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Flow and Thermal Characteristics of Hydrogen Near Its Critical Point in a Heated Cylindrical Tube

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

Printed in the United States of America. Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

Written: May 1969
Distributed: June 13, 1969

LA-4172
UC-34, PHYSICS
TID-4500

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Flow and Thermal Characteristics of Hydrogen Near Its Critical Point in a Heated Cylindrical Tube*

by

Mahlon T. Wilson

*This report is derived from a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Engineering from the Graduate School of the University of New Mexico.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of his dissertation committee: Professors Victor J. Skoglund, Chairman, M. W. Wildin, and G. A. Whan of the University of New Mexico; and Dr. J. D. Rogers of the Los Alamos Scientific Laboratory. Professor Skoglund guided the investigation and critically reviewed the dissertation, and his insight was helpful in the development of the correlations. The test facility was designed by Dr. Rogers and he provided direction throughout the experimental investigation. Personnel and facilities were made available by Groups CMF-9, CMB-14, and MP-6 of the Los Alamos Scientific Laboratory. The author is grateful to Dr. R. D. Baker and Mr. J. W. Schulte whose support resulted in a doctorial fellowship from the Los Alamos Scientific Laboratory.

ABSTRACT

FLOW AND THERMAL CHARACTERISTICS OF HYDROGEN NEAR ITS CRITICAL POINT IN A HEATED CYLINDRICAL TUBE

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The University of New Mexico, 1969

The purpose of this investigation was to determine the flow conditions and mechanism of hydrogen near its critical point in a heated cylindrical tube. The experimental apparatus consisted of a 1.376 inch inside diameter, 180 inch long, electrically heated vertical tube. Thermocouples and potential taps were located along the tube. An instrumented probe traversed the tube near the exit end. The probe carried a pitot tube, a thermopile, and a hot wire anemometer sensor. Dynamic pressure, temperature, and hot wire anemometer bridge average and RMS voltages were measured as a function of test section radius. The data was represented by empirical equations. A special boiling number was found to be effective in correlating temperature differences for pressures greater than the critical pressure. Correlations were also obtained as a

function of reduced pseudocritical temperatures. With pseudocritical temperatures slightly less than one, dynamic pressure, temperature, and average hot wire current were more nearly constant with respect to radius than at other temperatures. "M" shaped velocity profiles were observed at pseudocritical temperatures above one. The experimental tests produced conditions at the probe in which the reduced temperature ranged from 0.66 to 1.22, the reduced pressure varied from 1.003 to 1.351, and the Reynolds number was from 4.0×10^5 to 3.2×10^6.

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1. INTRODUCTION

1.1 Motivation

Cryogenic fluids are widely used in manufacturing, environmental conditioning, and as propellants for chemical and nuclear propulsion systems. Customary uses of cryogens often bring them near their critical states. The properties of any fluid in the vicinity of the critical state vary appreciably and for this reason it has been difficult to correlate forced convection heat transfer data. There was a need for experimental investigation of the details of the flow to improve correlations. Hydrogen was chosen as the test fluid since it was important as a propellant and cryogenic experimental facilities were available. The near critical properties of hydrogen were better known than those for any other fluid and computer codes were available to represent them. Hydrogen also has an experimentally convenient critical point.

1.2 Purpose

The purpose of this investigation was to determine temperature and flow characteristics of parahydrogen near its critical point during forced convection heating in a vertical cylindrical tube.

1.3 Scope of Investigation

The test section was a vertical 1.376 inch inside diameter tube that was 180 inches long with a movable instrumented probe for measuring temperature, dynamic pressure, and hot wire voltages as a function of radius near the exit of the tube. This data was represented by empirical equations. Parameters of the empirical equations were correlated as a function of a reduced pseudocritical temperature and a special boiling number. The data of one hundred forty two runs was analyzed. The runs represent conditions at the probe in which the reduced temperatures ranged from 0.66 to 1.22, reduced pressures varied from 1.003 to 1.351, and the Reynolds numbers varied from 4.0×10^5 to 3.2×10^6.

2. REVIEW

2.1 Introduction

The references that were useful in this investigation are reviewed in the following sections. Details of the references are reproduced in later sections when needed.

2.2 Hydrogen Properties

Hydrogen properties were obtained from references [3, 1969], [4, 1965], [6,1966], [12, 1961], [14, 1959], and [20, 1962].* The quasi-two phase properties of hydrogen were obtained from reference [19, 1966].

2.3 Flow and Heat Transfer

The theory and use of similitude was guided by references [16, 1969] and [17, 1967]. The theory of fluid mechanics utilized reference [15, 1963]. No references were found with successful correlations of flow or heat transfer data near the critical point. A large amount of data on hydrogen heat transfer was compiled to support the development of rocket engines [6, 1966].

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* Numbers in brackets [ ] are reference numbers and dates.

Axial wall temperature maximums were reported and were attributed to an effect of the bulk fluid temperature reaching a pseudocritical value [6, 1966] [21, 1963].

Velocity and temperature distributions for air flowing within heated tubes were available. One of the most accurate investigations employed a constant current hot wire anemometer for both velocity and temperature measurements [18, 1958]. The temperature of the tube wall was uniform at 15 to 20°R above the entering air temperature. The physical properties of air were assumed constant. Thermocouple and pitot tube traverses of mercury flowing through a heated tube were made by Brown [1, 1957]. The only near critical heat transfer investigation, that included radial velocity and temperature profiles, utilized carbon dioxide [21, 1963]. A pitot-static probe was used to measure dynamic pressure. The apparatus was then disassembled, and the pitot-static probe was replaced by a thermocouple probe. Flat temperature profiles and "M" shaped velocity profiles were observed. No attempt was made to represent the profiles by empirical equations or to correlate their shapes with test conditions.

2.4 Instrumentation

The interpretation of temperature sensors was aided by the following references [2, 1960], [9, 1960], [10, 1961], and [11, 1962]. In the design of the tubing to the pressure sensors, information from reference [7, 1950] was used in calculating response times. The use of water in calibrating the turbine flowmeter was justified in reference [5, 1959]. Information from reference [8, 1942] was used in the analysis of the heat leaks into the test section. The contraction coefficient of an abrupt change in flow cross section was obtained from reference [13, 1950].

3. THEORY

3.1 Introduction

The purpose of this chapter is to present the principal equations, the near critical properties of hydrogen, and to derive reference similarity numbers for correlating data.

3.2 Principal Equations

The principal equations are those of continuity, motion, energy, and state [15, 1963]. They are:

$$\rho,_t + (\rho v_i),_i = 0 \tag{1}$$

$$\rho \frac{Dv_i}{Dt} = b_i - p,_i + \left[\left(\eta - \frac{2}{3}\mu\right) v_{j,j}\right],_i + \left[\mu\left(v_{j,i} + v_{i,j}\right)\right],_j \tag{2}$$

$$\begin{aligned}\rho\left(\frac{Dh}{Dt} + v\frac{Dv}{Dt}\right) = {} & p,_t - q_{i,i} + b_i v_i \\ & + \left(\eta - \frac{2}{3}\mu\right) v_{i,i} v_{j,j} \\ & + \mu\left(v_{j,i} + v_{i,j}\right) v_{j,i} \\ & + v_i\left[\left(\eta - \frac{2}{3}\mu\right) v_{j,j}\right],_i \\ & + v_j\left[\mu\left(v_{j,i} + v_{i,j}\right)\right],_i\end{aligned} \tag{3}$$

$$u_i = f_i(p,T) \tag{4}$$

where:

b = specific body force per unit volume

h = specific enthalpy per unit mass

p = pressure

q_i = heat flux per unit time and area a_i

t = time

T = temperature

$u_i = h,\ c_p,\ k,\ \mu,\ \rho$

v_i = velocity component in the x_i direction

x_i = cartesian coordinate

η = bulk viscosity

μ = shearing viscosity

ρ = density

$(\ )_{,j}$ = derivative with respect to x_j

$(\ )_{,t}$ = derivative with respect to time

In converting equations (1) through (4) to a nondimensional form, the symbols of the new dimensionless variables without a subscript "o" are the same as those of the corresponding variable. Neglecting body forces and bulk viscosity, the nondimensional equations of continuity, motion, energy, and state are:

$$\rho_{,t} + (\rho v_i)_{,i} = 0 \tag{5}$$

$$\rho \frac{D v_i}{Dt} = - N_{po}\, p_{,i} + \frac{1}{N_{Ro}} \left\{ -\frac{2}{3} (\mu v_{j,j})_{,i} + \mu\, (v_{j,i} + v_{i,j})_{,j} \right\} \tag{6}$$

$$N_{ho} \rho \frac{Dh}{Dt} + \rho v \frac{Dv}{Dt} = N_{po}\, p_{,t} - N_{qo} q_{i,i} + \frac{1}{N_{Ro}} \left\{ -\frac{2}{3} \left[\mu\, v_{i,i} v_{j,j} + v_i\, (\mu v_{j,j})_{,i} \right] + \mu (v_{j,i} + v_{i,j})\, v_{j,i} + v_j \left[\mu\, (v_{j,i} + v_{i,j}) \right]_{,i} \right\} \tag{7}$$

$$u_i = f_i\, (p, T) \tag{8}$$

where:

$$N_{po} = \frac{p_o}{\rho_o v_o^{\,2}} \tag{9}$$

$$N_{Ro} = \frac{\rho_o v_o x_o}{\mu_o} \tag{10}$$

$$N_{ho} = \frac{h_o}{v_o^{\,2}} \tag{11}$$

$$N_{qo} = \frac{q_o}{\rho_o v_o^{\,3}} \tag{12}$$

N_o's are reference similarity numbers in terms of dimensional reference variables. An analytical solution of these equations was not attempted, however, they were useful as a guide in planning the investigation and interpreting the data.

3.3 Hydrogen Properties

The diatomic hydrogen molecule H_2 has allotropic ortho and para forms. The ortho form has nuclear spins in the same direction. The para form has nuclear spins in the opposite direction. In certain temperature ranges there is a large difference between the specific heats and thermal conductivities of the ortho and para forms. At room temperature, equilibrium hydrogen consists of 75 percent ortho and 25 percent para. At 36° R, equilibrium hydrogen consists of 0.21 percent ortho and 99.79 percent para [14,1959].

The hydrogen used in the tests was parahydrogen. The room temperature cover gas did not mix with the parahydrogen in the dewar as evidenced by a constant hydrogen temperature entering the test section.

Two similar Fortran IV codes exist for the numerical determination of eight properties of parahydrogen [4, 1965]. Properties from these codes are presented in

Figures 1 through 4. The TABTP code has temperature and pressure as inputs and covers the temperature range from 36 to 5000 degrees Rankine. The TABHP code has enthalpy and pressure as inputs and covers the enthalpy range from -115 to 20,000 Btu/pound. The maximum deviation of properties of the code from the source data is usually less than one percent. However, in the critical region, the deviations are as high as 2.5 percent in temperature, 2.1 percent in enthalpy, 3.0 percent in density, 1.2 percent in viscosity, and 3.7 percent in thermal conductivity. The deviations in specific heat are less than 6.5 percent except that values in the vicinity of the peak are only approximate representations of the source data. Recently reported thermal conductivities have a sharp peak within one degree of the critical point that is not represented by the codes [3, 1969].

Reduced pressure is defined as the system pressure divided by the pressure of the critical point which is 187.7 psia. Two bases were used for nondimensionalizing temperatures. Reduced temperature is the bulk temperature divided by the temperature of the critical point which is 59.37° R. Reduced pseudocritical temperature is the bulk temperature divided by the pseudocritical temperature.

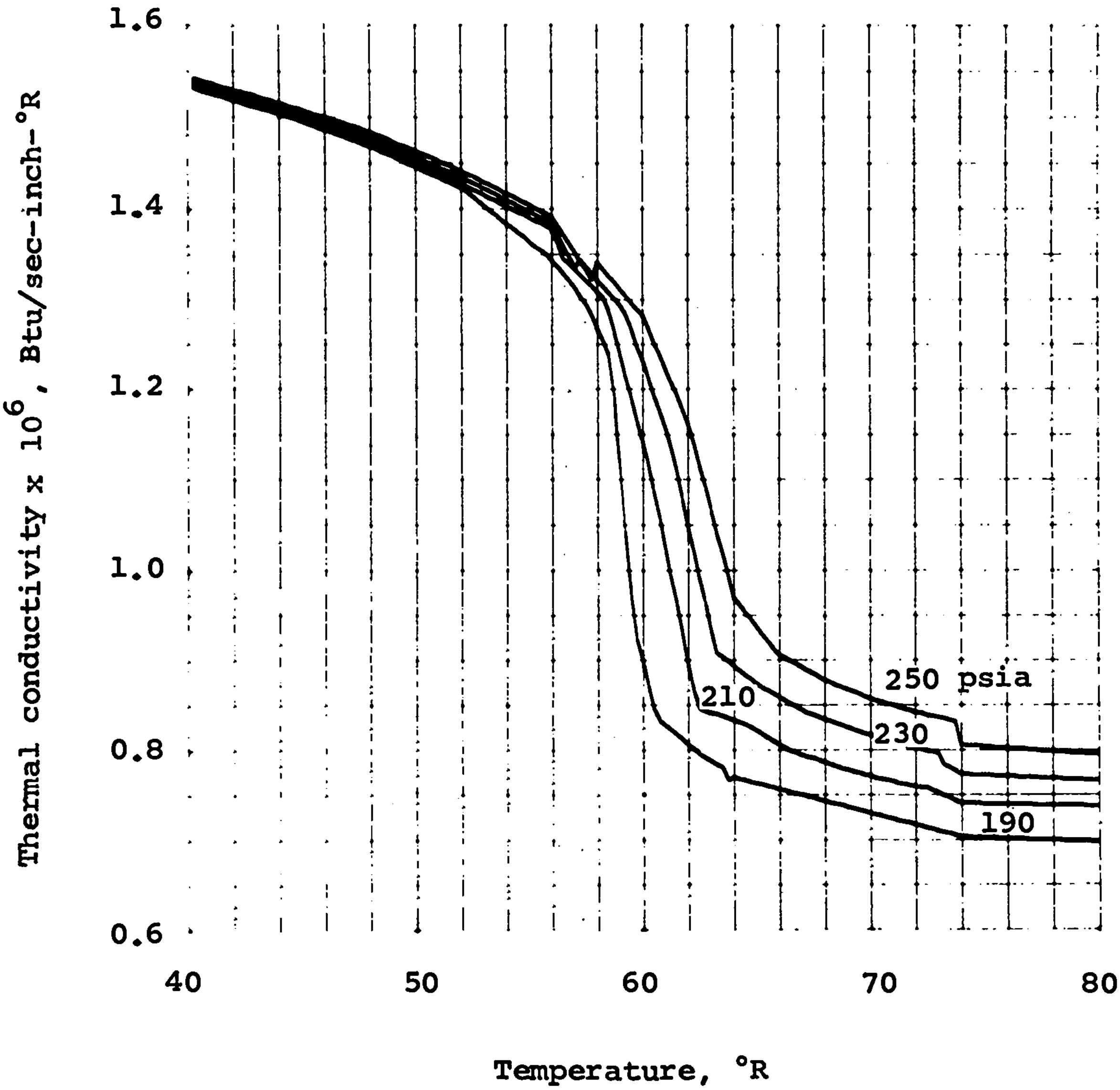

Figure 1. Thermal Conductivity of Parahydrogen

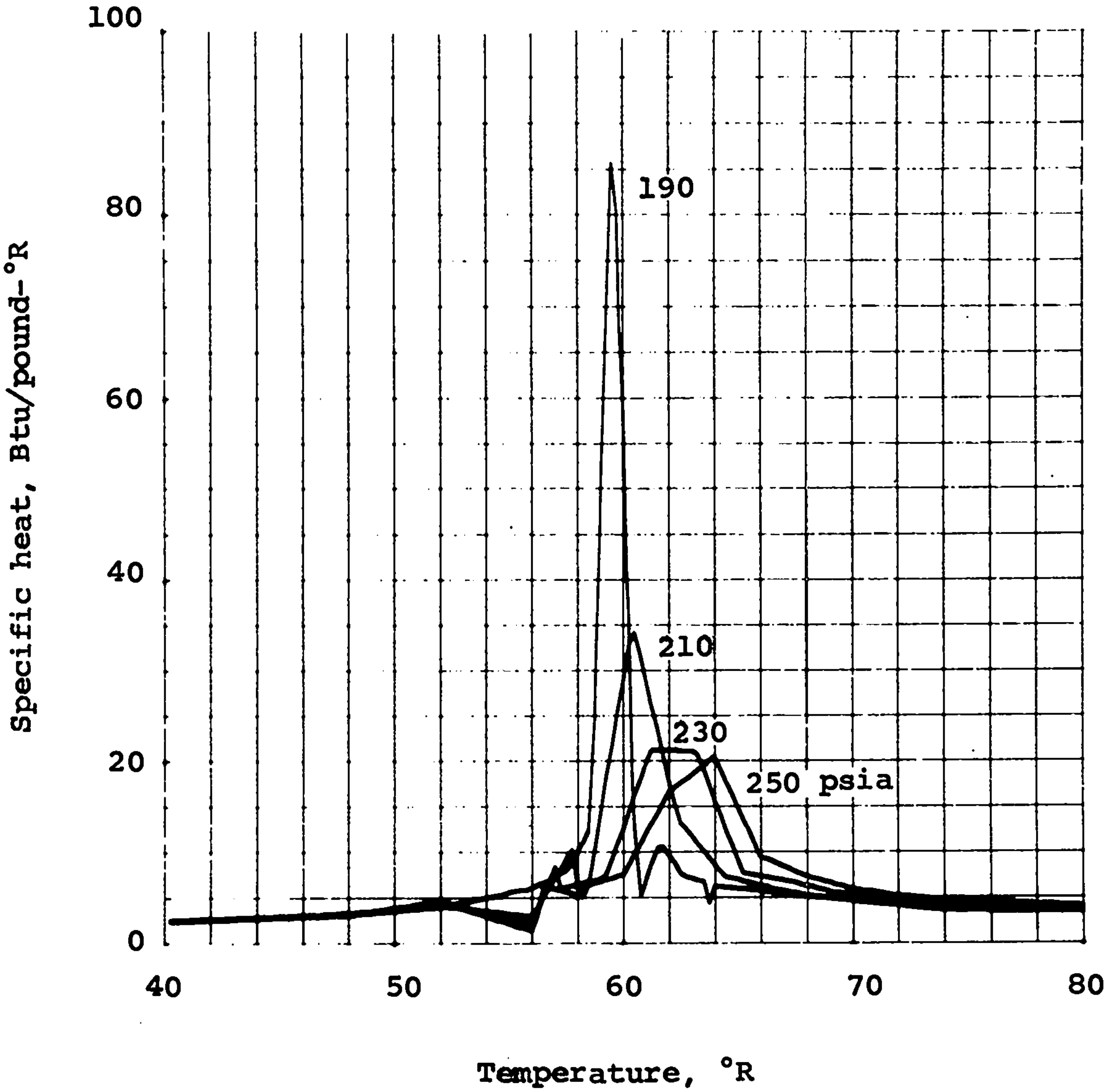

Figure 2. Specific Heat of Parahydrogen

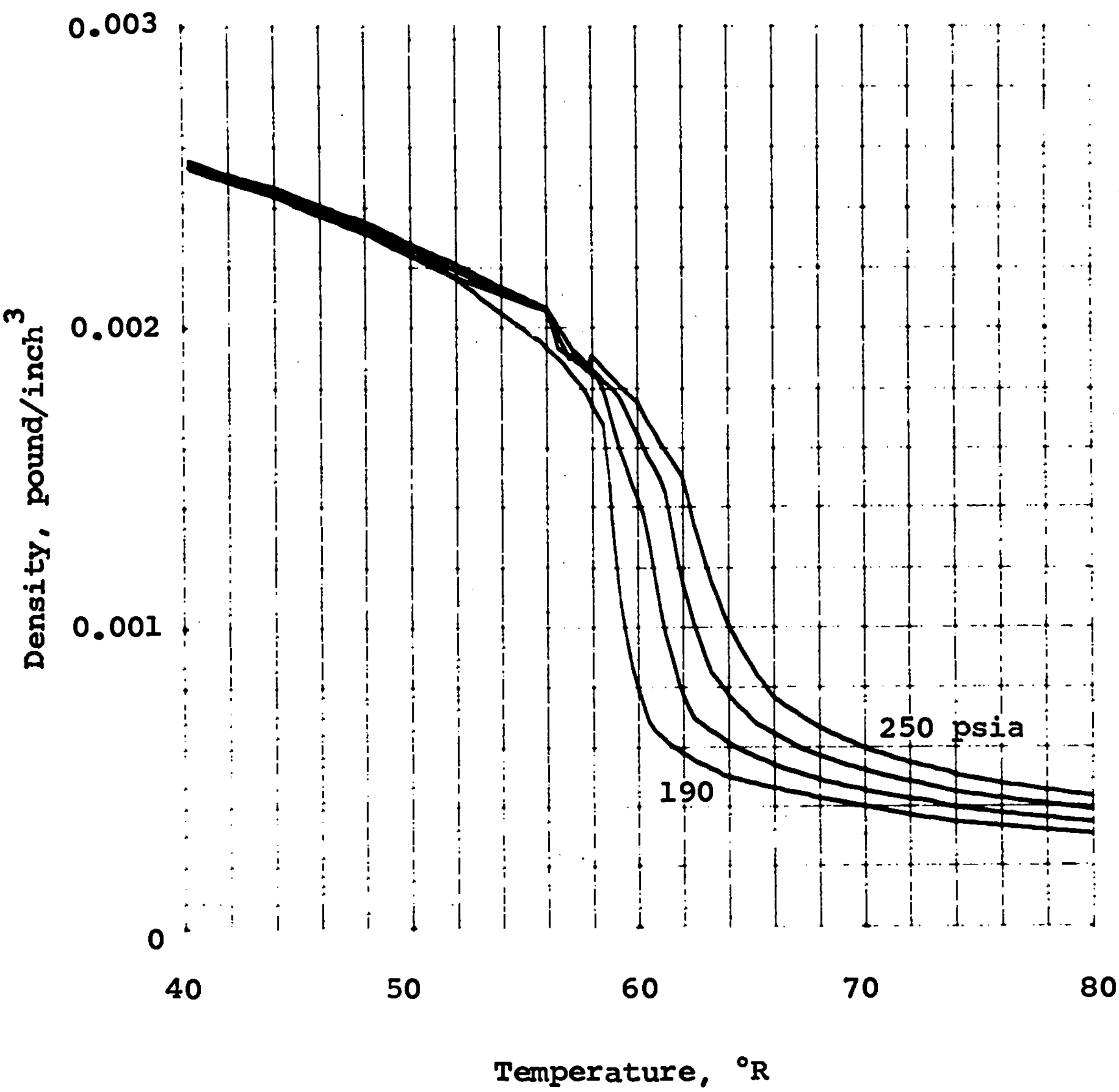

Figure 3. Density of Parahydrogen

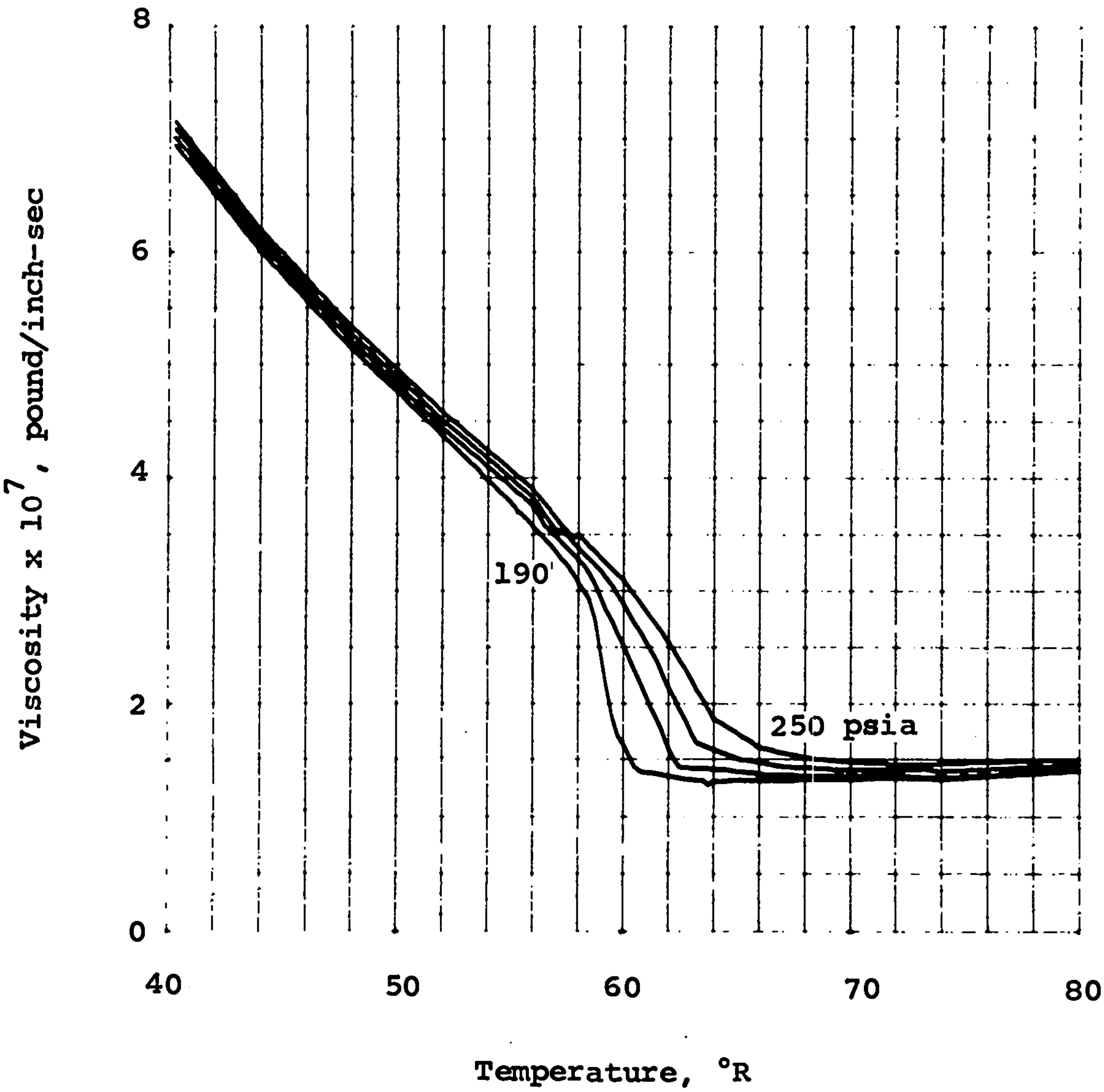

Figure 4. Viscosity of Parahydrogen

The pseudocritical temperature is defined as that temperature at which the specific heat is a maximum with respect to temperature at a constant pressure. The pseudocritical temperature as a function of pressure is a continuation of the saturated vapor line.

Thurston defined quasi-two phase properties of hydrogen to extend the concept of boiling into the supercritical pressure region [19, 1966]. He observed the shape of enthalpy versus temperature at constant pressures and approximated them with a quasi-vaporization process. The quasi-vaporization temperature equaled the pseudocritical temperature. The quasi-saturated liquid and vapor values were obtained by extrapolating parts of the enthalpy-temperature curves that were outside of the influence of the critical point. The quasi-saturated liquid phase was called the dense phase. The quasi-saturated vapor phase was called the light phase. The difference in enthalpies of the dense and light phases was equivalent to the enthalpy of vaporization. The extrapolation procedure and the phases are indicated in Figure 5. The following equations were derived from the curves presented by Thurston. The pseudocritical temperatures for pressures below 250 psia were

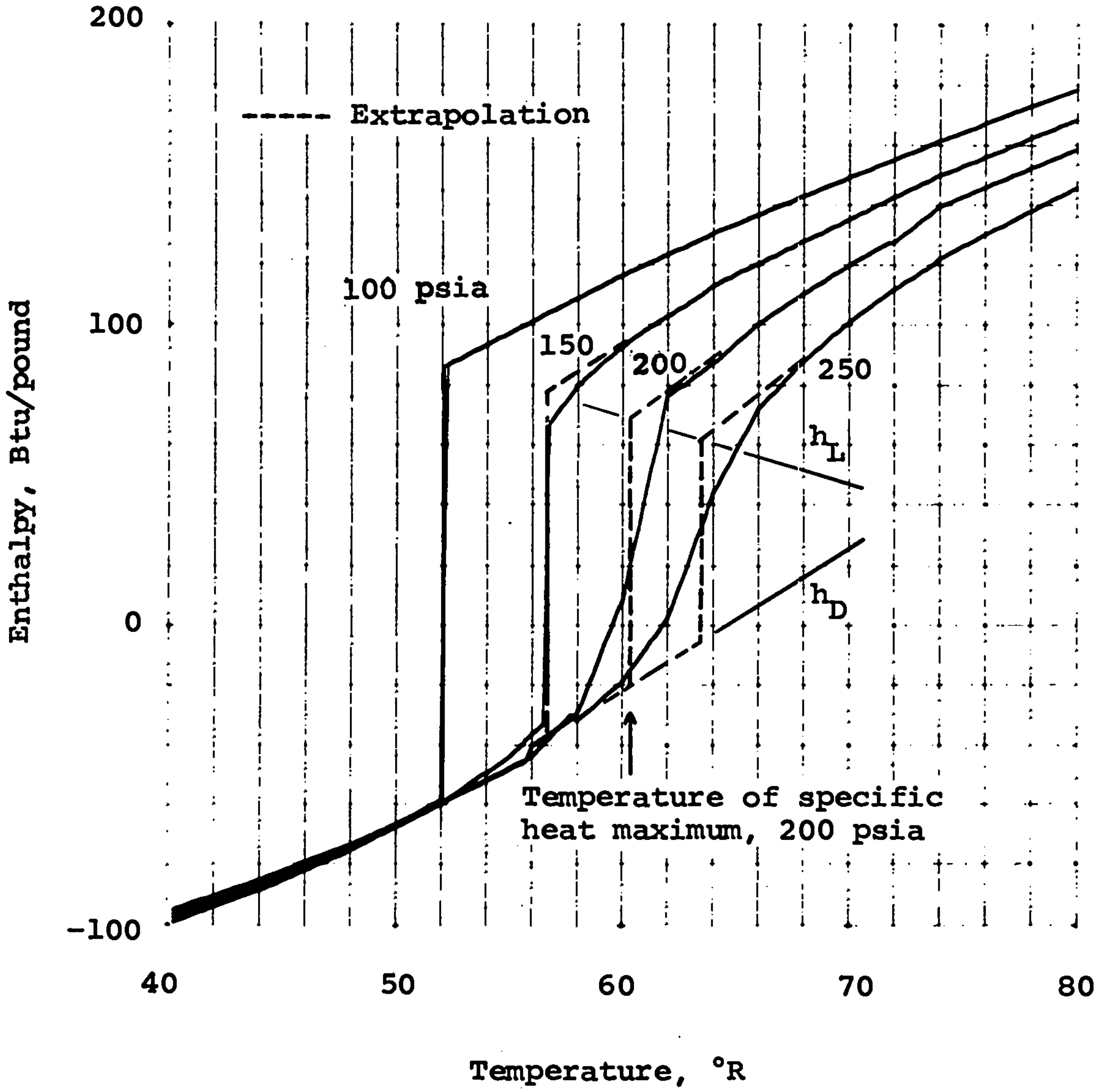

Figure 5. Extrapolation Technique for Quasi-Saturation Values

$$T_{pc} = 52.1 - 0.000273(p-100)^{1.9} + 0.0998(p-100) \quad (13)$$

where p = pressure in psia.

The dense phase enthalpy was

$$h_D = - 22.5 + 0.275(p-200) \quad (14)$$

The equivalent enthalpy of vaporization was

$$h_L - h_D = 102.0 - 0.425(p-200) \quad (15)$$

where h = enthalpy in Btu/pound.

3.4 Similitude

3.4.1 System Specifications. The system is illustrated in Figure 6.

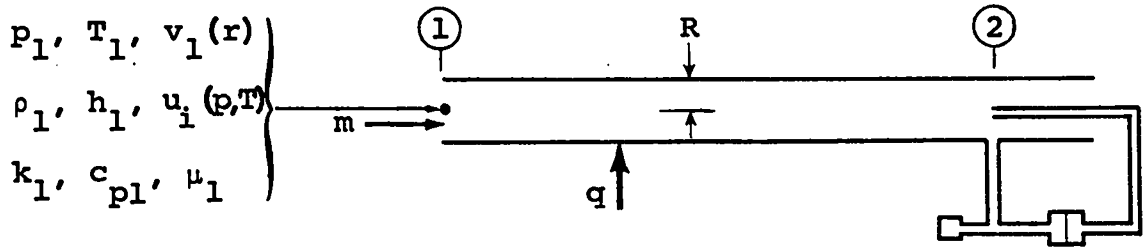

Figure 6. Specification of the System

The specified variables of the system and their dimensions are:

p_1 = inlet pressure, $ML^{-1}T^{-2}$

T_1 = inlet bulk temperature, θ

$v_1(r)$ = inlet velocity as a function of radius, LT^{-1}

ρ_1 = inlet density, ML^{-3}

k_1 = inlet thermal conductivity, $MLT^{-3}\theta^{-1}$

c_{p1} = inlet specific heat, $L^2T^{-2}\theta^{-1}$

μ_1 = inlet viscosity, $ML^{-1}T^{-1}$

R = inside radius of the test section, L

q = heat rate per unit area, MT^{-3}

m = mass flow rate, MT^{-1}

u_i = f(p,T) equation of state of hydrogen

T_c = critical temperature, θ

a_c = πR^2 cross section area of test section, L^2

h_L, h_D = light and dense phase enthalpies per unit mass, L^2T^{-2}

3.4.2 Problem. The problem was to determine functions for the following dependent variables:

T_2 = exit bulb fluid temperature, θ

$\Delta p(r)$ = dynamic pressure as a function of radius at the test section exit, $ML^{-1}T^{-2}$

h_2-h_1 = enthalpy increase from inlet to outlet, L^2T^{-2}

$\theta(r)$ = temperature difference as a function of radius at the test section exit, θ

3.4.3 Principles. From [17, 1967], the principles of similarity are

$$N_{om} = N_{op} \tag{16}$$

$$n_u (\chi_i, \tau)_m = n_u (\chi_i, \tau)_p \tag{17}$$

where:

N_o = reference similarity number

u = dimensional variable

n = nondimensional variable

χ_i = nondimensional coordinate

τ = nondimensional time

$n_u(\chi_i, \tau)_m = n_u(\chi_i, \tau)_p$ includes geometrical requirements

$(\ )_m$ = model

$(\ )_p$ = prototype

3.4.4 Analysis. Reference dimensional variables are identified by a subscript "o". From sections 3.4.1 and 3.4.2, they are:

$x_o = R, \quad \rho_o = \rho_1, \quad p_o = p_1, \quad T_o = T_c, \quad k_o = k_1$

$c_{po} = c_{p1}, \quad \mu_o = \mu_1, \quad q_o = q, \quad m_o = m$

$v_o = m_o/\rho_o a_c, \quad h_o = h_L - h_D$

θ_o = a temperature difference

From sections 3.4.1 and 3.4.2, by dimensional analysis, reference similarity numbers of the system are:

$$N_{po} = \frac{p_o}{\rho_o v_o^2} \quad = \text{ pressure number} \tag{18}$$

$$N_{Ro} = \frac{\rho_o v_o x_o}{\mu_o} \quad = \text{ Reynolds number} \tag{19}$$

$$N_{Bo} = \frac{q_o a_s}{m_o h_o} \quad = \text{ boiling number} \tag{20}$$

$$N_{Pro} = \frac{\mu_o c_{po}}{k_o} \quad = \text{ Prandtl number} \tag{21}$$

$$N_{To} = \frac{k_o T_o}{q_o x_o} \quad = \text{ temperature number} \tag{22}$$

$$N_{\theta o} = \frac{k_o \theta_1}{q_o x_o} \quad = \text{ temperature difference number} \tag{23}$$

where $a_s = 2\pi RL$. Similarity numbers (18), (19), and (20) were involved in equations (6) and (7) of Section 3.2. Similarity numbers (20), (21), (22), and (23) resulted from boundary conditions.

