Questions (100 pts)

1. Briefly describe the general trends observed in the post-shock density, pressure, temperature, and velocity when thermochemical effects (including chemical and vibrational non-equilibrium) are incorporated in the calculation of normal shock waves in air at hypersonic speeds. Illustrate your response by giving equilibrium values of the post-shock density, pressure, velocity and temperature far downstream of the shock (in the equilibrated region) in the case of a pre-shock velocity $U_1 = 18,000 \text{ ft/s}$ at an altitude of 200,000 ft in the atmosphere (see figures in the class notes), and compare these values with those that would be obtained using the theory of calorically perfect gases.

2. Estimate the distance required for equilibration of the vibrational molecular motion in pure $N_2$ gas behind a Mach-8 normal shock in air at a pre-shock pressure $P_1 = 15 \text{ bar}$ and temperature $T_1 = 230 \text{ K}$. How many collisions have the gas molecules undergone along the equilibration distance?

3. Consider the re-entry of an ellipsoidal projectile in the terrestrial atmosphere. The projectile has semimajor axis $A = 10 \text{ cm}$ and semiminor axis $B = 5 \text{ cm}$, and is made of a heat resistant alloy of density $\rho_s = 10,000 \text{ kg/m}^3$. The angle of attack with respect to the semimajor axis is always zero. The ellipsoid enters the atmosphere at a velocity $V_E = 15 \text{ km/s}$ at an angle $\gamma_E = 45^\circ$ with respect to the local horizontal. Calculate the maximum acceleration of the projectile normalized with the acceleration of gravity, the altitude at which the maximum acceleration is attained, the kinetic energy upon collision with the ground, and the percentage of the initial kinetic energy that has been dissipated into heat during the re-entry. In your calculations, use the Newtonian theory of hypersonics to estimate the drag coefficient of the projectile (or see midterm exam solutions).