MECHANICAL & AEROSPACE ENGINEERING
GAS DYNAMICS LABORATORY

# AE 164 SHOCK TUNNEL EXPERIMENTS

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# AE 164 Shock Tunnel Experiments

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# AE 164 Shock Tunnel Experiments

## Purpose

The purpose of this experiment is to study hypersonic flow in the shock tunnel with emphasis on flow characteristics in the driven section and the test section. Flow past various geometric models in the test section will be studied with the aid of schlieren visualization techniques. The experiment allows direct comparisons of theory with measurements.

## Objectives

1. **Calibrate the flow in the test section.** Design an experiment and calculate from your measurements the effective Mach number ($M_e$) and the effective value of the specific heat ratio ($\gamma_e$) in the test section (nozzle exit). From these values you will then be able to calculate the free stream values for the temperature ($T_e$), pressure ($P_e$), and density ($\rho_e$) in the test section. Use 2 methods (i.e., design 2 separate experiments) to accomplish this:
   a. Using the **asymmetric wedge.**
   b. Using the **sphere.**

   In your design consider the following questions:
   a. What kind of pressure ratio $P_4 / P_1$ do I want? (How will this ratio affect the $M_e$ in the test section?)
   b. What kind of gas do I want as driver?
   c. What kind of gas do I want as driven?
   d. What kind of data do I need to collect to be able to calculate $M_e$ and $\gamma_e$?
2. **Design** and **perform** a shock tunnel experiment to study the hypersonic flow around a **sphere**, **compare** your results with theoretical predictions and **explain** any discrepancies. In your design consider the following questions:
   a. What kind of pressure ratio $P_4 / P_1$ do I want? (How will this ratio affect the $M_e$ in the test section?)
   b. What kind of gas do I want as driver?
   c. What kind of gas do I want as driven?
   d. How do the different gases in the driven section affect the flow over the sphere?

   4 gases are available in the lab: Ar, He, $CO_2$, $N_2$.
3. **Design** and **perform** a shock tunnel experiment to study the hypersonic flow around a **cone**, **compare** your results with theoretical predictions and **explain** any discrepancies. Also, compare your results from the cone with your results from the wedge with the same semi-apex angle and discuss any differences.

## Nomenclature

| | |
|---|---|
| $A$ | area of the nozzle at the exit |
| $A^*$ | area of the nozzle at its throat |
| $a_1$ | speed of sound for the driven gas |
| $a_2$ | speed of sound behind the incident shock wave |
| $a_3$ | speed of sound immediately behind the burst of the primary diaphragm |
| $a_4$ | speed of sound for the driver gas |
| $k$ | mean density ratio across the shock wave formed on the model in the test section |
| $M_6$ | Mach number immediately behind the shock wave formed on the model in the test section |
| $M_e$ | effective Mach number in the test section |
| $M_r$ | Mach number of gas ahead of the reflected wave relative to the wave |
| $M_s$ | Mach number of the incident shock wave |
| $P_1$ | local pressure of the driven gas |
| $P_2$ | local pressure behind the incident shock wave |
| $P_3$ | pressure immediately behind the burst of the primary diaphragm |
| $P_4$ | local pressure of the driver gas |
| $P_{05}$ | stagnation pressure behind the shock wave after it is reflected at the nozzle entrance |
| $P_{06}$ | stagnation pressure behind the shock wave formed on the model in the test section |
| $P_6$ | pressure immediately behind the shock wave formed on the model in the test section |
| $P_e$ | nozzle exit and test section free stream pressure |
| $R_s$ | radius of the sphere model |
| $T_1$ | initial temperature of the driven gas |
| $T_2$ | temperature behind the incident shock wave |
| $T_3$ | temperature immediately behind the burst of the primary diaphragm |
| $T_4$ | initial temperature of the driver gas |
| $T_e$ | nozzle exit and test section free stream temperature |
| $T_{05}$ | stagnation temperature behind the shock wave that is reflected at nozzle entrance |
| $T_{06}$ | stagnation temperature immediately behind the shock wave formed on the model in the test section |
| $T_6$ | temperature immediately behind the shock wave formed on the model in the test section |
| $U_p$ | velocity of the contact surface and mass motion that follows the incident shock wave |
| $W$ | velocity of the incident shock wave |
| $W_r$ | velocity of reflected shock wave |
| $\beta_1$ | smaller shock wave angle on the test model |
| $\beta_2$ | larger shock wave angle on the test model |
| $\Delta$ | bow shock standoff distance on the sphere model |
| $\gamma_1$ | specific heat ratio of the driven gas |

| | |
|---|---|
| $\gamma_2$ | specific heat ratio behind the incident shock wave |
| $\gamma_4$ | specific heat ratio of the driver gas |
| $\gamma_e$ | effective value of the specific heat ratio in the test section |
| $\rho_1$ | density of the driven gas |
| $\rho_2$ | density behind the incident shock wave |
| $\rho_{05}$ | stagnation density behind the shock wave that is reflected at the nozzle entrance |
| $\rho_6$ | density immediately behind the shock wave formed on the model in the test section |
| $\rho_{06}$ | stagnation density immediately behind the shock wave formed on the model in the test section |
| $\rho_e$ | nozzle exit and test section free stream density |
| $\theta_1$ | smaller geometric angle on the asymmetric wedge test model |
| $\theta_2$ | larger geometric angle on the asymmetric wedge test model |