From Section 3.4.3 the requirements of similarity are:

$$N_{om} = N_{op} \tag{24}$$

$$(n_{T1})_m = (n_{T1})_p \tag{25}$$

$$(n_{p1})_m = (n_{p1})_p \tag{26}$$

$$n_{v1}(n_r)_m = n_{v1}(n_r)_p \tag{27}$$

$$n_{ui}(n_p, n_T)_m = n_{ui}(n_p, n_T)_p \tag{28}$$

and geometrical similarity.

Where:

$$n_{T1} = T_1/T_o$$

$$n_{p1} = p_1/p_o$$

$$n_{v1} = v_1/v_o$$

$$n_r = r/R$$

$$n_{ui} = u_i/u_o$$

$$u_i = c_p,\ k,\ \mu,\ h$$

From equation (28),

$$\left(\frac{h_D}{h_o}\right)_m = \left(\frac{h_D}{h_o}\right)_p \tag{29}$$

$$\left(\frac{h_1}{h_o}\right)_m = \left(\frac{h_1}{h_o}\right)_p \tag{30}$$

Combining (29) and (30) and multiplying by the mass flow rate yields

$$\left[\frac{m\ (h_D - h_1)}{m\ h_o}\right]_m = \left[\frac{m\ (h_D - h_1)}{m\ h_o}\right]_p \tag{31}$$

Since $Q = q_o a_s$, equation (20) becomes

$$N_B = \left(\frac{Q}{m\ h_o}\right)_m = \left(\frac{Q}{m\ h_o}\right)_p \tag{32}$$

Subtraction of (31) from (32) results in a boiling number that was first suggested by Skoglund [16, 1969].

$$N_{Sk} = \frac{Q - m\ (h_D - h_1)}{m\ (h_L - h_D)} \tag{33}$$

The numerator of this equation is the heat rate available for quasi-vaporization. The denominator is the heat required for complete quasi-vaporization. When N_{Sk} is greater than zero quasi-vaporization occurs. From (31) and (32), a requirement of similarity is that

$$(N_{Sk})_m = (N_{Sk})_p \tag{34}$$

From Section 3.4.3 the results of similarity are:

$$\left(\frac{T_2 - T_1}{\theta_o}\right)_m = \left(\frac{T_2 - T_1}{\theta_o}\right)_p \tag{35}$$

$$\left(\frac{\Delta p}{p_o}\right)_m = \left(\frac{\Delta p}{p_o}\right)_p \tag{36}$$

$$\left(\frac{h_2 - h_1}{h_o}\right)_m = \left(\frac{h_2 - h_1}{h_o}\right)_p \tag{37}$$

$$\left(\frac{\theta}{\theta_o}\right)_m = \left(\frac{\theta}{\theta_o}\right)_p \tag{38}$$

where θ is any temperature difference at $x = L$.

3.5 Precision of Empirical Equations

Data acquired from the probe instrumentation was represented by empirical equations as a function f_i (r). The square of the standard deviation of f_{in} from a set of data points y_{in} (r_n) is

$$S_i^2 = \frac{1}{N} \sum_{n=1}^{N} (f_{in} - y_{in})^2 \tag{39}$$

where:

N = number of data points of the set

y_{in} = measured value of the variable i at the radius r_n

f_{in} = empirical value at r_n

The data was divided into ten zones each of which contained equal numbers of data. The data within a zone was numerically averaged, and the square of the standard deviation of the empirical equation from the means of the zones was defined as

$$SM_i^2 = \frac{1}{10} \sum_{j=1}^{10} (f_{ij} - \overline{y_{ij}})^2 \tag{40}$$

where:

$\overline{y_{ij}}$ = average value of the data in the j-th zone

f_{ij} = value of empirical equation at the radius of the midpoint of the j-th zone

The square of the adjusted standard deviation of the empirical equation from the means of the zones was

$$D^2 = \frac{1}{10} \sum_{j=1}^{10} \left(\frac{f_{ij} - \overline{y_{ij}}}{\overline{y_{ij}}} \right)^2 \qquad (41)$$

This standard deviation is approximately equivalent to a percent error. The zones were numbered from one to ten. The zone having the largest adjusted deviation

$$DL = \frac{f_{iL} - \overline{y_{iL}}}{\overline{y_{iL}}} \qquad (42)$$

was identified by zone number L.

4. APPARTUS

4.1 Introduction

This chapter describes the experimental apparatus. The flow system is illustrated in Figure 7. The high pressure dewar was filled from a liquid hydrogen storage dewar. Hydrogen gas was used to pressurize the dewar to force its contents through a metering and valving section to the inlet plenum. The inlet plenum directed the hydrogen into the electrically heated test section. A movable probe was located within and near the exit end of the test section. The system pressure was adjusted by throttling the flow with a valve on the exit of the test section. A vacuum jacket incased the test section and the piping that connected it to the dewar. Figure 8 is a photograph of the apparatus. The test section was mounted within the vertical portion of the vacuum jacket. Instrumentation and control leads were routed from the apparatus to a control room within the adjoining building.

4.2 Hydrogen Supply System

The system which supplied hydrogen to the test section consisted of a 132-gallon high pressure dewar, meters, and valves. Dewar pressure was measured by a Statham

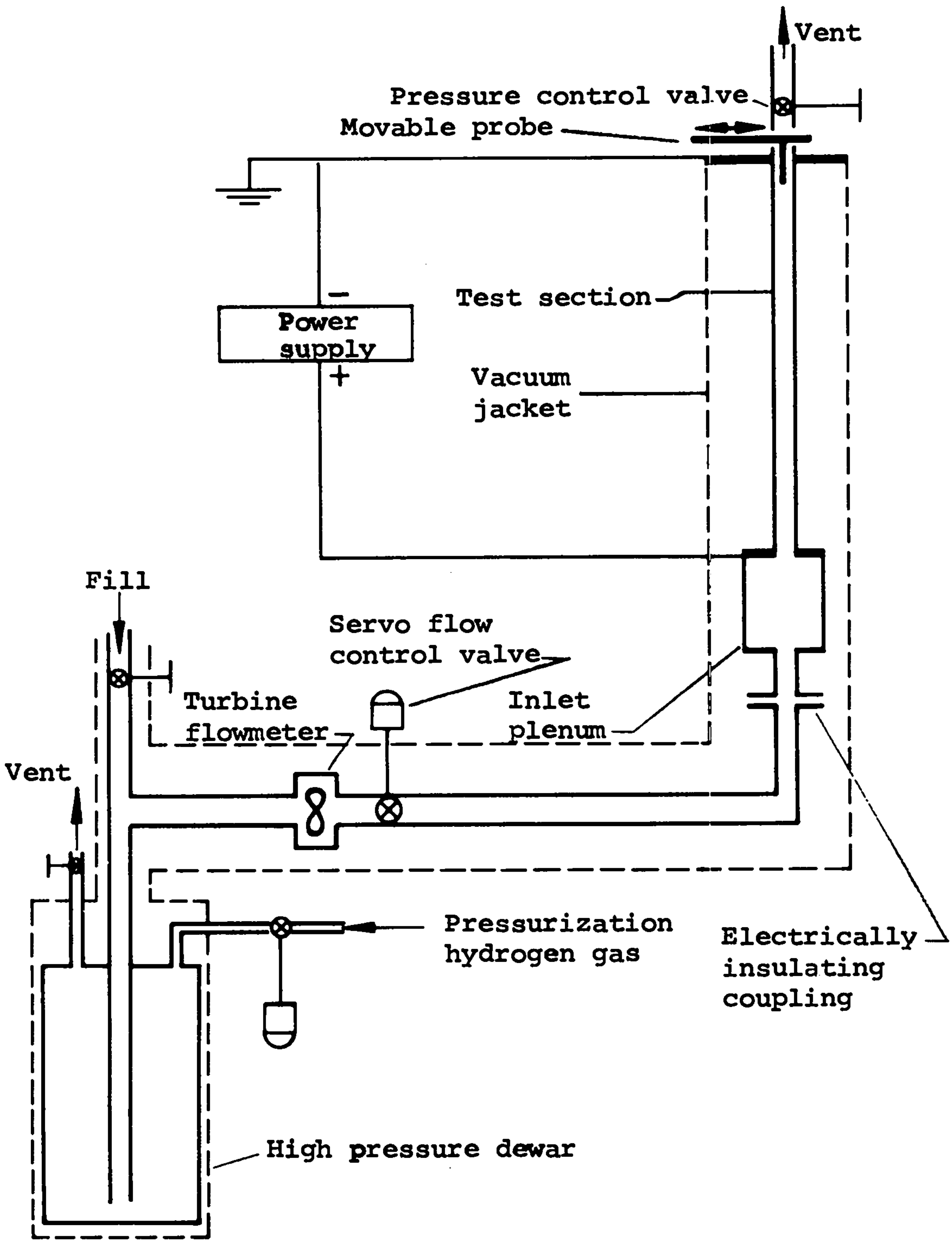

Figure 7. Flow System

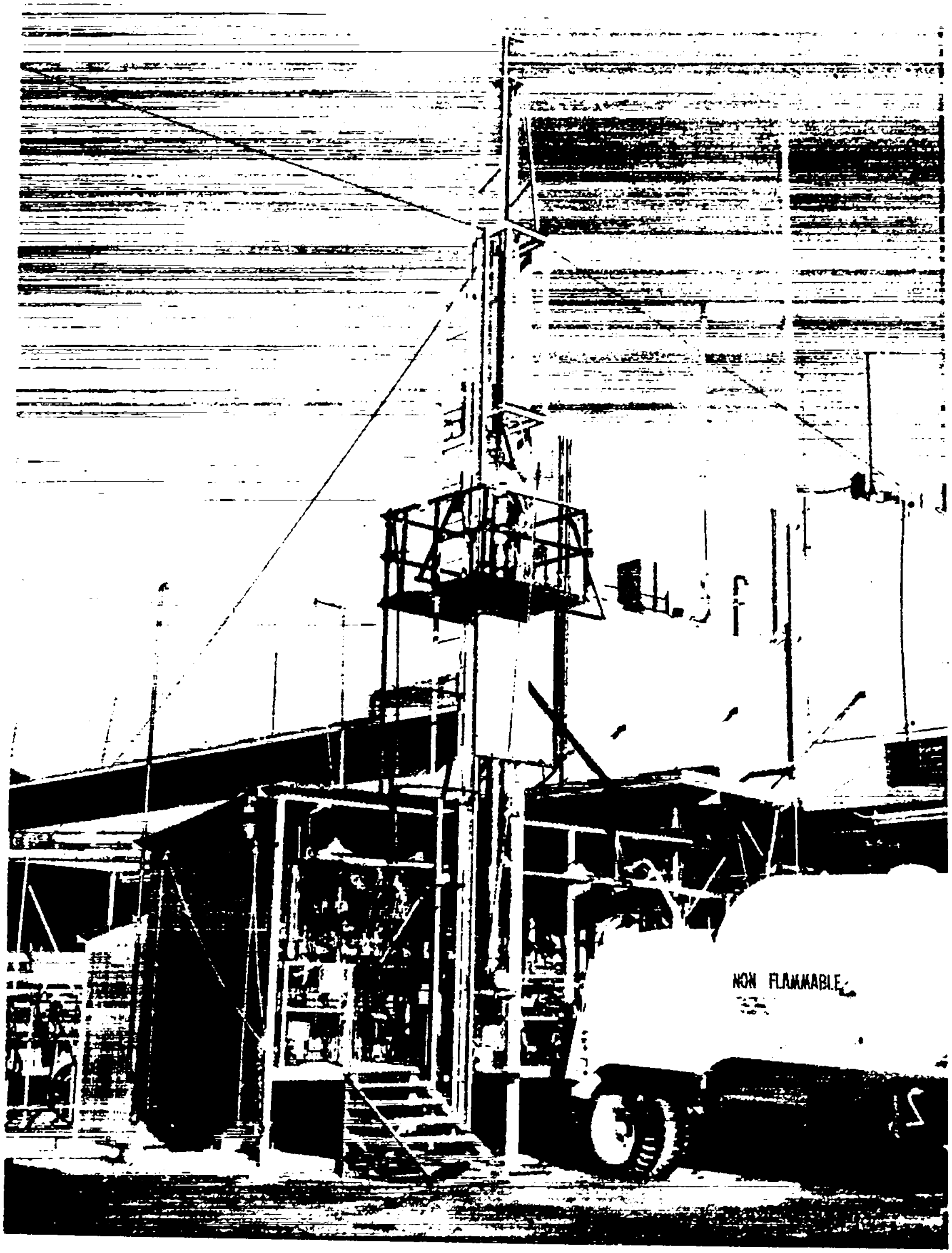

Figure 8. Apparatus

Model PA-707-TC temperature compensated pressure transducer. A one inch diameter Cox Model S-20-MB turbine flow transducer measured volume flow rate. The turbine transducer pulses were counted on a Hewlett-Packard Model 5212A electronic counter. A Hewlett-Packard Model HO-3571B clock and Model 562A printer provided a printed tape record. A Hewlett-Packard Model 580A digital-to-analog converter integrated the digital counter output to provide an analog signal for the data recorder. An Annin Model 24760 hydraulic, servo-controlled valve regulated the fluid flow. This valve could be controlled by the turbine flow transducer or set to a fixed opening.

The tubing for the flow system was one inch nominal outside diameter stainless steel with a wall thickness of 0.035 inches. Electrical insulation was provided by a conical faced SSP Fittings Corporation union that was coated on the mating surfaces with a fired-on glass enamel. Preliminary experiments with this type of union indicated that it would leak during rapid cooling. For this reason, a form-fitting copper container was installed around the union. Liquid nitrogen injected into the container prior to experimental runs precooled the union sufficiently to prevent leakage. The union was monitored with a sensitive voltage measuring meter which would shut off the heating power supply in case of electrical insulation failure.

The inlet plenum is shown in Figure 9. It was fabricated from one-eight inch thick 347 stainless steel tubing with an inside diameter of 2.75 inches and length of 22.5 inches. The fluid entered from the bottom through a one inch diameter sharp edged orifice. A thirty mesh stainless steel screen was mounted across the plenum at a distance of six inches from the inlet and a second identical screen was mounted at ten inches. A Rosemount Model 179-A10F platinum resistance thermometer was mounted midway between the screens. The plenum configuration resulted from velocity measurements in a full scale model of the plenum using gaseous nitrogen. Measured velocities versus plenum radius at the axial position of the test section inlet were symmetrical within 1.5 percent of the centerline velocity. The experimentally determined ratios of average velocity to maximum velocity varied from 0.63 to 0.67 for plenum-diameter based Reynolds numbers between 37600 and 90700. The axial-velocity variation that appeared as a ripple on the profile curves was less than one percent of the centerline velocity. Measurements in a plenum without screens at

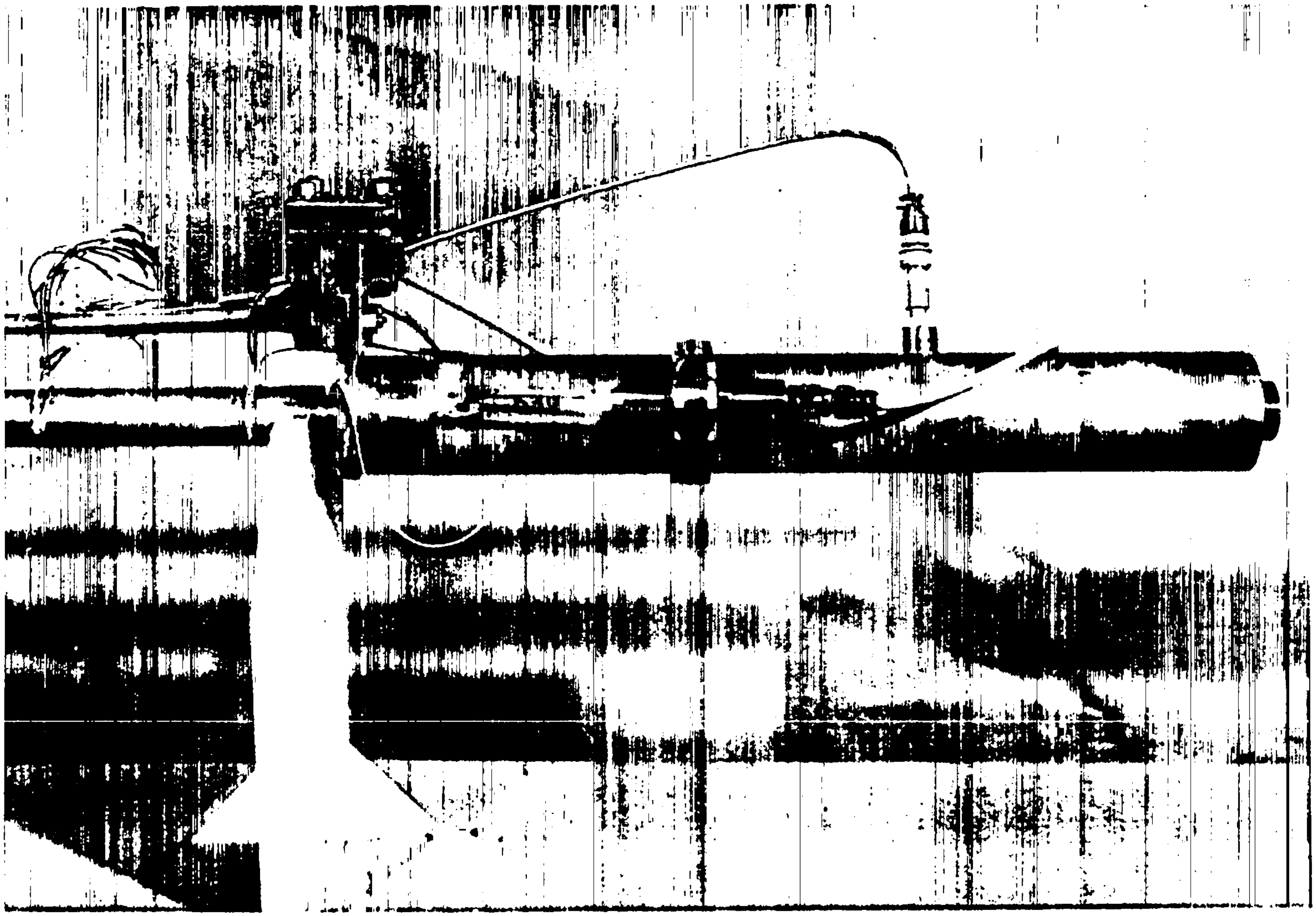

Figure 9. Inlet Plenum

a Reynold's number of 69600 yielded a velocity ratio of 0.76 and an axial-velocity variation of eight percent. A copper plate formed the top end of the plenum and served as the transition between the plenum and the test section. Electrical current for heating the test section was introduced into this plate. The inlet to the test section was sharp edged and had the same inside diameter as the test section. The absolute pressure of the fluid in the plenum was measured with a Statham Model PA-822 absolute pressure transducer connected to a 0.030 inch diameter hole in the plenum wall by an eight inch length of 0.055 inch inside diameter tubing. A 0.055 inch hole in the plenum wall, diametrically opposite the 0.030 inch hole, was connected by an 18 foot length of 0.044 inch inside diameter tubing to provide an upstream pressure indication for the test section pressure differential.

4.3 Power Supply

The test section was heated with a Dresser Electric Company Model 50-2000-4-FO direct current power supply. The output of the power supply was adjustable from 0 to 50 volts with a maximum current capacity of 2000 amperes. The power supply rectified three phase current and had a five percent voltage ripple. To reduce the ripple and its effects on instrumentation, an air gap iron choke was connected in series with the test section. The one millihenry, one-eighth microfarad filter was fabricated by Del Electronics Corporation and reduced the voltage ripple to 0.2 percent. Also in series with the test section was a 25.18 microhm current shunt constructed by the Empro Manufacturing Company. The electrical current was transmitted through two parallel 500,000 circular mil copper welding cables. The total resistance of the leads, test section, and connectors was 0.026 ohms. At high power levels, the power supply circuit breaker would frequently trip. An air cylinder was attached to the breaker handle to quickly reset it from within the control room.

4.4 Test Section and Instrumentation

The test section was fabricated from commercially available Inconel 600 tubing with a 1.500 inch nominal outside diameter and a 1.370 inch nominal inside diameter. The inside diameter actually measured between 1.3760 and 1.3770 inches. The length of the heated section was 179.25 inches or 130.8 nominal inside diameters. Vertical mounting of the test section was necessary for proper support. Upward flow eliminated unsymmetrical distortion of velocity profiles by the force of gravity.

Figure 10 shows the location of test section instrumentation. Potential taps and outside wall temperature thermocouples were soft soldered to the test section at distances that were 2, 6, 31, 56, 81, 106, 127.5, and 129.5 nominal inside diameters from the inlet of the test section. Figure 11 shows details of the attachment of instrumentation. The thermocouples were copper-constantan and were electrically insulated from their eight mil diameter sheaths. Six chromel P-constantan thermocouples were mounted in a 0.032 inch diameter sheath to form a thermocouple rake. The exposed junctions were one-eighth inch apart. Thermocouple rakes were mounted across the diameter of the test section at 6 and 31 nominal inside diameters from the inlet in an unsuccessful attempt to indicate fluid temperature profiles. The wall thermocouples and the rakes were obtained from the High Temperature Instruments Corporation. Thermocouple leads were run in flexible metallic tubing to reduce electrical noise. Additional potential taps were connected to the electrical power terminals on the test section. Three Endevco Model 2242C accelerometers were mounted at right angles to each other on the test section at a distance of 32.8 nominal inside diameters from

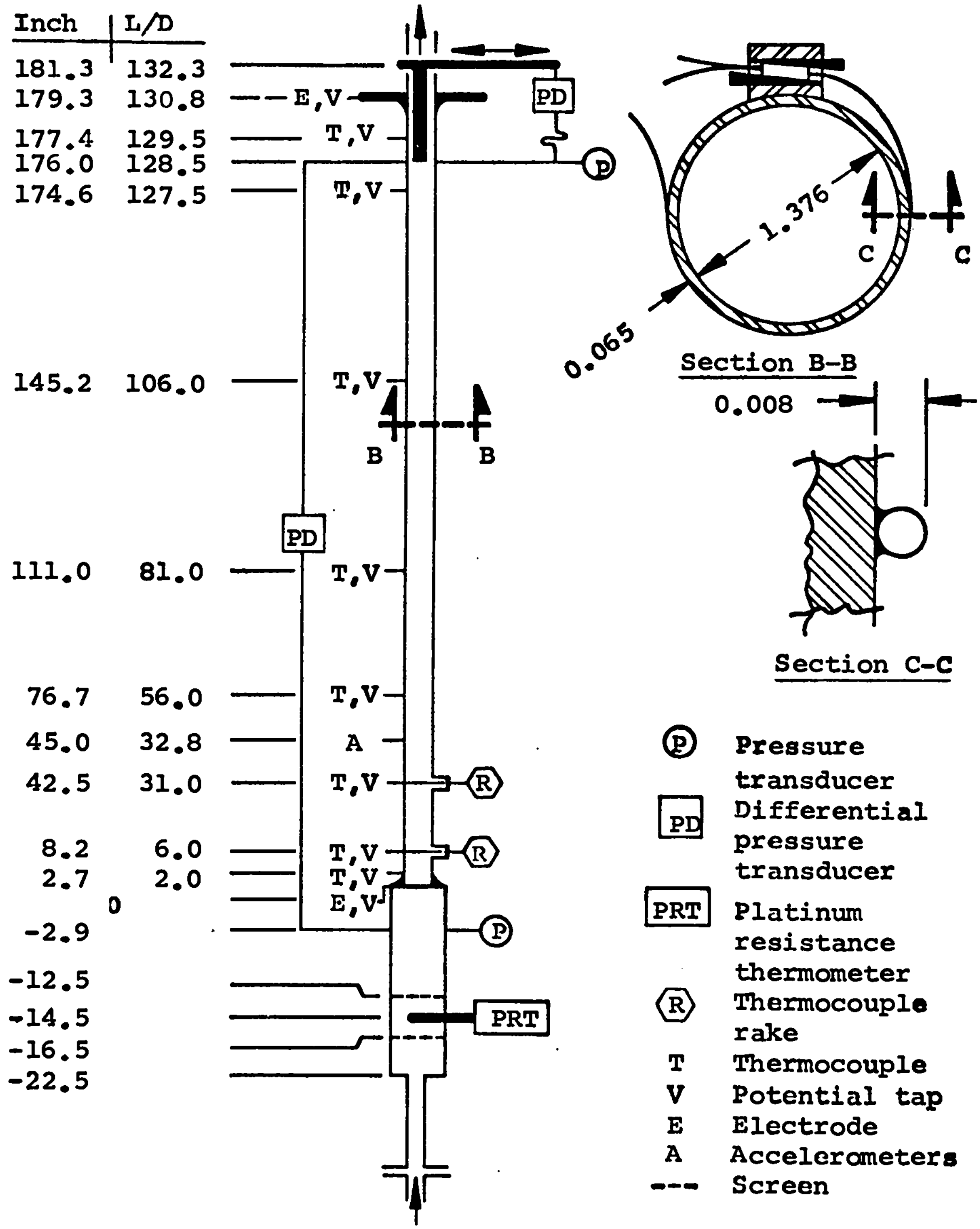

Figure 10. Test Section Instrumentation Location

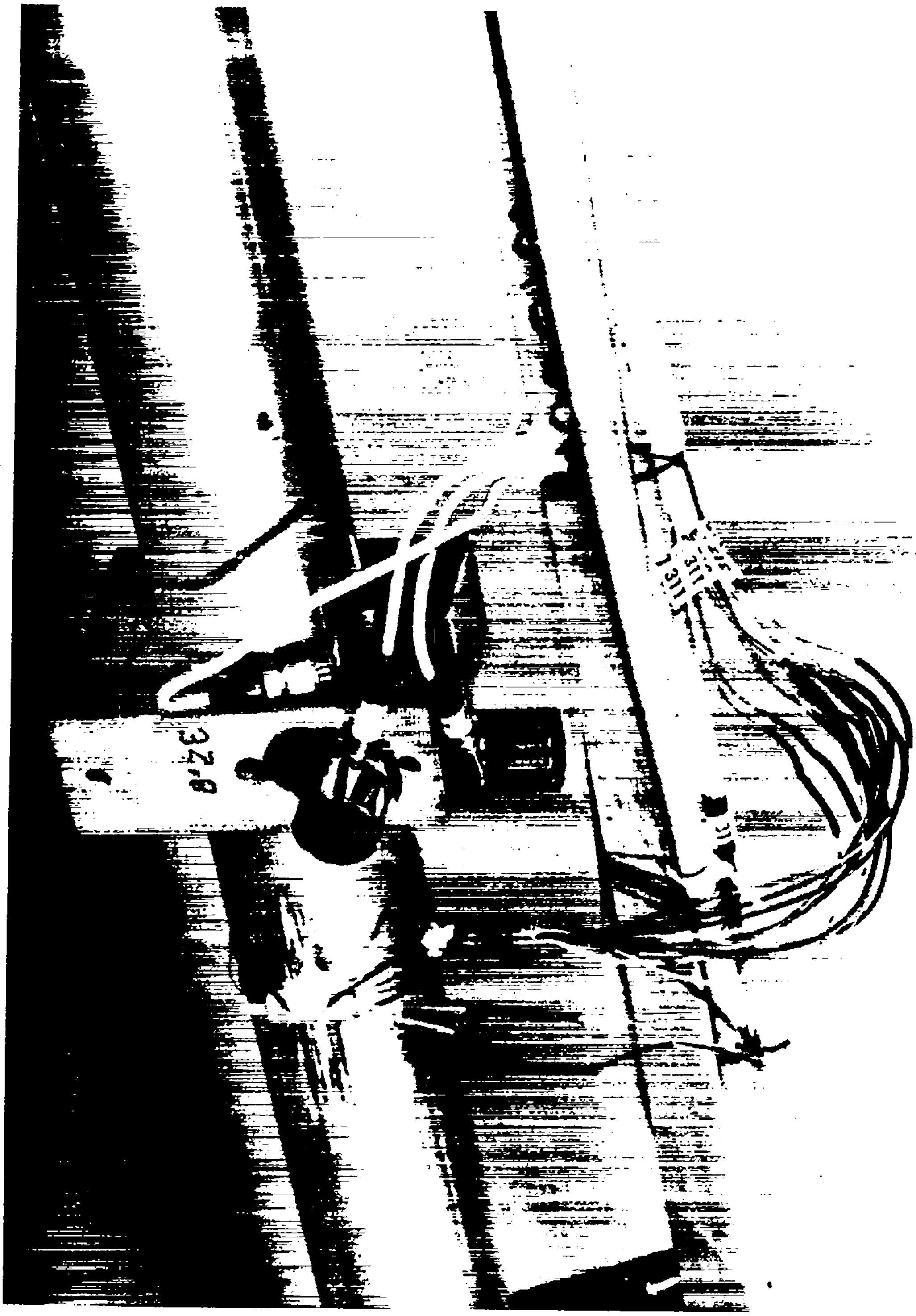

Figure 11. Test Section Instrumentation Location

the inlet.

Figure 12 shows the upper housing that supported the test section. This nickel housing contained the movable probe, formed the upper end of the vacuum jacket, and was the electrical ground for the test section. All test section instrumentation leads emerged from the vacuum jacket through this housing. The probe tip traversed the test section at an axial distance of 176 inches, or 128.5 nominal inside diameters, from the test section inlet. At this position and at right angles to the motion of the probe, there were two diametrically opposed wall static pressure ports which were 0.029 inches in diameter. One port was connected to a Statham Model PM-80-TC differential pressure transducer in conjunction with the inlet plenum to indicate pressure drop in the test section. The second port was connected to a Statham Model PA-822 absolute pressure transducer. It also provided the reference static pressure for the pitot tube of the movable probe. The inside of the test section was polished near the exit end with an automotive brake cylinder hone after the wall static ports were installed. All pressure transmission tubes leading from the test section and inlet plenum were electrically isolated.

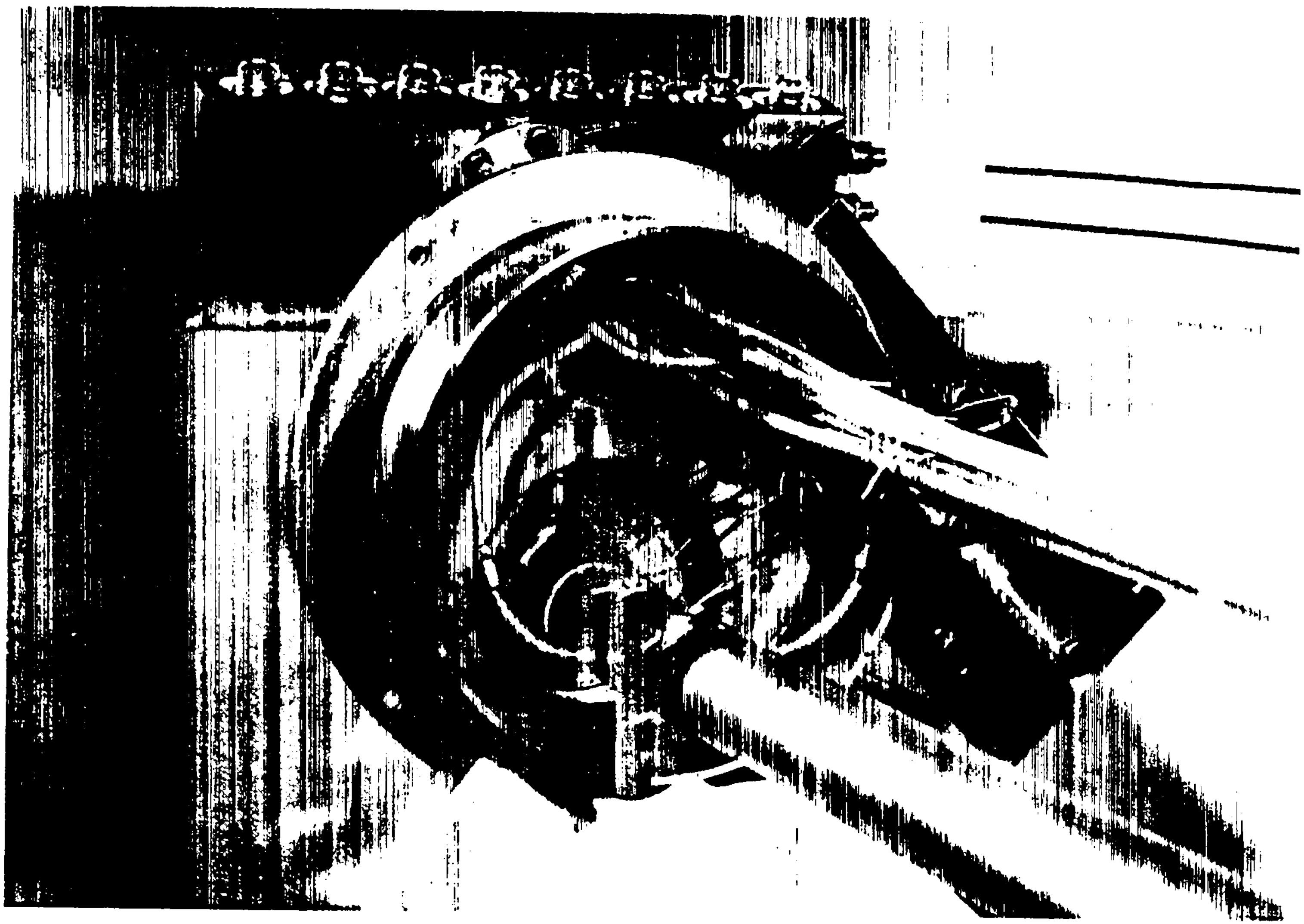

Figure 12. Upper Housing

Test section pressure was adjusted with an Annin Model 1510 valve that was downstream of the test section, as shown in Figure 13. This valve was manually operated from within the control room through a forty foot long shaft and a twelve foot long chain drive. A pressure relief valve and a rupture disk were connected in parallel with the valve to prevent excessive test section pressure. A 300 psi Heise pressure gauge and a Foxboro pressure transmitter were mounted near the Annin pressure valve to measure test section pressure. The Foxboro transmitter actuated a mercury manometer in the control room to give a visual indication of test section pressure during the experiments.

