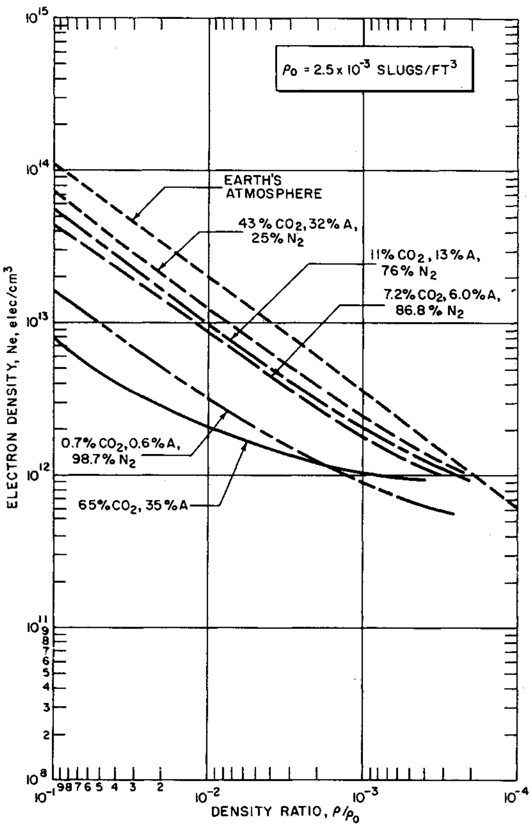

Fig. 7 Equilibrium electron density on Mars and Earth, temperature = 5000°K.

Table 2 Equilibrium electron density for 100% N_2 and 98.7% N_2, 0.6% CO_2, 0.7% A atmospheres

Temperature, °K	Density, slugs/ft³	N_e, elec/cm³ 100% N_2	N_e, elec/cm³ 98.7% N_2, 0.6% CO_2, 0.7% A
2000	2.3×10^{-6}	1.17×10^{-1}	7.1×10^{4}
2000	2.3×10^{-4}	1.17	4.8×10^{5}
3500	2.3×10^{-6}	4.82×10^{7}	8.1×10^{9}
3500	2.3×10^{-4}	4.72×10^{8}	2.1×10^{11}
5000	2.3×10^{-6}	2.37×10^{11}	8.3×10^{11}
5000	2.3×10^{-4}	1.64×10^{10}	1.55×10^{13}

that assumed by Davies are shown in Table 2. As can be seen, the electron concentrations predicted by a 100% nitrogen atmosphere are too small by several orders of magnitude at low temperatures. The preceding discrepancy brings out an important point in determining the properties of any reentry plasma, namely, that relatively small amounts of an easily ionizable species (e.g., NO) may be the dominant source of electrons.

References

[1] Kaplan, L., private communication from Jet Propulsion Laboratory to Avco/RAD (August 2, 1963).

[2] Spiegel, G. F., "Effects of Mars atmospheric uncertainties on entry vehicle design," Aerospace Eng. **21**, 62–63, 103–107 (December 1962).

[3] Feldman, S., "Trails of axi-symmetric hypersonic blunt bodies flying through the atmosphere," Avco Everett Res. Rept. 82 (December 1959).

[4] Davies, W. O., "Electrical properties of shock waves on Mars," AIAA J. **1**, 464–466 (1963).

[5] Kopal, Z., "Aerodynamic effects in planetary atmospheres," Aerospace Eng. **19**, 10–11, 36–46 (December 1960).

[6] Treanor, C. E. and Logan, J. G., Jr., "Thermodynamics of nitrogen from 2000°–8000°K," Cornell Aeronautical Lab. Rept. BE-1007-A-5 (January 1957).

Measurement of Uniform Flow Duration in a Chambered, Buffered Shock Tube

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THIS report shows results obtained in the investigation of uniform flow duration in a chambered, buffered tube. This testing has been done at lower density and higher Mach number than has been reported previously.

The investigation is being conducted in the Martin-Denver shock tube,[1] which uses a buffer section, cold driver gas, and an area contraction to give high shock Mach numbers. The tube has a 3-ft-long driver with a $10\frac{1}{8}$-in. i.d., a 10-ft-long buffer with the same i.d. as the driver, a $16\frac{1}{2}$-ft-long test section with a 4-in. i.d., and a dump tank 15 ft long with a $19\frac{1}{4}$-in. i.d. Air at pressures of 0.015 to 1.0 mm Hg at shock Mach numbers 12 and 15 was the test gas. Argon was used as the buffer gas, and hydrogen as the driver.