## THEORY

### Introduction

The shock tunnel concept was developed in the 1950's to study **hypersonic gas dynamics**. A shock tunnel is composed of five major parts: a **driver section**, a **driven section**, a **nozzle**, a **test section**, and a **dump tank** (figure 1). A **primary diaphragm**, located between the driver and the driven sections, is ruptured due to the difference in pressure between the driver gas ($P_4$) and the driven gas ($P_1$). The pressure discontinuity present after the rupture propagates into the driven gas as a **normal shock** and into the driver gas as an **expansion fan**. As the normal shock travels down the driven section with velocity W, it will increase the pressure behind it and **induce a following mass motion** with velocity $U_p$. An interface called the **contact surface** exists between the driver and driven gases; it also moves with velocity $U_p$ (figure 2).

### Incident Shock Wave in Driven Section

The flow in the shock tunnel is completely determined by the given conditions in the driver (region 4) and driven (region 1) sections at the instant the diaphragm ruptures. The incident shock strength, $P_2/P_1$, is related to the ratio $P_4/P_1$:

$$\frac{P_4}{P_1} = \frac{P_2}{P_1}\left[\, 1 - \frac{(\gamma_4-1)\left(\frac{a_1}{a_4}\right)\left(\frac{P_2}{P_1} - 1\right)}{\sqrt{2\gamma_1}\sqrt{2\gamma_1 + (\gamma_1+1)\left(\frac{P_2}{P_1} - 1\right)}}\,\right]^{\left[\frac{-2\gamma_4}{\gamma_4-1}\right]} \tag{1}$$

Once $P_2$ has been calculated, e.g., by using iteration, all the other properties including temperature, density, and velocity are easily found. The Mach number and the speed of the shock also can be determined in terms of $P_2$, $P_1$, and $\gamma_1$:

$$M_s = \sqrt{\frac{\gamma_1 - 1}{2\gamma_1} + \left(\frac{\gamma_1 + 1}{2\gamma_1}\right)\left(\frac{P_2}{P_1}\right)} \tag{2}$$

$$W = M_s a_1 \tag{3}$$

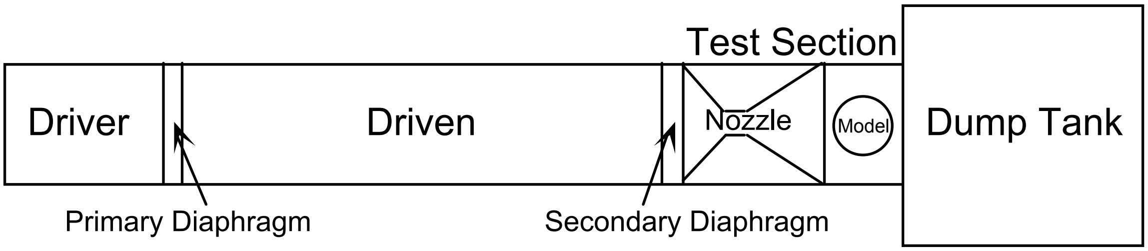

Figure 1. Shock Tunnel Main Components

The density in region 2, $\rho_2$, is found using the equation

$$\frac{\rho 2}{\rho 1} = \frac{1 + \left(\frac{P_2}{P_1}\right)\left(\frac{\gamma_1 + 1}{\gamma_1 - 1}\right)}{\frac{\gamma_1 + 1}{\gamma_1 - 1} + \frac{P_2}{P_1}} \tag{4}$$

The speed of the contact surface, $U_p$, can also be calculated:

$$Up = W\left[1 - \frac{\rho 1}{\rho 2}\right] \tag{5}$$

It is also possible to find $T_2$, the temperature in region 2:

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\left[\frac{\frac{\gamma_1 + 1}{\gamma_1 - 1} + \frac{P_2}{P_1}}{1 + \left(\frac{P_2}{P_1}\right)\left(\frac{\gamma_1 + 1}{\gamma_1 - 1}\right)}\right] \tag{6}$$

### Reflected Shock Wave in Driven Section

When the incident shock reaches the end of the driven section, it causes a secondary diaphragm located at the nozzle entrance to rupture. The incident shock is nearly completely reflected, creating a reservoir of stagnant and high enthalpy gas, which feeds the nozzle (figure 3). This reservoir of working gas expands through the nozzle into the test section.

