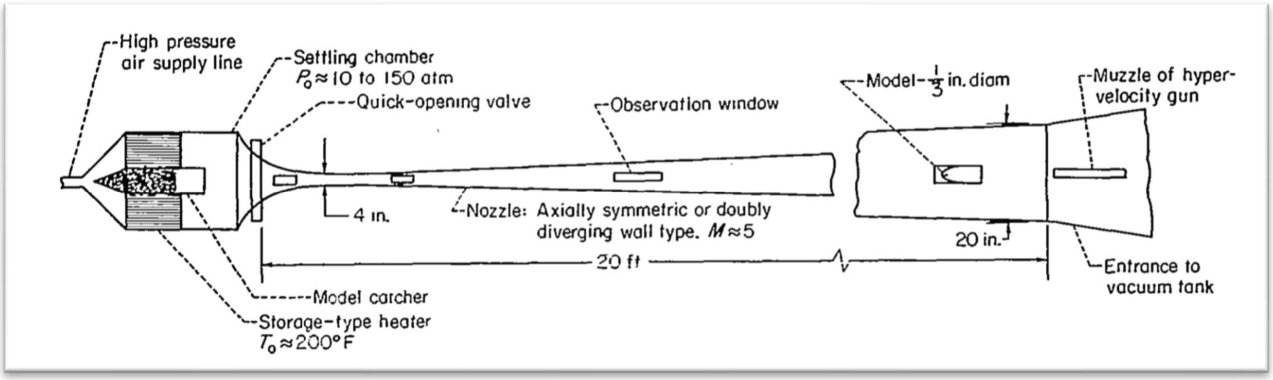

Figure 2. Early design of atmospheric entry simulator circa 1956. Eggers, 1958.

Arc Jet

Major drawbacks to the methods already addressed were the relatively short duration of test velocities and temperatures as well as the inability to reach the higher temperatures of reentry in a continuous flow wind tunnel. After investigating several possibilities, the solution appeared to be the use of an arc-jet heater. Research at Ames began in 1956 and resulted six years later in the Gas Dynamics Laboratory devoted to further arc-jet development for use in standalone testing of ablation materials. While arc-jet wind tunnels are used to study reentry phenomena in a step-wise manner, they are unable to simulate conditions of a constantly descending reentry vehicle.[14] Several different types of arc-jet heaters, including subsonic air arc-jet heaters and arc-jet radiant heaters also are used outside of a wind tunnel to study the ablative properties of materials. The arc-jet, with its more easily managed test conditions as well as longer test duration times, along with the fact that the test model was held in place, eventually replaced the AES for study of ablative materials at Ames.

Avco Corporation's Everett Research Laboratory and General Electric's Missile and Space Vehicle Division, among other labs, also employed variations of the arc-jet in their research and development of ablative materials for use on reentry vehicles. In 1958, James Fay, from the Massachusetts Institute of Technology and Avco's Frederick Riddell, published a theory that allowed calculation of boundary-layer conditions in high speed flight:

> The boundary-layer equations are developed in general for the case of very high-speed flight where the external flow is in a dissociated state. In particular the effects of diffusion and of atom recombination in the boundary layer are included. It is shown that at the stagnation point the equations can be reduced exactly to a set of nonlinear ordinary differential equations even when the chemical reactions proceed so slowly that the boundary-layer is not in thermochemical equilibrium.[15]

P.H. Rose and W. I. Stark at Avco published a paper at the same time comparing the theory against shock tube experimental results:

> Simulation of flight stagnation conditions at velocities up to satellite velocity of 26,000 feet per second is shown to be possible in shock tubes, and data has been obtained over a large altitude range at these velocities.[16]

These two papers extended that of Lester Lees published in 1956, which had been found to underestimate by as much as 30 percent, heat transfer rates at the reentry vehicle tip.[17] Now reentry vehicle researchers had a both experimental and theoretical methods for evaluating ICBM reentry vehicle materials and possible designs.

Rocket Motor Exhaust

Development of the Jupiter IRBM reentry vehicle took place at the Army Ballistic Missile Agency (ABMA) facilities at the Redstone Arsenal, Huntsville, Alabama. Researchers there used the exhaust from a number of different liquid rocket engines to test candidate jet vane materials to replace the troublesome graphite vanes used in the V-2 (Figure 3).[18]