Uniform flow duration was measured by detecting the passage of the shock front and contact surface using a monochromator and an attached 1P21 photomultiplier mounted at a quartz window in the test section. Photomultiplier output was monitored by a Tektronix 545A oscilloscope and an attached Polaroid camera. The monochromator was aligned so the optical axis was perpendicular to the axis of the test section, and light was collimated with a slit system. This arrangement eliminated scattered light and insured a narrow, sharp view of the shock front. The monochromator was set at 4500 Å with a 60 Å bandpass.

Figure 1 shows a typical oscilloscope intensity/time trace from this test configuration. The first peak is the nonequilibrium overshoot caused by the shock front passing through the air. The second rise has been attributed to the contact surface, containing highly radiative impurities from the tube wall, buffer-test section diaphragm, etc.

To verify the assumption that the second rise represents passage of the contact surface, chromium carbonyl [$Cr(CO)_6$] vapor was introduced into the buffer section before admitting the argon. This vapor readily decomposes into chromium and carbon monoxide, and, when shock heated, the neutral chromium atom emits a number of intense spectral lines in the 4500 Å region.[2] This radiation is readily distinguishable and thus validates the position of the contact surface. This, in turn, would define the maximum uniform flow time.

In Fig. 2, the chromium radiation appears as a spike between the two original rises (the gain setting of this trace is only $\frac{2}{5}$ that of Fig. 1). Its shape is similar to the nonequilibrium radiation overshoot produced by initial shock passage in

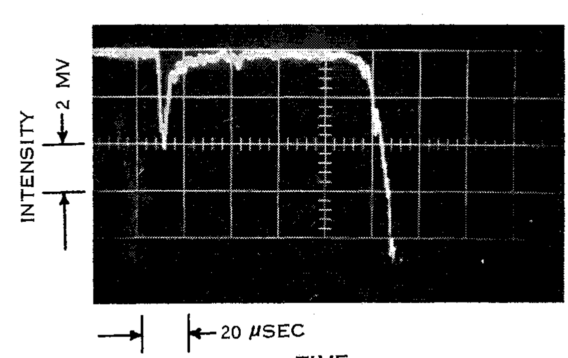

Fig. 1 Typical radiation profile; initial test pressure 0.2 mm Hg, M_s = 13.2.

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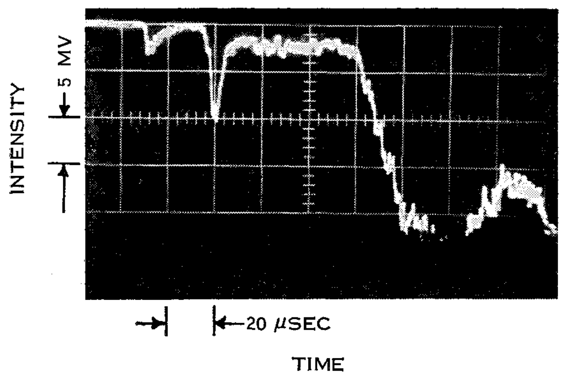

Fig. 2 Radiation profile with $Cr(CO)_6$ in buffer; initial test pressure 0.2 mm Hg, M_s = 13.0.

air. The equilibrium radiation that follows the chromium overshoot is greater, however, and the final abrupt rise is somewhat damped.

There appears to be no question that the new spike is caused by chromium. Similar tests, using carbon monoxide in the buffer, were run and produced no intermediate overshoot. If the chromium spike is considered the leading edge of the contact surface, then the uniform flow time is considerably shorter than previously believed. The rapid quenching of the chromium radiation is attributed to the fact that the argon in the buffer inefficiently transfers energy to the chromium by collision, and therefore the chromium temperature is effectively 400° to 500°C cooler than would be expected with a diatomic buffer gas.[3]

Roshko[4] and others[5, 6] have discussed the problem of flow duration in low-pressure shock tubes. By analyzing the effects of the laminar boundary-layer buildup behind the shock wave, Roshko has developed a theory that relates the various parameters affecting the uniform flow time such as initial test pressure, shock Mach number, and tube diameter. We have used this theory to calculate the uniform flow time for our tube using real gas properties for the various experimental conditions.