4.5 Movable Probe

Figure 14 shows the probe in its mount. The mount was secured to the upper housing with a "V" band clamp and sealed with a deformable aluminum gasket. The 4.7 inch long 0.20 inch outside diameter Inconel probe stem was mounted at right angles to and near one end of a 0.31 inch diameter 347 stainless steel supporting drive tube. The drive tube was electrically actuated so that the probe moved continuously back and forth across the diameter of the test section. The pressure seal between the sliding

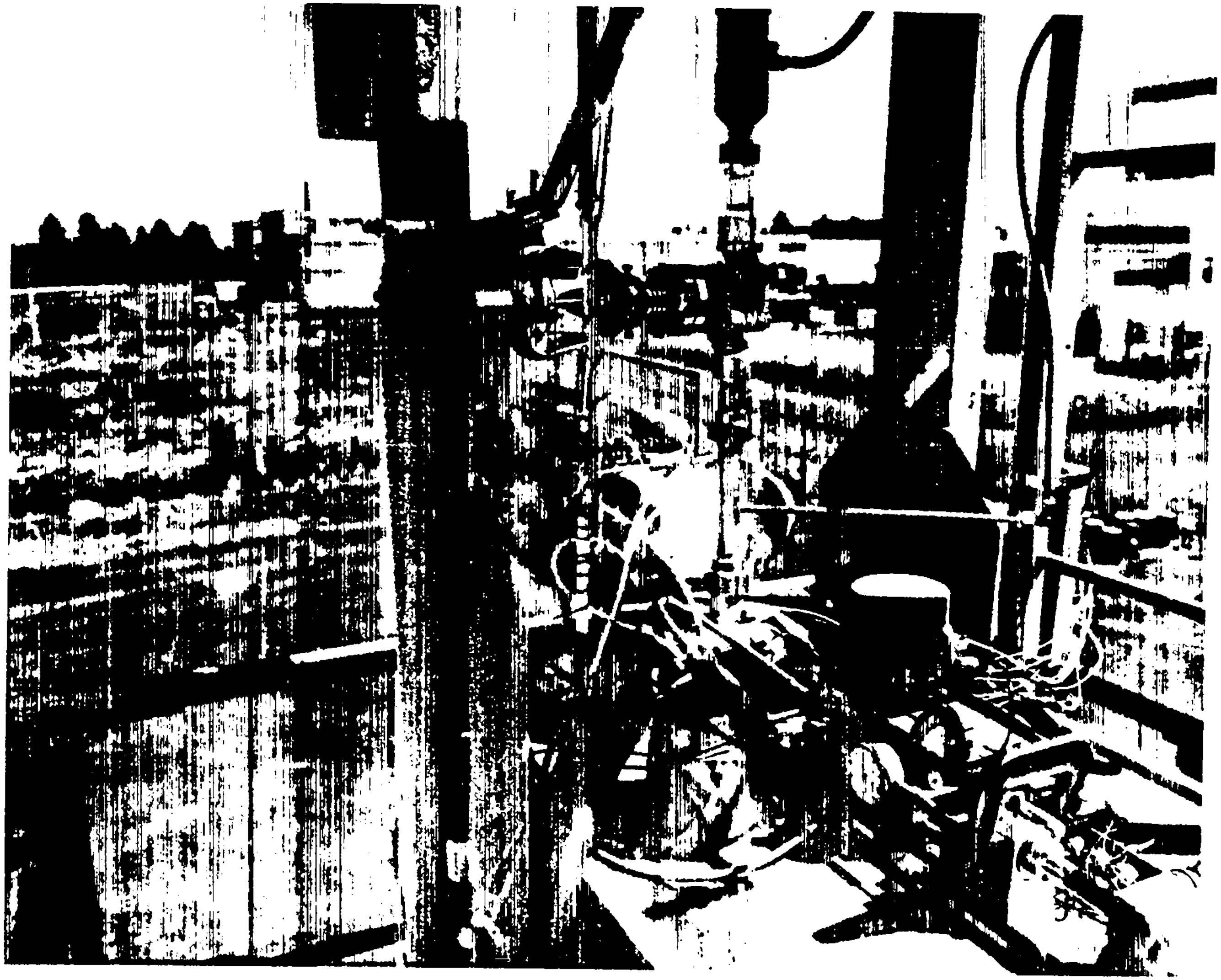

Figure 13. Probe Drive and Pressure Control Valve

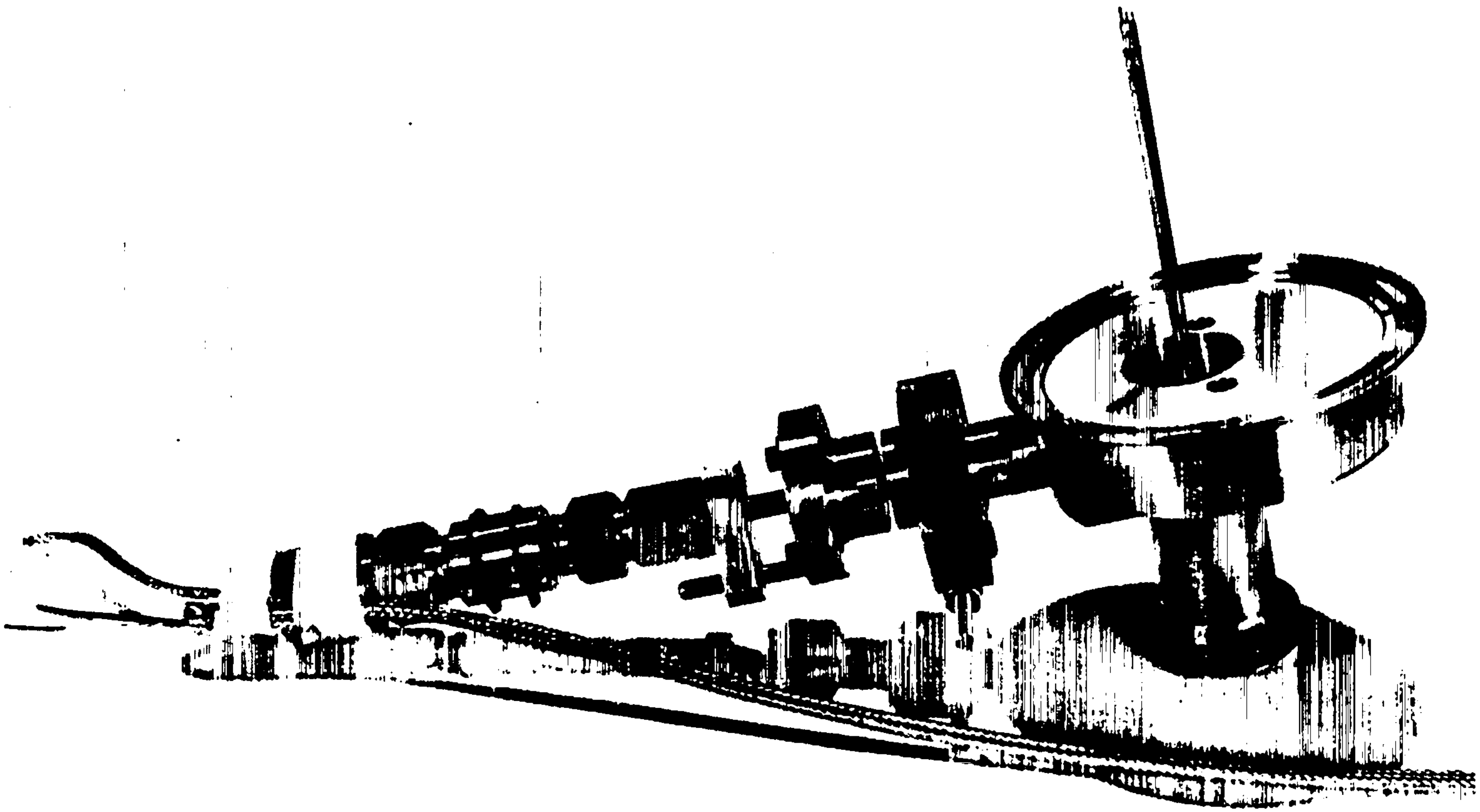

Figure 14. Probe Assembly

drive tube and the fluid pressure within the housing was provided by chevron-shaped Teflon rings. The time of traverse of the probe across the tube in one direction was adjustable from approximately 7 to 14 seconds. Electrical contact with the tube wall of a point on the probe stem provided a signal for reversing the probe drive motor. Auxiliary switches activated the reversing circuit if the probe contacts failed to function. Limit switches mounted on the probe drive provided additional protection. The position of the probe was indicated from a Bourns Corporation Model 108 linear potentiometer attached to the probe drive and powered by a mercury battery. Figure 13 shows the details of probe mounting.

The end of the probe is shown in Figure 15. It included a pitot tube, a thermopile, and a hot wire sensor for measuring intensity of turbulence. The chisel shaped mount was machined from lavite and fired to 2600°R. The distance from the centerline of the drive tube to the ends of the pitot tube and hot wire sensor was 5.306 inches. The thermopile was located between them and was 0.080 inches shorter. The distance between the centerlines of the hot wire sensor and the thermopile was 0.0650 inches, and the distance between the centerlines of the thermopile and the pitot tube

Figure 15 Probe Tip

was 0.0692 inches. Leads from the probe tip were routed through the stem and drive tubes and out through a Conax crushed lavite seal. The inside of the probe tubes were at test section pressure. The difference between pitot and test section static pressure was measured with a MKS Instruments Corporation Model 77H-30 Baratron, capacitance type differential pressure transducer. The connecting tube of the pitot was an 18 inch length of 0.028 inch inside diameter, 0.007 inch wall 321 stainless steel hypodermic tubing. The probe thermopile had five exposed chromel P-constantan junctions mounted in a 0.025 inch outside diameter sheath. It was obtained from High Temperature Instruments Corporation. A socket was fabricated into the probe tip to accept a Disa Model 55-A53 miniature hot wire sensor. The sensing wire was a platinum plated tungsten wire 2.0×10^{-4} inch diameter and 0.018 inch long. The wire was oriented at right angles to the fluid velocity and the probe movement. A sixty foot long Disa Model 06-A107 cable connected the hot wire probe to a Disa Model 55-A01 constant temperature anemometer. A Disa Model 55-D-20/21 power booster increased the maximum hot wire current to one ampere. A John Fluke Manufacturing Company Model 910-AR RMS voltmeter converted the anemometer signal to a root mean square value that was suitable for recording.

4.6 Recorders

Data was recorded on a 60 channel Systems Engineering Laboratories Mobidac multiplex data recording system. The voltage of each channel was sampled, digitized, converted into 12-bit binary words, and recorded on magnetic tape at intervals of 0.003 seconds. All signals from the apparatus, except those from the three accelerometers, were recorded by the Mobidac multiplexer. The outputs from the accelerometer charge amplifiers were indicated on a three sweep cathode ray oscilloscope. The outputs of a few select transducers were also recorded on strip charts for a visual indication during a run. These recorders were a 36 channel Honeywell Model 1612 Visicorder, a single channel and a two channel Brown ink-pen recorder, and a 12 channel Brown multipoint recorder.

5. PROCEDURE

5.1 Introduction

This chapter describes the activities involved with preparing for and conducting a test. The next chapter describes the instrumentation calibrations that occurred during test preparation.

5.2 Test Preparations

Prior to a test series, the high pressure dewar, the test section, and the transfer lines were dilution purged of air with helium. The dilution purge method consists of a number of cycles of pressurizing to the maximum safe limit with helium and then venting to just above atmospheric pressure. This method was required to remove most of the trapped air in small pockets such as pressure transducers. The initial fill of the high pressure dewar with hydrogen required about an hour. Approximately 100 gallons of hydrogen was vaporized in cooling down the transfer line and high pressure dewar. During this initial filling, the recording equipment was adjusted as outlined in Chapter 6.

A manual valve in the transfer line adjacent to the high pressure dewar was closed when the dewar was full. The manual dewar vent valve was also closed, allowing the dewar to be pressurized by hydrogen gas from tube trailers.

The dewar pressure was maintained greater than twice the test section pressure to prevent dewar pressure oscillations. At high flow rates trailer gas pressure had to be greater than 1000 psi to maintain dewar pressure. Refilling was possible within ten minutes, if the transfer line was kept full of liquid by allowing a small amount of flow through a line vent.

5.3 Testing

The desired operating conditions were translated into meter values which were monitored as equipment was adjusted to achieve them. During the adjustment the manual test section exit valve was partially opened, the servo flow control valve between the test section and the high pressure dewar was opened to the desired flow rate, and the power supply was turned on. During a test minor adjustments to the flow control valve, the power supply, and the exit pressure valve were required. The power was monitored on a strip recorder, and the pressure was indicated by the wall static pressure at the pitot position transducer channel on the Mobidac visual display. The mercury-filled "U" tube manometer connected to the Foxboro pressure transmitter at the test section exit indicated gross pressure behavior and was valuable as an aid to the prompt suppression of frequently observed violent pressure oscillations during starting of the flow. It was usually possible to stop oscillations by closing the exit flow valve, thereby increasing pressure and then slowly reopening it. The Visicorder was carefully monitored to indicate normal functioning of the probe position, hot wire outputs, and pressures. When it was evident that conditions had stabilized, the Mobidac recorder was turned on. Recording continued until run conditions began to drift, indicating the dewar was nearly empty. The Mobidac record numbers were handwritten on the Visicorder chart the instant that recording began and ended. The Visicorder was on at all times during hydrogen flow. A strip recorder indicated the temperature of a wall thermocouple near the exit of the test section and a limit on this recorder sounded a klaxon when the wall temperature rose to 70° F to warn against having the power on after hydrogen flow termination. At the end of a run, the system was vented to the atmosphere and the dewar was refilled. A test would result in from one-half minute to six minutes of recorded data, depending on flow rate. It was possible to conduct several tests per day and to test two days per week.

Some test conditions resulted in an inability to control pressure. In these cases it was felt that conditions at the exit valve seat were near critical so that large changes in density occurred for small changes in temperature. In many cases the pressure rises were so rapid that it was impossible to open the exit valve before the test section would relieve through the pressure limit valve or the rupture disk.

6. DATA INTERPRETATION

6.1 Introduction

The accuracy of the data was influenced by the details of installation, method of calibration and testing, stability of electronic equipment, and method of data conversion. These are described in the following sections for the various types of instrumentation. The calibration factors discussed in this chapter are presented in Appendix B.

6.2 Recorder

The Mobidac multiplex recorder was the main data recorder. Analog input voltage signals were sampled one at a time, digitized, and the voltage recorded on magnetic tape. The tape format consisted of twelve bit binary words. Therefore, the output voltage was indicated by 4096 integers. Zero represented minus full scale, 2048 represented zero input voltage, and 4096 indicated positive full scale. Channel gain could be selected to give full scale output for input signals of 5, 10, 20, 50, 100, 200, and 500 millivolts. Each channel was calibrated at the gain used prior to a test series. Calibration was effected by disconnecting the input cables from the recorder, shorting each input for zero setting, and then applying a known voltage for gain setting. A modified Medistor Model C-1A microvolt calibrator provided a stable voltage which was set using a Hewlett-Packard Model 3420A digital voltmeter. The digital voltmeter was calibrated with standards traceable to the National Bureau of Standards.

The Mobidac was turned on at least twelve hours prior to a test. It was found that day-to-day drift was usually less than five integers, and the drift during a day was less than the voltage noise on the calibration voltage line. The noise and drift were functions of channel gain, being worst for the five millivolt channels and unobservable for 20 millivolt and higher ranges. The accuracy of the representation of the input signal was believed to be between 0.04 and 0.12 percent of the channel full scale range when the resolving power of the analog-to-digital conversion and the method of calibration were considered. This is an uncertainty of from two to six microvolts on a five millivolt channel. Non-linearity was less than the uncertainty.

6.3 Electrical Current and Voltage

Signals from potential taps were passed through voltage-dividing resistor networks to reduce their levels to a range acceptable to the Mobidac recorder. The divider networks were adjusted with the Medistor calibrator and Hewlett-Packard voltmeter.

The shunt resistor manufacturer claimed two percent accuracy. A check at 25 amperes indicated the resistor was within one percent.

The signal from the shunt resistor and the potential taps carried the power supply ripple. The power supply was stable within observational limits. The recorded signals were numerically averaged for the time of a probe traverse to provide a mean value with an accuracy of approximately one percent.

6.4 Probe Position

The output of the linear potentiometer attached to the movable probe was used to determine probe turn around. The turn around times as provided by the data location on the magnetic tape coupled with the known recording rate of the Mobidac gave time of traverse. The probe position was measured by a dial indicator at turn around as a check against the probe wall contacts. During data reduction, the position data was scanned to determine the time of the traversing limits. The resolution of the wire-wound potentiometer was 0.0016 inches. Due to electrical noise, it was necessary to numerically average the data in groups. This procedure resulted in an uncertainty of 0.07 seconds in the time of traversing limits. At the usual probe traverse speed of 0.16 inches per second, a position error of the probe was less than 0.011 inches. The knowledge of probe position as a function of time and the geometry of the probe provided the position of the probe sensors as a function of time.

6.5 Pressures

The Statham absolute pressure transducers were calibrated in place at ambient temperature by pressurizing the system and observing the static pressure on a Heise gauge that had been calibrated on an air dead weight tester. These transducers were used as gauge pressure indicators to simplify pre-test adjustments. The transducer outputs were zeroed with the test section open to the atmosphere at ambient temperature with no flow. During data reduction, the transducer outputs were averaged during a traverse, converted to pressures by means of the calibration factor, and added to the barometric pressure measured during the run. The transducer on the inlet plenum was of no value because its calbiration shifted during chilling. The calibration shift of less than 0.01 percent per degree Rankine resulted in inlet pressures indicated lower than exit pressure. Inlet plenum pressure was calculated from wall static pressure at the pitot position and the differential pressure between the plenum and the wall static port. All other transducers were in warm environments. The Statham differential pressure transducers were calibrated with a mercury manometer. All Statham transducers were energized with individual power supplies that had a tendency to drift and required continuous monitoring and frequent adjustment. Maximum deviation from the smooth calibration curve was within one percent for all transducers.

The Baratron differential pressure transducer was factory-calibrated using an air dead weight tester and was checked later with a water manometer. Adjustments were made according to manufacturer's recommendations. The instrument was turned on at least an hour before tests began. The pressure head was heated internally on a programmed cycle prior to testing to assure the removal of possible moisture. The head was then allowed to cool to its thermostatically controlled operating temperature of 580°R. In calculating pitot differential pressure from Baratron signals the static head of fluid in the connecting lines was considered. It was assumed that the thin walled pitot tube was at the same temperature as the test fluid. Baratron output signal noise was of the order of the mean signal from some runs due to pressure oscillations within the test section. Attempts were made to minimize the noise by sizing the static pressure line so that the reference pressure side of the transducer had geometrical similarity with the pitot pressure side [7, 1950]. Static tests gave results that were reproducible within three percent for pressures greater than one millimeter of mercury.

6.6 Temperatures

Temperatures were measured at the test section inlet along the test section wall, and at the movable probe.

The temperature of the hydrogen entering the test section was obtained from a Rosemount platinum resistance thermometer. A Rosemount triple bridge unit powered by mercury batteries provided an output voltage. The thermometer was factory-calibrated at three points. Thermometer resistances at small increments were obtained using the Corruccini three point method from liquid helium to room temperature [2, 1960]. In data reduction a tenth order polynomial was used to fit the resistance as a function of temperature for the range from 24 to 60°R. The maximum deviation of the equation from the data was 0.03°R. A seventh order polynomial was used from 60 to 160°R with a maximum deviation of 0.009°R. The triple bridge unit was calibrated using a decade resistance box connected at the probe location. The decade box and its connector were calibrated with standards traceable to the National Bureau of Standards. The resulting output voltage as a function of input resistance was represented by a third order polynomial. Its maximum deviation was 0.039 ohms. To provide a system check of the resistance thermometer, it was immersed in liquid nitrogen and in liquid hydrogen. The output was read on the Mobidac. The error at liquid nitrogen temperature was less than 0.07°R. At liquid hydrogen temperature, the error was less than 0.1°R.

All thermocouple reference junctions were immersed in a common boiling liquid hydrogen bath at atmospheric pressure. The saturated liquid temperature for an average local barometric pressure of 582.06 millimeters of mercury is 34.92°R. The vapor pressure for hydrogen in the vicinity of the atmospheric pressure was represented by an equation [20,1962]. Actual bath temperature was calculated from the barometric pressure measured at intervals during a test. The thermocouple temperature indications were corrected to the actual cold junction temperatures.

The test section wall temperatures were measured with copper-constantan thermocouples. The output voltage as a function of temperature was calculated for a 34.92°R reference temperature from tables with zero degree reference published by the National Bureau of Standards [9, 1960]. A seventh order polynomial represented the values of voltage as a function of temperature with a maximum deviation of 0.06°R. The thermocouples were calibrated at two temperatures by flowing liquid nitrogen and liquid hydrogen through the test section without heating. The liquid temperature was obtained from the platinum resistance thermometer in the inlet plenum. Thermally induced voltages at a vacuum tight electrical connector and stray voltage combined to produce errors. During calibration, there were variations of 3° at 142° and 9° at 42°R. The error expected from heat transferred into the cold test fluid from the warm vacuum jacket was less than one-tenth degree at 40°R. A method suggested by Powell [10, 1961; 11, 1962] was used for data reduction. Output voltages were obtained during the two-temperature calibration for each thermocouple. The difference between the measured voltage and that expected from the standard curve was defined as a shift voltage and was a linear function of temperature. An iterative procedure was required for temperature calculation. A temperature was calculated from the output voltage using the standard curve. This temperature was used to calculate the shift voltage which was added to the original output voltage. The total voltage provided a new temperature which in turn gave an updated shift voltage. Iteration was continued until the changes were less than one degree. The wall temperature at the probe position was taken as the average of the values obtained at the 127.5 and 129.5 L/D positions.

The probe thermopile was calibrated with a secondary standard platinum resistance thermometer from liquid helium to room temperature. The calibration data from 16 to 142°R was represented by a seventh order polynomial. Two corrections were made to account for differing immersion conditions between calibration and testing. The first correction reduced fluctuations that were caused by the temperature variations of the leads which occurred when the probe traversed the test section [10, 1961; 11, 1962]. Voltage shifts as a function of probe position, temperature, and direction of travel were calculated from numerous unheated runs for which thermopile temperatures were known. The second correction was a temperature dependent correction of 1.75° at 47.2° and zero degrees above 132°R, due to the shorter lead immersion length in use. The corrected thermopile temperature was within 0.34° at 142° and

0.49° at 47°R of the temperature of the inlet platinum resistance thermometer without heating.

6.7 Flow Rate

A water calibration by the manufacturer was provided with the Cox turbine flowmeter. During this investigation, it was checked with water by timing and weighing an accumulation of the flow. The one inch diameter flowmeter was selected to match flow piping sizes. According to Gray, water calibrations are applicable to liquid hydrogen [5, 1959]. Theoretically, the low viscosity of hydrogen caused the turbine to rotate 0.6 percent slower than for water, but this was balanced by a 0.6 percent higher hydrogen velocity due to thermal contraction of the flowmeter. Suitable flow calibration facilities for liquid hydrogen were not available. Experience in the cryogenic industry indicated that water calibrations were reliable when corrected for viscosity and thermal contraction effects. Due to the large amount of data and the necessity of assigning run times to the flow, the Mobidac recording was used to provide flow information. Spot checks with the printed tape of the electronic counter indicated a maximum deviation of 2.2 percent in the Mobidac record.

The turbine flowmeter was sensitive to volume flow rate. The density of the fluid flowing through the meter was necessary to obtain a mass flow rate. Attempts to measure fluid temperature at the flowmeter with thermocouples and helium bulb thermometers were unsuccessful. The temperature and pressure were measured accurately at the inlet plenum. The enthalpy was constant from the inlet plenum to the flowmeter, assuming adaibatic flow through the flow control valve. The flowmeter pressure was very near that of the high pressure dewar. The density was obtained from hydrogen properties tables at dewar pressure and inlet plenum enthalpy. The manufacturer reported a deviation of 0.37 percent from linearity during calibration.

6.8 Hot Wire Anemometer

The anemometer was adjusted according to the manufacturer's recommendations. The output was filtered to pass only frequencies below 10,000 Hertz. The hot wire temperature was approximately 260° R for all tests. Calibration experiments indicated that the anemometer bridge voltage was 25.7 volts per ampere of current through the wire at the wire resistance of 1.5 ohms. The wires were experimentally found to have a temperature coefficient of 0.0028 ohms per degree Rankine at 260° R. The bridge voltage and wire position were calculated for each data point for the traverses used.

The fluctuating component of the bridge voltage was converted to a root mean square value or RMS. The RMS voltmeter was of the thermocouple type. Its experimentally determined time lag was from 0.25 to 0.30 seconds. The data was shifted two Mobidac records or 0.276 seconds to account for its lag. This produced symmetry in the RMS voltage with respect to the test section centerline.

7. DATA REDUCTION

7.1 Introduction

The tests were planned to map the range of possible operating conditions in a systematic fashion with additional tests near the critical point. Data was recorded for a maximum accumulated time of six minutes on a 2400 foot long reel of magnetic tape. Forty reels were used to record the data from 136 tests. The data was scanned to select acceptable tests. This chapter describes the method of selecting tests, the special manipulations of probe data, and the methods employed to calculate power input and fluid bulk conditions.

7.2 Data Acceptance

Mobidac data of selected variables was computer plotted for all tests. Tests were selected in which conditions had remained steady for at least four consecutive probe traverses. Stability was defined as a drift of less than 0.5 pounds per square inch in pressure, 0.25 degrees in inlet temperature, and 0.5 gallons per minute in flow. The second and third traverses of the steady portion of the selected tests were assigned run numbers. Both directions of probe travel were inherent in a pair of runs which were at essentially identical test conditions. The resulting number of runs was one hundred forty two. Each run involved approximately 2000 data points per sensor.

7.3 Probe Data Collation

Figures 14 and 15 of the moving probe show the pitot tube and thermopile at different radii. The distance between them was 0.0692 inches. To compensate for the different sensor locations, the time index of the second sensor was shifted so that its data corresponded to the radius of the first sensor. Velocities were calculated from the expression

$$v = \sqrt{\frac{2 \ \Delta p}{\rho}} \tag{43}$$

where:

Δp = dynamic pressure calculated from pitot tube pressure minus the pitot position wall static pressure

ρ = hydrogen density

Mass flow rates per unit area were calculated from

$$\rho v = \sqrt{2 \ \rho \ \Delta p} \tag{44}$$

The densities were obtained from the TABTP code with thermopile temperatures and wall static pressures. The velocity and the mass flow rate per unit area values were tabulated as a function of distance across the test section. This table was the basis of empirical equations (47) and (48) in Section 8.3.

7.4 Power Input and Wall Temperatures

The measured thermal coefficient of electrical resistivity of the Inconel test section was less than 5×10^{-9} ohm-cm/°R. With a constant current and resistivity along the test section, the power input per unit length was constant. The deviation from a straight line, of measured potential tap voltages versus length, was negligible. Power input was calculated from the electrical current and the potential drop.

The inside wall temperatures of the test section were calculated from measured outside wall temperatures, the power input, and the Inconel thermal conductivity. In the calculation the thermal conductivity of Inconel as a function of temperature was represented by an empirical expression. The temperature drop across the tube wall was as large as 15 degrees for high power inputs. Typical temperatures as a function of length are illustrated in Figure 16. The calculated inside wall temperatures are tabulated in Table 5 in Appendix C.

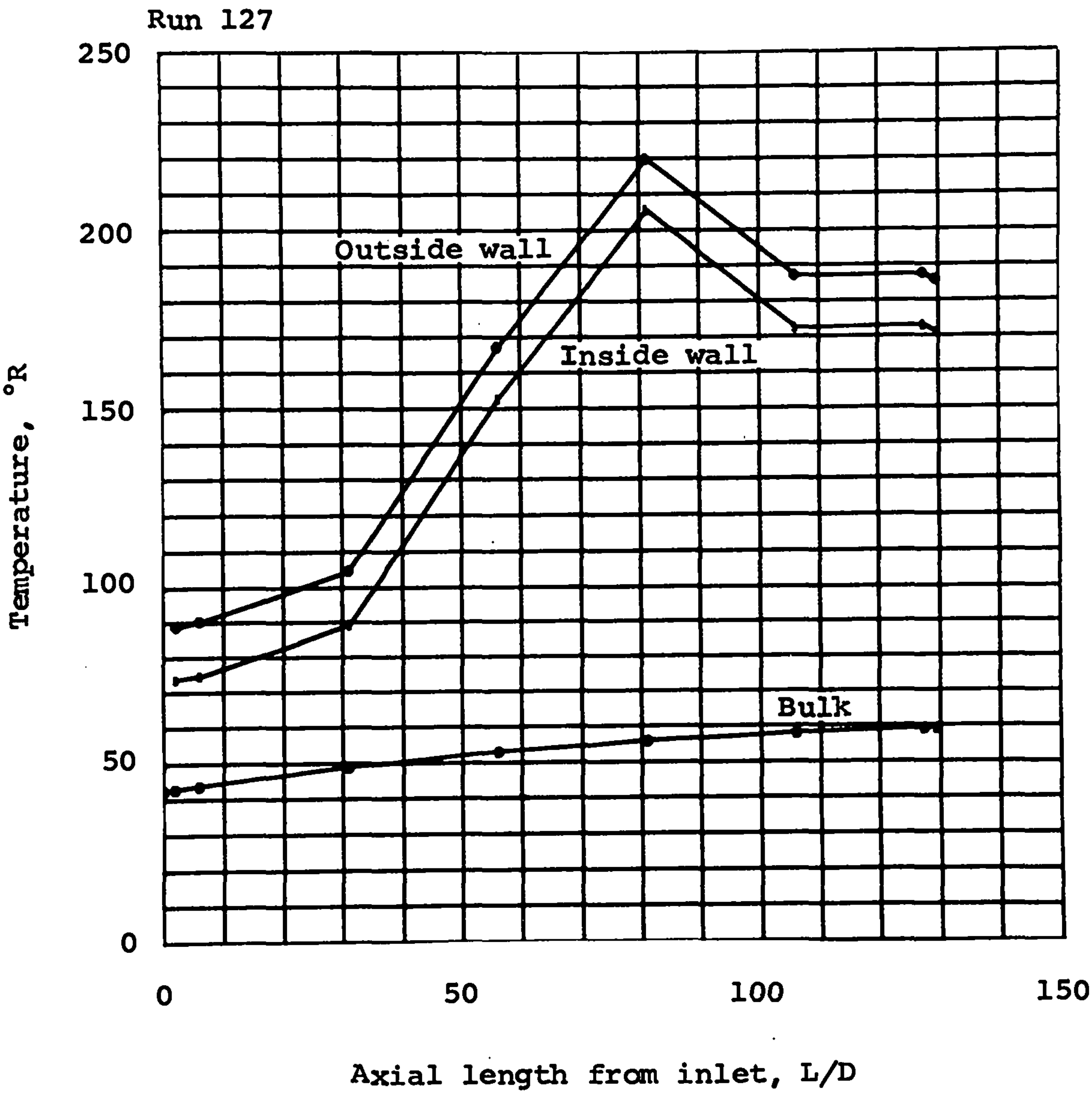

Figure 16. Temperatures Along the Test Section

7.5 Bulk Fluid Conditions

The inlet hydrogen properties were obtained at the inlet plenum temperature and pressure from the TABTP code. The uniform power input, inlet enthalpy, and mass flow rate were sufficient to determine the bulk enthalpy of the fluid at any axial position along the test section. The test section cross sectional area was approximately 0.25 times that of the plenum. The contraction coefficient of the sharp entrance of the test section was 0.433 [13, 1950]. Since pressure drops were small, it was assumed that the pressure was a linear function of axial position within the test section. The TABHP code was used to compute the bulk temperatures as a function of length from pressures and bulk enthalpies.

8. DATA SUMMARY

8.1 Introduction

The purpose of this chapter is to summarize system conditions and to present empirical equations which represent probe data. The total number of runs was 142.

8.2 System Conditions

System conditions are summarized in Tables 1 and 2. Temperatures, enthalpies, velocities, Prandtl, and Reynolds numbers are bulk averages that were calculated from mass flow rate and power input.

8.3 Empirical Equations

The data was stored on magnetic tape. For each run and probe variable, there were about 2000 data points as a function of distance across the test section. The data was represented by a variety of empirical equations. From these, equations were selected which had a minimum number of parameters and acceptable standard deviations. These selected equations are:

Hydrogen temperature at the probe

$$T = TT1 - TT2\left[1 - \left(\frac{|R-y|}{R}\right)^2\right]^{\frac{1}{2}} \qquad (45)$$

The dynamic pressure

$$\Delta p = PP1 \left[1 - \left(\frac{|R-y|}{R} \right)^{PP2} \right] \tag{46}$$

The velocity

$$v = VV1 \left[1 - \left(\frac{|R-y|}{R} \right)^{VV2} \right] + VV3 \sin \frac{3\pi y}{2R} \tag{47}$$

The mass flow rate per unit area

$$\rho v = MM1 \left(\frac{y}{R} \right)^{1/9.5} + MM2 \sin \frac{\pi y}{2R} + MM3 \sin \frac{3\pi y}{2R} \tag{48}$$

The hot wire bridge voltage

$$e_1 = WW1 \left[1 - \left(\frac{|R-y|}{R} \right)^{WW2} \right] + WW3 \tag{49}$$

The RMS value of the hot wire bridge voltage

$$e_2 = RR1 + RR2 \sin \frac{\pi y}{2R} + RR3 \sin \frac{3\pi y}{2R} + RR4 \sin \frac{5\pi y}{2R} \tag{50}$$

Where the units are:

$[T]$ = degrees Rankine

$[\Delta p]$ = pounds/inch^2

$[v]$ = feet/second

$[\rho v]$ = pounds/second-inch^2

$[e_1]$ = volts

$[e_2]$ = millivolts

R = 0.688 inches is the test section radius

y = distance from the test section reference wall

The temperature and hot wire profiles were not specified at the wall. Samples of typical data and equations are illustrated in Figures 17 to 22. The boxes that are plotted among the data in the figures represent the numerical averages of data groups that contain ten percent of all the data points. The parameters and the deviations of Section 3.5 of the empirical equations are presented in Tables 6 to 11 in Appendix C.

Excluding RMS voltages, the adjusted deviation of empirical equations from the mean of a subset of data was less than 11 percent in all cases and was less than one percent in many cases. The deviation between mass flow rates obtained by integration of the ρv empirical equation and from the turbine flow meter ranged from -32 to 18 percent except near the critical point where some deviations were as large as 24 percent. A reason for the latter deviation is described in Section 9.4. Except for the critical point region, only 10 percent of the data had deviations larger than 10 percent.