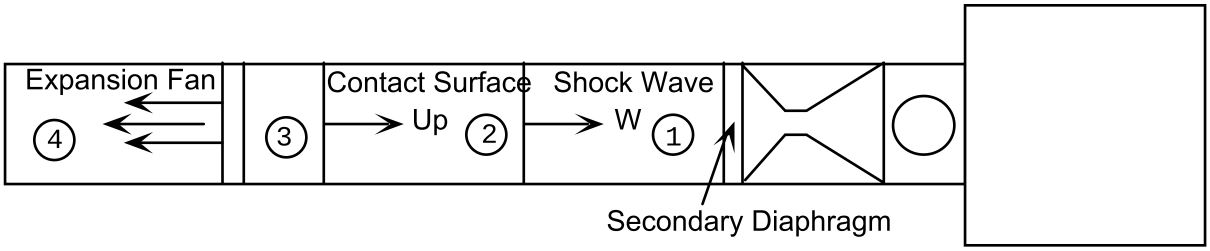

Figure 2. Shock Tunnel Incident Waves

As the reflected shock wave travels back through the driven section at speed $W_r$ away from the nozzle, it travels only a relatively short distance before striking the contact surface between the driver and driven gas. Upon striking this contact surface, the reflected shock wave will do one of three things:

1. Reflect back as a compression wave, tending to increase the nozzle reservoir pressure. This condition is called **overtailored**.
2. Reflect back as an expansion fan, tending to decrease the nozzle reservoir pressure. This condition is called **undertailored**.
3. Match a special condition with the contact surface so that the two will cancel each other out. This is called the **tailored condition**.

In the first and second conditions, there will be a resultant change in the pressure and temperature of the gas at the nozzle reservoir. If this change is significant, the reservoir will not be quasi-constant and the resulting test time of useful flow (quasi-constant conditions) will be terminated. In the third condition, however, testing times are increased, because the pressure rise across the reflected shock wave will be the same in the driven and driver gases. i.e. the pressure reservoir ($P_{05}$ history) is undisturbed. In this case, the useful flow (test time) is terminated by either the driver gas coming through the nozzle or by the reflection of the expansion waves from the driver section when they reach the nozzle end of the driven section.

Knowing the incident shock Mach number $M_1$, the reflected shock Mach number $M_r$ can be found by solving the quadratic equation:

$$\frac{M_r}{M_r^2 - 1} = \frac{M_s}{M_s^2 - 1}\sqrt{1 + \left(\frac{2(\gamma_1 - 1)(M_s^2 - 1)}{(\gamma_1 + 1)^2}\right)\left[\gamma_1 + \frac{1}{M_s^2}\right]} \tag{7}$$

Once $M_r$ is known, $W_r$ can be calculated using the two equations:

$$\boxed{a_2 = a_1\sqrt{\frac{T_2}{T_1}}} \tag{8}$$

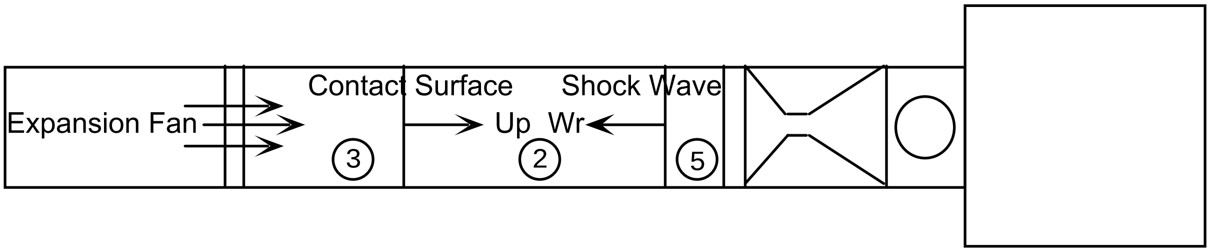

Figure 3. Shock Tunnel Reflected Waves

and

$$\boxed{W_r = M_r a_2 - U_p} \tag{9}$$

Using the value for $W_r$ , $\rho_{05}$ can be found:

$$\boxed{\rho_{05} = \frac{\rho_2(W_r + U_p)}{W_r}} \tag{10}$$

With $\rho_{05}$ now known, $P_{05}$ can be calculated from either of the two equations (remember static properties are equal to stagnation properties in the stagnant reservoir of region 5):

$$\boxed{P_{05} = P_2 + \rho_2(W_r + U_p)^2 - \rho_5 W_r^2} \tag{11a}$$

or

$$\frac{P_{05}}{P_2} = 1 + \frac{2\gamma_2}{\gamma_2 + 1}\left[M_r^2 - 1\right] \quad \text{where} \quad \boxed{\gamma_2 = \frac{a_2^2}{RT_2}} \tag{11b}$$

The equation for $T_{05}$ is:

$$\frac{T_{05}}{T_2} = \left(\frac{P_{05}}{P_2}\right)\left(\frac{\dfrac{\gamma_2 + 1}{\gamma_2 - 1} + \dfrac{P_{05}}{P_2}}{1 + \dfrac{\gamma_2 + 1}{\gamma_2 - 1}\dfrac{P_{05}}{P_2}}\right) \tag{12}$$

**Nozzle Flow Properties**

As the incident shock reflects off the nozzle entrance, the reservoir pressure of the nozzle $P_{05}$ builds up quickly, and then is affected by the tailoring conditions. The reservoir pressure $P_{05}$ will then begin to drop smoothly as the gas leaves and flows into the converging / diverging nozzle. The nozzle geometry, along with gas chemistry effects, will establish the Mach number, and change the specific heat ratio of the flow exiting the nozzle into the test section. The nozzle exit properties are very important; they will be calculated in this experiment with the crude approximation that the nozzle flow is isentropic.

