Shocking Discovery

By Paul Dorman and Rebecca Wright

Loud noises were heard coming from a University of Michigan aerospace lab Wednesday afternoon, November 16, 2005, as students performed experiments with shock tubes. Shock tubes, in this case, are not tubes that produce electrical shocks, but tubes in which shock waves travel through the air. The noises were not screams from students being electrocuted, but bangs from shock waves hitting the end of the tube. Shock waves are pressure waves moving through the air at above the speed of sound, creating regions of extremely high pressure and temperature behind them. Here, the students were using them to create conditions similar to those inside a burning rocket motor, to test possible propellants for use in a Mars mission.

"Those're my kids," TA Dan Macy said wistfully. It was his last day working with the undergrads for that lab class, since he would be leaving just a few short hours later for a job interview with Scaled Composites, the first private company to launch a human into space. Macy removed his omnipresent beret, took off his glasses, and wiped a tear from his eye. "These kids are the future of aerospace, right here. The kind of things they're learning about right now, they'll soon be applying on the job, getting us to Mars."

Shock waves are created by dividing the tube into two portions with an aluminum diaphragm, and pressurizing one side until the diaphragm bursts, creating a high pressure zone that rushes to the low pressure side behind a shock wave. The wave itself is very thin, less than a millimeter thick. When the shock wave passes through, the air jumps instantaneously from the lower pressure and temperature to the high pressure and temperature behind the wave. The students started by cutting out a diaphragm of aluminum foil to place between the two pieces of the tube, which were then clamped together. The aluminum burst at only 6 psi above atmospheric pressure, however, creating a shock wave going *only* about Mach 1.25, a disappointment to the students, who were hoping to achieve much higher Mach numbers and much louder bangs.

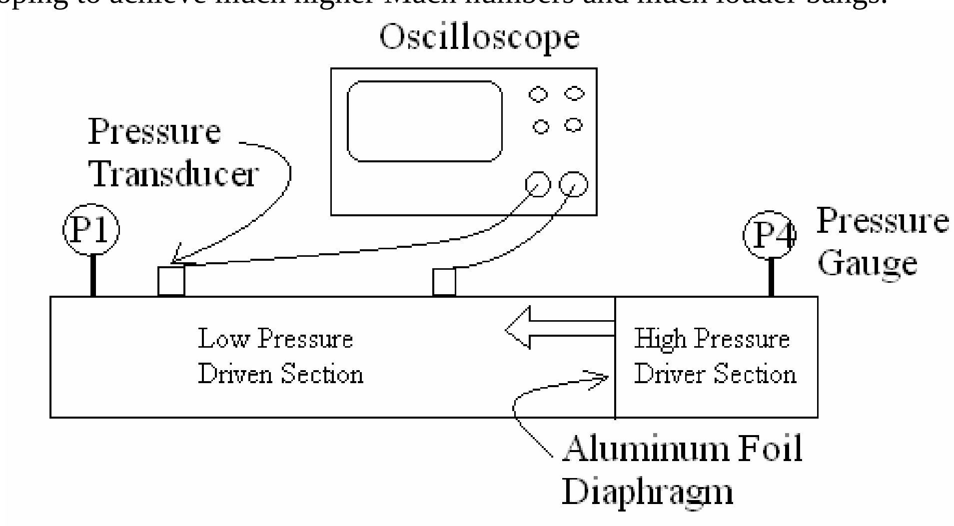


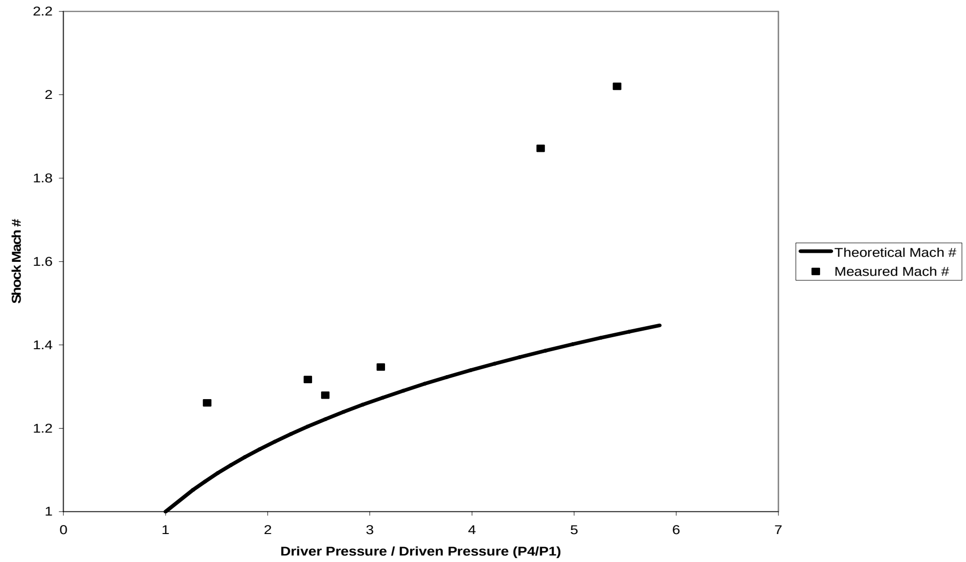
Diagram of shock tube setup.

