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# A TECHNIQUE FOR DETERMINING THE NOZZLE FLOW PROPERTIES OF AIR IN AN EQUILIBRIUM, NONEQUILIBRIUM, OR FROZEN STATE

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One of the problems associated with the development of high-enthalpy hypersonic test facilities has been the determination of nozzle flow properties. This note presents a technique for determining the flow properties of air in an equilibrium, nonequilibrium, or frozen state using two test section measurements.

A knowledge of two stagnation properties is required before the technique can be applied. The stagnation pressure can be measured, and reference 1 offers a method for determining stagnation enthalpy. Results of the calculations using the method of reference 1 are presented in reference 2 in a chart (chart 21) which can be readily used to determine the stagnation enthalpy from measurements of stagnation pressure, mass flow of air through the tunnel, and throat diameter. Experimental enthalpies obtained using the method of reference 1 have been compared with those obtained using an energy-balance technique for 50 runs in a small hypersonic arc-heated tunnel of the High-Temperature Fluid Mechanics Section of the NASA, Langley Research Center, and were found to agree within 4 percent.

In illustrating the technique for determining nozzle flow properties a stagnation pressure [illegible] stagnation enthalpy of 4500 BTU/lb is assumed. It is also assumed that the test section static pressure and pressure behind a normal shock can be measured.

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Although the following discussion is based on the measurement of these two pressures, the technique would still be applicable if any two test section properties, such as velocity, speed of sound, density, temperature or even the shock detachment distance, were known. The key to the technique is to construct a chart such as figure 1. Figure 1 presents calculated curves of the variation of stagnation pressure behind a normal shock with free-stream static pressure for equilibrium, nonequilibrium, and frozen flow. The equilibrium curve can be calculated by using the method described in reference 3. The frozen (frozen reactions and frozen vibrations) results were calculated assuming air to be composed of 23 per cent oxygen and 77 per cent nitrogen (see reference 4). The nonequilibrium calculations were made by using Bray's approximate method (see reference 5), which assumes the air is in equilibrium up to a point and then freezes rapidly, remaining frozen until passing through a normal shock, whence it returns to a state of equilibrium. Bray indicates that the assumption of equilibrium flow behind the shock is reasonable. The methods of references 3 and 4 were used to calculate the equilibrium and frozen parts of the nonequilibrium flow respectively. Points of freezing were chosen at effective area ratios, $A/A^*$, of 1, 2, and 4. Measurement of the free-stream static pressure and the stagnation pressure behind a normal shock enables the curve corresponding to the state of the flow to be determined from figure 1. (If the shock detachment distance and stagnation pressure behind a normal shock are the measured quantities in the test section, then the state of the flow could be determined from a figure showing the variation of shock detachment distance with stagnation pressure behind a normal shock for equilibrium, nonequilibrium, and frozen flow.) Several additional measurements along the axis of the nozzle of the stagnation pressure behind a normal shock and the static pressure, will determine if a nonequilibrium expansion remains frozen to the same degree along the nozzle, thus giving a check on Bray's assumption of rapid freezing. The effective area ratio corresponding to the pressure measurements can also be determined from figure 1. Once the effective area ratio is known, the flow properties, the effective boundary layer displacemant thickness, and the size of the test "core" can be determined.

The flow properties can be obtained from plots such as figure 2. This figure presents the variation of free-stream Mach number with static pressure for equilibrium, nonequilibrium, and frozen flow. (Similar plots can be constructed for other flow properties.) Once the free-stream static pressure has been measured and the state of the air determined from figure 1, Mach number can be obtained by use of figure 2.

[1] Warren, W.R., "Determination of Air Stagnation Properties in a High-Enthalpy Test Facility", Journal of the Aero-Space Sciences, Readers' Forum, Vol. 26, No. 12, pp. 835-836, Dec., 1959.

[2] Yoshikawa, K.K., and Katzen, E.D., "Charts for Air-Flow Properties in Equilibrium and Frozen Flows in Hypervelocity Nozzles", NASA TN D-693, April, 1961.

[3] Erickson, W.D., and Creekmore, H.S., "A Study of Equilibrium Real-Gas Effects in Hypersonic Air Nozzles, Including Charts of Thermodynamic Properties for Equilibrium Air", NASA TN D-231, April, 1960.