Unfortunately, not all of these properties are easy to calculate even with the isentropic assumption. Due to gas chemistry and molecular vibrational modes at elevated temperatures, the ratio of specific heats (gamma) is a function of temperature and pressure. The design Mach numbers for the nozzles used in the SJSU shock tunnel facility correspond to a monatomic gas value for gamma, i.e., 1.67. The high-temperature effects experienced by the flow in this facility require the freestream test section flow to be calibrated. This involves using two different methods in the present experiment to determine the effective Mach number $M_e$ and the specific heat ratio $\gamma_e$ in the test section freestream flow. The two methods for determining $\gamma_e$ and $M_e$ are presented in the following sections. Keep in mind, however, that $\gamma_e$ and $M_e$ must be determined in order to use the nozzle flow relations.

The nozzle exit temperature $T_e$, pressure $P_e$, and density $\rho_e$, can be found from the following equations:

$$\frac{T_{05}}{T_e} = 1 + \frac{\gamma_e - 1}{2} M_e^2 \tag{13}$$

$$\frac{P_{05}}{P_e} = \left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)^{\frac{\gamma_e}{\gamma_e - 1}} \tag{14}$$

$$\frac{\rho_{05}}{\rho_e} = \left(1 + \frac{\gamma_e - 1}{2} M_e^2\right)^{\frac{1}{\gamma_e - 1}} \tag{15}$$

These flow conditions at the exit of the nozzle will be used later for calculating properties of the flow past the model in the test section.

## References

1. Thompson, Phillip, *Compressible Fluid Dynamics*, McGraw-Hill, Chapter 7, 1972.
2. Saad, Mitchell, *Compressible Fluid Flow*, Prentice-Hall, 1985.
3. Bleakney, Walker & Emrich, R. J., *High Speed Aerodynamics and Jet Propulsion*, *"The Shock Tube,"* (available in the lab)
4. Pope, A. & Goin, Kenneth, *High Speed Wind Tunnel Testing*, Drieger Publishing, 1978.
5. Anderson, John, *Modern Compressible Flow*, McGraw-Hill, 3rd ed., 2003.
6. Anderson, John, *Fundamentals of Aerodynamics*, McGraw-Hill, 3rd ed., 2001.
7. Glass & J. Gordon Hall, *Shock Tubes, Section 18 of the Handbook of Supersonic Aerodynamics*, ed. I. I., Department of the Navy, NAVORD Report 1488 (Volume 6), 1959.

## Equipment List

| | Item | Model/Part Number |
|---|---|---|
| 1. | Tektronix Dual Power Supply | PS503A |
| 2. | PCB Charge Amplifiers (3 each) | 464A |
| 3. | Shutter Driver Circuit (Open/Close Shutter) | None |
| 4. | Uniblitz Shutter Drive Unit | 100-2 |
| 5. | Timing Generator | SP-387-3 |
| 6. | PCB 6-Channel Voltage Amplifier | 484A08 |
| 7. | IBM-AT Clone Computer | PC TECH |
| 8. | Computer Display | NEC Multisync II |
| 9. | Epson Printer | LQ510 |
| 10. | Omega Digital Pressure Indicators (2 each) | DP41-S |
| 11. | Omega Pressure Sensor, 0-15psia | PX811-015AV |
| 12. | Omega Pressure Sensor, 0-900psia | PX811-900AV |
| 13. | RC Electronics A/D Converter | 386261 |
| 14. | RC Electronics Scope Software | 386261 |
| 15. | RC Electronics Compuscope Board | 386261 |
| 16. | Duniway Dual Thermocouple Vacuum Gauge | TCG-531/2 |
| 17. | Duniway Thermocouple Gauge Tubes (3 each) | DST-531 |
| 18. | Matheson Two Stage Regulator with Gauges (Driven) | 8H-580 |
| 19. | Matheson Two Stage Regulator with Gauges (Driver) | 2-580 |
| 20. | PCB Piezoelectric Pressure Sensors, Charge Mode (3 ea) | 113A |
| 21. | PCB Piezoelectric Pressure Sensors, ICP Mode (2 each) | 105AO2, 105B02 |
| 22. | Uniblitz Normally Closed Shutter | 214L2A1T5 |
| 23. | Oriel 3 Inch 600mm Converging Lenses (2 each) | 42760 |
| 24. | Oriel 2 Inch 200mm Converging Lens | 42650 |
| 25. | Oriel 2 Inch 100mm Converging Lens | 42629 |
| 26. | Oriel 2 Inch 400mm Converging Lens | 42670 |
| 27. | Optical Rails [50mm (2), 100mm (1), 25mm (1)] | None |
| 28. | Hi Voltage Components Power Supply | S300 |

|  |  |  |  |
|---|---|---|---|
| 29. | Hi Voltage Components Spark Gap Light Source |  | SS55P |
| 30. | Optical Rods and Mounts (7) |  | None |
| 31. | Duo-Seal Vacuum Pumps (2 each) | 1397 |  |
| 32. | Omega Condenser Enlarger |  | D5V-XL |
| 33. | Gralab Timer |  | 505 |
| 34. | Kodak 4” x 5” Black and White Film | 4147 |  |

**Data Analysis**

There are five piezoelectric pressure sensors mounted along the shock tunnel at several locations. The data acquisition system processes data from these sensors and from two electronic circuits that control the photographic system. Please note that the third channel (S3) may occasionally malfunction. If this occurs, use the $P_{05}$ sensor to get a third shock arrival time.