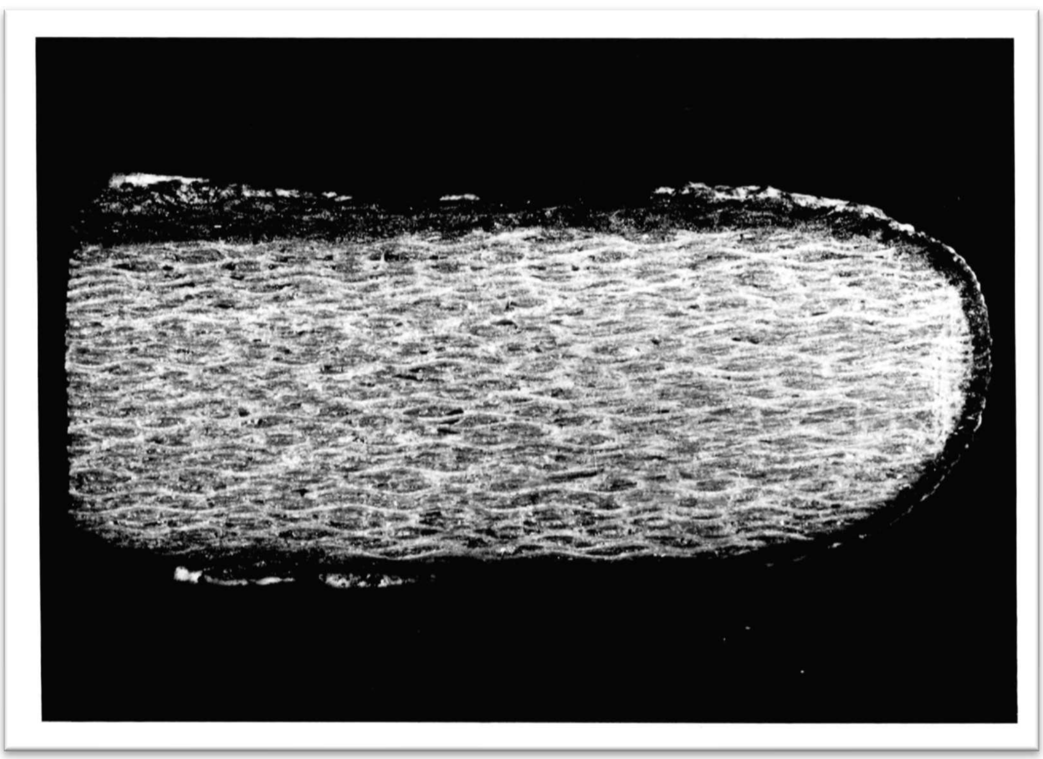

Figure 3. Reinforced plastic jet vane after exposure to rocket exhaust. The char layer is negligible. Lucas and Kingsbury 1960.

Endnotes

1. J.V. Becker, "Results of Recent Hypersonic and Unsteady Flow Research at the Langley Aeronautical Laboratory," *Journal of Applied Physics*, (July 1950), 620.

2. D. Schmidt, "Hypersonic Atmospheric Flight," in *Environmental Effects of Polymeric Materials*, (New York: Interscience Publishers, 1968), 489.

3. P. Vielle, "Sur Les Discontinuities Produites par la Brusque de Gas Comprises," 1899, *Comptes Rendus* 129, 1899, 1228.

4. W. Payman and C.F. Shepard, "Explosion Waves and Shock Waves. VI. The Disturbances Produced by Bursting Diaphragms with Compressed Air," 1946, *Proceedings of the Royal Science Academy*, Vol 186, (1946), 293.

5. B.D. Henshall, "On Some Aspects of the Use of Shock Tubes in Aerodynamic Research," (Aeronautical Research Council, Great Britain, 1957) Reports and Memoranda, No. 3044, 6.

6. H.J. Davis and H.D. Curchack, "Shock Tube Techniques and Instrumentation," (U.S. Army Material Command, Harry Diamond Laboratories, March 1969), Available as Defense Technology Information Center (DTIC) AD692295, TR-1429, 1-16.

7. Hartman, *Adventures in Research,* 241.

8. J.A. Shortal, *A New Dimension: Wallops Island Flight Test Range, the First Fifteen Years,* (National Aeronautics and Space Administration, Scientific and Technical Information Office, 1978), NASA Reference Publication 1028, 433.

9. G.H. Stine, *ICBM: The Making of the Weapon That Changed the World,* (New York: Orion Books, 1991), 187.

10. H.F. Swift, "Light-Gas Gun Technology: A Historical Perspective," in *High Pressure Shock Compressions of Solids, Vol. VIII,* (Berlin Heidelberg, Germany, 2005), 1-6.

11. A.J. Eggers "A Method for Simulating Atmospheric Entry of Long-Range Ballistic Missiles," (National Advisory Committee for Aeronautics, Ames Aeronautical Laboratory, 1958), TR-1378, 1009-1012.

12. Hartman, *Adventures in Research,* 238.

13. Ibid., 264.

14. Ibid., 339.

15. J.A. Fay and F.R. Ridell, “Theory of Stagnation Point Heat Transfer in Dissociated Air,” *Journal of Aeronautical Sciences*, Vol 25, No 2, (February 1958), 73-85.

16. P.H. Rose and W. I. Stark, “Stagnation Point Heat-Transfer Measurements in Dissociated Air,” *Journal of Aeronautical Sciences*, Vol 25, No 2, (February 1958), 86-97.

17. L. Lees, “Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Speeds,” *Jet Propulsion*, (April 1956), 259-269.

18. W.R. Lucas and J.E. Kingsbury, “A Brief Review of the ABMA Ablation Material Program,” (Redstone Arsenal, AL: Army Ballistic Missile Agency, 12 May 1960), ABMA DSN-TM-7-60 1, 3.