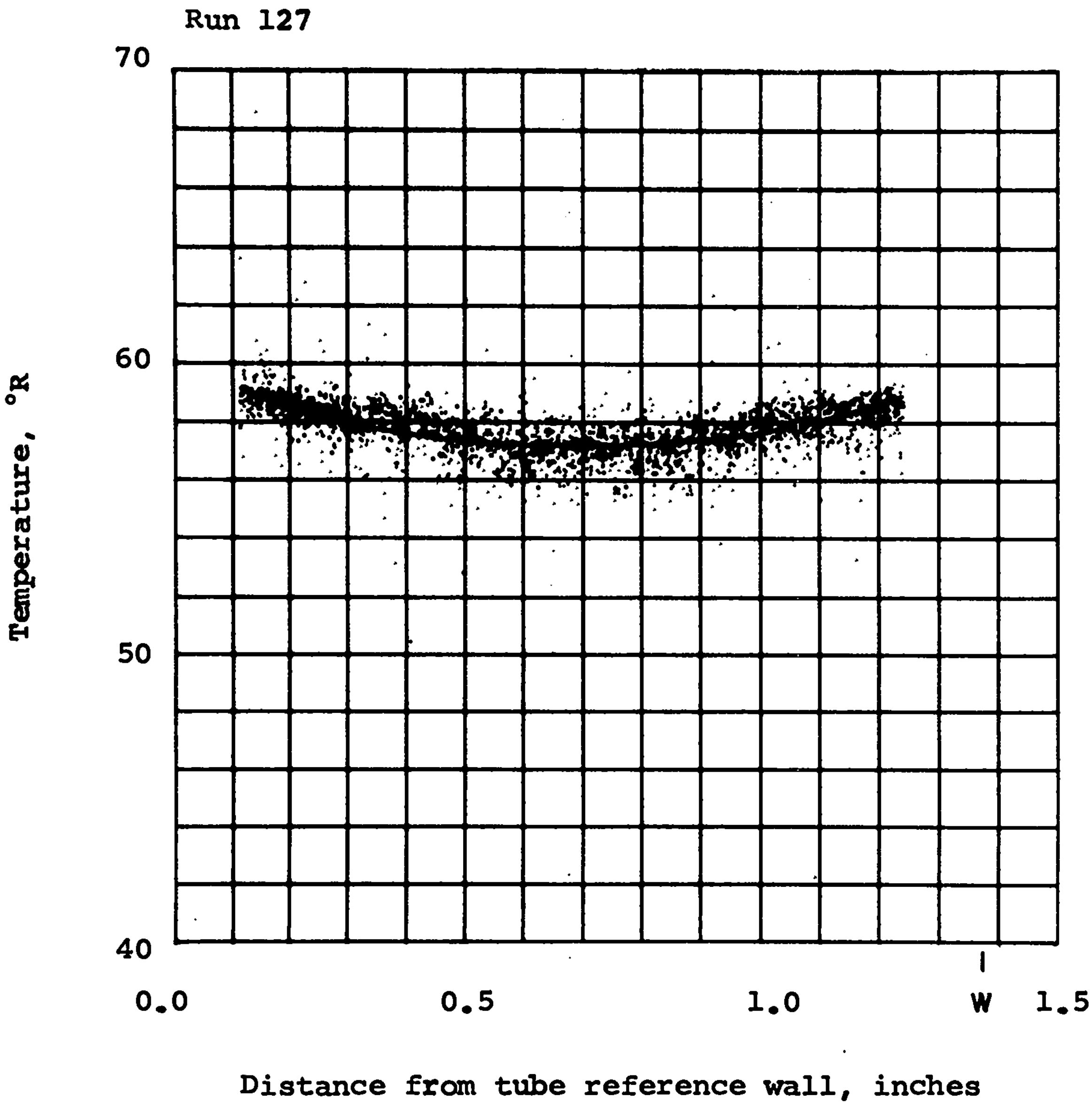

Figure 17. Temperature Profile

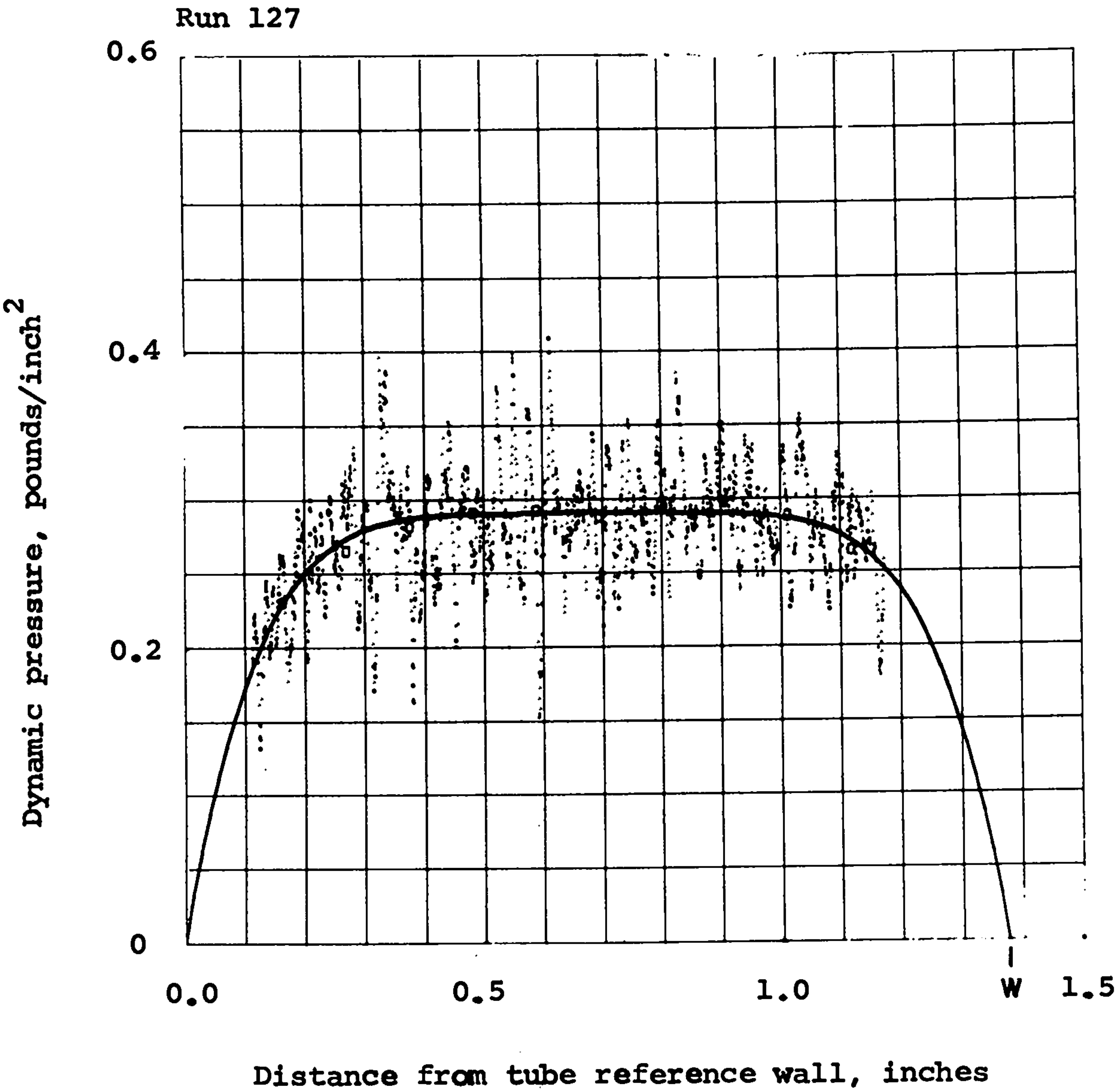

Figure 18. Dynamic Pressure Profile

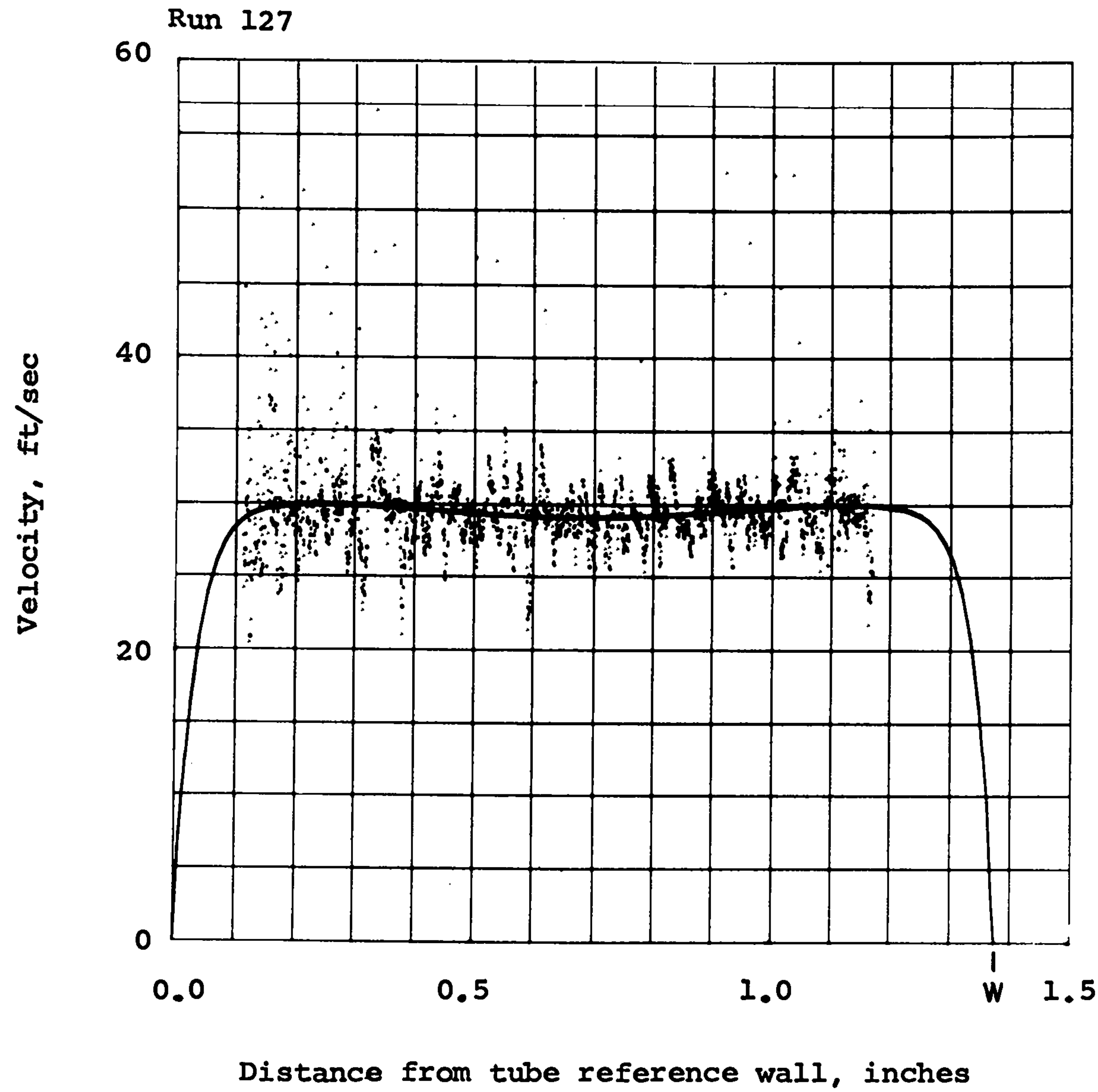

Figure 19. Velocity Profile

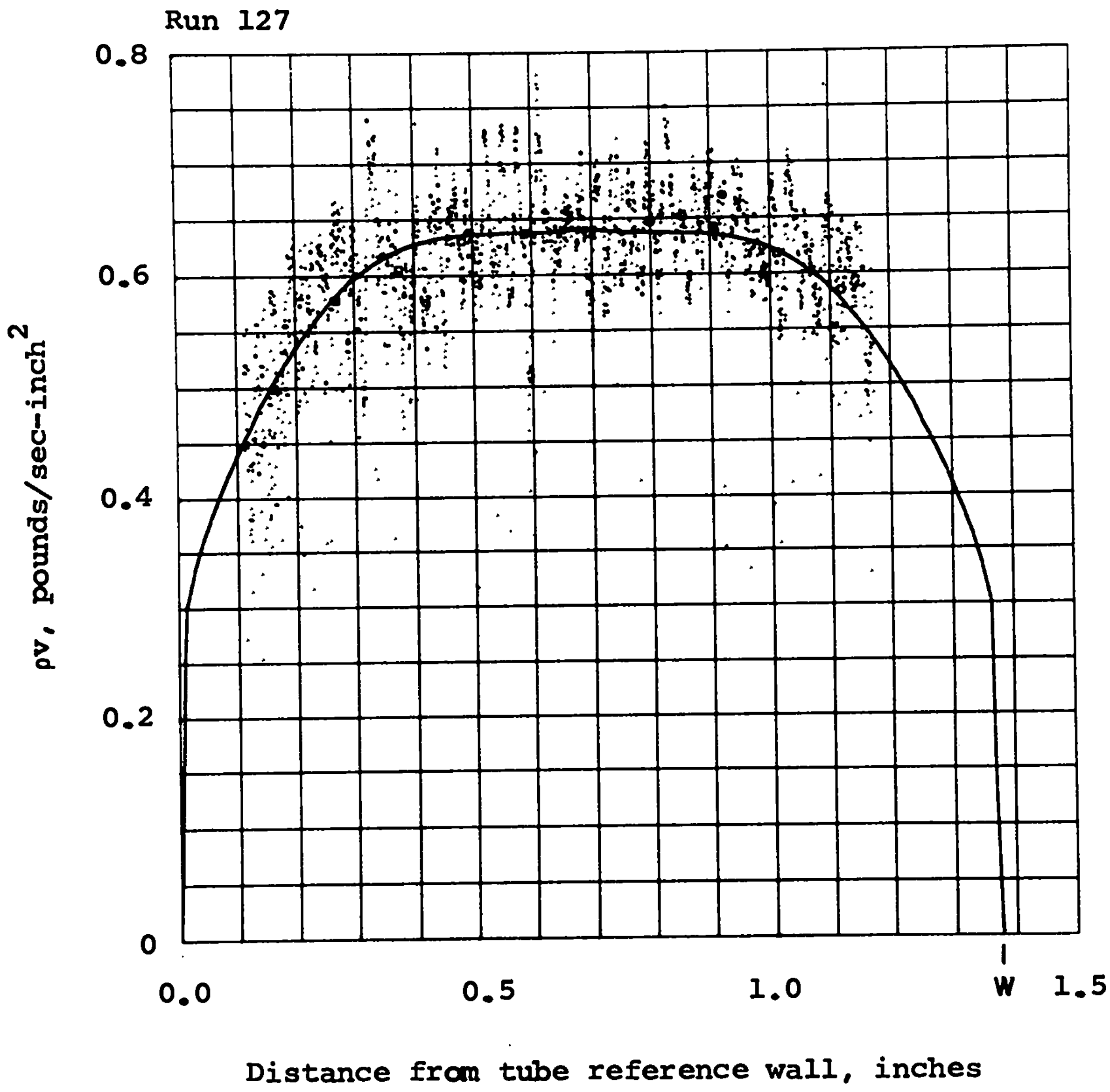

Figure 20. ρv Profile

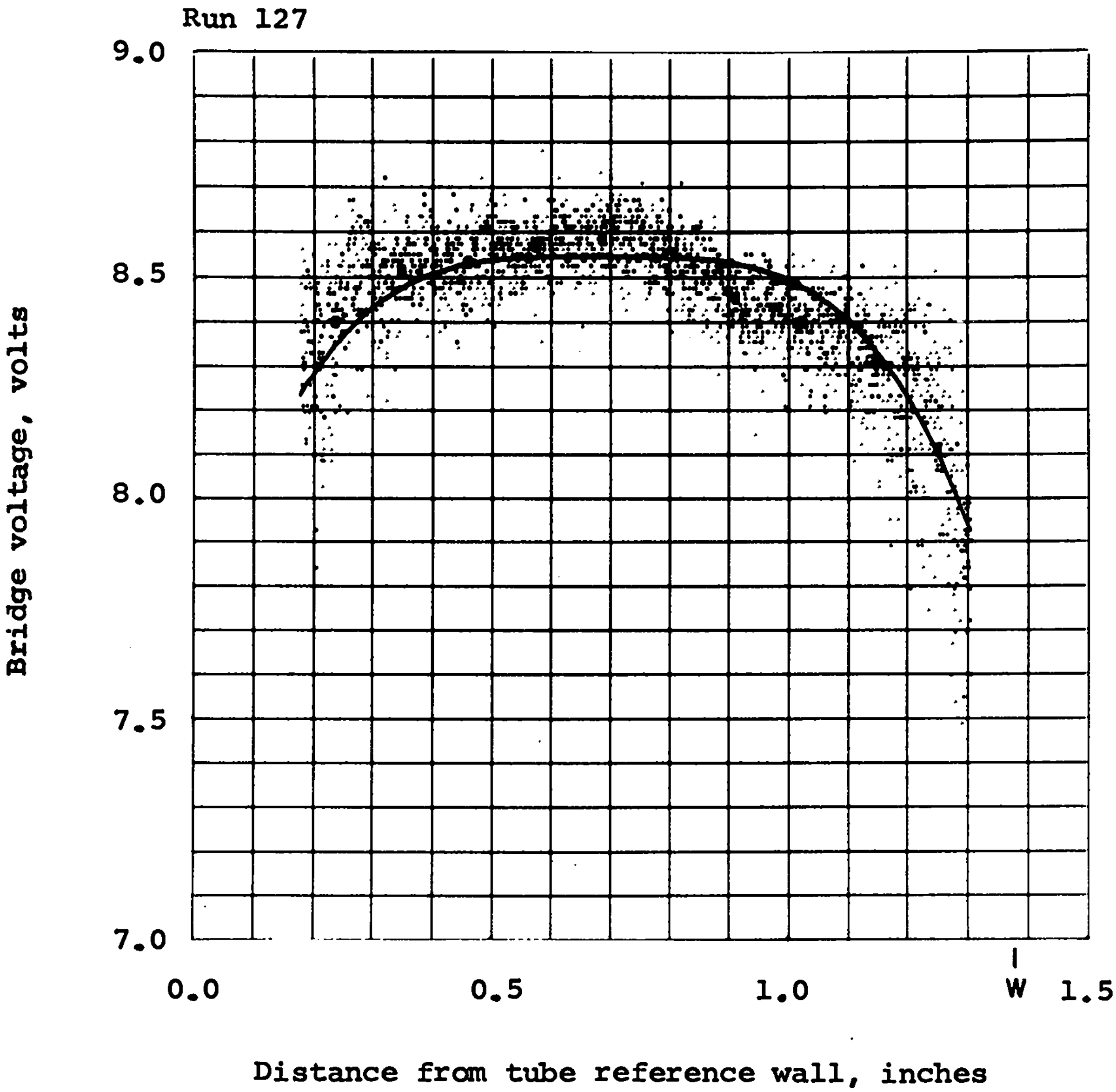

Figure 21. Hot Wire Bridge Voltage Profile

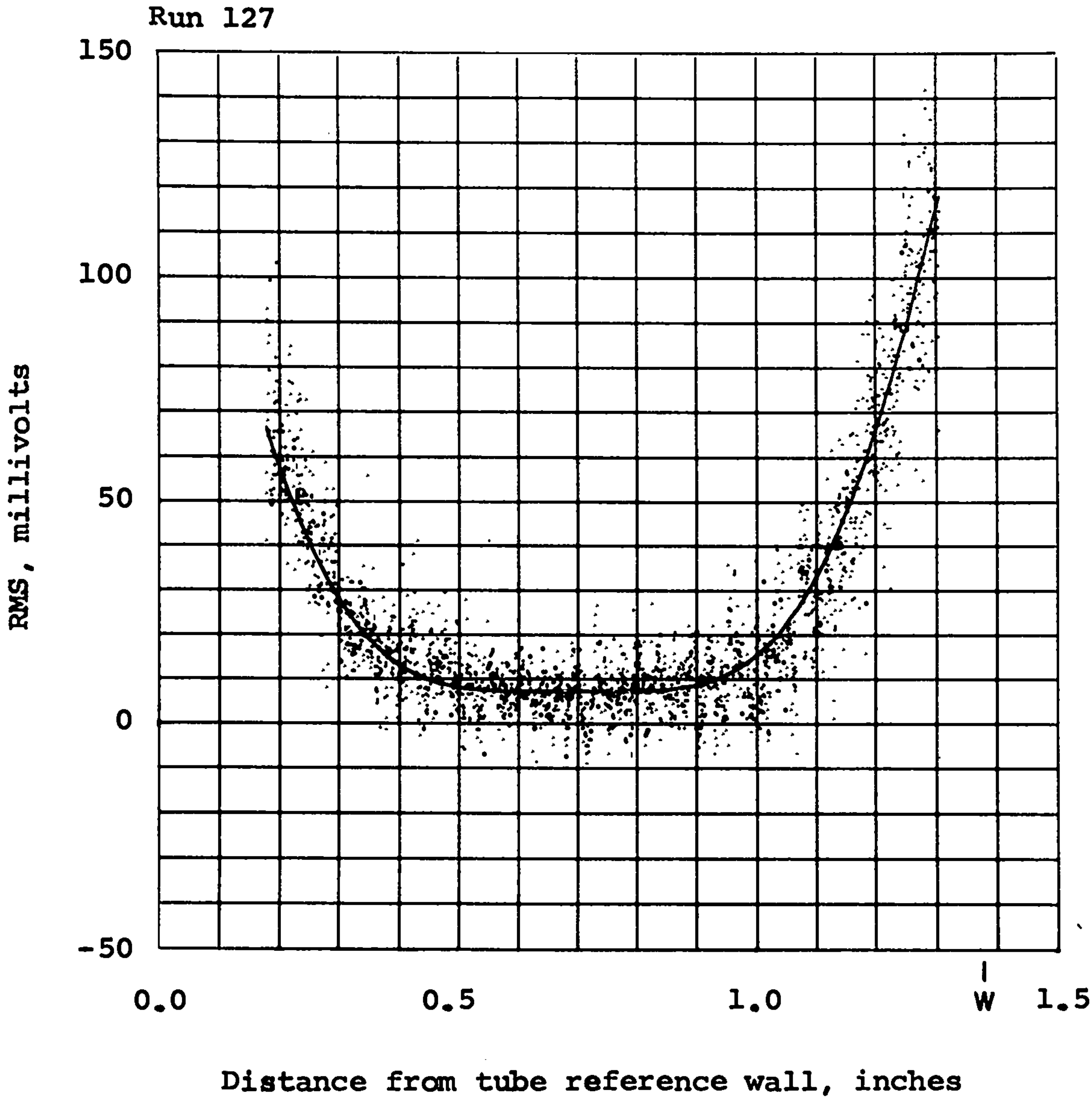

Figure 22. Hot Wire RMS Profile

TABLE 1.

SYSTEM CONDITIONS, PART 1. †

RUN	P	M	Q/A	RP	RT	DIFF	PD	T1	T2
1	195.1	.478	22945	1.039	.995	-.9	.437	44.4	59.1
2	195.2	.478	22951	1.040	.996	-.9	.439	44.5	59.1
3	191.5	.411	23266	1.020	1.002	-.3	.402	46.6	59.5
4	191.2	.410	23228	1.019	1.002	-.3	.402	46.7	59.5
5	190.2	.425	23204	1.013	.997	-.4	.408	45.1	59.2
6	190.5	.425	23213	1.015	.998	-.4	.413	45.1	59.3
7	201.9	.513	29686	1.076	1.013	-.3	.469	46.3	60.2
8	202.2	.511	29669	1.077	1.014	-.3	.475	46.7	60.2
9	216.3	.369	0	1.152	.754	-16.6	.454	44.8	44.8
10	217.0	.370	0	1.156	.754	-16.6	.455	44.8	44.8
11	193.0	.287	4277	1.028	.898	-6.5	.412	47.4	53.3
12	193.3	.287	4278	1.030	.898	-6.6	.411	47.4	53.3
13	189.7	.286	16522	1.011	1.000	-.2	.362	46.4	59.4
14	190.1	.286	16521	1.013	1.001	-.2	.374	46.5	59.4
15	248.6	.287	4148	1.325	.872	-11.5	.430	45.3	51.8
16	248.7	.289	4146	1.325	.872	-11.5	.429	45.4	51.8
17	250.3	.274	4145	1.333	.880	-11.1	.425	45.6	52.3
18	250.2	.271	4146	1.333	.882	-11.0	.425	45.6	52.4
19	225.1	.281	4133	1.199	.876	-9.9	.429	45.7	52.0
20	225.4	.281	4129	1.201	.876	-9.9	.430	45.7	52.1
21	200.4	.274	4152	1.068	.889	-7.6	.421	46.5	52.8
22	199.6	.271	4154	1.064	.891	-7.4	.420	46.6	52.9
23	251.4	.381	4132	1.339	.848	-13.1	.458	45.4	50.3
24	251.0	.381	4130	1.337	.848	-13.0	.456	45.5	50.4
25	250.6	.368	4135	1.335	.854	-12.6	.453	45.7	50.7
26	250.9	.369	4132	1.337	.856	-12.5	.452	45.8	50.9
27	251.2	.468	4133	1.338	.817	-14.9	.500	44.3	48.6
28	250.8	.467	4137	1.336	.818	-14.8	.502	44.3	48.6
29	250.3	.711	4103	1.334	.766	-17.9	.617	42.4	45.5
30	249.9	.706	4103	1.331	.767	-17.8	.621	42.5	45.5
31	190.1	.381	4078	1.013	.834	-10.2	.466	44.7	49.5
32	191.1	.381	4080	1.018	.835	-10.1	.468	44.8	49.6
33	189.8	.377	17346	1.011	.986	-1.1	.422	44.1	58.6
34	190.5	.377	17364	1.015	.987	-1.1	.420	44.2	58.6
35	189.1	.467	17026	1.007	.967	-2.2	.471	45.1	57.4
36	189.1	.465	17034	1.008	.968	-2.1	.466	45.2	57.5
37	199.8	.682	17588	1.065	.910	-6.3	.608	43.2	54.1
38	199.9	.680	17584	1.065	.912	-6.2	.598	43.4	54.2
39	224.8	.660	17428	1.198	.922	-7.2	.591	43.9	54.8
40	224.8	.657	17436	1.197	.923	-7.1	.594	43.9	54.8
41	250.9	.653	17443	1.337	.934	-7.9	.587	44.5	55.5
42	250.7	.656	17444	1.336	.933	-7.9	.585	44.5	55.4
43	248.6	.475	17343	1.324	.982	-4.9	.480	45.0	58.4
44	248.1	.475	17341	1.322	.982	-4.9	.482	45.0	58.3
45	251.2	.379	17486	1.338	1.014	-3.2	.430	44.6	60.2
46	250.8	.379	17487	1.336	1.014	-3.2	.429	44.6	60.2
47	250.1	.281	17440	1.333	1.047	-1.2	.384	45.2	62.2
48	250.0	.281	17451	1.332	1.047	-1.2	.380	45.2	62.2

TABLE 1, CONTINUED.

SYSTEM CONDITIONS, PART 1.

RUN	P	M	Q/A	RP	RT	DIFF	PD	T1	T2
49	225.0	.262	17489	1.199	1.034	-.5	.373	46.1	61.4
50	225.4	.262	17486	1.201	1.034	-.5	.370	46.2	61.4
51	200.5	.274	17565	1.068	1.014	-.2	.380	46.2	60.2
52	200.6	.274	17578	1.069	1.014	-.2	.377	46.2	60.2
53	200.0	.273	17601	1.065	1.013	-.2	.375	46.2	60.1
54	199.6	.273	17601	1.063	1.012	-.2	.373	46.3	60.1
55	190.4	.685	17412	1.014	.917	-5.3	.614	44.4	54.4
56	189.5	.684	17423	1.009	.917	-5.2	.608	44.4	54.5
57	249.4	.696	0	1.329	.662	-24.0	.593	39.3	39.3
58	250.4	.693	0	1.334	.665	-23.9	.600	39.5	39.5
59	188.7	.659	0	1.005	.771	-13.8	.574	45.8	45.8
60	189.1	.657	0	1.007	.772	-13.8	.568	45.8	45.8
61	189.1	.669	4132	1.007	.821	-10.8	.570	45.9	48.8
62	188.3	.668	4130	1.003	.821	-10.8	.565	45.9	48.8
63	200.3	.674	4153	1.067	.829	-11.2	.569	46.5	49.2
64	199.8	.674	4154	1.064	.829	-11.1	.567	46.5	49.3
65	224.1	.675	4154	1.194	.831	-12.5	.572	46.6	49.4
66	224.0	.675	4155	1.193	.831	-12.5	.575	46.6	49.4
67	190.7	.678	16355	1.016	.923	-4.9	.563	45.6	54.8
68	191.5	.677	16374	1.020	.924	-4.9	.570	45.7	54.9
69	248.8	.665	39364	1.326	1.046	-1.2	.613	46.7	62.1
70	249.1	.665	39374	1.327	1.046	-1.2	.606	46.8	62.1
71	191.2	.466	4223	1.019	.860	-8.7	.481	47.4	51.1
72	190.6	.463	4221	1.016	.860	-8.6	.482	47.4	51.1
73	190.6	.376	16534	1.015	.994	-.7	.395	47.4	59.1
74	190.5	.376	16519	1.015	.994	-.6	.395	47.5	59.1
75	224.4	.269	17267	1.196	1.034	-.5	.360	47.5	61.4
76	224.7	.269	17291	1.197	1.034	-.5	.359	47.6	61.4
77	228.2	.680	17191	1.216	.925	-7.2	.607	44.7	54.9
78	228.1	.679	17200	1.215	.926	-7.1	.610	44.7	55.0
79	190.2	.272	4089	1.014	.906	-5.9	.398	48.2	53.8
80	190.3	.272	4091	1.014	.906	-5.9	.398	48.2	53.8
81	191.5	.671	38278	1.020	1.002	-.2	.659	47.3	59.5
82	191.5	.667	38259	1.020	1.002	-.2	.668	47.4	59.5
83	248.0	.663	0	1.321	.801	-15.7	.563	47.6	47.6
84	247.6	.663	0	1.319	.803	-15.6	.567	47.7	47.7
85	191.2	.565	16776	1.019	.964	-2.5	.525	47.8	57.3
86	191.2	.565	16768	1.018	.965	-2.4	.524	47.9	57.3
87	190.2	.269	14806	1.013	1.001	-.2	.355	49.1	59.5
88	190.2	.269	14803	1.014	1.001	-.2	.352	49.2	59.5
89	191.2	.364	18115	1.019	1.001	-.3	.388	49.0	59.4
90	191.6	.364	18119	1.021	1.001	-.3	.391	49.0	59.5
91	190.6	.463	22352	1.015	.998	-.5	.446	48.0	59.3
92	191.1	.465	22353	1.018	.998	-.5	.446	48.0	59.3
93	190.9	.268	16831	1.017	1.003	-.2	.347	49.2	59.6
94	190.9	.268	16835	1.017	1.003	-.2	.345	49.2	59.6
95	190.6	.267	0	1.015	.836	-10.0	.417	49.7	49.7
96	190.4	.267	0	1.014	.838	-9.9	.416	49.8	49.8

TABLE 1, CONTINUED.

SYSTEM CONDITIONS, PART 1.

RUN	P	M	Q/A	RP	RT	DIFF	PD	T1	T2
97	196.0	.274	0	1.044	.815	-11.7	.430	48.4	48.4
98	195.8	.274	0	1.043	.816	-11.6	.430	48.5	48.5
99	253.1	.291	0	1.348	.707	-21.5	.467	42.0	42.0
100	253.6	.291	0	1.351	.707	-21.5	.467	42.0	42.0
101	189.2	.461	4244	1.008	.872	-7.8	.485	48.2	51.8
102	188.8	.462	4241	1.006	.872	-7.8	.486	48.2	51.8
103	189.1	.466	4246	1.007	.874	-7.7	.484	48.4	51.9
104	188.9	.464	4243	1.007	.876	-7.5	.482	48.5	52.1
105	250.7	.664	4243	1.336	.848	-13.0	.583	47.7	50.4
106	251.7	.666	4245	1.341	.849	-13.0	.584	47.8	50.5
107	250.6	.658	4234	1.335	.852	-12.7	.580	48.0	50.6
108	250.2	.658	4234	1.333	.853	-12.7	.579	48.0	50.7
109	189.3	.272	17279	1.008	1.001	-.2	.357	48.9	59.4
110	189.0	.272	17281	1.007	1.000	-.2	.346	48.9	59.4
111	189.6	.272	17277	1.010	1.001	-.2	.354	49.0	59.5
112	189.7	.272	17279	1.011	1.001	-.2	.355	49.1	59.5
113	190.7	.277	17292	1.016	1.002	-.2	.355	49.1	59.5
114	190.5	.277	17278	1.015	1.002	-.2	.355	49.1	59.5
115	248.1	.658	17282	1.322	.963	-6.1	.566	47.6	57.2
116	248.3	.662	17265	1.323	.963	-6.1	.559	47.7	57.2
117	192.1	.278	37842	1.024	1.205	11.7	.535	48.9	71.6
118	191.9	.279	37874	1.022	1.202	11.6	.549	48.9	71.4
119	192.5	.291	37588	1.025	1.099	5.4	.545	42.9	65.3
120	192.7	.290	37577	1.027	1.101	5.5	.567	43.1	65.4
121	250.5	.280	37985	1.334	1.215	8.8	.481	44.3	72.2
122	251.5	.283	37973	1.340	1.211	8.5	.481	44.4	71.9
123	252.6	.359	38885	1.346	1.147	4.7	.515	49.2	68.1
124	252.3	.359	38885	1.344	1.148	4.7	.504	49.3	68.2
125	193.1	.366	38695	1.029	1.058	2.9	.619	49.1	62.8
126	193.2	.366	38680	1.030	1.058	2.9	.599	49.1	62.8
127	189.9	.700	38802	1.012	.995	-.6	.653	42.4	59.1
128	190.3	.699	38819	1.014	.995	-.6	.659	42.5	59.1
129	192.6	.566	38658	1.026	1.006	-.1	.647	49.3	59.7
130	192.2	.562	38652	1.024	1.006	-.1	.668	49.6	59.7
131	190.8	.338	21471	1.017	1.000	-.4	.409	41.9	59.4
132	191.0	.339	21464	1.017	1.000	-.3	.411	42.0	59.4
133	189.9	.311	18152	1.012	1.001	-.2	.376	49.9	59.5
134	190.7	.311	18133	1.016	1.002	-.2	.376	50.0	59.5
135	189.8	.412	19597	1.011	.998	-.4	.414	49.2	59.3
136	190.0	.411	19632	1.012	.999	-.4	.409	49.3	59.3
137	202.1	.514	25689	1.077	1.008	-.6	.477	47.5	59.9
138	201.8	.512	25684	1.075	1.008	-.6	.479	47.5	59.9
139	191.1	.521	25551	1.018	.998	-.4	.484	47.9	59.3
140	191.4	.520	25518	1.019	.999	-.4	.479	48.1	59.3
141	192.1	.613	29895	1.023	.999	-.5	.553	48.1	59.4
142	192.1	.613	29902	1.023	.999	-.5	.554	48.1	59.4

† Table 1. Continued, System Conditions, Part 1

Symbol	Meaning	Units
P	absolute pressure	$pound/inch^2$
M	mass flow rate	pound/sec
Q/A	heat rate per unit area	$Btu/hr\text{-}ft^2$
RP	reduced pressure	
RT	reduced temperature	
DIFF	$T_2 - T_{pc}$	°R
PD	test section pressure drop	$pound/inch^2$
T1	inlet hydrogen temperature	°R
T2	hydrogen temperature at axial position of the probe tip	°R

TABLE 2.

SYSTEM CONDITIONS, PART 2. †

RUN	H1	H2	RE1	RE2	PR1	PR2	V1	V2
1	-85.2	-15.0	746500	1696900	1.12	9.48	11.03	18.79
2	-85.1	-14.9	747400	1698400	1.13	9.60	11.03	18.79
3	-78.7	3.9	697710	1898300	1.15	16.73	9.76	22.31
4	-78.5	4.3	697460	1906000	1.15	16.59	9.74	22.48
5	-83.3	-3.5	681770	1801000	1.13	13.42	9.90	21.59
6	-83.1	-3.3	682900	1801000	1.13	13.66	9.91	21.52
7	-79.5	5.1	854520	2146900	1.11	8.36	12.10	23.58
8	-78.3	6.5	865490	2144700	1.11	8.25	12.12	23.64
9	-83.7	-83.7	576810	576960	1.12	1.12	8.52	8.52
10	-83.6	-83.6	579690	579850	1.12	1.12	8.55	8.56
11	-76.2	-54.3	502830	643720	1.15	1.36	6.88	7.68
12	-76.1	-54.3	503260	644080	1.15	1.36	6.88	7.68
13	-79.2	5.4	482550	1353400	1.15	15.63	6.78	16.21
14	-79.0	5.7	483470	1351300	1.15	15.93	6.78	16.11
15	-81.3	-60.2	450200	575240	1.12	1.29	6.63	7.25
16	-81.0	-60.1	454950	580280	1.12	1.29	6.69	7.31
17	-80.6	-58.5	432930	558890	1.12	1.26	6.34	6.97
18	-80.5	-58.2	428630	554760	1.12	1.25	6.28	6.91
19	-80.9	-59.4	450960	579060	1.12	1.37	6.54	7.19
20	-80.8	-59.3	451350	579330	1.12	1.37	6.54	7.19
21	-78.8	-56.7	460840	593560	1.11	1.20	6.48	7.18
22	-78.6	-56.2	458400	592490	1.11	1.30	6.43	7.15
23	-81.1	-65.2	598850	720730	1.12	1.23	8.82	9.42
24	-80.9	-65.1	599960	721880	1.12	1.23	8.82	9.42
25	-80.2	-63.9	584150	706750	1.12	1.25	8.54	9.15
26	-79.8	-63.5	588650	711340	1.12	1.25	8.57	9.19
27	-84.4	-71.5	705500	827360	1.12	1.14	10.67	11.24
28	-84.4	-71.4	704450	826360	1.12	1.14	10.64	11.22
29	-89.2	-80.8	997670	1119400	1.13	1.12	15.93	16.44
30	-89.1	-80.6	992790	1114500	1.13	1.12	15.83	16.35
31	-84.5	-68.9	602680	727170	1.13	1.19	8.83	9.46
32	-84.2	-68.6	603890	728460	1.13	1.19	8.84	9.46
33	-86.3	-19.0	583830	1199300	1.12	2.98	8.67	12.64
34	-86.1	-18.7	584290	1201100	1.12	2.98	8.67	12.65
35	-83.2	-29.9	751630	1334200	1.13	1.98	10.90	14.43
36	-83.1	-29.5	748930	1331500	1.13	1.99	10.85	14.39
37	-88.4	-50.7	1013300	1572500	1.13	1.39	15.54	18.55
38	-87.9	-50.1	1017300	1575500	1.13	1.40	15.51	18.54
39	-86.1	-47.5	993640	1520900	1.12	.77	15.04	17.62
40	-86.1	-47.3	989330	1516700	1.12	.76	14.97	17.54
41	-83.8	-44.8	991710	1513800	1.12	.89	14.92	17.54
42	-83.7	-44.8	997170	1519600	1.12	.89	14.99	17.61
43	-82.4	-29.0	733960	1281900	1.12	1.61	10.91	14.16
44	-82.5	-29.1	734270	1282400	1.12	1.61	10.91	14.16
45	-83.5	-16.2	578130	1152200	1.12	1.98	8.68	12.31
46	-83.5	-16.1	578690	1153800	1.12	2.00	8.68	12.33
47	-81.7	9.1	437560	1042100	1.12	3.65	6.47	10.88
48	-81.6	9.3	437990	1043200	1.12	3.66	6.47	10.90

TABLE 2, CONTINUED.

SYSTEM CONDITIONS, PART 2.