| Channel | Data Source |
|---|---|
| 1 | Charge sensor (S1), mounted in the center of the driven section (S1 is also the trigger sensor). |
| 2 | Charge sensor (S2), mounted on the driven section downstream of S1. |
| 3 | Charge sensor (S3), mounted near the end of the driven section before the nozzle reservoir $P_{05}$ sensor. |
| 4 | Spark gap light source trigger (This tells when the spark source fired). |
| 5 | Voltage sensor ($P_{05}$), mounted at the end of the driven section at the nozzle entrance. |
| 6 | Voltage sensor ($P_3$), mounted on the primary diaphragm. |
| 7 | Shutter driver circuit output (This tells when the shutter is open; it takes about 2.2 milliseconds for the shut |

This table is a short reference sheet on the commands needed to operate the scope data acquisition software. Refer to Appendix A for a step-by-step tutorial.

| Key | Function(s) |
|---|---|
| <u>Main Screen</u> |  |
| Esc | aborts or quits the current operation, including exiting the program when no operations are being carried out (Do **<u>not</u>** save the default file when exiting the program). |
| L | loads a data file from the disk |
| M | modifies any of the parameters visible on the screen (Do **<u>not</u>** modify anything except the title). |
| S | saves the current data onto the disk |
| V | switches to the scope mode |

### Scope Mode

| | |
|---|---|
| 1… 8 | allows the channel whose number corresponds to the key hit to be adjusted horizontally or vertically with the cursor keys (All channels move if a horizontal adjustment is made. The rate of movement can be changed by entering a number between 1 and 9. The default is 1, which is slow; try using 5 for fast scrolling). |
| Esc | aborts or quits the current operation |
| Cntrl V | invokes a cursor mode for getting accurate voltage (pressure) and time data. Enter channel numbers for the left and right cursor and use the cursor keys to move them. To change channels, enter L for the left channel or R for the right channel and then enter the new channel number. |
| Shift > | decreases the time scale, showing more detail but fewer data points |
| Shift < | increases the time scale, showing less detail but more data points |
| F1 | switches out of the scope mode back to the main screen |

Using this function reference table, fill out a data sheet (found in Appendix B) for each run. Your experimental value for $P_2$ is the difference between the average pressure before and after the shock wave plus the value of $P_1$. The experimental value for $P_{05}$ is the average of the first three values after the first jump in $P_{05}$ plus the value of $P_1$.

In order to acquire data from the models, enlarged prints must be developed from the negatives. This will be done only **once** during the laboratory experiment. A laboratory assistant will provide instruction, and supervision for using the enlarger. Do **<u>not</u>** try to make prints without assistance!

### Pre-Laboratory Preparation

Using eq.(1) and assuming room temperatures prior to membrane rupture, prepare a wide-range graph of $P_{41}$ (semilog) vs $P_{21}$ for each driver gas / test gas combination in the Table of Runs. Compare the Helium / Nitrogen graph to that in Appendix D. Use the graphs you have generated for guidance in the expected $P_{41}$ / $P_{21}$ performance of the tunnel in the laboratory.

### Report Inclusions: Calculations & Discussion

1. Calculate theoretical and experimental values for $M_s$, W, $M_r$ and $W_r$ for each run.
2. Calculate the following properties for each run: $P_2$, $T_2$, $\rho_2$, $P_{05}$, $T_{05}$, $\rho_{05}$, $U_p$. Compare the experimental values for $P_{05}$ with your theoretical calculations.

3a. For the asymmetric wedge model runs, calculate $M_e$ and $\gamma_e$. This will calibrate the flow entering the test section.

3b. Using data from the sphere runs, calculate $M_e$ and $\gamma_e$. This should also calibrate the flow in the test section.

3c. Compare the results of part (a) and part (b) and explain any differences in the two identical runs (with different models).

3d. Discuss briefly why the $\gamma_e$ values determined in parts (3a) and (3b) are not equal to the gas's ideal (room temperature) value; compare the inferred (calculated) values with real values as a function of temperature as given by the graphs in Appendix D (estimate the nozzle exit temperature).

4a. Calculate the anticipated results for $P_6$, $T_6$, $\rho_6$, $P_{06}$, $T_{06}$, $\rho_{06}$, the downstream conditions for the wedge, using ideal correlations and the calibrated test section flow. Remember that there are two different region 6 areas for the wedge.

4b. How would you expect the cone shock angle and strength would compare to those of the wedge (no calculations necessary)? Do the experimental observations support your conclusions?

4c. For the sphere model runs, calculate the following properties of the flow immediately behind its detached shock wave: $P_6$, $T_6$, $\rho_6$, $T_{06}$, $P_{06}$, $\rho_{06}$.

5. Describe why the results for $P_2$ and $M_s$ between sensors S1, S2, and S3 varied among each other and deviated from the theoretical calculations.

6. Do a brief error analysis and make suggestions for improving the experiment. Please be specific. Especially comment on to which measurements the $M_e$, $\gamma_e$ results are most sensitive.