The resourceful students quickly began cutting up more aluminum foil, placing sheets on top of each other to make thicker diaphragms capable of withstanding higher pressures, to generate higher Mach number shock waves. Templates were drawn on the aluminum and the scissors began to fly. Diaphragms with thicknesses from two to six layers of foil were created. Then someone discovered that the roll of aluminum foil had been used up. As long as each experiment ran as expected, they would be fine. But if for any reason they failed to collect the data for one of the diaphragms, it would be too late. Macy had to run the lab again in two hours for another group of students, so he donned his jacket and went in search of more aluminum foil, leaving the students to their own devices.

Then it happened. One of the runs failed, and the needed data were not taken. The shock tube has two pressure transducers along its length, which record the passage of the shock wave by creating a blip on an oscilloscope display. By finding the time between blips, the speed of the shock wave could be determined, since the distance between the two transducers was known. Unfortunately, the whole transducer/oscilloscope setup is rather subtle and sensitive. If it was not properly configured, it would not record the shock wave passing, and the speed could not be experimentally determined. The diaphragm had burst, the shock wave had sped by, and the oscilloscope had not shown the time. The situation seemed hopeless: all the aluminum foil had been used; there would be a massive hole in the data. Without their TA to give them direction, the students began milling about aimlessly for a little while, but then they began to look around for something they could use. And then they found a small section of aluminum foil, hidden beneath the scraps left over from creating the diaphragms. They carefully measured it to ensure it would be big enough, and then folded it to create the proper thickness and cut another diaphragm. This time through, everything worked perfectly, and they recorded the proper data. All the other test runs also succeeded, so all the data collection was done.

After the final run, with a diaphragm comprising six layers of aluminum foil, the students were ecstatic with the results: a measured speed of Mach 2.03 for the shock wave they created. This had required the high pressure region to be taken up to 5.42 atmospheres of pressure. Immediately after the shock wave had passed, their air was raised to 4.67 atmospheres and the temperature to 512°F. Then the shock wave hit the back of the tube and reflected, passing through the already heated and pressurized air to raise the temperature and pressure even further: 1108°F and 15.9 atmospheres. At least, if the measurement of the shock wave speed was accurate.

Unfortunately, the measured shock waves were not measuring up with the theoretically computed values. According to their equations, the last run, for which they measured the shock wave to be going at Mach 2.03, should have only had a shock wave Mach number of about 1.4, based on the pressure achieved in the high pressure driver section before the diaphragm burst. In fact, in comparing the measured values with the theoretical values, as shown in the figure below, the measured values were dramatically higher than their theoretical counterparts. They had not yet determined the source of the error at the time of printing, but they were quite hopeful that it was due to an improper equipment setup, most likely somewhere in the transducer/oscilloscope pairing.



Comparison of measured shock wave Mach number to theoretical value

The purpose of these experiments had been to achieve conditions similar to those inside a rocket in which magnesium and carbon-dioxide would burn, which requires 10 atmospheres of pressure and 3141°F. Clearly, even if the measured Mach numbers were accurate, these conditions would still be insufficient, since the Mg-CO_2 mixture would need to be about 2000°F hotter to burn.

Undeterred, the students decided to see if they could find a stronger diaphragm that would withstand greater pressure and result in a stronger shock wave to create hotter, higher-pressure conditions, suitable for testing rocket fuels. Casting about the lab room for a hapless object to employ as a diaphragm, they came upon a thick plastic bag, whose functionality as a container they sacrificed in order to further the cause of science. They cut a piece out large enough to cover the cross section, and clamped the tube shut. As the pressure rose, students began betting on when it would burst. 10, 35, and 50 psi above atmospheric pressure were offered as possible bursting points. Then, with all eyes on the pressure gauge, the bag popped at 4 psi above atmospheric pressure. The students were sorely disappointed in the performance of this material that they had thought would bring them glory. Alas, it was time for the next group to come in and do their experiments.