RUN	H1	H2	RE1	RE2	PR1	PR2	V1	V2
49	-79.5	17.9	429380	1063400	1.12	4.63	6.15	11.65
50	-79.2	18.3	430590	1064500	1.12	4.61	6.15	11.68
51	-79.9	13.9	454820	1176800	1.12	8.17	6.46	13.27
52	-79.8	14.1	454590	1175700	1.12	8.14	6.45	13.27
53	-79.7	14.4	455090	1196900	1.12	20.38	6.45	12.98
54	-79.6	14.6	456020	1201400	1.14	20.40	6.46	13.07
55	-85.5	-48.4	1070700	1629900	1.12	1.47	15.82	18.96
56	-85.5	-48.2	1069500	1629900	1.12	1.47	15.79	18.94
57	-97.0	-97.0	865420	865710	1.13	1.13	15.15	15.15
58	-96.6	-96.6	868080	868380	1.13	1.13	15.09	15.09
59	-81.2	-81.2	1086300	1086700	1.14	1.14	15.50	15.50
60	-81.1	-81.1	1085100	1085500	1.14	1.14	15.47	15.47
61	-80.7	-71.7	1109400	1240900	1.14	1.17	15.78	16.40
62	-80.8	-71.7	1107000	1238500	1.14	1.17	15.74	16.36
63	-78.9	-69.9	1132900	1261800	1.11	1.22	15.95	16.62
64	-78.8	-69.8	1135300	1263300	1.11	1.18	15.96	16.60
65	-78.0	-69.0	1125100	1250600	1.12	1.21	15.90	16.54
66	-78.0	-69.0	1126200	1251600	1.12	1.21	15.91	16.55
67	-81.6	-46.4	1109900	1642800	1.14	1.50	15.92	18.94
68	-81.4	-46.0	1110500	1644000	1.14	1.50	15.90	18.93
69	-77.4	9.2	1096000	2474600	1.12	3.71	15.60	25.86
70	-77.0	9.5	1100500	2479100	1.12	3.70	15.62	25.94
71	-76.3	-63.1	815950	945230	1.15	1.21	11.17	11.85
72	-76.2	-62.9	812920	942280	1.15	1.21	11.11	11.79
73	-76.1	-11.8	661060	1442400	1.15	10.64	9.03	16.96
74	-76.0	-11.8	661970	1445000	1.15	10.63	9.03	17.02
75	-75.4	18.6	464000	1094200	1.11	4.69	6.39	12.03
76	-75.2	18.9	464560	1095000	1.11	4.65	6.40	12.05
77	-83.7	-46.7	1053200	1574600	1.12	.76	15.65	18.19
78	-83.6	-46.5	1053100	1574800	1.12	.75	15.63	18.17
79	-73.9	-51.9	491550	625100	1.16	1.41	6.58	7.38
80	-73.8	-51.8	491950	625610	1.16	1.41	6.58	7.38
81	-76.4	6.9	1174200	3160500	1.15	17.17	16.10	37.05
82	-76.4	7.4	1168000	3145200	1.15	17.20	16.00	36.86
83	-74.8	-74.8	1131700	1132100	1.11	1.11	15.71	15.71
84	-74.5	-74.5	1136800	1137200	1.11	1.11	15.74	15.74
85	-75.1	-31.7	1007800	1589500	1.15	1.91	13.63	17.28
86	-74.8	-31.5	1010300	1591300	1.15	1.92	13.63	17.29
87	-70.4	10.0	505000	1284600	1.18	16.21	6.63	15.28
88	-70.2	10.3	505810	1284200	1.18	16.26	6.63	15.26
89	-70.9	2.0	679060	1639300	1.18	15.86	8.94	19.39
90	-70.8	2.1	679550	1637800	1.18	16.18	8.94	19.29
91	-74.4	-3.9	833960	1949800	1.15	13.50	11.20	23.28
92	-74.3	-4.1	837270	1944000	1.15	13.67	11.25	23.07
93	-70.3	21.4	504710	1311300	1.18	17.34	6.62	15.39
94	-70.2	21.5	505160	1311600	1.18	17.31	6.62	15.40
95	-68.4	-68.4	512030	512200	1.19	1.19	6.64	6.64
96	-68.1	-68.1	513380	513550	1.19	1.19	6.64	6.64

TABLE 2, CONTINUED.

SYSTEM CONDITIONS, PART 2.

RUN	H1	H2	RE1	RE2	PR1	PR2	V1	V2
97	-72.9	-72.9	499770	499920	1.16	1.16	6.67	6.67
98	-72.7	-72.7	500690	500840	1.16	1.16	6.68	6.68
99	-90.3	-90.3	401400	401490	1.13	1.13	6.50	6.50
100	-90.2	-90.2	401670	401760	1.13	1.13	6.50	6.50
101	-73.8	-60.4	835500	966730	1.16	1.22	11.18	11.87
102	-73.8	-60.4	838170	969360	1.16	1.22	11.21	11.91
103	-73.1	-59.8	850650	983450	1.16	1.22	11.34	12.03
104	-72.7	-59.3	851510	985440	1.16	1.23	11.32	12.02
105	-74.4	-65.1	1135700	1256700	1.11	1.23	15.74	16.41
106	-74.2	-64.9	1142700	1263200	1.11	1.23	15.80	16.47
107	-73.6	-64.2	1138500	1258100	1.11	1.24	15.65	16.33
108	-73.5	-64.1	1141300	1260800	1.11	1.24	15.66	16.35
109	-71.1	21.6	507900	1338700	1.17	15.91	6.69	16.01
110	-71.1	21.6	508110	1339600	1.17	15.64	6.69	16.08
111	-70.8	21.9	509350	1338300	1.18	16.21	6.70	15.94
112	-70.7	22.1	509800	1337800	1.18	16.28	6.70	15.93
113	-70.4	20.7	520300	1353600	1.18	17.09	6.83	15.94
114	-70.4	20.7	520780	1354900	1.18	16.91	6.83	15.99
115	-74.8	-36.5	1122700	1696200	1.11	2.15	15.60	19.23
116	-74.6	-36.4	1132200	1705500	1.11	2.16	15.69	19.33
117	-71.2	127.9	516400	1921600	1.17	.78	6.81	40.56
118	-71.1	127.3	518990	1930800	1.17	.79	6.84	40.57
119	-89.4	99.3	427860	2036800	1.12	1.02	6.61	33.55
120	-89.0	100.0	429950	2032100	1.12	1.02	6.61	33.61
121	-84.3	113.8	423170	1775500	1.12	.88	6.39	28.82
122	-83.9	112.3	428860	1787100	1.12	.90	6.46	28.61
123	-69.2	88.9	650060	2176600	1.17	1.26	8.71	30.04
124	-69.1	89.1	650740	2177900	1.18	1.26	8.72	30.11
125	-70.5	84.0	684290	2522100	1.18	1.25	9.00	36.65
126	-70.4	83.8	686370	2525100	1.18	1.25	9.02	36.65
127	-90.8	-9.8	1011800	2764500	1.13	11.21	15.85	32.92
128	-90.6	-9.5	1012800	2762000	1.13	11.41	15.83	32.80
129	-69.9	29.9	1066600	2803200	1.18	18.47	13.97	32.35
130	-68.8	31.6	1072900	2817600	1.19	18.17	13.95	32.65
131	-92.1	.6	478880	1501900	1.13	15.12	7.61	17.88
132	-91.8	.8	481380	1505800	1.13	15.29	7.63	17.89
133	-67.7	17.5	602660	1514000	1.19	16.27	7.77	18.02
134	-67.3	17.9	603600	1507600	1.20	17.00	7.77	17.76
135	-70.1	-.7	777020	1813600	1.18	14.08	10.18	21.83
136	-69.9	-.2	777110	1818800	1.18	14.38	10.16	21.84
137	-75.9	-2.9	899280	2007800	1.10	8.14	12.31	21.59
138	-75.7	-2.5	897590	2010800	1.10	8.26	12.27	21.62
139	-74.7	-3.1	933360	2203800	1.15	14.03	12.58	26.16
140	-74.0	-2.4	939200	2215700	1.15	14.45	12.59	26.23
141	-74.2	-3.0	1104600	2577500	1.15	14.66	14.83	30.25
142	-74.0	-2.8	1106100	2583100	1.15	14.73	14.84	30.32

† Table 2, Continued, System Conditions, Part 2

Symbol	Meaning	Units
H1	inlet hydrogen enthalpy	Btu/pound
H2	hydrogen enthalpy at axial position of the probe tip	Btu/pound
RE1	inlet Reynolds number	
RE2	Reynolds number at axial position of the probe tip	
PR1	inlet Prandtl number	
PR2	Prandtl number at axial position of the probe tip	
V1	average inlet velocity	ft/sec
V2	average velocity at axial position of the probe tip	ft/sec

9. RESULTS

9.1 Introduction

This chapter describes the calculations and correlations of experimentally significant similarity numbers.

9.2 Calculation of Results

The special boiling number (33) and the temperature difference number (23) described in Section 3.4.4 and the reduced pseudocritical temperature were found to be significant. The special boiling number is

$$N_{Sk} = \frac{Q - m\ (h_D - h_1)}{m\ (h_L - h_D)} \qquad (51)$$

where:

Q = heat input rate from Section 7.4

m = mass flow rate from Section 6.7

h_1 = inlet enthalpy from Section 7.5

h_D = dense phase enthalpy from Section 3.3

$h_L - h_D$ = equivalent enthalpy of vaporization from Section 3.3

The temperature difference number was used in five forms. The first related wall and bulk temperatures

$$NT1 = \frac{k_w\ (T_w - T_2)}{2qR} \qquad (52)$$

where:

T_w = measured wall temperature from Section 7.4

T_2 = calculated bulk temperature at the axial position of the probe from Section 7.5

k_w = parahydrogen thermal conductivity at the temperature of the tube inside wall from Section 3.3

q = heat rate per unit area from Section 7.4

R = test section radius

The remaining four temperature difference numbers were of two types. The first type was related to the shape of the measured temperature profile.

$$NT2B = \frac{k_B\ (TT2)}{2qR} \tag{53}$$

$$NT2W = \frac{k_w\ (TT2)}{2qR} \tag{54}$$

where:

TT2 = second parameter of the empirical equation expressing the temperature profile, equation (45)

k_B = parahydrogen thermal conductivity at temperature T_2 from Section 3.3

The second type of temperature difference number related the bulk and measured centerline temperatures

$$NT3B = \frac{k_B\ (T_2 - TT1 + TT2)}{2qR} \tag{55}$$

$$NT3W = \frac{k_w (T_2 - TT1 + TT2)}{2qR} \tag{56}$$

where TT1 - TT2 = centerline temperature obtained from the empirical temperature equation (45).

The reduced pseudocritical temperature was

$$RTP = \frac{T_2}{T_{pc}} \tag{57}$$

where T_{pc} was the pseudocritical temperature obtained from equation (13) using the wall static pressure adjacent to the probe.

9.3 Summary of Results

The results are expressed in terms of boiling numbers, temperature difference numbers, reduced temperatures, and parameters of the empirical equations. The range of conditions at the probe position in this investigation is given in Table 3. Table 4 lists the values obtained from the equations of the previous section. Figures 23 to 27 present correlations of results expressed by NT1, NT2B, NT2W, NT3B, and NT3W as functions of the boiling number of equation (51). The lines in Figure 23 are a least squares fit to the data. For boiling numbers less than -0.2, the data was represented by

$$NT1 = 1.03344 \times 10^{-4} - 1.70809 \times 10^{-3} (N_{Sk}) \tag{58}$$

with a standard deviation of 1.13×10^{-4}. For boiling numbers larger than -0.2, the data was represented by

$$NT1 = 7.86780 \times 10^{-4} + 1.61302 \times 10^{-3} (N_{Sk}) \qquad (59)$$

with a standard deviation of 1.95×10^{-4}. Runs in which the wall to bulk temperature difference was less than 5 degrees Rankine are not included in Figure 23 because the uncertainties in the measured wall temperatures would be misleading. The plotting characters used in the figures are related to the wall to bulk temperature difference of that data point. The relation was

Plotting Character	Wall to Bulk Temperature Difference, °R
1	0 - 5
2	5 - 10
3	10 - 25
4	25 - 100
5	Greater than 100

The technique of using assigned plotting characters was used in many correlation attempts. The characters were assigned according to the values of run conditions, property ratios, Reynolds numbers, Prandtl numbers, and combinations of them; however, none of these revealed a significant secondary correlation.

Figures 28 and 29 present the second parameter of the empirical equation of dynamic pressure versus boiling number and reduced pseudocritical temperature. The variations of that parameter indicate that the dynamic pressure profiles flatten with increasing boiling number and temperature. The strong peak in PP2 at $N_{Sk} = 0.3$ and RTP = 0.99 indicates very flat profiles. For N_{Sk} between zero and one the hydrogen was in the quasi-two phase region. For this investigation the bulk temperature had a strong influence on profile shape. Figures 30, 31, and 32 present the parameter of velocity, and hot wire bridge and RMS voltages that is most influenced by profile shape, versus reduced pseudocritical temperature. Positive values of VV3 in Figure 30 indicate flat or "M" shaped velocity profiles. Runs for which RTP was greater than one produced "M" shaped velocity profiles in this investigation. Figure 31 shows that for temperatures slightly less than the pseudocritical, the average power required to maintain a fixed hot wire temperature was constant across the diameter of the test section. The hot wire RMS, however, is observed in Figure 32 to have the largest maximum to centerline values in this same temperature region. Figure 33 indicates that as the wall temperature increased, the bulk fluid temperature increased to the pseudocritical temperature. Further wall temperature increases did not produce a fluid temperature increase until the wall temperature had doubled.

Table 3. Range of Test Conditions

Variable	Range	Units
Reduced Bulk Temperature	0.662 - 1.215	
Reduced Pressure	1.003 - 1.351	
Mass Flow Rate	0.2624 - 0.7108	pounds/sec
Heating Rate	0 - 39374	Btu/hr-ft^2
Reynolds Number	$4.0 \times 10^5 - 3.2 \times 10^6$	
Prandtl Number	0.75 - 20.4	
Average Velocity	6.5 - 37.1	ft/sec

9.4 Discussion of Results

In Figures 29 to 32, there is a large variation in parameters of empirical equations for reduced pseudocritical temperature RTP slightly less than one. In effect, there is a thermal barrier at T_{pc} because of the very large specific heat at that point. These results would be improbable if the measured mass flow rates, power input, and inlet pressures and temperatures were not correct.

System pressure pulsations of the order of one-tenth percent produced variations in the dynamic pressure indications as large as 100 percent for some runs. This was due to differing signal transit times through the pitot and static lines. The large viscosity variations near the critical point precluded the matching of transit times. Electrical noise was induced onto the thermopile signal by the test section voltage ripple and building electrical services. The scatter in temperature data was magnified in the determination of properties near the critical point where a small change in temperature caused a large change in properties. The data was approximated by statistical fitting of empirical equations. The acceptable precision of the empirical equations indicated the value of this method of overcoming data scatter.

The integral of the empirical ρv equation (48) with respect to area equals flow rate. This value was compared to the value obtained from the turbine flowmeter. Their deviations are presented in Table 9 in Appendix C along with the parameters of the empirical equation of ρv. The deviations are given as a fraction of the turbine flow rate. A line drawn through the data of a plot of deviations versus reduced pseudocritical temperature RTP shows an increase with temperature from approximately -9 percent at RTP = 0.75 to +15 percent at RTP = 1.15. The negative sign indicates that the flow rate by integration was lower than that of the turbine flowmeter. For RTP between 0.98 and 1.0 the deviations vary from +6 percent to a maximum of +24 percent. Correction of the observed dynamic pressures for the effect of the axial component of turbulence was analyzed. Attempts were made to infer turbulence level from the probe data. The hot wire operated at a constant temperature and the power required to maintain the temperature was calculated from the fixed resistance of the wire and the current flowing through the wire as measured by the hot wire bridge voltage. Heat transfer from heated surfaces is often related to c (Prandtl number)^m (Reynolds number)^n (fluid thermal conductivity). No information was available for heat transfer from very hot slender cylinders in rapidly moving fluids. Equations with $m = 0.33$ or 0.4, $n = 0.5$ or 0.8 and $c = 0.34$ or 0.57 were tried. Properties were obtained from the TABTP code, measured pressures, and the empirical equations for temperature. The Reynolds number profiles were calculated from the properties and the empirical equations for velocity. The RMS value of the bridge voltage was due to the fluctuation in the power required to maintain the wire at a constant temperature. The power variation was assumed to be exclusively due to velocity fluctuations of turbulence.

The velocity in the Reynolds number of the heat transfer equation was varied in proportion to the power fluctuation. The dynamic pressure of the fluctuating velocity was subtracted from the measured pitot pressure to obtain a corrected dynamic pressure. The corrected flow rates that were obtained by integrating a corrected ρv were less than the uncorrected values. This produced a substantial decrease in the deviation between the integral of ρv and the turbine flowmeter near the critical point.

The assumptions of this analysis cannot be justified, particularly the one in which velocity fluctuations were assumed the sole cause of power fluctuations. For example, fluctuations in the density are a strong contributor to the RMS. Near the critical point density may change by a factor of two per degree change in temperature. This should produce large turbulent fluctuations in density. A proper resolution of this question requires an experimental program to determine the form of the heat transfer equation. Attempts to arrive at an equation from the data of this investigation were unsuccessful.

The peaks in Figures 29 to 32 indicate that when the bulk fluid temperature was slightly below the pseudocritical temperature, the fluid properties and mixing combined to produce uniform conditions in the central portion of the flow. At this temperature the large specific heat produced only small temperature changes. The fluid mixing was enhanced by a viscosity minimum. Figure 33 indicates that the pseudocritical temperature was a partial barrier to production of bulk temperatures greater than T_{pc}. For many runs large difference in power input resulted in similar temperatures due to the large specific heat. This produced a concentration of the data just below RTP = 1 which would not be expected from a map of the test conditions.

The empirical equation of temperature (45) was an elipse whose major axis was the tube diameter. The minor axis of the elipse was TT2 and represented the curvature of the temperature profile. Figures 24 and 25 show that at $N_{Sk} = 0.3$ the temperature profiles were flat. This value of the boiling number produced fluid temperatures close to the pseudocritical value. Figures 26 and 27 show the expected result that when the temperature profiles were flat the centerline measured temperature and the calculated bulk temperature were approximately equal. The data scatter in Figures 24 to 27 at N_{Sk} less than zero indicates that a boiling type correlation is not succesful in predicting results within fluid that is subcooled below the dense phase saturated enthalpy. Both bulk and wall temperature thermal conductivities provided correlations which are included for the convenience of the designer.

The minimum in NT1 in Figure 23 indicated that a heat transfer maximum occured at $N_{Sk} = -0.2$. At this boiling number the bulk of the hydrogen was in the dense phase and the fluid in the vicinity of the wall was near the pseudocritical temperature. The large specific heat and low viscosity of the fluid near the wall provided a good mechanism for transporting heat away from the wall. Most of the tests with heating in this investigation produced wall temperatures above the pseudocritical. Therefore the hydrogen adjacent to the wall was within the quasi-two phase region and the boiling correlation was successful.

The results as presented should be useful to designers of systems involving fluids near the critical point. The NT1 correlation, Figure 23, provides wall temperatures. The NT2 and NT3 correlations provide temperature details within the flow. Theoretical explanation of the results was not attempted because of the complex nature of the problem. It is hoped the results may provide a basis for theoretical investigations in the future.

The results are inherently limited due to experimental conditions. One test fluid was used within one size test section having unique inlet conditions. The flow was vertically upward and the heated length was fixed.

TABLE 4.

RESULTS

RUN	NSK	RTP	NT1 X10+3	NT2B X10+4	NT2W X10+4	NT3B X10+4	NT3W X10+4	TW-T2 DEG.R
1	.0879	.985	.996	.532	.385	.510	.369	72.3
2	.0890	.985	.981	.676	.488	.579	.418	71.4
3	.2762	.995	1.403	.146	.137	.189	.178	92.0
4	.2804	.996	1.409	.040	.038	.162	.154	92.2
5	.2083	.993	1.292	.184	.161	.323	.282	87.2
6	.2098	.993	1.289	.192	.167	.376	.328	87.1
7	.2710	.995	1.314	.252	.240	.215	.205	102.2
8	.2852	.995	1.307	.164	.156	.170	.162	101.8
9	-.6906	.729	0.000	0.000	0.000	0.000	0.000	0.0
10	-.6937	.729	0.000	0.000	0.000	0.000	0.000	0.0
11	-.2844	.891	.570	5.908	5.255	.845	.751	5.2
12	-.2848	.891	.573	4.540	4.031	.455	.404	5.2
13	.2912	.996	1.230	-.051	-.042	.146	.120	66.4
14	.2929	.996	1.210	.096	.079	.191	.157	65.5
15	-.6271	.818	1.281	5.268	3.195	.005	.003	16.1
16	-.6254	.819	1.274	5.754	3.495	.339	.206	16.0
17	-.6160	.825	1.298	6.885	4.168	.590	.357	16.4
18	-.6114	.827	1.282	5.719	3.469	.436	.265	16.2
19	-.4778	.840	1.067	5.668	3.361	-.047	-.028	13.8
20	-.4787	.840	1.066	6.667	3.958	.384	.228	13.7
21	-.3350	.874	.706	6.550	4.901	.992	.742	7.4
22	-.3280	.877	.678	5.954	4.393	.832	.614	7.2
23	-.7084	.794	1.119	3.476	3.063	-.477	-.421	9.5
24	-.7035	.795	1.125	4.489	3.945	.058	.051	9.6
25	-.6858	.801	1.100	4.214	3.667	.064	.056	9.5
26	-.6828	.802	1.080	4.862	4.261	.473	.414	9.3
27	-.7855	.766	-.149	4.330	4.359	-.036	-.037	-1.1
28	-.7814	.766	-.131	2.721	2.738	-.456	-.459	-1.0
29	-.8942	.718	-.708	1.955	2.004	-.537	-.551	-5.0
30	-.8885	.719	-.709	3.208	3.289	.037	.038	-5.0
31	-.4101	.830	.758	5.548	5.170	-.195	-.182	6.1
32	-.4116	.830	.750	3.298	3.076	-1.028	-.958	6.0
33	.0621	.982	.811	.702	.423	.267	.161	50.1
34	.0624	.981	.834	.715	.435	.211	.128	51.2
35	-.0397	.963	.743	3.759	2.109	1.158	.650	46.2
36	-.0362	.964	.691	3.063	1.705	1.000	.557	43.4
37	-.2740	.896	.128	2.061	1.270	.291	.179	7.0
38	-.2684	.898	.127	2.115	1.305	.350	.216	6.9
39	-.3469	.884	.179	2.097	1.310	.250	.156	9.5
40	-.3439	.885	.180	1.903	1.186	.197	.123	9.5
41	-.4494	.875	.192	1.970	1.329	.222	.150	9.4
42	-.4487	.875	.193	2.104	1.416	.270	.181	9.5
43	-.2419	.922	.409	4.607	2.733	.969	.575	23.9
44	-.2401	.922	.423	3.810	2.255	.926	.548	24.7
45	-.0930	.950	.611	1.482	.924	.432	.269	35.8
46	-.0906	.950	.625	1.612	1.007	.448	.280	36.6
47	.2252	.981	1.377	.597	.468	.205	.161	70.9
48	.2279	.981	1.399	.609	.479	.187	.147	71.8

TABLE 4, CONTINUED.

RESULTS

RUN	NSK	RTP	NT1 X10+3	NT2B X10+4	NT2W X10+4	NT3B X10+4	NT3W X10+4	TW-T2 DEG.R
49	.3717	.991	1.668	.326	.280	.190	.164	83.0
50	.3753	.992	1.679	.339	.293	.206	.178	83.3
51	.3602	.997	1.583	.020	.017	.111	.096	81.9
52	.3620	.997	1.617	.110	.096	.129	.112	83.1
53	.3655	.997	1.628	.139	.122	.125	.109	83.9
54	.3676	.997	1.646	.103	.091	.095	.084	84.5
55	-.2176	.912	.168	1.417	.789	.254	.141	10.2
56	-.2132	.913	.169	1.537	.853	.267	.148	10.2
57	-1.0879	.621	0.000	0.000	0.000	0.000	0.000	0.0
58	-1.0915	.623	0.000	0.000	0.000	0.000	0.000	0.0
59	-.5204	.769	0.000	0.000	0.000	0.000	0.000	0.0
60	-.5208	.769	0.000	0.000	0.000	0.000	0.000	0.0
61	-.4332	.818	.923	2.131	1.199	.905	.509	12.3
62	-.4297	.819	.916	1.964	1.103	.962	.541	12.2
63	-.4658	.815	1.020	2.372	1.578	1.076	.716	11.6
64	-.4621	.816	.944	1.835	1.140	.915	.569	11.5
65	-.5789	.798	1.171	2.069	1.489	.978	.704	12.3
66	-.5780	.798	1.168	2.217	1.591	.940	.675	12.3
67	-.2001	.918	.299	2.064	1.072	.626	.325	18.3
68	-.1992	.918	.296	2.077	1.083	.633	.330	18.1
69	.2289	.982	1.282	.656	.658	.255	.255	116.8
70	.2323	.982	1.283	.675	.677	.254	.255	116.8
71	-.3603	.855	.611	3.109	2.902	.814	.760	5.1
72	-.3564	.856	.615	2.667	2.486	.802	.748	5.2
73	.1273	.989	.725	.465	.305	.354	.233	43.8
74	.1280	.989	.739	.456	.300	.365	.240	44.5
75	.3795	.992	1.545	.328	.275	.233	.195	78.1
76	.3823	.992	1.547	.315	.264	.234	.196	78.2
77	-.3540	.884	.234	1.647	.980	.368	.219	12.9
78	-.3513	.885	.232	1.658	.988	.398	.237	12.7
79	-.2506	.901	.518	5.003	3.617	1.262	.912	5.6
80	-.2495	.901	.514	5.489	3.930	1.341	.960	5.6
81	.3035	.996	1.202	.154	.167	.130	.141	113.9
82	.3084	.996	1.238	.115	.126	.125	.136	115.9
83	-.8023	.752	0.000	0.000	0.000	0.000	0.000	0.0
84	-.7964	.754	0.000	0.000	0.000	0.000	0.000	0.0
85	-.0624	.959	.166	1.415	.816	.409	.236	9.8
86	-.0601	.959	.163	1.222	.706	.394	.228	9.7
87	.3346	.996	1.129	.012	.010	.182	.144	57.1
88	.3370	.996	1.134	.073	.058	.207	.164	57.3
89	.2569	.995	1.029	.119	.094	.151	.118	62.1
90	.2575	.995	1.032	.113	.089	.153	.120	62.2
91	.2030	.992	.877	.227	.174	.174	.133	64.6
92	.1996	.992	.872	.215	.164	.191	.145	64.3
93	.4417	.997	1.581	.065	.059	.106	.096	80.5
94	.4433	.997	1.558	.072	.065	.109	.098	79.8
95	-.4090	.832	0.000	0.000	0.000	0.000	0.000	0.0
96	-.4051	.834	0.000	0.000	0.000	0.000	0.000	0.0

TABLE 4, CONTINUED.

RESULTS

RUN	NSK	RTP	NT1 X10+3	NT2B X10+4	NT2W X10+4	NT3B X10+4	NT3W X10+4	TW-T2 DEG.R
97	-.4750	.806	0.000	0.000	0.000	0.000	0.000	0.0
98	-.4723	.807	0.000	0.000	0.000	0.000	0.000	0.0
99	-1.0373	.661	0.000	0.000	0.000	0.000	0.000	0.0
100	-1.0411	.661	0.000	0.000	0.000	0.000	0.000	0.0
101	-.3268	.869	-.424	2.846	2.921	.818	.840	-3.3
102	-.3258	.869	-.373	2.776	2.840	.928	.949	-2.9
103	-.3213	.871	-.370	2.393	2.448	1.065	1.090	-2.9
104	-.3159	.873	-.379	2.777	2.844	1.130	1.157	-2.9
105	-.7024	.795	-.189	1.687	1.704	.833	.842	-1.4
106	-.7061	.795	-.194	1.792	1.811	.820	.828	-1.5
107	-.6910	.799	.273	2.392	2.353	.826	.812	2.1
108	-.6859	.800	.286	2.054	2.018	.890	.875	2.2
109	.4453	.997	1.574	.100	.091	.094	.086	81.8
110	.4461	.997	1.587	.060	.055	.106	.097	82.3
111	.4481	.997	1.600	.082	.075	.101	.092	82.7
112	.4499	.997	1.606	.125	.115	.117	.108	82.9
113	.4357	.997	1.595	.111	.101	.126	.115	82.4
114	.4356	.997	1.594	.056	.051	.115	.105	82.4
115	-.3314	.904	.225	1.867	1.197	.530	.340	12.0
116	-.3319	.904	.227	1.645	1.055	.501	.321	12.1
117	1.4576	1.196	3.156	2.709	6.132	.598	1.353	193.5
118	1.4511	1.194	3.125	2.738	6.169	.613	1.382	192.5
119	1.1868	1.091	3.132	1.647	3.448	.322	.675	194.4
120	1.1937	1.093	3.139	1.674	3.510	.340	.714	194.5
121	1.5322	1.139	3.099	2.197	4.303	.490	.959	189.7
122	1.5170	1.134	3.094	2.370	4.615	.465	.906	189.6
123	1.2262	1.074	2.418	1.693	2.876	.314	.533	166.9
124	1.2283	1.074	2.412	1.449	2.461	.309	.524	166.6
125	1.0402	1.049	2.416	1.262	2.297	.234	.426	170.5
126	1.0383	1.049	2.413	1.417	2.576	.236	.430	170.3
127	.1488	.990	1.165	.462	.451	.203	.198	113.0
128	.1513	.990	1.197	.480	.473	.216	.213	114.8
129	.5224	.998	1.491	.176	.215	.077	.093	129.8
130	.5385	.998	1.495	.244	.299	.080	.098	130.0
131	.2459	.994	1.420	.178	.160	.189	.170	88.1
132	.2478	.994	1.445	.202	.183	.202	.183	89.0
133	.4059	.997	1.332	.139	.121	.142	.124	75.5
134	.4088	.997	1.313	.131	.113	.145	.126	74.6
135	.2347	.994	.857	.288	.218	.181	.137	57.4
136	.2393	.994	.868	.304	.232	.192	.146	58.0
137	.1914	.990	.865	.500	.384	.201	.154	69.7
138	.1960	.990	.881	.507	.391	.210	.162	70.6
139	.2094	.992	.896	.328	.262	.140	.112	72.5
140	.2164	.993	.895	.345	.277	.144	.116	72.4
141	.2093	.992	.843	.427	.350	.113	.092	77.7
142	.2110	.992	.851	.422	.347	.119	.098	78.2