# Appendix A:
# General Shock Tunnel Operation Instructions

## Preparation for Pumping

1. Make sure that Valves 1, 3 and 4 are closed.
2. Turn on both vacuum pumps. Both pumps will be operating continuously throughout the laboratory periods.
3. Allow the vacuum pumps to run for at least 20 minutes when first started so that they can warm up. If you fail to allow warmup before pumping the tunnel, you will strain the pumps and it will take longer for a reasonable vacuum to be achieved.
4. Make sure that both the primary and secondary diaphragms are new, and they have the proper thicknesses for the run that you are planning to do. If they have been used or you need to change the thickness, unbolt the shock tunnel at the appropriate place and replace the diaphragms.

   Guidelines for Changing Diaphragms

   a. Never recycle used mylar diaphragms, even if they are unbroken.
   b. When changing the secondary (test section) diaphragm, use the large "ratchet" socket wrench instead of the power drill. Also avoid bumping any part of the schlieren optical system, watch out for the wire coming from the P5 sensor, and make sure the wrench does not touch the S3 sensor mounted on the tube.
   c. When changing the primary diaphragm, use the power drill to save time and energy.
   d. When bolting and unbolting the nuts, always work on the nut directly opposite from the nut you last tightened or untightened. Do not overtighten any nuts! If you cannot turn them with your hand, they are tight enough. The sealing is done by the o-rings, not the nuts!
   f. **Never** work on both diaphragms at the same time. Someone will probably get their fingers smashed if you ignore this warning and open up and work both ends of the tube at the same time.
   g. Always use as many 0.010 inch mylar diaphragms as possible to achieve the desired thickness for the primary diaphragm. If you use several 0.005 inch or 0.001 inch pieces of mylar, you will get a different burst pressure ($P_4$) than you would normally expect.
   h. Always inspect the o-rings briefly when changing diaphragms. If they are obviously damaged, replace them. If they are falling out of their groove, gently push them back in. If they are dry, apply a thin coating of Dow Corning vacuum grease.
   i. Never leave the tube unbolted for a long period of time. Dirt and grim from the lab room will quietly find their way onto the o-rings and prevent a good seal.

5. Open Valve 2 and turn the thermocouple vacuum gauge on. Channel 2 gives the pressure in the test section and Channel 1 is connected to the driven section. It is necessary to monitor the driven section because the pressure in the driven section can affect $P_1$.
6. Turn on all of the electronic equipment on the table, except for the spark source power supply and the shutter driver circuit. (There is a pushbutton switch on the Tektronix power supply that toggles the power to the shutter driver circuit on/off).
7. Make sure that all three PCB 464A charge amplifiers are grounded. (A toggle switch near the bottom controls the condition of the amplifier. It should be in the down position).
8. After the AT-clone computer has booted up, press the V key to enter the scope mode.
9. Load a sheet of Kodak 4147 film into a film holder in the darkroom. This must be done in absolute darkness and the notched edge of the film should be in the lower right corner of the film holder (the film is held in the fight handand the film holder in the left with the cover slid open to the left). If a viewing screen is mounted on the camera, remove it before mounting the film holder on the camera. Ask a lab assistant for assistance if you are unfamiliar with this process.
10. Check the amount of driver gas in the gas bottle by briefly opening Valve 8 and taking a reading from the pressure gauge. If the pressure of the bottle does not exceed the expected $P_4$ by 25%, you should change gas bottles (ask lab assistant). Make sure that Valve 8 is tightly shut when you are finished.

*Shortcut for Experienced Operators: If you change the secondary diaphragm first, you can immediately open Valve 1 and begin evacuating the air from the test section, which usually takes longer than evacuating the driver and driven sections.*

**Pumping a Vacuum**

1. Open valves 1, 3 and 4. This will allow both pumps to begin evacuating the air from the shock tunnel.
2. Wait until the vacuum in the test section is less than 200 millitorrs before proceeding. This should take about 20 to 30 minutes if the pumps were allowed to warm up properly. If the vacuum does not materialize, there is probably a leak. Ask a lab assistant for help.
3. When the test section is ready, check the vacuum in the driven section. It should be less than (roughly) 300 millitorrs. If the thermocouple vacuum gauge is not giving a reading in that range, consult a lab technician. Usually either the pump is not working properly or there is a leak in the tunnel.

**Preparing the Gases and Data Acquisition Systems**

1. **Close Valves 2, 3 and 4**.

   *Note: From this point you must work rapidly or you will lose the vacuum you need to run the shock tunnel. These instructions should be executed in less than **two minutes**!*
2. To load the driven gas, open Valve 6 briefly (with Valve 7 closed) and close it. Open Valve 7 slightly and slowly fill the driven section. If you need about 1 psia or more for $P_1$, you will need to close Valve 7 and repeat the procedure until you have reached the desired $P_1$. **Close Valve 5**.
3. Make sure that **Valves 5, 6 and 7 are closed tightly** after the driven gas has been loaded.
4. **Close Valve 1**, throw the toggle switch in the lower right corner of all three PCB charge amplifiers up to the operational mode, and activate the data acquisition system by pressing the Control and "S" keys on the computer keyboard simultaneously.
5. Open Valves 8 and 9, but make sure that Valve 9 is only slightly open, so that you will build up pressure slowly and be able to get an accurate reading for $P_4$.
6. Turn on the spark source power supply and the shutter driver circuit when $P_4$ reaches about 250 psia. (There is a pushbutton switch on the Tektronix power supply that toggles the power to the shutter driver circuit on/off). The LED on the circuit board indicates that the power is on. Press the pushbutton switch on the board once to prepare the circuit for triggering. The LED should turn off.
7. Slide the cover out of the film holder when $P_4$ reaches 250 psia (the cover should already be mounted on the camera) so that the film can be exposed.
8. Watch the Omega high-pressure indicator rise to the anticipated $P_4$ value and prepare for a brief bang sound.