[4] Heims, S.P., "Effects of Chemical Dissociation and Molecular Vibrations on Steady One-Dimensional Flow", NASA TN D-87, August, 1959.

[5] Bray, K.N.C., "Departure from Dissociation Equilibrium in a Hypersonic Nozzle", Aero. Research Council, No. 19,983, March, 1958.

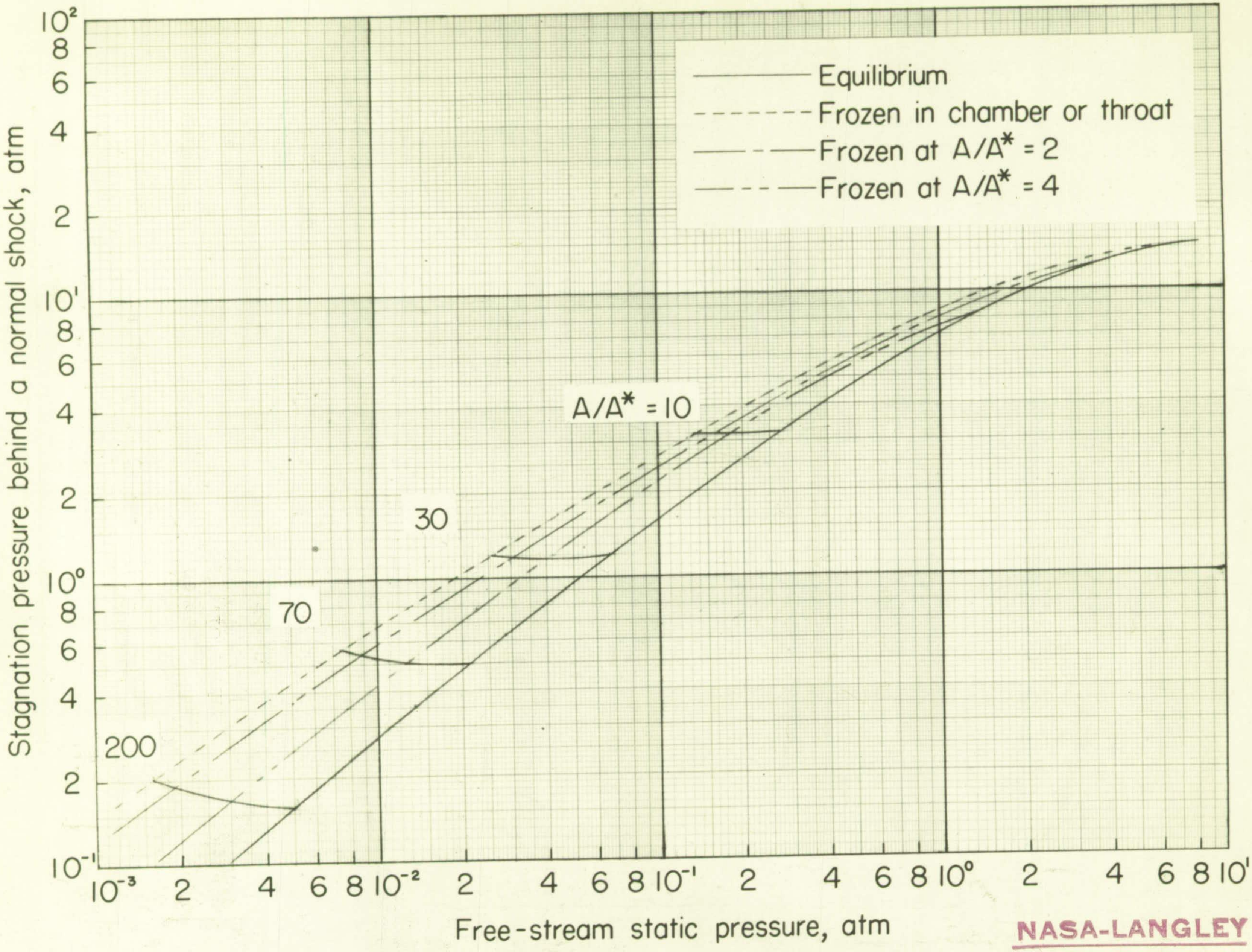

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Fig. 1. Variation of stagnation pressure behind a normal shock with free-stream static pressure at a stagnation pressure of 20 atm and stagnation enthalpy of 4500 BTU/lb.