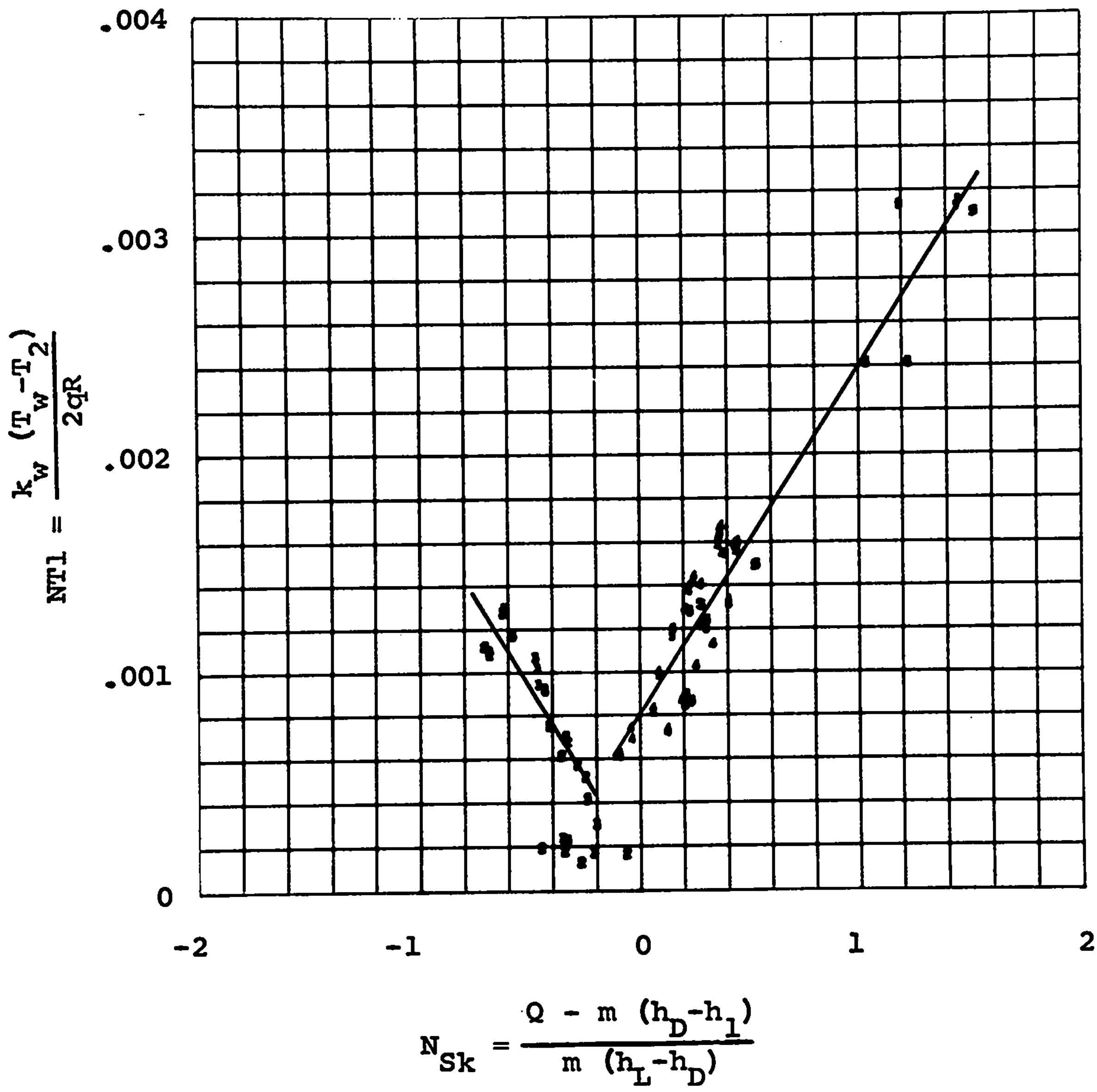

Figure 23. Temperature Number NT1
versus Boiling Number N_{Sk}

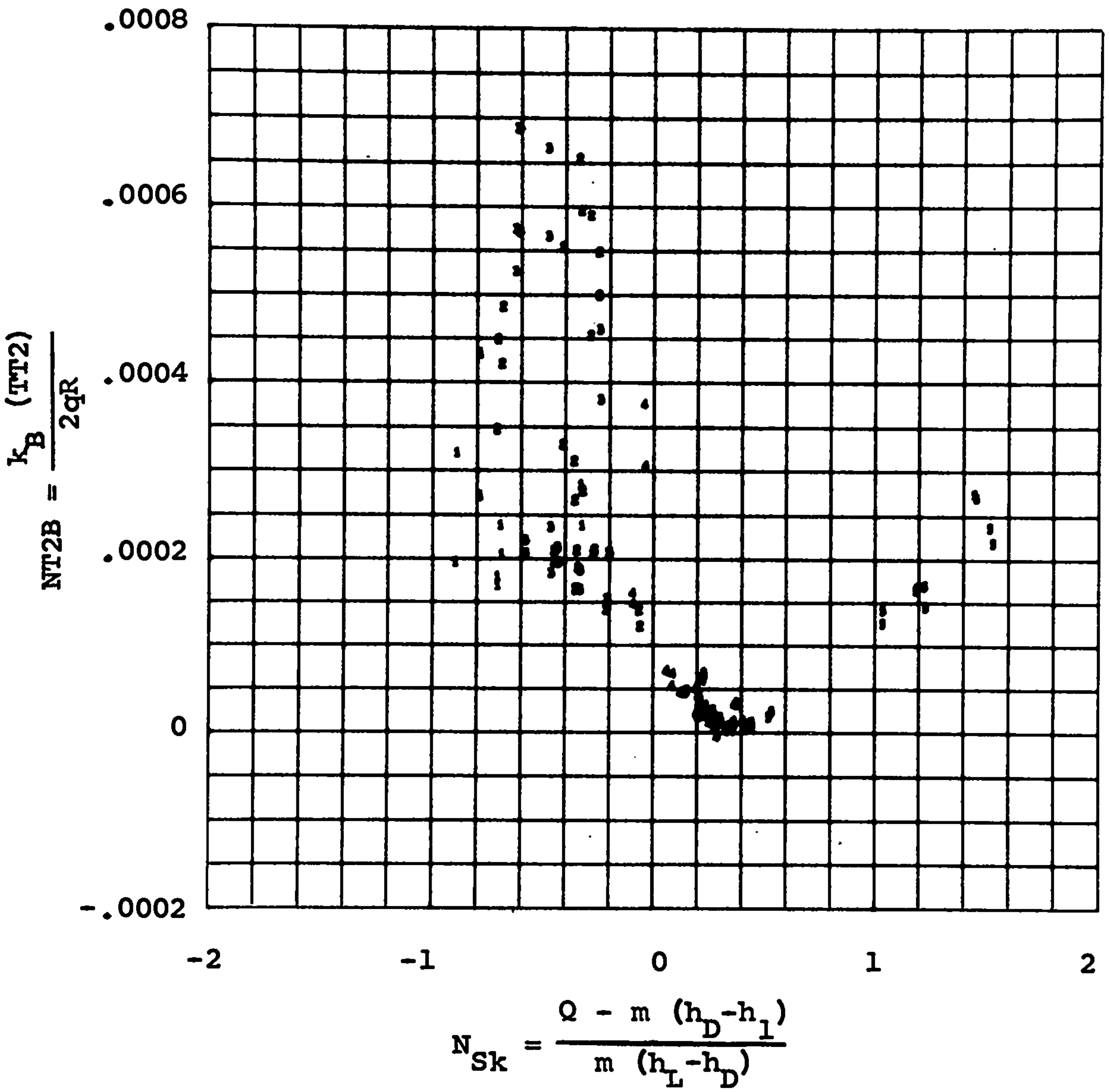

Figure 24. Temperature Number NT2B versus Boiling Number N_{Sk}

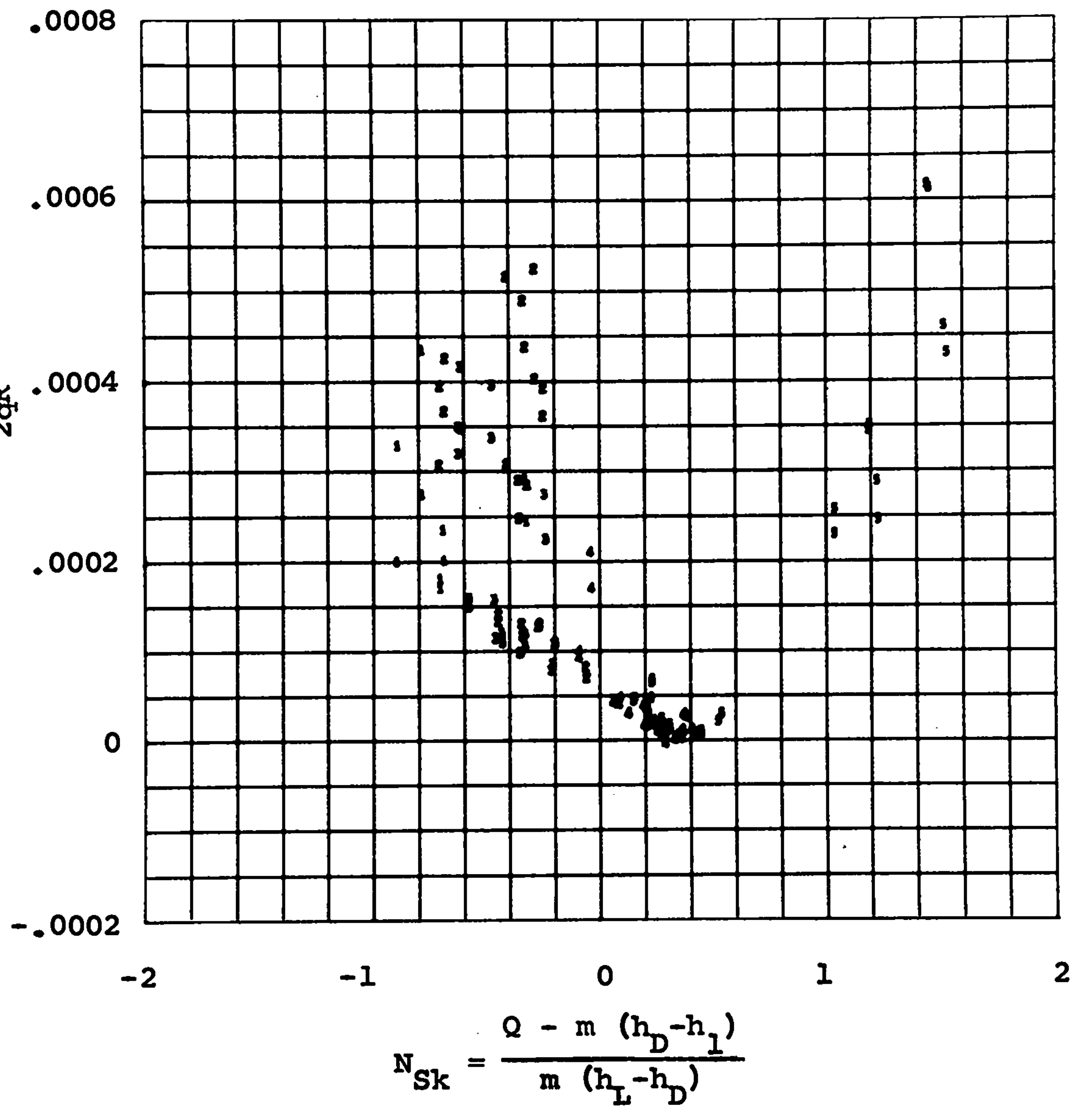

Figure 25. Temperature Number NT2W versus Boiling Number N_{Sk}

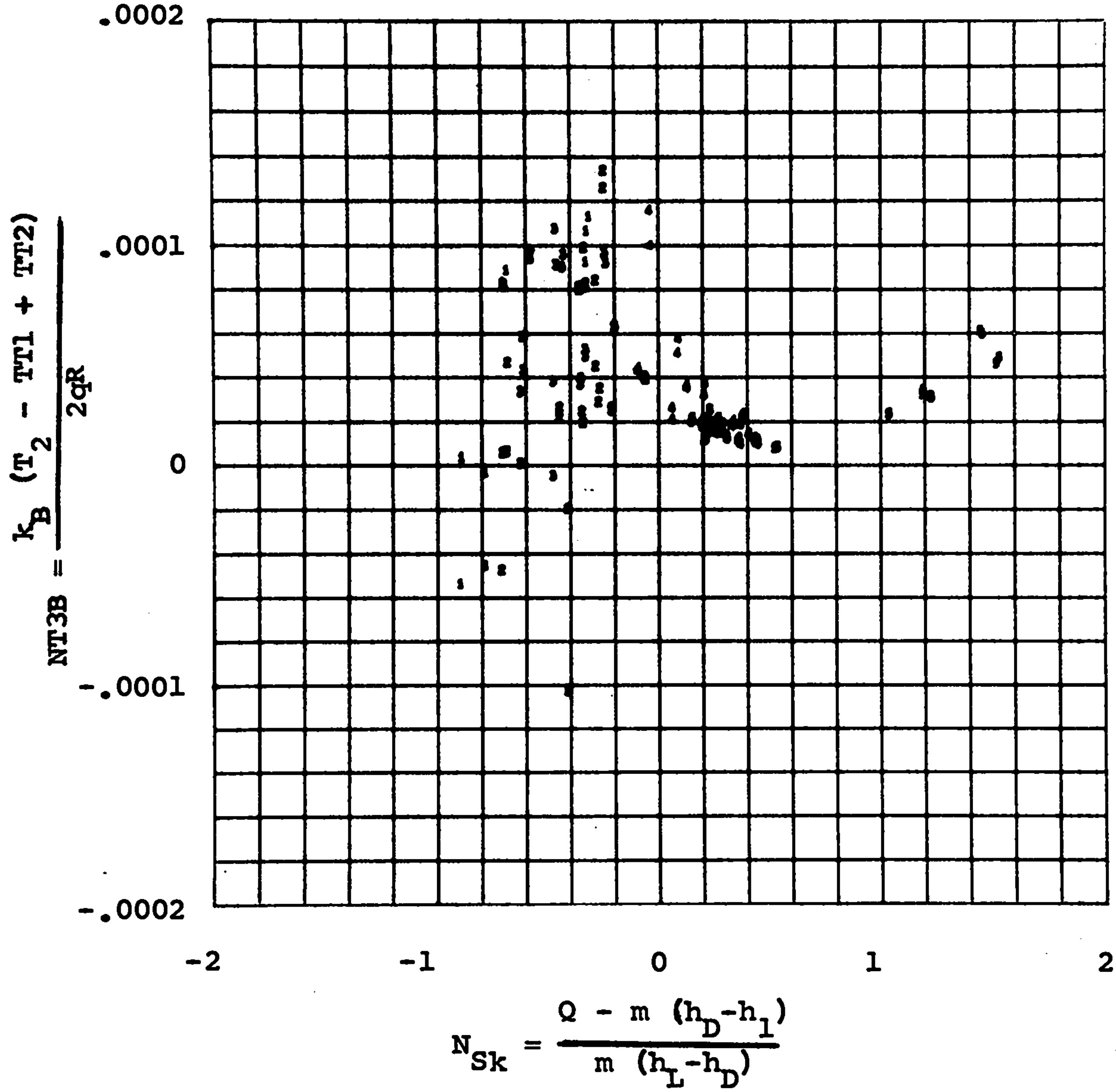

Figure 26. Temperature Number NT3B
versus Boiling Number N_{Sk}

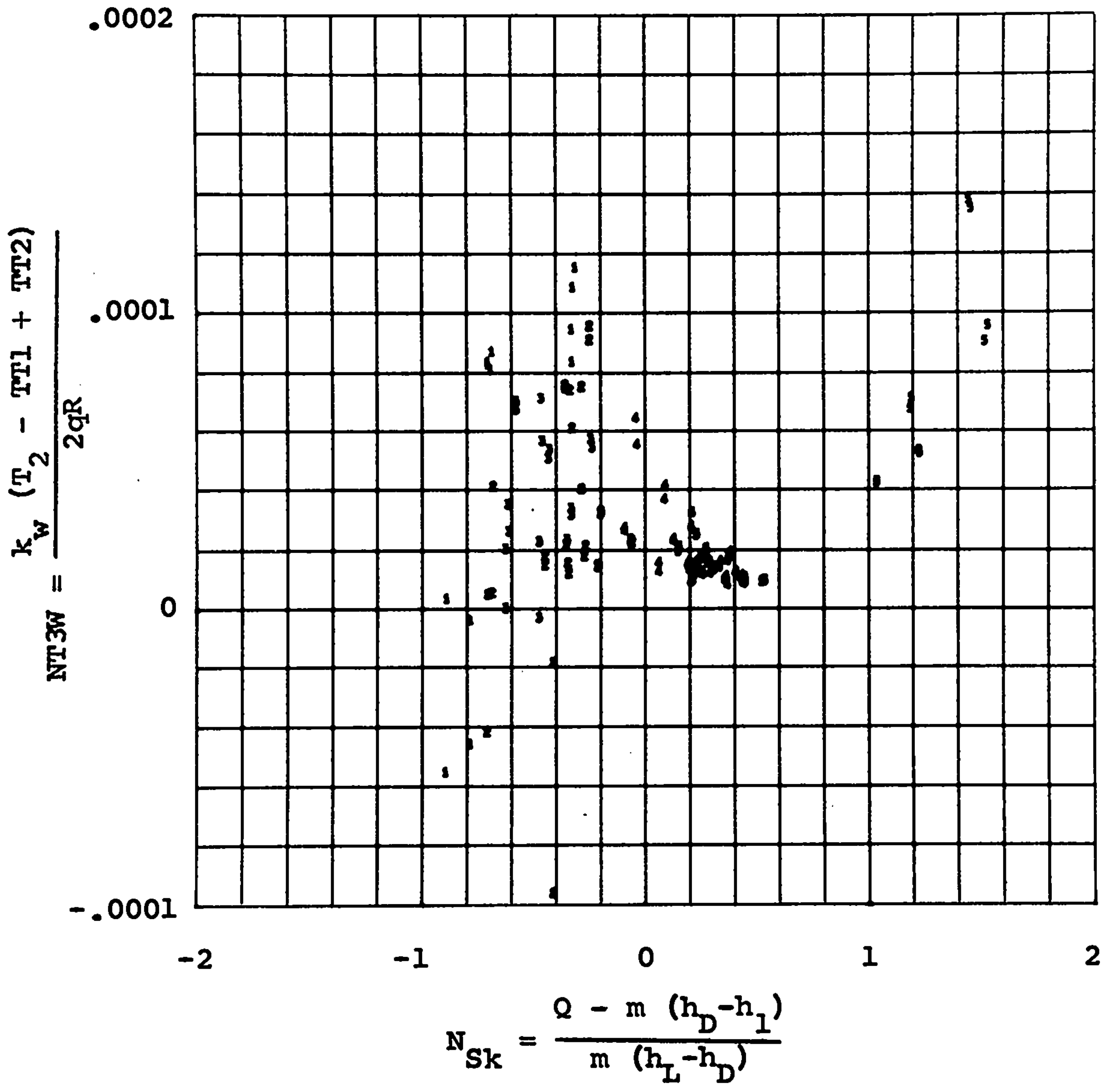

Figure 27. Temperature Number NT3W versus Boiling Number N_{Sk}

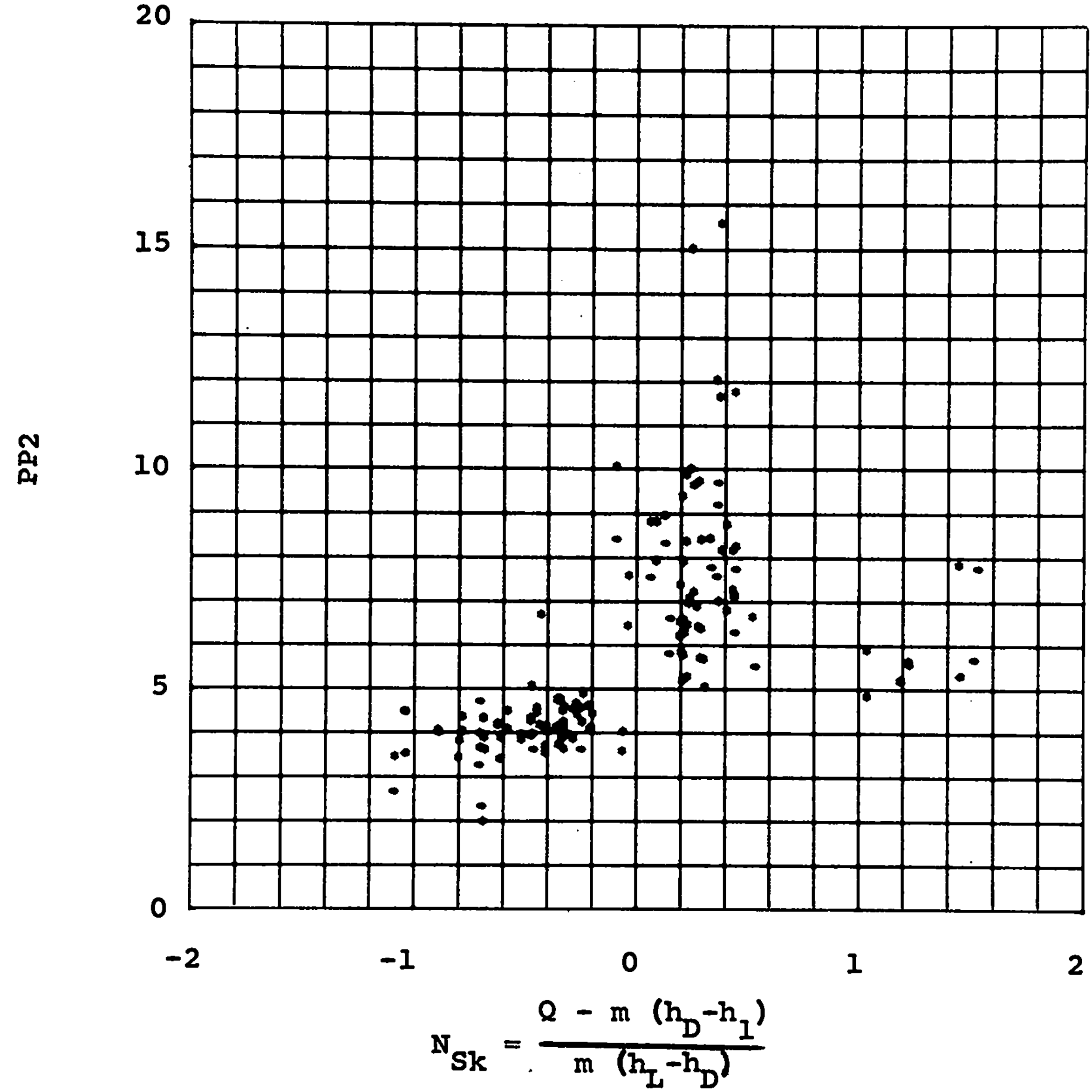

Figure 28. Dynamic Pressure Parameter PP2 versus Boiling Number N_{Sk}

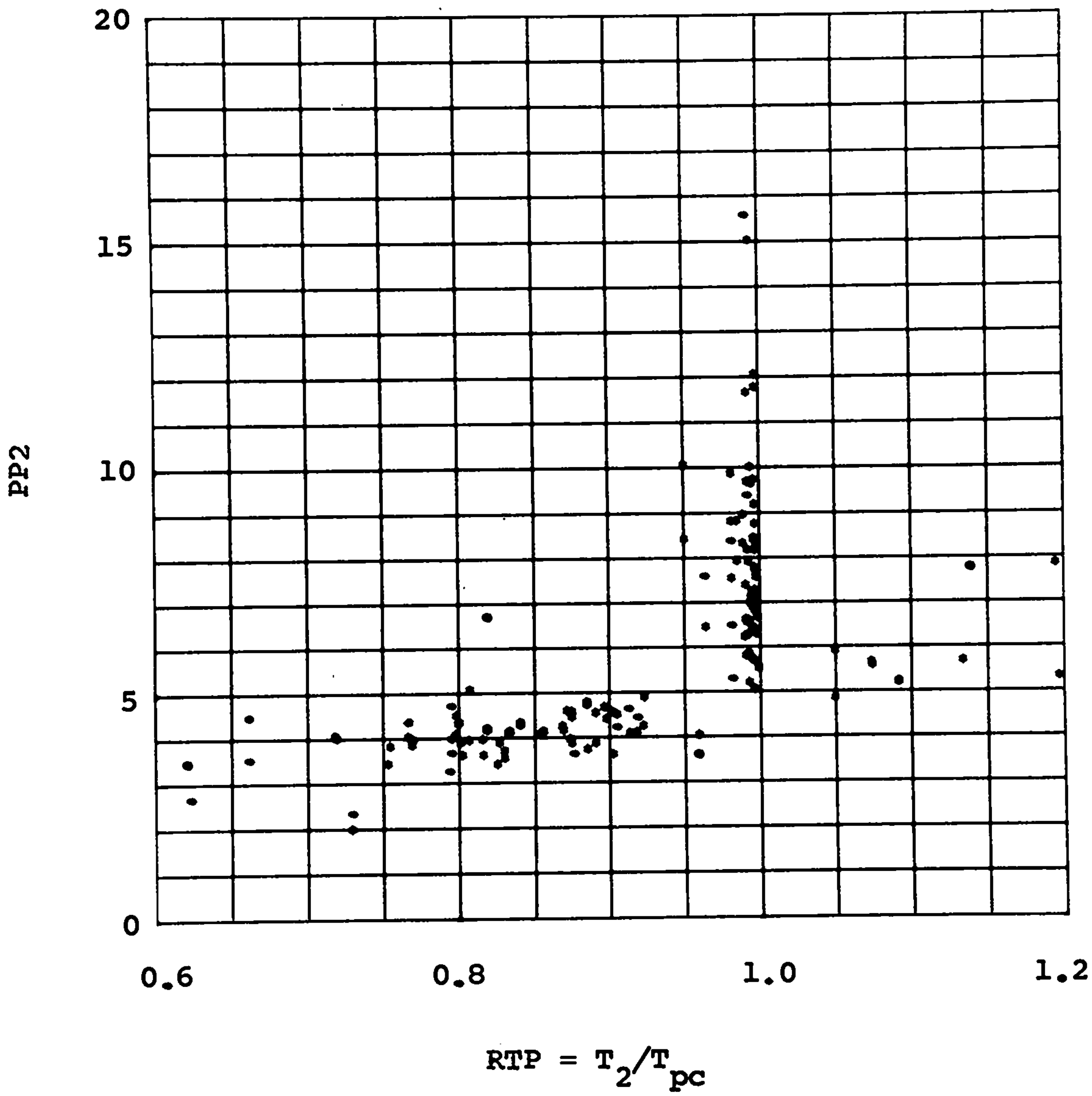

Figure 29. Dynamic Pressure Parameter PP2 versus Reduced Pseudocritical Temperature

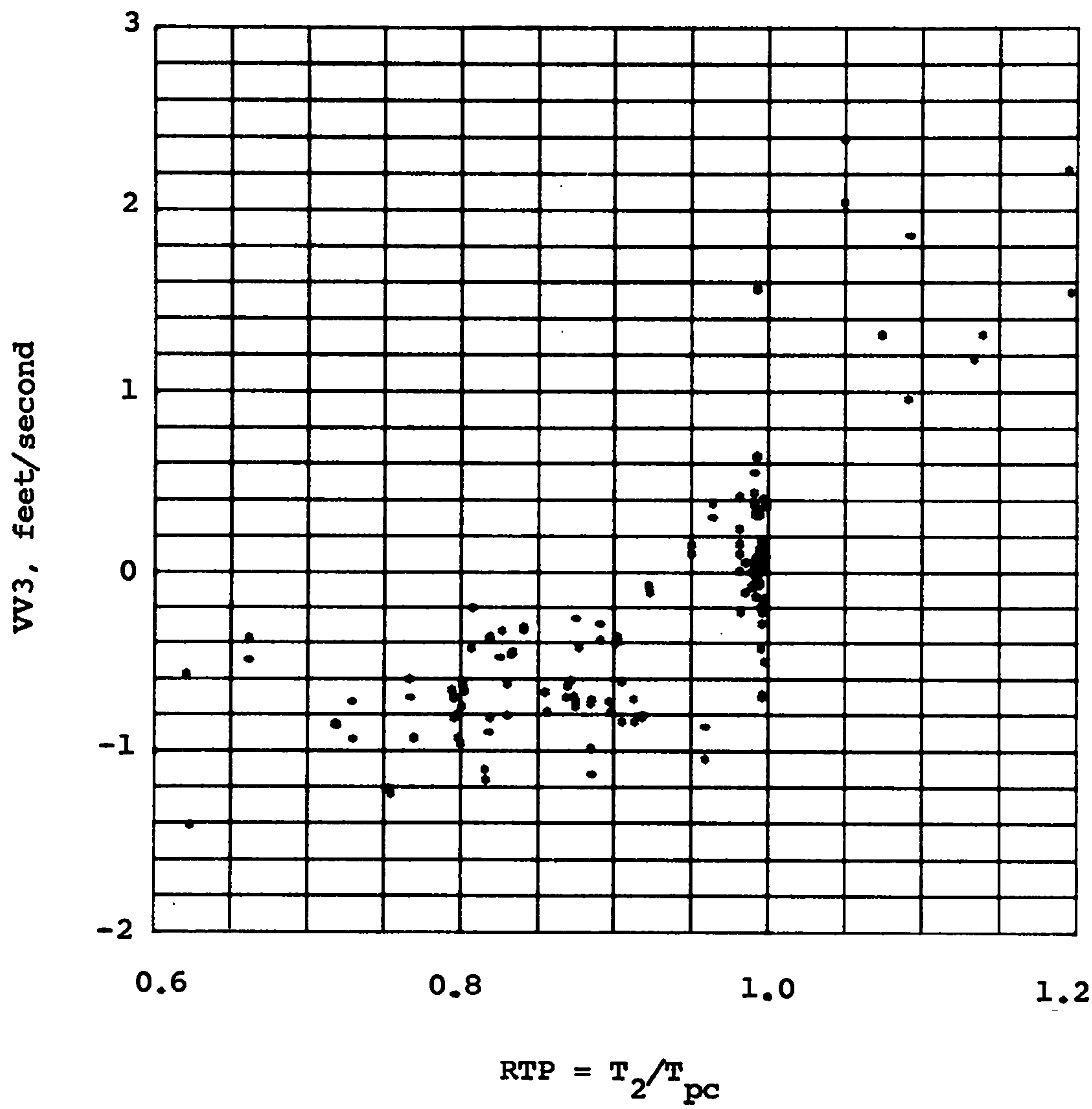

Figure 30. Velocity Parameter VV3 versus Reduced Pseudocritical Temperature

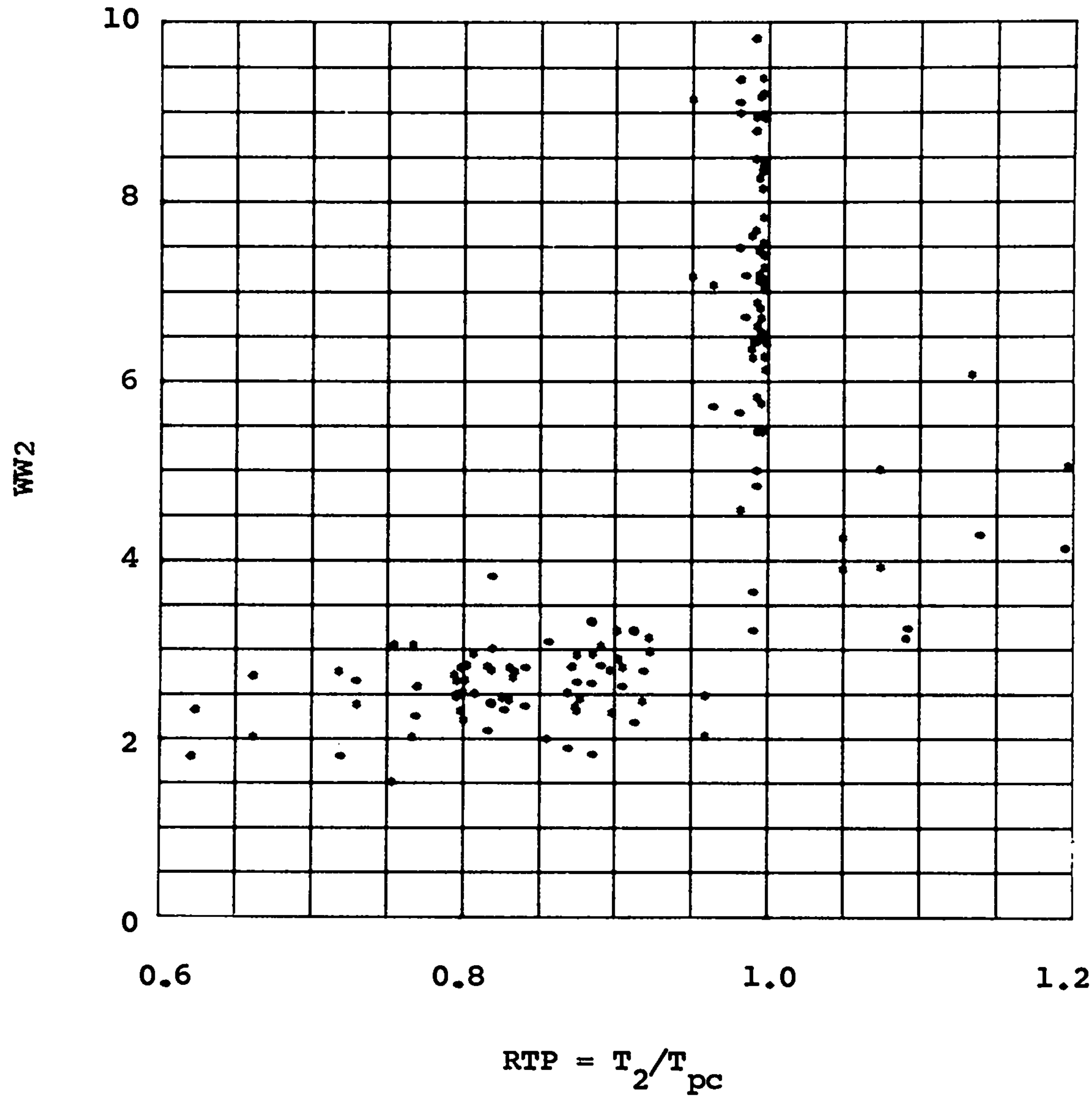

Figure 31. Hot Wire Bridge Voltage Parameter WW2 versus Reduced Pseudocritical Temperature

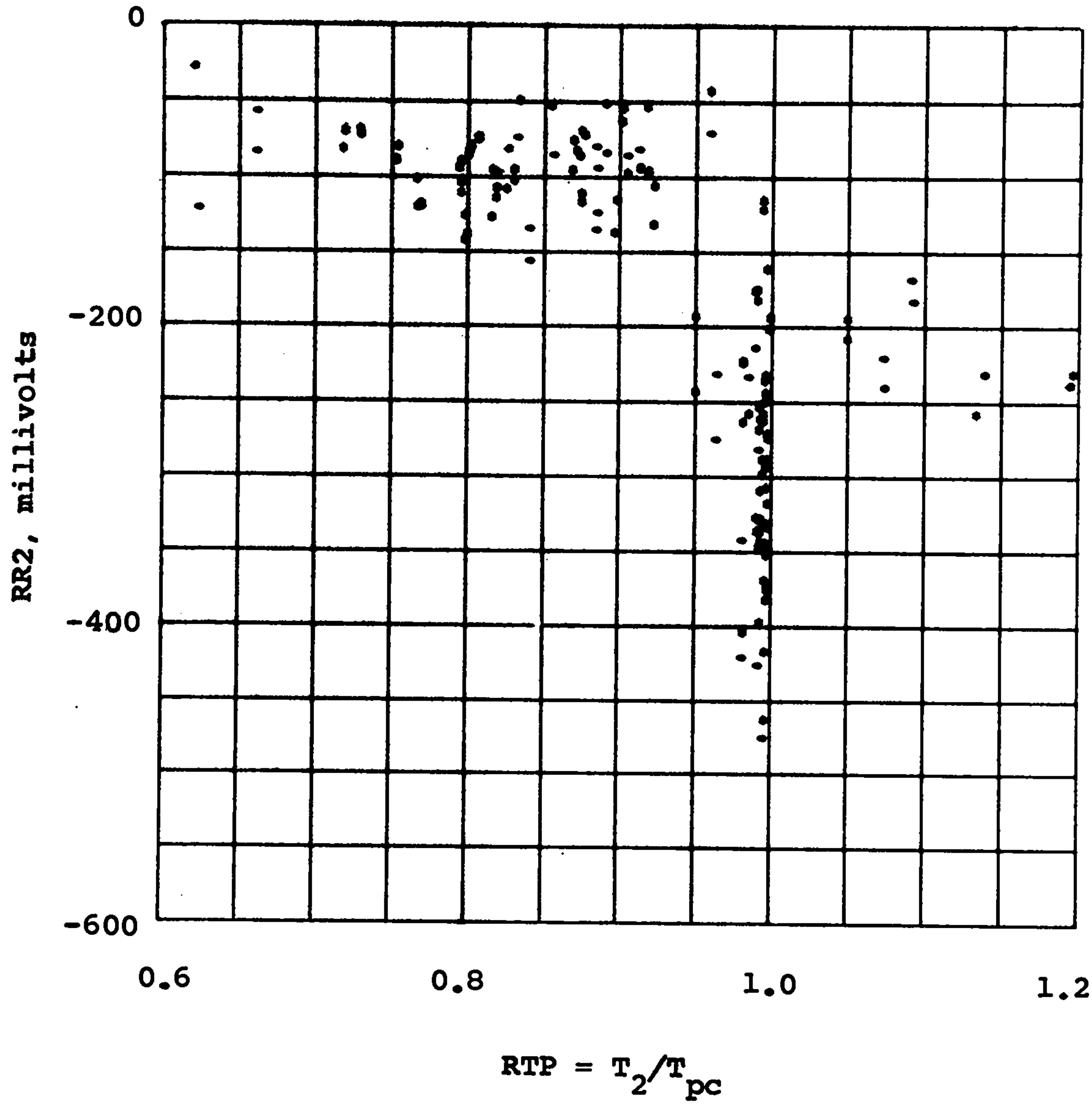

Figure 32. Hot Wire RMS Parameter RR2 versus Reduced Pseudocritical Temperature

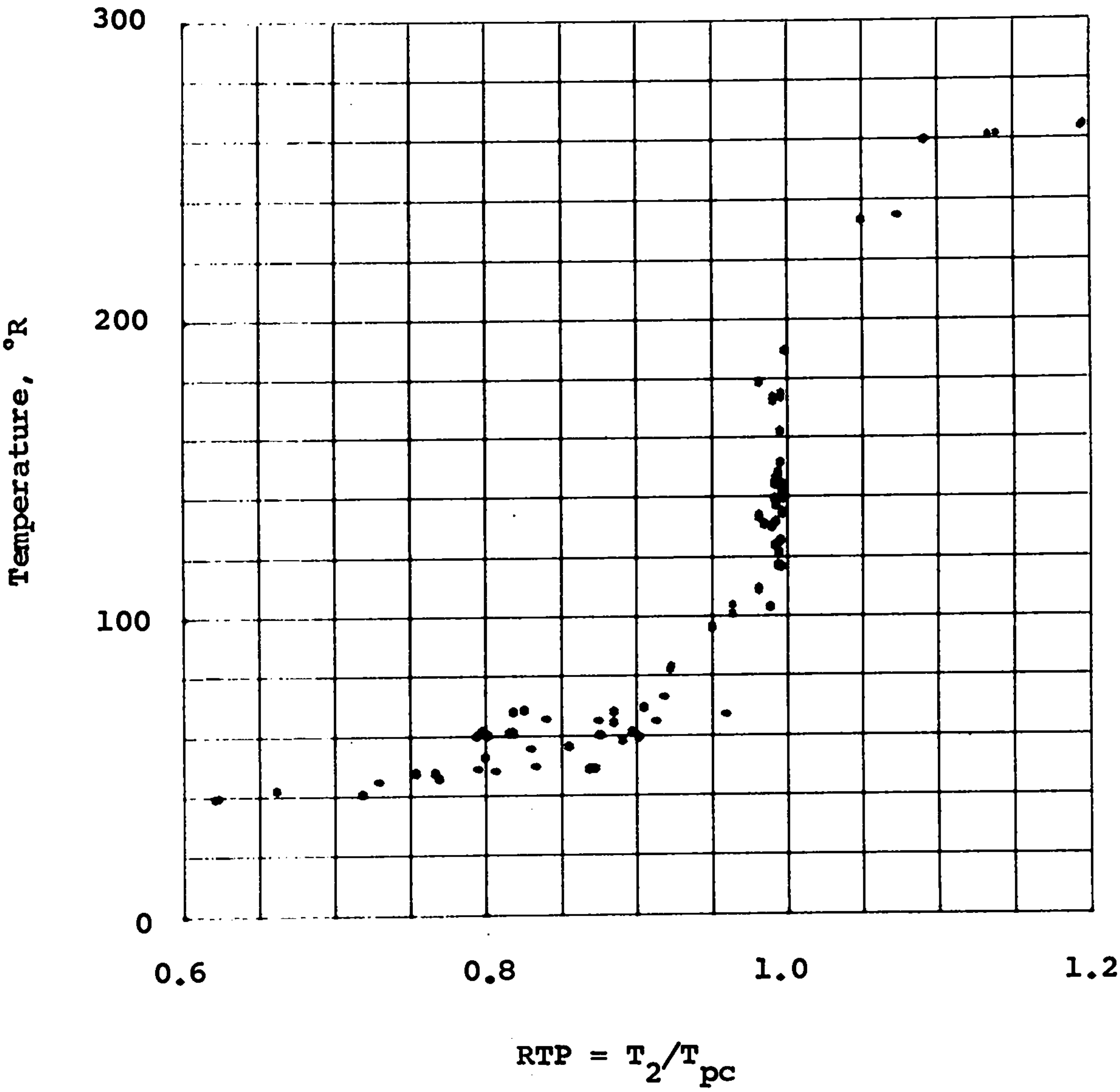

Figure 33. Test Section Inside Wall Temperature versus Reduced Pseudocritical Temperature

10. CONCLUSIONS

1. Property variations near the critical point have an important effect on flow and heat transfer. With pseudocritical temperatures slightly less than one, dynamic pressure, temperature, and hot wire average current were more nearly constant with respect to radius than at other temperatures.