*Note: It is often convenient for one person to execute Steps 4-6 while another person does Steps 7-8. Make sure that the person doing Steps 4-6 has enough time to do everything before the primary diaphragm bursts!*

**Activities Immediately After Firing**

1. **Close Valves 8 and 9 immediately** and open any or all of Valves 10, 11 and 12 - the relief valves for the Driver, Driven and Dump Tank Sections, respectively..
2. Slide the cover for the film back into place before removing the film holder from the camera.
3. Turn off the spark source power supply and the shutter driver circuit. (The LED on the circuit board will be on if the camera shutter was triggered).
4. Throw the toggle switch on the PCB charge amplifiers back to the ground position.
5. Print data first (see computer instructions at the end of this section). Then save the data collected by the computer by first pressing the F1 key. Check the title at the top and make sure that the information on $P_4$, $P_1$, the model, and the gases is correct. If it needs to be modified, press the "M" key and type in the changes. When the title is correct,

press the escape key and follow the prompts at the bottom of the screen. To save the file on floppy disk, press "S" key, enter a unique name for your run (without any spaces or special characters), and follow the prompts at the bottom of the screen. After your data is saved you may analyze it and print out a copy. (See the section in the lab instructions on data analysis).

6. Take the film holder into the darkroom and remove the film from it in total darkness. Place the film in a metal frame holder for developing. First, put the film into the developer for 7 minutes, then move it to the acid stop bath solution for 30 seconds before putting the film into the rapid fixer for 2 minutes. Use the digital timer on the enlarger to keep track of the time. When the film is removed from the fixer, you can turn on the lights and wash the negative in water for a few minutes until it is clear. Put the negative in the photoflow tray for several seconds and then shake the excess solution off. Mark your file name on the negative. Hang the negative in a dustless environment for drying. After an hour it should be dry enough so that it can be removed from the metal holder and stored in a safe place. If you are unfamiliar with the process of film development, ask the lab technician for assistance.

**Preparation for Another Run**

1. Change the primary and secondary diaphragms following the guidelines on the first page.
2. Repeat Steps 9-11 from the section "Preparation for Pumping" and then proceed to the section "Pumping a Vacuum."

*Note: Make sure that all of the electronic equipment is turned off and the computer and printer covered when you are finished using the shock tunnel!*

## LIST OF VALVES & LOCATIONS

| Valve # | Location |
|---|---|
| 1 | Test Section / Dump Tank Vacuum Source |
| 2 | Test Section / Dump Tank Thermocouple Pressure Sensor |
| 3 | Driver Section Vacuum Source |
| 4 | Driven Section Vacuum Source |
| 5 | Driven Section Pressure Sensor |
| 6 | Test Gas Bottle Source |
| 7 | Test Gas Delivery |
| 8 | Driver Gas Bottle Source |
| 9 | Driver Gas Delivery |
| 10 | Driver Section Residual Pressure Bleed |
| 11 | Driven Section Residual Pressure Bleed |
| 12 | Test Section / Dump Tank Residual Pressure Bleed |

## INSTRUCTIONS FOR PCTECH COMPUTER

### Opening / Closing a Session

1. Turn Computer on.
2. Press **F1**.
3. Type **Scope**.
4. Then parameter input screen comes up with input choices at bottom of menu.
5. Record the conversions of S1, S2, S3 and P5 from the top of the menu.
6. Change only top 2 lines of parameters as appropriate.
7. Press **V** to view scope showing the default file.
8. Press **Control-S** when ready to activate.
9. Press **Control-Shift-Prt-Sc** to print after the data are captured, and mark an appropriate file name on the printout (e.g., M1R4 for Monday Team 1, Run 4).
10. Press **Control-V** to show the cursors and record the readings.
11. Press **Esc** to discard cursors.
12. Press **F1** to return to main menu.
13. Press **S** to save file on floppy disk (have floppy in top drive, drive A, and drive locked).
14. Filename?: **A:XY** (same filename as used in step 9)
15. Save Buffer (Y/N)? **Y**
16. Press **ESC** to quit SCOPE.
17. Save system Status onto Default File (Y/N)? **N**
18. Turn computer off.