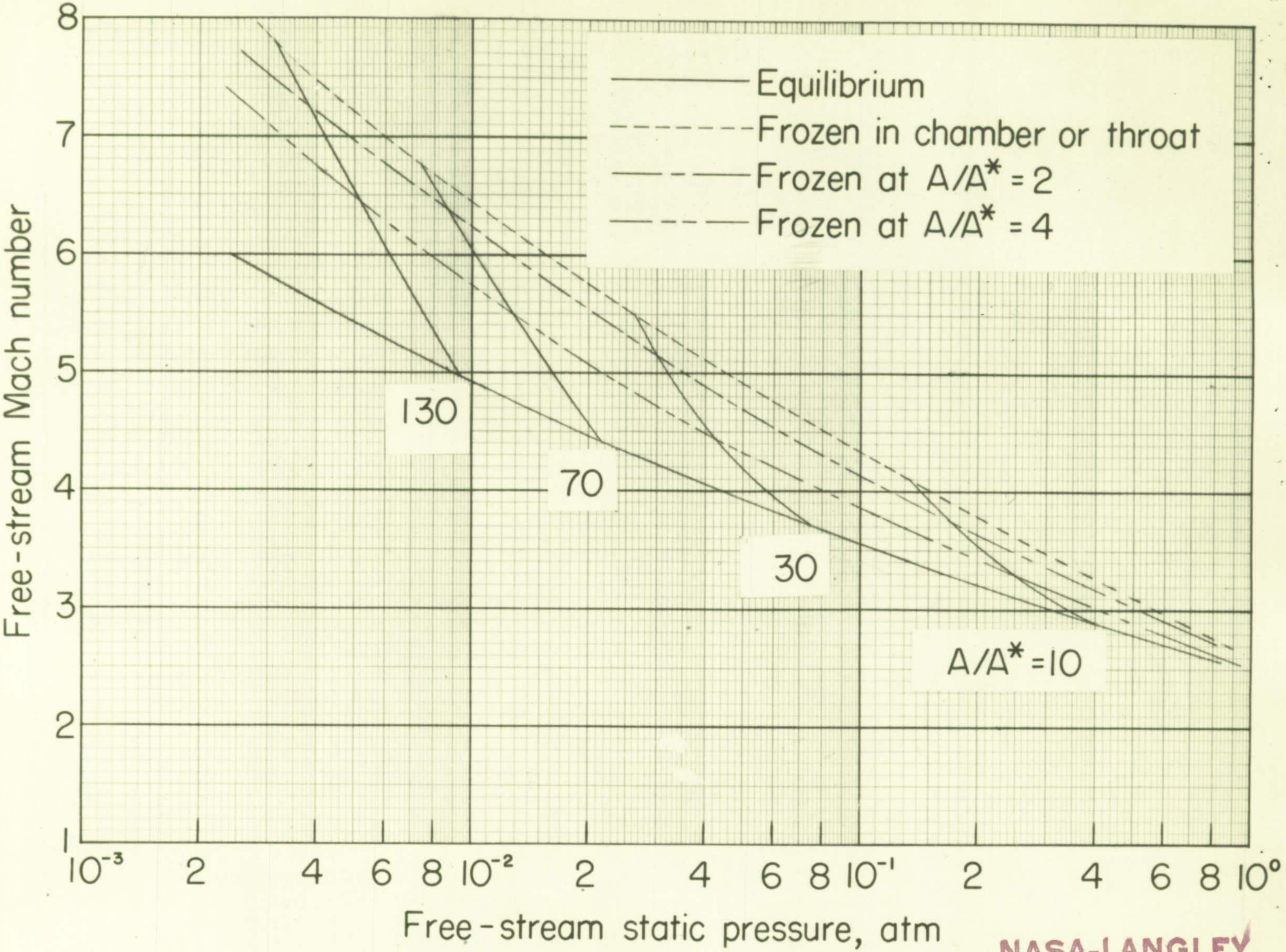

Fig. 2. Variation of free-stream Mach number with free-stream static pressure at a stagnation pressure of 20 atm and stagnation enthalpy of 4500 BTU/lb.