2. A special boiling number involving quasi-two phase enthalpies of dense and light phases was significant for reduced pressures from 1.003 to at least 1.351.

3. A correlation was obtained between a similarity number involving the difference in temperatures of the tube wall and fluid and the special boiling number.

4. The variation of measured RMS voltages of a hot wire as a function of radius was much larger for pseudocritical temperatures slightly less than one than at other temperature.

APPENDIX A

Symbols

Symbol	Meaning	Units
a_c	= πR^2, cross section of test section	ft^2
a_s	= $2\pi RL$, surface area of test section	ft^2
b	= specific body force	$slug/ft^2\text{-}sec^2$
c_p	= isobaric specific heat	$ft^2/sec^2\text{-}°R$
D	= adjusted standard deviation	
DL	= largest adjusted deviation	
h	= specific enthalpy per unit mass	ft^2/sec^2
h_D	= dense phase enthalpy	ft^2/sec^2
$h_L - h_D$	= equivalent enthalpy of vaporization	ft^2/sec^2
k	= thermal conductivity	$slug\text{-}ft/sec^3\text{-}°R$
L	= zone number of DL	
MM	= parameter of mass flow rate per unit area empirical equation	
N_o	= reference similarity numbers	
n	= nondimensional variable	
PP	= parameter of dynamic pressure empirical equation	
p	= pressure	$slug/ft\text{-}sec^2$
Q	= heat flux per unit time	$slug\text{-}ft^2/sec^3$

Symbol		Meaning	Units
q	=	heat flux per unit time and area	slug/sec^3
R	=	0.688 inches, inside radius of the test section	ft
RR	=	parameter of hot wire bridge RMS voltage empirical equation	
RTP	=	T_2/T_{pc}, reduced pseudocritical temperature	
r	=	radius	ft
S	=	standard deviation from data	
SM	=	standard deviation from means of data	
T	=	temperature	°R
T_c	=	critical temperature, 59.37°R	°R
T_{pc}	=	pseudocritical temperature	°R
TT	=	parameter of temperature empirical equation	
t	=	time	sec
u_i	=	hydrogen property i	
$V(r)$	=	velocity as a function of radius	ft/sec
VV	=	parameter of velocity empirical equation	
v	=	velocity	ft/sec

Symbol		Meaning	Units
WW	=	parameter of hot wire bridge voltage empirical equation	
x	=	length	ft
y	=	distance from the test section reference wall	ft
$\Delta p(r)$	=	dynamic pressure as a function of radius	slug/ft-sec^2
η	=	bulk viscosity	slug/ft-sec
$\theta(r)$	=	temperature difference as a function of radius	°R
μ	=	shearing viscosity	slug/ft-sec
ρ	=	density	slug/ft^3
ρv	=	mass flow rate per unit area	slug/ft^2-sec
$(\ )_o$	=	reference dimensional variable	
$(\ )_1$	=	test section inlet	
$(\ )_2$	=	axial length of test section from inlet to probe tip, 176 inches	
$(\ )_B$	=	bulk average	
$(\ )_i$	=	component in the x_i direction	
$(\ )_{,i}$	=	derivative with respect to x_i	
$(\ )_m$	=	model	
$(\ )_p$	=	prototype	

Symbol	Meaning
$(\ )_{,t}$	= derivative with respect to time
$(\ )_w$	= test section inside wall
N_{Bo}	$= \dfrac{q_o a_s}{m_o h_o}$, boiling number
N_{ho}	$= \dfrac{h_o}{v_o^{\,2}}$
N_{po}	$= \dfrac{p_o}{\rho_o v_o^{\,2}}$
N_{Pr_o}	$= \dfrac{\mu_o c_{po}}{k_o}$, Prandtl number
N_{qo}	$= \dfrac{q_o}{\rho_o v_o^{\,3}}$
N_{Ro}	$= \dfrac{\rho_o v_o x_o}{\mu_o}$, Reynolds number
N_{Sk}	$= \dfrac{Q - m(h_D - h_1)}{m(h_L - h_D)}$, special boiling number
N_{To}	$= \dfrac{k_o T_o}{q_o x_o}$
NT1	$= \dfrac{k_w (T_w - T_2)}{2qR}$

Symbol		Meaning
NT2B	$= \dfrac{k_B(TT2)}{2qR}$	
NT2W	$= \dfrac{k_w(TT2)}{2qR}$	
NT3B	$= \dfrac{k_B(T_2-TT1+TT2)}{2qR}$	
NT3W	$= \dfrac{k_w(T_2-TT1+TT2)}{2qR}$	
$N_{\theta o}$	$= \dfrac{k_o \theta_o}{q_o x_o}$	

APPENDIX B

Instrumentation Calibration Factors

1. Pressure Transducers

Dewar pressure	7.70 psi/mV
Inlet plenum	17.78 psi/mV
Pitot position wall static pressure	17.45 psi/mV
Test section pressure differential	0.100 psi/mV
Pitot differential pressure, Baratron 10 mm full scale range	0.100 mm-Hg/mV
30 mm full scale range	0.317 mm-Hg/mV

where:

psi = pressure, pound/inch^2

mV = output voltage, millivolts

mm-Hg = pressure, millimeters mercury

2. Rosemount platinum resistance thermometer,

No. 179A10/2028

Range 24-60°R

$$T = 3.8126536 + 42.914962(R) - 31.067817(R^2) + 15.254059(R^3) - 4.8961214(R^4) + 1.0447286(R^5) - 0.14901324(R^6) + 0.014018260(R^7) - 8.3374922 \times 10^{-4}(R^8)$$

$$+ 2.8379306 \times 10^{-5} (R^9)$$

$$- 4.2092957 \times 10^{-7} (R^{10})$$

Standard deviation = 0.0142

Range 60-160°R

$$T = 36.824537 + 2.4181278(R) - 5.3827240 \times 10^{-2}(R^2)$$

$$+ 1.1510626 \times 10^{-3}(R^3)$$

$$- 1.5630588 \times 10^{-5}(R^4)$$

$$+ 1.2886923 \times 10^{-7}(R^5)$$

$$- 5.8447099 \times 10^{-10}(R^6)$$

$$+ 1.1146391 \times 10^{-12}(R^7)$$

Standard deviation = 0.0049

where:

T = Temperature, °R

R = Resistance, ohms

3. Rosemount triple bridge unit

$$R = - 0.35745216 + 4.6732166(E) + 0.016319025(E^2)$$

$$+ 8.5945361 \times 10^{-5} (E^3)$$

where:

E = voltage, millivolts

4. Copper-constantan wall thermocouples, 34.92°R reference junction

Range 36-170°R

$$T = 35.100337 + 302.88924(E) - 755.90174(E^2)$$

$$+ 2246.3585(E^3) - 4449.1310(E^4)$$
$$+ 5268.7891(E^5) - 3355.4663(E^6)$$
$$+ 880.47247(E^7)$$

Standard deviation = 0.031

Range 36-282°R

$$T = 36.449728 + 251.93901(E) - 281.38495(E^2)$$
$$+ 297.24141(E^3) - 181.06708(E^4)$$
$$+ 56.473775(E^5) - 6.9907397(E^6)$$

Standard deviation = 0.288

Thermocouple	Shift Voltage, millivolts	
L/D	42°R	142°R
2	-0.06038	-0.0317
6	-0.05811	-0.0223
31	-0.09385	-0.0286
56	-0.10690	-0.0566
81	-0.07275	-0.0344
106	-0.22990	-0.0320
127.5	-0.15151	-0.0425
129.5	-0.07447	-0.0258

5. Thermopile, 34.92°R reference junction

Range 16-142°R

$$T = 27.098720 + 48.270650(E) - 21.259577(E^2) + 10.510992(E^3) - 3.4888403(E^4) + 0.69108267(E^5) - 0.072950230(E^6) + 0.0031322624(E^7)$$

Standard deviation = 0.0687

Correction for insertion length cycling due to probe motion.

where:

y = distance from reference tube wall, $[y]$ = inches,

$0 < y < 1.376$

Approaching the reference wall

$$E = -0.0044 + 0.0408(y) - 0.022(y^2)$$

Leaving the reference wall

$$E = -0.001 + 0.0095(y)$$

Correction for test insertion length shorter than initial calibration insertion length.

$$\Delta T = -3.915 \log (132/T)$$

$$\Delta T = 0.0 \text{ for } T > 132$$

6. Turbine flowmeter, Cox S-20-MB, No. 4316

   1074.2 cycles/gallon, ± 0.371 percent deviation from linearity.

7. Shunt resistor 25.18×10^{-6} ohms.

8. Hot wire anemometer, 25.7 volts per ampere of current

through the wire at a wire resistance of 1.5 ohms.

9. Temperature of the liquid hydrogen reference junction

$$T = 1.8\ [A + (A^2 + 2158.5779)^{1/2}]$$

where:

$$A = (\log P/0.04110936) - 113.19232$$

and:

P = Barometric pressure, mm-Hg

10. Thermal conductivity of Inconel 600.

$$k_I = 74.3 + 0.05375(T),\ \frac{\text{Btu-inch}}{\text{hr-ft}^2\text{-}^\circ\text{R}}$$

APPENDIX C

Data Summaries

TABLE 5.

CALCULATED INSIDE WALL TEMPERATURES †

RUN	L/D=2	6	31	56	81	106	127.5	129.5
1	79.1	79.9	86.2	123.5	143.3	119.7	129.5	133.2
2	79.2	79.9	85.8	122.2	145.6	118.9	128.8	132.4
3	82.2	82.6	94.8	146.7	137.0	147.4	152.3	150.7
4	82.3	82.9	96.8	143.9	138.8	148.9	152.7	150.6
5	75.4	77.9	87.4	150.6	130.6	139.1	147.4	145.5
6	75.3	77.5	87.0	151.2	131.2	139.8	147.2	145.5
7	74.5	74.7	88.9	187.4	151.9	155.5	164.9	159.9
8	74.8	75.1	89.1	188.5	152.3	155.8	164.4	159.7
11	50.2	48.8	49.3	58.0	54.9	54.9	59.3	57.7
12	50.4	49.1	49.0	58.0	54.8	55.2	59.4	57.8
13	69.4	74.0	94.0	106.9	112.1	115.5	125.9	125.7
14	68.4	72.8	93.4	106.5	110.8	114.5	125.1	124.8
15	60.5	61.2	62.4	67.8	65.5	76.7	68.6	67.2
16	60.2	61.2	61.9	67.7	65.5	77.0	68.7	67.0
17	60.4	61.7	61.8	68.2	66.2	76.9	69.4	68.0
18	60.4	61.5	61.8	68.1	66.1	77.2	69.4	67.7
19	56.9	58.2	58.8	64.6	63.0	71.6	66.6	65.1
20	56.7	57.9	58.5	64.7	62.9	71.2	66.7	64.9
21	49.1	50.4	48.6	58.2	56.5	63.4	61.5	58.9
22	48.9	50.3	49.1	58.4	56.5	63.3	61.3	58.8
23	48.8	49.8	48.4	56.8	55.1	64.3	61.1	58.7
4	48.8	49.8	48.1	57.0	55.2	64.2	61.0	59.0
25	48.8	50.2	48.3	57.4	55.2	64.3	61.4	59.2
26	48.5	50.0	48.3	57.2	54.8	64.3	61.1	59.2
27	37.0	38.0	36.6	45.8	43.3	49.7	49.4	45.5
28	37.5	38.2	36.4	46.1	43.8	50.3	49.4	45.8
29	36.5	36.9	34.3	42.5	39.1	46.4	42.3	38.7
30	36.4	36.8	33.9	42.8	39.1	47.1	42.2	38.9
31	47.9	47.6	49.4	54.9	52.7	53.3	57.7	53.5
32	47.4	47.1	48.8	54.7	52.8	53.4	57.8	53.4
33	60.7	61.8	68.7	113.3	94.2	85.3	107.8	109.6
34	60.5	61.2	68.6	113.7	94.4	86.2	108.9	110.7
35	55.9	56.3	59.8	76.1	79.7	70.2	102.9	104.3
36	56.3	56.5	59.8	76.7	81.2	74.7	100.4	101.3
37	51.9	51.7	52.6	62.5	62.3	45.3	60.3	61.8
38	51.9	52.5	52.4	62.9	62.5	45.3	60.3	62.0
39	54.8	54.5	56.3	65.5	64.9	46.9	63.2	65.3
40	54.5	54.8	56.2	65.5	65.3	47.4	63.3	65.4
41	55.7	55.8	57.3	67.0	65.9	46.6	63.6	66.2
42	55.7	56.1	57.1	66.9	65.9	46.8	63.5	66.4
43	59.7	59.9	62.5	76.7	77.5	57.5	79.9	84.7
44	59.6	59.9	61.9	77.1	78.1	56.4	80.8	85.3
45	62.8	64.1	70.7	93.5	115.7	83.8	94.2	97.9
46	62.8	64.0	70.4	93.0	115.7	86.0	94.9	98.7
47	72.1	78.4	97.3	110.4	118.8	124.6	132.8	133.4
48	71.9	78.1	97.3	109.9	119.6	125.2	133.7	134.3
49	75.9	81.1	97.3	118.2	129.1	136.9	144.7	144.0
50	75.9	80.8	97.0	117.8	130.0	137.4	145.1	144.4

TABLE 5, CONTINUED.

CALCULATED INSIDE WALL TEMPERATURES

RUN	L/D=2	6	31	56	81	106	127.5	129.5
51	76.4	80.2	97.5	117.2	128.8	136.2	142.3	141.9
52	76.1	79.8	96.9	118.0	128.6	137.3	143.5	143.1
53	76.4	80.9	96.4	117.6	129.7	138.1	144.3	143.9
54	77.0	80.9	95.9	118.4	130.2	138.8	145.0	144.3
55	56.4	56.7	58.6	63.1	63.7	50.8	63.4	65.7
56	56.3	56.5	58.3	63.4	64.0	51.0	63.6	65.8
61	55.3	56.2	60.1	57.7	57.0	66.0	60.4	61.7
62	55.2	56.5	59.3	57.6	57.2	66.0	60.3	61.7
63	55.0	56.1	57.5	57.5	57.3	65.6	60.1	61.5
64	54.7	56.2	56.8	57.5	57.1	66.0	60.0	61.5
65	56.0	56.0	61.3	57.8	58.3	67.4	61.1	62.2
66	55.9	56.3	60.3	57.7	58.2	67.6	61.0	62.3
67	64.6	65.9	69.8	71.9	72.5	65.8	71.1	75.1
68	64.7	66.0	69.3	71.8	72.3	65.7	70.9	75.1
69	82.9	85.4	101.2	174.4	210.1	178.4	178.5	179.2
70	82.9	85.4	100.4	173.9	208.9	177.6	178.6	179.2
71	48.3	49.6	48.8	52.9	53.0	61.2	55.2	57.1
72	48.4	49.9	48.3	52.8	53.0	60.9	55.5	57.0
73	65.3	69.6	74.4	101.6	98.2	82.2	100.0	105.7
74	65.4	69.7	74.2	103.2	96.7	80.6	100.7	106.3
75	76.0	81.2	106.6	115.5	126.5	133.5	138.8	140.2
76	76.4	81.6	106.4	115.7	126.4	134.0	138.9	140.4
77	59.9	59.8	65.0	65.9	66.8	60.2	66.0	69.6
78	59.6	60.2	64.1	65.8	66.5	59.9	65.9	69.5
79	52.0	53.8	56.5	57.5	57.0	62.4	58.9	59.9
80	51.9	53.8	55.8	57.5	57.1	62.2	59.0	59.9
81	77.5	79.7	97.5	200.6	187.3	172.7	173.3	173.6
82	77.3	79.7	98.5	208.2	184.5	173.4	175.4	175.4
85	60.2	61.2	66.4	67.0	66.6	56.3	64.2	70.1
86	60.2	61.1	65.7	66.5	66.3	56.5	63.8	70.1
87	73.2	77.0	96.4	100.9	107.1	107.5	114.9	118.3
88	73.1	76.9	97.3	101.2	106.7	107.9	115.1	118.5
89	70.5	73.6	85.0	127.7	106.0	109.3	120.1	123.0
90	70.1	73.1	84.1	130.1	106.0	109.0	120.2	123.1
91	70.4	73.0	87.8	125.0	131.1	112.7	121.8	125.9
92	69.8	72.8	86.2	123.4	130.8	111.6	121.3	125.8
93	79.6	83.0	104.8	119.3	128.3	134.6	139.2	141.0
94	79.8	82.9	105.1	119.3	127.6	134.6	138.3	140.3
101	42.0	42.6	40.6	42.8	47.9	50.2	51.6	45.4
102	42.0	42.9	39.9	42.9	48.1	50.4	52.1	45.7
103	42.7	43.7	38.5	43.5	48.7	50.5	52.0	46.1
104	42.9	43.9	38.4	43.9	49.0	50.7	52.0	46.2
105	45.5	46.0	41.7	45.2	48.3	51.2	51.5	46.4
106	45.3	45.9	41.0	45.5	48.2	51.5	51.5	46.5
107	48.6	49.5	46.9	49.2	51.4	56.5	54.6	50.9
108	48.7	49.6	46.1	48.9	51.4	56.6	55.0	50.9
109	81.2	83.2	102.8	117.7	129.1	134.5	141.5	140.9
110	81.7	83.6	102.3	118.1	129.4	136.1	142.1	141.3

TABLE 5, CONTINUED.

CALCULATED INSIDE WALL TEMPERATURES

RUN	L/D=2	6	31	56	81	106	127.5	129.5
111	81.4	83.1	102.8	118.8	130.1	135.7	142.3	141.9
112	81.2	83.5	103.0	119.2	130.4	136.2	142.7	142.0
113	81.2	83.2	104.1	118.1	129.3	135.7	142.4	141.5
114	81.3	83.0	104.5	118.0	128.8	135.7	142.3	141.6
115	59.7	60.3	61.2	65.4	69.9	55.2	68.4	70.0
116	59.4	60.2	60.8	65.5	69.9	55.2	68.4	70.1
117	115.2	120.6	130.8	209.9	256.8	263.1	266.6	263.5
118	115.2	121.1	131.2	210.4	255.7	262.4	265.5	262.3
119	114.6	117.7	124.2	185.9	236.1	256.1	261.4	258.0
120	114.5	117.3	124.9	185.9	236.9	256.1	261.6	258.2
121	114.0	117.8	130.4	204.3	247.8	258.8	263.7	260.1
122	113.9	117.7	130.2	203.7	247.2	258.2	263.3	259.7
123	108.6	115.2	140.5	209.9	230.2	233.4	236.9	233.1
124	108.2	115.2	140.9	210.1	230.9	233.5	236.6	232.9
125	106.2	112.2	128.5	192.2	223.6	230.9	235.2	231.5
126	106.1	111.9	128.1	190.1	222.3	230.7	235.1	231.3
127	73.6	74.9	89.5	152.8	205.7	172.6	173.1	171.2
128	73.4	74.8	89.2	155.3	204.0	172.3	175.1	172.8
129	84.7	87.2	115.1	191.2	185.1	186.2	191.0	188.2
130	85.3	88.3	116.2	190.5	185.4	187.2	191.1	188.4
131	71.7	77.5	99.1	122.6	133.4	143.8	148.6	146.4
132	71.9	77.8	99.7	123.0	133.1	143.6	149.7	147.1
133	74.1	76.7	102.5	115.3	122.7	130.8	135.6	134.4
134	73.5	76.0	101.7	115.3	122.6	129.6	134.7	133.6
135	67.7	69.9	77.1	116.5	115.2	100.2	116.0	117.4
136	67.6	69.9	77.2	118.5	115.3	101.1	116.6	118.1
137	71.2	73.2	84.3	121.0	168.3	129.5	129.1	130.0
138	70.9	73.1	83.7	120.7	168.4	129.0	130.1	130.9
139	70.6	72.5	81.3	121.5	161.9	128.2	131.6	132.1
140	70.6	72.3	81.1	122.2	163.0	127.6	131.4	132.0
141	72.6	73.0	88.9	119.9	186.4	147.5	137.2	137.0
142	72.6	73.3	88.0	121.1	186.2	147.9	137.7	137.4

† Temperatures are in degrees Rankine.

TABLE 6.

PARAMETERS OF EMPIRICAL EQUATION OF TEMPERATURE †

RUN	TT1	TT2	S	SM	D	DL	L
1	59.24	2.794	.992	.112	.0020	-.0041	3
2	59.64	3.553	.838	.088	.0015	-.0025	1
3	59.24	.899	.669	.054	.0009	.0017	9
4	58.74	.250	.758	.041	.0007	-.0011	4
5	58.43	1.085	.616	.084	.0015	-.0029	2
6	58.18	1.131	.733	.160	.0028	.0048	10
7	60.47	1.864	.734	.078	.0013	-.0022	9
8	60.18	1.213	.631	.093	.0016	.0032	7
9	44.70	.150	.711	.092	.0021	.0032	3
10	44.42	-.300	.781	.059	.0013	.0022	10
11	57.45	4.798	.838	.110	.0021	-.0041	9
12	56.67	3.688	.629	.122	.0023	.0042	1
13	58.54	-.226	.535	.043	.0007	-.0016	10
14	59.02	.428	.490	.048	.0008	-.0014	1
15	55.79	4.019	.778	.148	.0028	-.0052	2
16	55.96	4.389	.929	.105	.0020	-.0044	8
17	57.09	5.267	.969	.105	.0020	.0032	10
18	56.41	4.380	.731	.163	.0031	-.0076	2
19	56.43	4.343	.876	.171	.0033	.0060	8
20	56.87	5.104	.869	.139	.0026	.0045	1
21	57.14	5.107	.962	.157	.0030	-.0052	9
22	56.91	4.657	.893	.166	.0031	-.0059	2
23	53.32	2.612	.802	.151	.0030	.0041	7
24	53.72	3.373	.948	.153	.0030	.0051	1
25	53.87	3.179	.952	.101	.0020	-.0036	3
26	54.17	3.668	.882	.078	.0015	.0027	1
27	51.79	3.214	1.063	.092	.0019	-.0032	7
28	50.94	2.022	.742	.111	.0023	-.0038	3
29	47.28	1.416	1.014	.182	.0039	-.0070	3
30	47.83	2.324	1.220	.132	.0029	-.0046	10
31	53.81	4.139	1.192	.147	.0029	-.0067	9
32	52.83	2.463	1.148	.125	.0025	-.0042	2
33	60.18	2.618	1.018	.119	.0021	.0037	2
34	60.48	2.671	1.079	.081	.0014	.0021	9
35	66.51	13.113	1.421	.212	.0038	-.0070	2
36	64.68	10.702	1.397	.399	.0071	-.0152	9
37	60.01	6.931	.874	.250	.0046	-.0091	10
38	60.12	7.123	1.053	.154	.0028	-.0061	2
39	60.88	6.939	1.183	.162	.0029	.0056	10
40	60.47	6.304	.887	.132	.0024	-.0044	9
41	61.24	6.522	.832	.136	.0024	-.0049	9
42	61.52	6.967	.937	.183	.0033	-.0061	2
43	70.96	15.959	1.182	.474	.0081	-.0180	2
44	68.34	13.197	1.210	.456	.0080	-.0161	8
45	64.07	5.415	1.204	.071	.0012	-.0025	9
46	64.49	5.896	1.039	.141	.0024	.0042	3
47	63.75	2.409	.809	.079	.0013	.0021	8
48	63.88	2.461	.698	.066	.0011	-.0021	10

TABLE 6, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF TEMPERATURE

RUN	TT1	TT2	S	SM	D	DL	L
49	61.99	1.392	.648	.052	.0009	-.0016	4
50	62.02	1.453	.668	.084	.0014	-.0026	1
51	59.83	.089	.818	.053	.0009	-.0015	10
52	60.15	.491	1.120	.114	.0019	-.0038	1
53	60.21	.626	.729	.052	.0009	.0015	7
54	60.16	.466	.531	.065	.0011	.0025	9
58	39.33	.002	.919	.074	.0019	.0031	2
55	58.35	4.764	1.231	.210	.0039	.0075	6
56	58.74	5.172	.972	.175	.0032	-.0046	3
57	39.04	-.182	1.103	.104	.0027	.0049	1
59	45.58	-.037	.747	.045	.0010	.0022	2
60	45.40	-.270	1.256	.104	.0023	.0042	7
61	49.68	1.602	.745	.065	.0014	-.0027	2
62	49.52	1.475	.826	.136	.0028	-.0064	10
63	50.20	1.795	.904	.086	.0018	-.0034	10
64	49.95	1.388	.825	.080	.0016	-.0035	2
65	50.19	1.560	.972	.048	.0010	-.0017	7
66	50.34	1.673	.846	.054	.0011	-.0022	2
67	59.39	6.552	1.171	.331	.0061	-.0112	2
68	59.48	6.603	1.348	.346	.0064	-.0088	9
69	65.79	5.991	1.071	.144	.0023	-.0053	10
70	66.00	6.168	.990	.081	.0013	-.0025	7
71	52.86	2.430	.609	.045	.0009	-.0014	8
72	52.56	2.085	.929	.107	.0021	-.0036	10
73	59.50	1.844	1.011	.093	.0016	-.0032	8
74	59.42	1.808	.724	.026	.0004	.0009	2
75	61.81	1.390	.616	.057	.0009	-.0015	4
76	61.77	1.336	.620	.050	.0008	-.0014	8
77	59.12	5.379	1.180	.185	.0034	-.0049	10
78	59.10	5.422	.989	.113	.0021	-.0053	2
79	56.72	3.913	.902	.109	.0020	-.0040	3
80	57.06	4.297	.812	.063	.0012	.0021	5
81	59.78	1.579	.715	.124	.0021	-.0045	7
82	59.45	1.184	.799	.112	.0019	-.0033	5
83	47.39	-.259	.799	.037	.0008	-.0015	4
84	47.66	.021	.916	.049	.0010	.0020	8
85	60.73	4.837	.703	.235	.0041	-.0078	2
86	60.14	4.177	.593	.257	.0045	-.0071	9
87	58.78	.048	.666	.050	.0009	.0021	9
88	58.93	.291	.566	.048	.0008	.0018	6
89	59.28	.564	.796	.043	.0007	-.0012	3
90	59.27	.535	.945	.055	.0009	-.0020	3
91	59.55	1.279	.671	.054	.0009	.0019	7
92	59.41	1.208	1.000	.061	.0010	.0016	7
93	59.37	.298	.581	.076	.0013	.0031	9
94	59.39	.333	.573	.054	.0009	.0017	1
95	50.55	.294	.744	.066	.0013	.0021	8
96	50.62	.264	.769	.043	.0009	-.0016	3

TABLE 6, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF TEMPERATURE

RUN	TT1	TT2	S	SM	D	DL	L
97	48.53	.152	.740	.029	.0006	-.0013	3
98	48.53	.097	.665	.037	.0008	.0013	8
99	42.54	.485	1.048	.085	.0020	.0034	3
100	42.17	.041	.997	.078	.0018	.0028	8
101	53.38	2.250	.834	.058	.0011	.0020	8
102	53.23	2.193	.551	.034	.0007	-.0010	4
103	52.98	1.895	.670	.070	.0014	.0021	1
104	53.36	2.201	.808	.074	.0014	.0029	3
105	51.04	1.302	.880	.048	.0010	-.0019	3
106	51.20	1.385	1.090	.082	.0016	-.0041	8
107	51.84	1.847	.710	.039	.0008	-.0017	3
108	51.58	1.586	.644	.038	.0008	.0013	9
109	59.47	.473	.712	.063	.0011	.0019	9
110	59.20	.285	.919	.060	.0010	.0025	2
111	59.38	.387	.588	.022	.0004	-.0008	4
112	59.51	.595	1.104	.122	.0021	-.0047	1
113	59.47	.524	.851	.050	.0008	.0020	7
114	59.25	.265	.711	.050	.0009	.0015	9
115	61.76	6.383	.697	.201	.0035	-.0079	1
116	61.11	5.620	.673	.264	.0047	-.0085	9
117	100.86	37.589	3.584	.832	.0122	.0195	2
118	100.89	38.007	3.595	.996	.0144	.0234	2
119	82.48	21.402	2.475	.791	.0118	-.0248	1
120	82.73	21.755	2.480	.506	.0079	.0123	9
121	92.67	26.348	2.854	.657	.0095	.0199	2
122	94.64	28.280	3.128	.737	.0104	-.0172	1
123	84.32	19.844	2.247	.543	.0081	.0187	2
124	81.54	16.998	1.987	.431	.0064	.0107	2
125	76.04	16.211	1.859	.505	.0081	.0146	2
126	77.98	18.182	2.208	.643	.0101	-.0190	1
127	61.54	4.374	.899	.168	.0029	-.0059	3
128	61.60	4.542	.871	.134	.0023	-.0056	8
129	60.80	1.868	.842	.201	.0034	.0062	10
130	61.48	2.604	.698	.174	.0029	-.0061	6
131	59.32	.995	.545	.038	.0007	-.0013	5
132	59.39	1.129	.640	.075	.0013	-.0021	1
133	59.45	.689	.634	.057	.0010	.0017	8
134	59.46	.644	.795	.092	.0016	-.0033	1
135	59.83	1.462	.931	.065	.0011	.0021	9
136	59.88	1.548	.719	.056	.0009	.0017	1
137	61.72	3.090	.956	.071	.0012	.0024	10
138	61.72	3.139	.884	.063	.0011	-.0020	2
139	60.51	2.118	.642	.052	.0009	.0019	5
140	60.63	2.238	.752	.062	.0011	-.0015	8
141	61.73	3.222	.845	.090	.0015	.0026	5
142	61.65	3.188	.770	.079	.0013	-.0022	9

† TT1, TT2, S, and SM are in degrees Rankine.

TABLE 7.

PARAMETERS OF EMPIRICAL EQUATION OF DYNAMIC PRESSURE †

RUN	PP1	PP2	S	SM	D	DL	L
1	.118116	7.9466	.00792	.002460	.02103	.03524	10
2	.117889	8.8255	.00826	.002735	.02379	.05081	1
3	.112147	6.4280	.01056	.002365	.02129	.03763	5
4	.110407	9.7406	.01142	.002717	.02490	.04061	9
5	.106136	9.3785	.01314	.004818	.04568	-.07794	2
6	.107806	7.9086	.01134	.003233	.03106	.06070	9
7	.168636	6.9020	.01425	.003622	.02188	.03302	7
8	.171864	5.7049	.01312	.004189	.02706	.05411	10
9	.031720	1.9785	.01086	.001869	.08733	.20800	2
10	.031913	2.3277	.01111	.002624	.10480	.15680	6
11	.029749	4.5564	.00282	.001355	.05067	.11720	2
12	.030562	3.8611	.00295	.001300	.04566	.07353	9
13	.053274	8.4309	.00732	.002217	.04320	.09621	10
14	.054286	6.3952	.00700	.001164	.02276	.05688	1
15	.026499	4.1994	.00291	.001255	.05183	.08942	4
16	.026104	4.1754	.00299	.001239	.05408	.09777	2
17	.023787	3.4012	.00300	.001153	.05957	-.11390	10
18	.023801	3.8934	.00264	.000810	.04321	.09508	2
19	.025448	4.2585	.00282	.001190	.05541	.12660	2
20	.026294	4.3470	.00249	.000991	.04252	.08595	9
21	.026404	3.8645	.00285	.000915	.03903	.10040	8
22	.026434	3.6464	.00292	.000944	.04551	-.10270	1
23	.042374	3.2717	.00547	.002854	.08455	-.16970	1
24	.041008	3.9777	.00625	.003006	.08149	.14090	8
25	.038879	3.8887	.00589	.002694	.08159	-.14930	1
26	.039595	3.6216	.00562	.002356	.07366	-.15890	10
27	.064960	4.0243	.00621	.002377	.04283	-.07783	10
28	.066057	4.3606	.00701	.003854	.06731	-.14210	1
29	.143381	4.0692	.01071	.005444	.04490	-.09161	1
30	.144125	4.0092	.01033	.005242	.04171	.09798	2
31	.048971	3.7108	.00446	.002637	.06741	-.14700	10
32	.049271	3.5462	.00467	.003303	.08575	-.19520	1
33	.067108	8.8319	.00618	.001233	.01896	.04553	1
34	.068896	7.5505	.00661	.001663	.02538	.06492	2
35	.102067	6.4486	.00769	.001212	.01204	.02732	8
36	.100082	7.5990	.00782	.001512	.01523	-.02510	9
37	.166382	4.6618	.01441	.007325	.05186	.11020	10
38	.165021	4.4052	.01441	.006440	.04443	-.07756	10
39	.154459	4.7521	.01335	.005016	.03573	.05521	2
40	.155094	4.7503	.01326	.005315	.03781	-.06401	1
41	.154556	4.5640	.01186	.005962	.04377	.08504	9
42	.156428	4.4435	.01165	.005849	.04197	.07259	2
43	.100476	4.2353	.00753	.002128	.02552	.05109	1
44	.099648	4.8985	.00787	.002389	.02700	.04396	10
45	.063094	10.0640	.00589	.000778	.01257	.03300	3
46	.063086	8.4343	.00584	.001316	.02185	.04172	9
47	.045820	9.8626	.00640	.000791	.01753	.03944	2
48	.045595	8.3752	.00614	.000895	.01953	.03356	8

TABLE 7, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF DYNAMIC PRESSURE

RUN	PP1	PP2	S	SM	D	DL	L
49	.049840	9.6760	.01026	.001983	.04051	.07355	2
50	.049047	11.6621	.01058	.002663	.05541	.10590	5
51	.052373	12.0665	.00992	.002562	.05269	.13780	2
52	.053020	7.5700	.01016	.002006	.03808	-.07843	9
53	.053698	9.2016	.01061	.002118	.03961	-.06843	2
54	.054537	7.0060	.01040	.002742	.05277	.12340	10
55	.172914	4.6232	.01605	.006369	.04160	-.07271	1
56	.172546	4.0873	.01535	.005725	.03919	.07134	9
57	.113472	3.4536	.02121	.005667	.05664	.15280	4
58	.117086	2.6652	.02320	.005440	.06402	-.15490	10
59	.125375	3.8476	.01066	.005916	.05540	.09598	2
60	.122618	3.9537	.01150	.006752	.06697	.13250	10
61	.135425	4.1765	.01030	.005026	.04112	-.07234	10
62	.131293	6.7035	.01288	.009786	.08546	.20400	10
63	.139403	3.9721	.01277	.007645	.06549	-.13210	1
64	.139456	3.6247	.01340	.007879	.06515	-.12040	10
65	.140989	4.0855	.01193	.006229	.05055	.08833	8
66	.138908	4.5104	.01204	.006221	.05280	.10980	10
67	.169935	4.1077	.01765	.006690	.04545	.09291	2
68	.170478	4.4333	.01964	.007588	.05442	.12610	10
69	.294990	6.4654	.02420	.008662	.03147	.06686	10
70	.296858	5.2978	.02632	.005458	.01815	-.04515	4
71	.076071	4.0970	.00539	.002965	.04441	-.07715	10
72	.076149	4.1319	.00581	.003987	.06233	-.13440	1
73	.074731	8.3279	.00630	.000953	.01299	.02777	10
74	.075117	8.9682	.00651	.001555	.02113	.04414	9
75	.052419	15.5860	.00982	.001019	.01952	.03879	8
76	.054440	8.1741	.00986	.002107	.03980	.07873	2
77	.176039	4.7585	.01470	.008502	.05530	.09394	10
78	.178956	3.7352	.01341	.007216	.04788	.09991	2
79	.029711	4.5712	.00474	.001257	.04760	-.08712	1
80	.030443	3.6250	.00316	.001005	.03870	-.06848	10
81	.335181	5.6894	.04014	.013100	.04057	.05810	8
82	.342103	5.0627	.04679	.011710	.03544	.07422	9
83	.124273	3.4202	.01476	.006001	.05985	-.14050	10
84	.120924	3.8267	.01603	.008959	.08874	-.17140	1
85	.144220	3.6039	.01544	.007320	.06126	-.13080	10
86	.142385	4.0304	.01480	.006964	.05832	-.10940	1
87	.053371	8.4579	.00851	.002006	.03996	.09345	10
88	.054217	7.7750	.00862	.002337	.04455	-.06625	9
89	.086992	9.6511	.00978	.001926	.02223	-.03353	4
90	.088835	7.2165	.01022	.002098	.02444	.04628	10
91	.136875	5.8383	.01266	.002693	.02022	.03578	9
92	.133615	6.5410	.01215	.002702	.02212	.05446	1
93	.062786	7.1333	.00998	.002104	.03494	.06982	8
94	.064588	7.1273	.01001	.001477	.02365	-.03924	4
95	.026536	4.1086	.00238	.001584	.06607	.12310	9
96	.026852	4.1282	.00227	.001301	.05597	.08935	8

TABLE 7, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF DYNAMIC PRESSURE

RUN	PP1	PP2	S	SM	D	DL	L
97	.026035	3.9494	.00251	.001340	.05907	-.12040	10
98	.025000	5.0892	.00345	.001294	.05582	.13370	4
99	.026940	3.5315	.00278	.001320	.05685	.10840	8
100	.025713	4.4821	.00257	.001285	.06048	-.12880	1
101	.075917	4.2484	.00524	.003767	.05749	-.10090	1
102	.076680	4.1625	.00465	.002769	.04172	-.07961	10
103	.076767	4.5828	.00464	.002830	.04190	.07494	10
104	.077130	3.9584	.00522	.002484	.03800	-.07804	10
105	.138011	4.7134	.01106	.006102	.05062	.10120	9
106	.143051	3.6692	.00876	.003217	.02676	-.04650	10
107	.137696	4.3169	.01069	.006366	.05356	-.10040	1
108	.139276	4.3329	.00923	.005209	.04082	-.06306	10
109	.060621	11.7808	.00925	.002420	.03896	-.08126	6
110	.062792	6.2857	.00946	.001295	.02123	-.03199	9
111	.061589	7.7400	.00935	.001174	.01958	-.02858	9
112	.061501	8.2661	.00930	.001278	.02117	.04616	1
113	.061716	8.1734	.00864	.001388	.02385	.06237	10
114	.061146	7.2693	.01016	.001995	.03452	.07414	1
115	.170547	4.1991	.01238	.007147	.05054	.10310	1
116	.169855	4.4932	.01165	.006112	.04152	.07430	9
117	.198585	5.3041	.03713	.004870	.02723	.06237	10
118	.195144	7.8511	.04793	.010350	.05123	-.10140	6
119	.170673	5.2036	.05518	.010960	.07488	.19310	2
120	.172000	7.8174	.04140	.011190	.07545	.18920	9
121	.145436	7.7482	.04246	.005456	.03732	.06198	4
122	.147061	5.6598	.03635	.008322	.06224	.12680	1
123	.187220	5.6394	.03333	.010110	.06159	.11510	1
124	.190254	5.5761	.02986	.006052	.03290	-.05886	2
125	.235271	5.9007	.06813	.021250	.09850	.17560	8
126	.229226	4.8555	.05725	.006731	.03181	.07058	10
127	.290252	5.7918	.03581	.004950	.01774	.03223	2
128	.288984	6.6084	.03998	.005121	.01864	.04592	1
129	.285041	6.6643	.06579	.016470	.06035	.10190	9
130	.291745	5.5215	.06171	.014040	.04903	-.07904	6
131	.078915	10.0182	.01606	.002781	.03598	.07404	6
132	.076093	15.0384	.01675	.003350	.04436	.09637	9
133	.075861	6.8051	.01043	.001667	.02253	.04551	8
134	.074203	8.7588	.01165	.002724	.03826	.07641	8
135	.100826	6.9742	.01032	.002310	.02506	.07028	1
136	.102296	7.0832	.00992	.001965	.02025	.04515	10
137	.153304	6.2281	.01308	.002956	.02051	.04673	1
138	.153976	7.3762	.01340	.003313	.02238	.04923	10
139	.162693	5.7760	.01350	.002844	.01941	.04985	10
140	.160504	6.2882	.01567	.004915	.03339	.07362	1
141	.239392	5.2077	.02062	.005606	.02426	.04407	9
142	.240153	6.6045	.01884	.006249	.02778	.05837	10

† PP1, S, and SM are in pounds/inch^2

TABLE 8.