Note: To bring back up a data set already captured: **L**

then: **A:XY**

# Appendix B: Data Sheets

The next several pages contain data sheets for each run. Make sure that your team has at least two complete sets of data for all of the runs. One set of data should be included in your final report. Even after you have filled out the data sheets, you should keep a copy of the scope data files on one of your own floppy disks just in case you need to check the data. **Do not plan on using the hard disk on the computer to store anything!**

# Data Sheet 1.1 (Run # 1)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 1.2 (Run # 1)

## Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

## $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

## Wedge Angles

| | |
|---|---|
| $\theta_1$ | |
| $\beta_1$ | |
| $\theta_2$ | |
| $\beta_2$ | |

**Notes and Observations (like $P_{05}$ history)**

# Data Sheet 2.1 (Run # 2)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 2.2 (Run # 2)

## Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

## $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

## Sphere Data

| | |
|---|---|
| $\Delta$ | |
| $R_s$ | |

**Notes and Observations (like $P_{05}$ history)**

# Data Sheet 3.1 (Run # 3)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 3.2 (Run # 3)

## Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

## $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

## Cone Angles

| | |
|---|---|
| $\theta_1$ | |
| $\beta_1$ | |
| $\theta_2$ | |
| $\beta_2$ | |

**Notes and Observations (like $P_{05}$ history)**

# Data Sheet 4.1 (Run # 4)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 4.2 (Run # 4)

### Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

### $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

### Sphere Data

| | |
|---|---|
| $\Delta$ | |
| $R_s$ | |

**Notes and Observations (like $P_{05}$ history)**

# Data Sheet 5.1 (Run # 5)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 5.2 (Run # 5)

## Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

## $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

## Sphere Data

| | |
|---|---|
| $\Delta$ | |
| $R_s$ | |

**Notes and Observations (like $P_{05}$ history)**

# Data Sheet 6.1 (Run # 6)

| | |
|---|---|
| $T_1$ | |
| $P_1$ | |
| $T_4$ | |
| $P_4$ | |
| Primary Diaphragm Thickness | |
| Secondary Diaphragm Thickness | |
| Distance between sensors S1 and S2 | |
| Distance between sensors S2 and S3 | |
| Distance between sensors S1 and $P_{05}$ | |

**Sensor S1**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

**Sensor S2**

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

# Data Sheet 6.2 (Run # 6)

## Sensor S3

| | |
|---|---|
| Incident Shock Arrival Time | |
| Reflected Shock Arrival Time | |

| | Before Shock | After Shock |
|---|---|---|
| 1. | | |
| 2. | | |
| 3. | | |
| 4. | | |
| Average | | |

$P_2$ (After Shock Average - Before Shock Average + $P_1$):

## $P_{05}$ Sensor

| | |
|---|---|
| Incident Shock Arrival Time | |

| | After Shock |
|---|---|
| 1 | |
| 2 | |
| 3 | |
| Average | |
| $P_{05}$ (After Shock Average + $P_1$) | |

## Sphere Data

| | |
|---|---|
| $\Delta$ | |
| $R_s$ | |

**Notes and Observations (like $P_{05}$ history)**

# Appendix C: Computer Programs

### Asymmetric Wedge

The Program Wedge is located in the directory called BASIC. It will calculate the nozzle exit flow effective gamma and Mach number for the asymmetric wedge. You will be asked to enter $\beta_1$ and $\beta_2$, the shock wave angles, which must be measured carefully from an enlarged schlieren picture. The $15^o$ and $25^o$ values for $\theta_1$ and $\theta_2$, respectively, have been installed in the program. Note that since $\theta_1$ is the smaller angle, $\beta_1$ must be entered as the smaller shock wave angle.

The program performs an iterative calculation through a for/next loop using the two equations that express gamma as a function of Mach number. If no convergence occurs, then either the Mach number range or the step value of the loop may have to be changed. The computer solution can be checked (and students should do this) by showing with manual calculations that the two equations are satisfied with the determined values of gamma and Mach number.

### Sphere

The Program Sphere is also located in the directory called BASIC. It calculates the nozzle exit flow effective gamma and Mach number using the measured bow shock location for the sphere. You will be asked to enter $\Delta$ and $R_s$; note that $\Delta$ must be accurately measured on enlarged prints of the schlieren visualization negative images. You will also be asked some information about the nozzle being used. The nozzle used in your experiment has an area ratio of 9.72 corresponding to a Mach number of 5.0 for a gas gamma equal to 1.67. After this information is entered, you will be asked to indicate the acceptable deviation of results or to accept the stored value. The program listing and a portion of a sample run follows after the information on the Wedge program.

Note: Since these computer programs have not been compiled, you will need Microsoft BASIC or GWBASIC to run these programs. Unless you have access to either of these two applications, it is strongly advised that you get the data from the photographs and run the programs on the laboratory computer before your scheduled periods in the laboratory are completed. However, if you wish (and you have your own compiler), you may copy the two programs to a floppy disk and run them outside of the laboratory.

# Appendix D: Graphs

## Gamma Graphs

The next page has two graphs of gamma. The top graph shows gamma as a function of temperature at one atmosphere for the driven gases that you will be using. This will give you a general idea if your values for $\gamma_e$ are reasonable. The bottom graph shows gamma as a function of temperature and pressure for air. This graph will only be useful for the nitrogen run, but it shows that gamma is actually a complex function of temperature and pressure.

## Pressure/Mach Number Graphs

The following several pages have some helpful graphs showing the relationship of $P_4/P_1$ to both $P_2/P_1$ and the Mach number of the incident shock wave. There are two sets of graphs, one set for each of the two driven gases. These graphs will help you solve eq.(1), and give you a better understanding of shock tunnel performance.