Figures 3 and 4 plot flow duration against initial pressure in the test section at Mach 12 and 15, respectively, and include a curve representing the calculated maximum values. The circles are experimental times from initial air radiation overshoot to chromium peak, and the squares are times from initial overshoot to final rise in radiation intensity.

In summary, the buffer gas, as indicated by the chromium carbonyl experiments, arrives substantially earlier than previously assumed from other indications of arrival of the contact region. Computed flow duration values (an upper limit, according to Roshko's treatment) correlated well with the time of appearance of the chromium spike for the higher test pressures. At very low pressures, however, flow times appear to be longer (Figs. 3 and 4) than predictions based on Roshko, and may indicate the onset of a slip condition at the

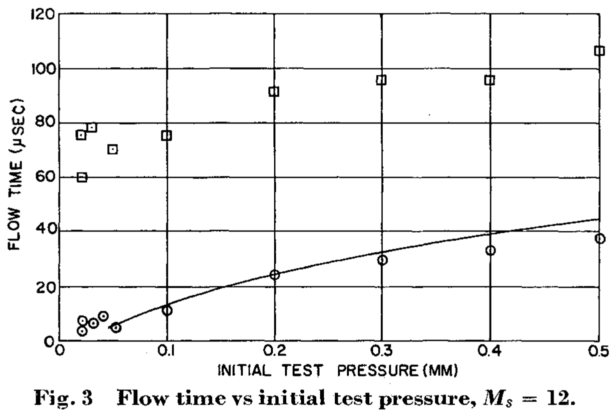

Fig. 3 Flow time vs initial test pressure, M_S = 12.

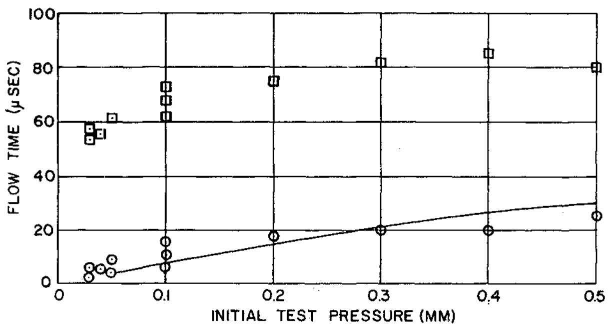

Fig. 4 Flow time vs initial test pressure, M_S = 15.

walls. Preliminary data at even lower pressures appear to substantiate this difference. This work is continuing.

References

[1] Chapin, S. G. and Heyman, R. J., "Performance characteristics of the high performance shock tube," Rept. R-60-37, Martin Co., Denver, Colo. (November 1960).

[2] Wilkerson, T., "The use of the shock tube as a spectroscopic source with an application to the measurement of gf-values for lines of neutral and singly ionized chromium," PhD Thesis, Univ. of Michigan (1961).

[3] Hurle, I. R., private communication, Cornell Aeronautical Lab. Inc., Cornell Univ. (January 1964).

[4] Roshko, A., "On flow duration in low-pressure shock tubes," Phys. Fluids **3**, 835 (1960).

[5] Hooker, W. J., "Testing time and contact-zone phenomena in shock-tube flows," Phys. Fluids **4**, 1451 (1961).

[6] Mirels, H., "Test time in low-pressure shock tubes," Phys. Fluids **6**, 1201 (1963).

Turbulent Boundary Layers with Transpiration

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A UNIVERSAL equation is presented for the mean velocity in the outer region of turbulent boundary layers with suction or injection through a porous wall. The equation includes $F(y/\delta)$, the universal function of y/δ which occurs in the velocity defect equation for zero pressure gradient and zero blowing velocity, but the equation contains no additional empirical constants. Many authors have attempted, with limited success, to generalize the velocity defect equation for zero pressure gradient to include the cases of suction and injection. Mickley and Smith,[1] for instance, propose an equation for the outer region of turbulent boundary layers with injection, but their equation possibly needs modifying when there is suction. Mickley and Smith's equation is

$$(u_1 - u)/u_\tau^* = F(y/\delta) \tag{1}$$

where $F(y/\delta)$ is the same function as that in the velocity defect law for zero pressure gradient and zero blowing velocity, and $u_\tau^*[=(\tau/\rho)^{1/2}]$ is based on the maximum total shear stress. When there is zero blowing velocity, the maximum shear stress occurs at the wall, and Eq. (1) is then the accepted velocity defect law for zero pressure gradient and zero blowing velocity. When there is suction, the maximum shear stress again occurs

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