PARAMETERS OF EMPIRICAL EQUATION OF VELOCITY †

RUN	VV1	VV2	VV3	S	SM	D	DL	L
1	18.341	12.090	.063	1.166	.24	.0129	-.0270	3
2	18.158	16.850	-.113	.868	.19	.0105	.0134	1
3	19.058	11.461	.009	1.832	.35	.0185	-.0322	8
4	19.183	19.605	-.200	1.785	.32	.0167	-.0260	3
5	17.760	11.295	.351	1.437	.42	.0241	.0434	10
6	17.753	11.280	-.040	1.282	.30	.0173	.0280	9
7	23.628	12.730	.181	1.683	.35	.0150	.0288	1
8	24.340	12.287	-.426	1.590	.31	.0132	.0282	10
9	7.622	5.572	-.724	1.680	.37	.0546	.1102	2
10	7.617	12.769	-.934	1.770	.48	.0642	.1020	6
11	8.565	9.785	-.288	.486	.16	.0186	.0344	2
12	8.626	9.209	-.381	.471	.18	.0214	.0492	5
13	14.032	14.141	-.285	1.464	.35	.0255	.0470	10
14	13.693	12.356	-.193	1.360	.20	.0150	.0332	10
15	7.850	10.294	-.377	.445	.16	.0202	-.0435	3
16	7.779	10.144	-.361	.481	.15	.0188	.0340	6
17	7.344	10.165	-.482	.492	.12	.0173	-.0334	2
18	7.437	9.170	-.330	.456	.14	.0190	.0358	2
19	7.761	9.934	-.313	.476	.19	.0253	.0517	2
20	7.892	9.735	-.323	.376	.09	.0122	.0287	9
21	7.970	7.663	-.260	.529	.12	.0155	.0346	8
22	7.905	10.085	-.421	.535	.14	.0174	-.0393	3
23	9.683	9.203	-.660	.686	.25	.0284	.0564	10
24	9.579	14.423	-.699	.726	.13	.0139	.0263	3
25	9.346	12.324	-.625	.735	.18	.0200	.0452	10
26	9.370	12.813	-.667	.700	.21	.0236	.0494	1
27	11.960	9.898	-.600	.589	.14	.0116	.0193	1
28	12.077	14.245	-.700	.650	.23	.0195	.0299	10
29	17.491	9.432	-.851	.649	.18	.0107	.0223	10
30	17.490	9.484	-.855	.641	.21	.0127	-.0245	8
31	10.517	11.087	-.627	.580	.20	.0205	.0502	1
32	10.543	13.791	-.805	.687	.24	.0254	.0667	10
33	14.529	200.000*	.248	1.506	.27	.0180	.0292	1
34	14.937	17.326	.424	1.621	.14	.0092	-.0167	3
35	16.453	29.028	.313	1.169	.19	.0112	.0199	8
36	16.409	200.000	.382	1.090	.16	.0099	-.0142	9
37	20.339	11.690	-.726	.877	.30	.0156	.0395	10
38	20.207	11.665	-.782	1.089	.19	.0099	.0196	1
39	19.548	12.074	-.738	1.103	.16	.0085	.0181	10
40	19.596	11.475	-.711	.845	.17	.0088	-.0137	3
41	19.606	11.268	-.716	.856	.12	.0065	.0119	9
42	19.654	11.412	-.751	.703	.18	.0093	-.0167	8
43	16.107	10.707	-.070	.728	.12	.0078	.0175	10
44	16.074	13.444	-.112	.815	.16	.0100	-.0207	9
45	13.678	18.219	.155	.744	.11	.0079	.0210	3
46	13.638	20.743	.108	.739	.12	.0088	.0173	10
47	12.620	20.281	.163	1.093	.18	.0142	.0248	2
48	12.618	20.807	.009	.967	.13	.0103	.0232	8

TABLE 8, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF VELOCITY

RUN	VV1	VV2	VV3	S	SM	D	DL	L
49	$							
50	13.203	200.000	.323	1.616	.33	.0246	-.0415	2
51	$							
52	14.535	9.735	.077	1.731	.27	.0185	.0273	10
53	14.261	15.818	.094	1.789	.35	.0243	-.0381	2
54	14.582	13.721	-.173	1.778	.44	.0309	.0728	10
55	20.945	10.249	-.711	1.251	.25	.0119	-.0271	3
56	20.811	10.115	-.840	1.463	.28	.0139	.0297	9
57	14.977	6.105	-.571	1.637	.38	.0263	.0640	4
58	14.683	9.484	-1.411	1.787	.29	.0194	-.0427	3
59	16.363	9.530	-.927	.676	.24	.0154	.0348	1
60	16.193	10.299	-.935	.875	.37	.0242	.0571	10
61	17.353	10.495	-.896	.631	.20	.0120	-.0203	2
62	17.324	23.667	-.816	.717	.45	.0270	.0591	10
63	17.552	11.868	-1.100	.757	.25	.0152	.0330	10
64	17.498	10.365	-1.162	.795	.22	.0126	-.0261	8
65	17.697	9.891	-.929	.698	.16	.0090	-.0205	3
66	17.645	10.596	-.796	.822	.34	.0201	.0451	10
67	20.470	10.026	-.811	1.425	.18	.0092	.0153	1
68	20.571	11.523	-.807	1.733	.35	.0180	.0420	10
69	30.399	19.300	.110	1.931	.36	.0121	.0241	5
70	30.345	200.000	-.224	2.102	.28	.0092	-.0162	4
71	13.270	10.007	-.674	.488	.12	.0096	.0169	9
72	13.251	12.312	-.780	.581	.22	.0167	-.0309	3
73	15.130	14.209	.002	1.204	.05	.0036	.0080	1
74	15.137	19.400	-.077	1.140	.09	.0057	.0112	5
75	13.626	37.280	.024	1.442	.20	.0144	-.0284	10
76	13.849	15.157	-.135	1.406	.21	.0155	.0248	7
77	20.776	13.795	-.986	1.221	.33	.0162	-.0321	3
78	20.694	10.171	-1.130	.764	.25	.0124	-.0198	8
79	8.527	12.200	-.393	.767	.09	.0114	-.0202	3
80	8.585	8.476	-.362	.515	.11	.0138	.0286	1
81	32.558	13.997	-.703	2.993	.36	.0109	.0155	8
82	32.915	10.469	-.681	3.503	.39	.0118	-.0278	4
83	16.175	11.418	-1.213	.974	.22	.0143	.0246	1
84	16.046	15.567	-1.234	1.057	.39	.0247	-.0509	3
85	19.494	11.429	-1.043	1.258	.25	.0127	.0188	1
86	19.500	10.653	-.862	1.013	.27	.0140	-.0325	3
87	13.890	13.829	-.223	1.594	.23	.0169	.0417	10
88	13.855	8.739	.410	1.488	.21	.0154	.0279	2
89	17.879	19.158	.083	1.773	.11	.0059	-.0116	2
90	18.063	12.394	-.059	1.822	.19	.0108	-.0201	3
91	21.276	10.099	.090	2.179	.24	.0112	-.0210	2
92	20.847	12.786	-.064	2.082	.25	.0121	-.0270	8
93	16.416	20.775	-.503	1.826	.38	.0233	-.0419	2
94	16.672	10.344	-.142	1.839	.12	.0073	-.0127	4
95	7.806	10.751	-.463	.319	.12	.0159	-.0239	2
96	7.862	11.063	-.451	.361	.11	.0147	.0269	9

TABLE 8, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF VELOCITY

RUN	VV1	VV2	VV3	S	SM	D	DL	L
97	7.593	9.793	-.426	.360	.10	.0141	.0273	1
98	7.525	9.697	-.203	.555	.21	.0277	.0614	4
99	7.344	9.880	-.489	.389	.11	.0151	-.0243	3
100	7.260	11.755	-.368	.368	.14	.0198	.0430	10
101	13.344	11.492	-.698	.620	.19	.0145	.0249	6
102	13.403	9.896	-.637	.374	.11	.0079	-.0122	7
103	13.461	10.807	-.605	.364	.16	.0126	.0269	10
104	13.423	9.843	-.692	.514	.14	.0109	-.0195	8
105	17.697	11.049	-.820	.660	.24	.0143	.0249	10
106	17.933	7.651	-.705	.847	.27	.0155	.0307	1
107	17.624	11.805	-.964	.615	.27	.0156	.0300	10
108	17.794	9.397	-.755	.560	.22	.0120	-.0283	3
109	16.533	200.000	-.179	1.889	.24	.0142	-.0230	6
110	16.470	9.702	.033	1.936	.27	.0166	.0282	1
111	16.368	12.875	.093	1.906	.21	.0131	.0241	7
112	16.062	12.366	.014	1.859	.22	.0138	-.0211	2
113	16.042	13.911	.023	1.752	.26	.0164	.0380	10
114	15.869	11.900	-.182	1.934	.20	.0127	.0249	1
115	20.653	12.203	-.843	.736	.29	.0148	.0343	1
116	20.740	10.793	-.613	.767	.22	.0111	.0188	10
117	46.945	200.000	1.552	5.133	.69	.0145	-.0247	1
118	46.729	200.000	2.225	6.681	1.61	.0338	-.0596	6
119	38.933	200.000	.954	7.357	1.48	.0388	.0839	2
120	39.167	200.000	1.862	6.013	1.89	.0478	.0849	9
121	33.977	21.448	1.314	5.589	.77	.0233	.0510	4
122	33.978	200.000	1.180	4.887	1.09	.0325	.0667	3
123	$							
124	34.850	200.000	1.312	3.563	.68	.0191	.0343	9
125	41.298	24.112	2.044	7.571	2.33	.0544	-.1008	10
126	40.903	17.589	2.390	6.712	.87	.0215	.0359	3
127	29.535	19.398	.437	3.107	.33	.0113	.0271	10
128	29.332	18.485	.549	2.783	.27	.0091	.0185	2
129	$							
130	34.304	200.000	.371	5.078	1.59	.0460	-.0797	6
131	16.057	18.064	.318	2.080	.22	.0136	.0259	6
132	15.728	200.000	-.066	2.114	.39	.0245	-.0395	5
133	17.102	11.025	.156	1.964	.26	.0157	.0327	8
134	16.890	200.000	-.212	2.066	.24	.0147	.0335	8
135	18.608	18.106	.133	1.903	.18	.0099	.0199	7
136	18.620	15.011	.326	1.867	.12	.0066	.0114	3
137	22.717	200.000	.063	1.735	.22	.0097	.0190	10
138	22.854	19.059	.377	1.879	.23	.0099	.0160	8
139	23.754	13.651	.640	2.413	.28	.0117	.0294	10
140	$							
141	29.724	17.532	1.570	3.436	.32	.0104	.0249	2
142	$							

* Program limits the maximum value of VV2 to 200.

$ Parameters would not converge for these runs.

† VV1, VV3, S, and SM are in feet/second.

TABLE 9.

PARAMETERS OF EMPIRICAL EQUATION OF ρV †

RUN	MM1	MM2	MM3	S	SM	D	DL	L	DEV
1	.4197	.015218	.016691	.021	.0038	.009	.015	8	.172
2	.4511	-.017152	.007603	.018	.0039	.010	.015	1	.196
3	.3274	.076386	.026175	.030	.0027	.007	.012	5	.196
4	.4347	-.053933	-.000449	.031	.0026	.007	-.016	3	.267
5	.3988	.003286	.019459	.028	.0081	.021	.035	8	.241
6	.4178	-.011826	.009203	.026	.0048	.013	.020	8	.256
7	.4103	.078064	.023211	.031	.0048	.011	.018	7	.163
8	.3943	.085522	.021378	.027	.0059	.013	-.024	7	.134
9	.1358	.109901	.003811	.049	.0100	.052	.121	2	-.316
10	.2174	.018329	-.012616	.051	.0126	.058	.095	6	-.241
11	.2068	.022566	.002177	.011	.0037	.018	.037	2	-.017
12	.1927	.039403	.003798	.011	.0040	.018	.043	5	-.036
13	.2694	-.016336	.007916	.027	.0050	.020	-.041	8	.189
14	.2424	.025426	.010973	.026	.0039	.016	.039	1	.177
15	.2010	.019047	.000918	.012	.0040	.019	.040	4	-.056
16	.1968	.022257	.001842	.013	.0037	.018	.030	6	-.071
17	.1877	.017569	-.003347	.013	.0026	.014	.025	9	-.088
18	.1729	.037090	.004256	.012	.0028	.015	.037	2	-.077
19	.1822	.034167	.005256	.012	.0045	.023	.054	2	-.071
20	.1980	.020713	.001714	.010	.0021	.011	.023	9	-.042
21	.1654	.055508	.008447	.013	.0033	.017	.044	8	-.063
22	.1775	.040083	.002880	.013	.0024	.012	-.025	3	-.053
23	.2414	.036540	-.001677	.018	.0062	.026	.057	8	-.128
24	.2970	-.028960	-.013824	.020	.0034	.014	.024	8	-.084
25	.2695	-.006484	-.007939	.020	.0053	.022	.045	10	-.092
26	.2618	.004539	-.006416	.019	.0049	.020	.041	1	-.097
27	.3186	.034900	.001875	.017	.0025	.007	.013	5	-.075
28	.3528	-.000754	-.004093	.018	.0061	.018	.027	10	-.041
29	.4766	.059737	.006438	.018	.0041	.008	-.012	4	-.077
30	.4755	.063206	.006158	.018	.0051	.010	.027	2	-.070
31	.2750	.023928	-.002356	.014	.0053	.020	.050	1	-.038
32	.2933	.000867	-.008333	.015	.0057	.023	.060	10	-.030
33	.2666	.053511	.014523	.026	.0022	.008	.018	9	.032
34	.2517	.068676	.015614	.028	.0057	.020	.048	2	.012
35	.2774	.158531	.030837	.022	.0037	.009	.020	8	.043
36	.3341	.086308	.021649	.023	.0050	.013	.022	3	.082
37	.4940	.044463	.002574	.022	.0078	.016	.040	10	-.025
38	.4854	.050526	.000492	.024	.0047	.009	.016	2	-.034
39	.4725	.049833	.005827	.024	.0030	.006	-.012	3	-.025
40	.4684	.055537	.006913	.022	.0040	.008	.013	8	-.021
41	.4584	.063288	.005790	.020	.0044	.009	.023	9	-.029
42	.4623	.062514	.004518	.018	.0055	.012	.017	1	-.027
43	.2955	.125781	.009553	.017	.0040	.012	.032	1	-.006
44	.2996	.123315	.016445	.019	.0061	.016	.033	9	.013
45	.3112	-.000921	.008015	.017	.0020	.007	.015	3	.064
46	.2878	.026012	.011783	.017	.0040	.014	.025	9	.041
47	.2351	.010070	.008742	.019	.0019	.008	.024	2	.120
48	.2373	.005467	.004298	.019	.0018	.008	-.013	2	.107

TABLE 9, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF ρV

RUN	MM1	MM2	MM3	S	SM	D	DL	L	DEV
49	.2552	-.007231	.002898	.028	.0044	.019	-.034	3	.234
50	.2201	.032302	.018985	.029	.0059	.026	.055	1	.214
51	.2691	-.031141	.000850	.026	.0057	.026	.062	2	.182
52	.2339	.011583	.010787	.028	.0054	.023	-.051	9	.154
53	.2462	.006033	.012148	.030	.0046	.019	.027	3	.201
54	.2286	.023094	.009724	.029	.0058	.025	.045	10	.156
55	.4958	.048956	.005537	.027	.0066	.013	.024	8	-.019
56	.4706	.073720	.005277	.026	.0039	.008	.014	9	-.040
57	.3317	.171359	.024151	.051	.0122	.028	.072	4	-.194
58	.4310	.050220	-.015266	.055	.0072	.016	-.037	3	-.171
59	.4556	.039736	.000198	.020	.0062	.014	.024	1	-.074
60	.4703	.016812	-.004353	.023	.0097	.022	.047	10	-.072
61	.4805	.026056	-.000493	.017	.0032	.007	-.011	2	-.055
62	.5856	-.095235	-.017772	.020	.0132	.029	.066	10	.004
63	.5062	.001604	-.009333	.020	.0065	.014	.030	10	-.048
64	.4877	.019371	-.008708	.022	.0061	.013	.022	2	-.064
65	.4861	.030731	-.000858	.020	.0044	.009	.019	8	-.048
66	.4871	.027882	.003170	.021	.0074	.016	.037	10	-.045
67	.4783	.065265	.001777	.030	.0072	.015	.031	2	-.029
68	.4883	.056408	.003450	.035	.0107	.023	.056	10	-.016
69	.5267	.138777	.028136	.035	.0084	.014	.029	10	.189
70	.4447	.231327	.039693	.037	.0069	.011	-.021	4	.141
71	.3441	.029062	.001088	.012	.0020	.006	.013	9	-.010
72	.3693	-.000252	-.005703	.012	.0044	.013	.028	10	.011
73	.3322	.000065	.008694	.021	.0023	.007	-.012	2	.148
74	.3441	-.011702	.006080	.021	.0034	.011	.020	5	.162
75	.2905	-.037498	.000652	.026	.0023	.009	-.016	6	.289
76	.2677	-.006097	.002256	.026	.0033	.013	.023	2	.266
77	.5508	.001374	-.004999	.024	.0083	.016	-.032	3	.032
78	.4937	.065991	.000374	.019	.0056	.011	.023	2	-.003
79	.2194	.006520	-.001666	.019	.0016	.008	.013	10	.045
80	.1802	.052770	.005258	.013	.0026	.013	.023	1	-.003
81	.6310	.058317	.007015	.053	.0094	.015	.033	7	.270
82	.5866	.112607	.023452	.059	.0158	.025	.048	9	.267
83	.4699	.012347	-.010470	.027	.0044	.010	.019	1	-.092
84	.5218	-.052176	-.022747	.028	.0100	.023	-.040	3	-.074
85	.4205	.054655	-.006174	.026	.0076	.018	.030	1	.010
86	.4349	.038643	-.004026	.024	.0085	.020	.039	10	.026
87	.2800	-.024974	.001308	.029	.0044	.018	.028	3	.271
88	.2333	.034766	.020143	.028	.0041	.016	.033	2	.257
89	.3534	-.028350	-.001318	.031	.0042	.013	-.024	7	.187
90	.3341	-.004217	.003183	.032	.0026	.008	-.016	8	.174
91	.3384	.106298	.023231	.036	.0051	.013	.021	9	.131
92	.3859	.050229	.014220	.035	.0046	.012	.022	1	.159
93	.2418	.015741	.011899	.029	.0050	.020	-.037	9	.226
94	.2497	.011736	.011288	.029	.0040	.016	-.027	4	.253
95	.2190	-.000591	-.003607	.009	.0031	.015	.027	9	.038
96	.2200	-.000437	-.003112	.009	.0027	.014	-.028	1	.046

TABLE 9, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF ρV

RUN	MM1	MM2	MM3	S	SM	D	DL	L	DEV
97	.2077	.013855	-.000496	.010	.0028	.013	-.024	6	.001
98	.2000	.020322	.006818	.015	.0055	.027	.068	4	.003
99	.2167	.017007	-.002228	.012	.0032	.015	.025	8	-.014
100	.2221	.008256	.000799	.011	.0039	.019	.041	10	-.003
101	.3525	.016988	-.001066	.012	.0053	.015	.026	6	.002
102	.3398	.034209	.003206	.009	.0021	.006	.011	2	-.003
103	.3561	.017386	.001808	.009	.0031	.009	.021	10	.006
104	.3329	.041650	.003446	.012	.0017	.005	-.008	8	-.015
105	.4997	.009959	-.000066	.018	.0063	.014	.026	9	-.027
106	.4032	.124979	.018191	.018	.0050	.010	.022	6	-.075
107	.4989	.006291	-.004410	.016	.0057	.012	.025	10	-.029
108	.4632	.051779	.007410	.015	.0049	.010	-.023	3	-.037
109	.2676	-.022025	.003141	.030	.0047	.020	-.027	9	.210
110	.2119	.050337	.017816	.031	.0019	.008	-.015	9	.173
111	.2251	.032154	.015592	.030	.0028	.012	.026	3	.183
112	.2688	-.012752	.004225	.030	.0049	.020	.041	1	.243
113	.2505	.009843	.009572	.029	.0021	.009	-.014	8	.207
114	.2382	.023098	.012617	.032	.0063	.027	.057	1	.191
115	.4664	.076330	.003502	.019	.0085	.018	.046	1	-.010
116	.4631	.080495	.007538	.019	.0088	.018	.030	10	-.012
117	.1568	.140595	.016450	.028	.0035	.014	.024	10	.117
118	.1909	.102711	.010545	.035	.0069	.026	-.047	2	.158
119	.1743	.125971	.011107	.051	.0091	.037	.086	2	.094
120	.2259	.070436	.003724	.040	.0070	.027	.050	9	.172
121	.2022	.094102	.011334	.043	.0047	.017	.032	8	.186
122	.1819	.118271	.011532	.038	.0080	.031	.062	3	.142
123	.2086	.172125	.016396	.037	.0083	.028	-.051	10	.108
124	.2061	.180121	.021021	.034	.0071	.021	-.043	2	.124
125	.2441	.153866	.001940	.064	.0115	.034	.066	8	.147
126	.1528	.249250	.024075	.058	.0061	.018	.038	10	.052
127	.4338	.252693	.045526	.054	.0077	.013	.027	3	.091
128	.5147	.163006	.032889	.054	.0053	.009	.017	1	.138
129	.4305	.151470	.017156	.086	.0270	.052	.086	9	.181
130	.3091	.296133	.047159	.077	.0141	.026	.049	3	.130
131	.2971	.037176	.019384	.038	.0057	.019	.033	6	.243
132	.3740	-.056644	-.005394	.039	.0046	.015	-.027	8	.286
133	.2609	.042677	.013186	.033	.0036	.013	.020	4	.199
134	.2972	-.001789	.006840	.034	.0063	.023	-.040	9	.236
135	.3028	.070569	.017582	.034	.0073	.023	.057	1	.090
136	.3138	.064341	.013013	.032	.0040	.012	-.022	1	.108
137	.3915	.066551	.008982	.032	.0034	.008	-.015	2	.076
138	.3824	.081446	.014408	.031	.0036	.008	-.014	4	.086
139	.3201	.159286	.023191	.041	.0038	.009	.016	3	.030
140	.3636	.106059	.009677	.039	.0058	.014	.028	1	.049
141	.3246	.246010	.017692	.052	.0105	.021	.032	8	-.025
142	.4076	.158445	.004275	.050	.0064	.013	.023	10	.034

† MM1, MM2, MM3, S, and SM are in pounds/second-inch^2.
DEV is in pounds/second.

TABLE 10.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE BRIDGE VOLTAGE †

RUN	WW1	WW2	WW3	S	SM	D	DL	L
1	.8840	7.1933	7.5337	.0625	.0130	.0016	.0037	10
2	.7907	6.7207	7.6494	.0602	.0079	.0009	.0018	1
3	.6594	6.5425	6.7704	.0636	.0076	.0010	.0018	3
4	.7195	6.5236	6.7094	.0656	.0116	.0016	.0027	10
5	.6650	6.4428	7.4471	.0687	.0048	.0006	.0013	10
6	.7859	5.8165	7.3587	.0735	.0076	.0010	.0027	1
7	.6705	5.7502	7.9039	.0787	.0077	.0009	.0019	9
8	1.1072	6.7078	7.4466	.0810	.0111	.0013	.0023	2
9	.4308	2.6397	8.0390	.0582	.0056	.0007	.0012	8
10	.4235	2.3751	8.0622	.0569	.0100	.0012	-.0021	10
11	.5131	3.0357	7.3609	.0502	.0151	.0019	.0033	3
12	.4444	2.8231	7.4258	.0506	.0147	.0019	-.0038	1
13	.7459	8.3559	7.1643	.0644	.0104	.0013	.0031	10
14	.6459	8.1397	7.2766	.0582	.0064	.0008	.0015	2
15	.4954	2.7578	7.7344	.0577	.0105	.0013	.0031	2
16	.5177	3.0059	7.7172	.0593	.0117	.0014	.0031	8
17	.4818	2.4603	7.6953	.0568	.0093	.0012	-.0025	10
18	.3915	2.3218	7.7698	.0576	.0121	.0015	-.0031	9
19	.4735	2.8011	7.6825	.0590	.0132	.0016	.0029	10
20	.4381	2.3645	7.7374	.0576	.0064	.0008	.0015	3
21	.4197	2.6333	7.6308	.0560	.0129	.0016	-.0027	2
22	.4159	2.4441	7.6196	.0518	.0068	.0009	.0019	7
23	.4899	2.7161	8.0952	.0613	.0093	.0011	.0024	8
24	.4258	2.4696	8.1642	.0600	.0069	.0008	.0015	9
25	.4507	2.6583	8.0729	.0596	.0123	.0015	.0024	8
26	.5060	2.8160	8.0259	.0653	.0094	.0011	.0017	3
27	.4205	2.0187	7.9393	.0665	.0186	.0023	-.0053	2
28	.5923	3.0556	7.6930	.0747	.0382	.0047	-.0081	1
29	.5365	2.7448	7.9862	.0729	.0375	.0045	-.0078	1
30	.3747	1.7960	8.0477	.0683	.0256	.0031	.0046	10
31	.4336	2.4348	7.8874	.0601	.0103	.0013	-.0031	2
32	.5258	2.7973	7.7773	.0596	.0113	.0014	-.0033	1
33	.6484	9.1270	7.4946	.0570	.0098	.0012	.0028	10
34	.9489	9.3640	7.1789	.0581	.0092	.0011	.0022	1
35	.8209	5.7130	7.5830	.0511	.0136	.0016	.0031	10
36	.8425	7.0798	7.5247	.0516	.0067	.0008	.0015	10
37	.5551	2.7673	8.2009	.0680	.0278	.0032	.0053	7
38	.4565	2.2863	8.2932	.0589	.0056	.0006	.0011	4
39	.4938	2.6203	8.5343	.0620	.0119	.0013	.0027	9
40	.5524	2.9439	8.4404	.0635	.0174	.0020	.0038	7
41	.5725	2.9310	8.5353	.0651	.0175	.0019	-.0030	1
42	.4963	2.3098	8.5902	.0640	.0057	.0006	.0015	3
43	.6093	3.1305	8.2279	.0507	.0073	.0008	.0014	9
44	.5702	2.9731	8.2479	.0533	.0189	.0022	.0040	8
45	.9973	9.1565	7.2673	.0581	.0115	.0014	.0028	9
46	.6505	7.1679	7.6127	.0536	.0088	.0011	.0022	10
47	.7263	8.9980	7.5216	.0596	.0075	.0009	.0020	10
48	.6410	7.4786	7.5939	.0658	.0091	.0011	.0024	8

TABLE 10, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE BRIDGE VOLTAGE

RUN	WW1	WW2	WW3	S	SM	D	DL	L
49	.9507	8.4841	7.1866	.0711	.0102	.0013	.0036	10
50	.9133	9.8235	7.2272	.0643	.0080	.0010	.0018	2
51	.6744	8.9407	7.4569	.0624	.0073	.0009	.0020	1
52	.8202	8.3514	7.3391	.0679	.0088	.0011	.0024	1
53	.6845	7.1409	7.4652	.0719	.0092	.0011	.0024	1
54	.7427	9.2175	7.3830	.0619	.0081	.0010	.0018	6
55	.6082	3.2090	7.8502	.0627	.0136	.0016	.0032	8
56	.4859	2.1851	7.9676	.0691	.0294	.0035	.0057	10
57	.2959	1.7926	9.0276	.0666	.0210	.0023	.0049	1
58	.5423	2.3247	8.7805	.0725	.0101	.0011	.0020	8
59	.4622	2.2462	8.5398	.0636	.0041	.0005	.0012	9
60	.5332	2.5882	8.4423	.0635	.0099	.0011	.0022	8
61	.4983	2.3993	8.4923	.0614	.0094	.0011	-.0026	2
62	.6768	3.8248	8.2778	.0763	.0439	.0050	-.0099	1
63	.5752	2.8056	8.4353	.0675	.0132	.0015	.0028	7
64	.4734	2.0865	8.5491	.0635	.0045	.0005	.0010	8
65	.4980	2.3110	8.6332	.0684	.0093	.0010	.0021	8
66	.6178	2.8022	8.4996	.0681	.0160	.0018	-.0034	1
67	.5187	2.4202	8.3317	.0600	.0071	.0008	.0013	3
68	.5914	2.7614	8.2472	.0632	.0233	.0027	.0048	8
69	1.5643	5.6562	7.1180	.1101	.0370	.0044	-.0094	1
70	.8916	4.5598	7.7503	.1076	.0390	.0046	.0082	10
71	.4138	1.9992	7.9895	.0621	.0118	.0014	.0027	10
72	.5719	3.0903	7.7833	.0652	.0247	.0030	-.0057	1
73	.7886	6.3689	7.4079	.0591	.0163	.0020	-.0034	4
74	.6653	7.6254	7.5256	.0517	.0072	.0009	.0015	10
75	.8053	8.8021	7.2732	.0649	.0077	.0010	.0018	1
76	.7502	8.9473	7.3161	.0619	.0068	.0008	.0018	10
77	.7522	3.3137	6.9065	.0901	.0549	.0073	-.0123	1
78	.3653	1.8151	7.1244	.0824	.0412	.0056	.0108	10
79	.4590	3.2096	7.3913	.0483	.0112	.0014	-.0028	1
80	.4417	2.8922	7.4195	.0492	.0080	.0010	-.0022	2
81	.9571	6.5008	6.9098	.1037	.0354	.0045	.0090	10
82	1.1710	5.4315	6.5852	.1055	.0472	.0061	-.0107	1
83	.3836	1.5093	7.9891	.0883	.0562	.0068	.0120	10
84	.7593	3.0495	7.4360	.0910	.0591	.0073	-.0135	1
85	.4831	2.0319	6.9215	.0669	.0154	.0021	.0047	10
86	.6116	2.4805	6.7176	.0724	.0363	.0050	-.0104	1
87	.9747	9.3902	6.8618	.0592	.0117	.0015	.0030	10
88	.2749	8.9876	7.5300	.0548	.0141	.0018	.0045	10
89	.9582	9.1801	6.7100	.0662	.0155	.0020	.0046	10
90	.7426	6.8060	6.8892	.0694	.0171	.0022	-.0057	4
91	.8395	4.9979	7.2308	.0802	.0291	.0036	-.0070	4
92	1.0423	7.6820	6.9413	.0737	.0234	.0029	.0049	9
93	.5641	6.2704	6.9400	.0701	.0237	.0032	.0064	10
94	.9970	7.1021	6.4304	.0775	.0331	.0045	-.0078	1
95	.5080	2.6821	6.6830	.0625	.0196	.0028	-.0058	1
96	.4299	2.7540	6.7510	.0592	.0110	.0015	.0029	9

TABLE 10, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE BRIDGE VOLTAGE

RUN	WW1	WW2	WW3	S	SM	D	DL	L
97	.5641	2.9521	7.3960	.0635	.0123	.0016	-.0027	10
98	.4683	2.5038	7.4834	.0612	.0076	.0010	.0020	8
99	.4052	2.0215	7.9143	.0654	.0073	.0009	.0016	10
100	.5248	2.7011	7.7728	.0681	.0169	.0021	.0038	7
101	.4832	2.5163	7.9762	.0640	.0128	.0015	-.0030	4
102	.4277	1.8840	8.0664	.0648	.0108	.0013	.0025	9
103	.4705	2.8131	7.9582	.0595	.0161	.0019	-.0039	1
104	.4508	2.3518	7.9952	.0613	.0146	.0018	-.0036	2
105	.5684	2.6486	8.4724	.0691	.0216	.0024	-.0042	1
106	.5808	2.4917	8.4510	.0712	.0182	.0021	.0041	9
107	.5252	2.5148	8.6519	.0716	.0152	.0017	.0035	7
108	.4737	2.1992	8.7043	.0669	.0168	.0018	.0030	9
109	.7000	6.4869	7.3742	.0707	.0185	.0023	-.0057	4
110	.7439	7.2682	7.3372	.0665	.0157	.0019	.0033	10
111	.6705	7.3962	7.3937	.0676	.0141	.0017	-.0045	4
112	.7711	7.0252	7.3034	.0657	.0107	.0013	-.0021	6
113	.8872	7.5458	7.1750	.0694	.0114	.0014	.0027	10
114	.7818	8.3863	7.2830	.0644	.0085	.0011	.0023	10
115	.5913	2.5778	8.0250	.0689	.0192	.0023	-.0052	2
116	.6856	2.7977	7.8757	.0750	.0364	.0043	-.0075	1
117	1.6215	5.0382	6.7654	.1206	.0407	.0049	-.0087	4
118	1.2920	4.1315	7.0884	.1177	.0353	.0043	.0077	9
119	.9494	3.1221	6.7395	.1199	.0373	.0049	.0105	7
120	.8572	3.2376	6.7535	.1211	.0391	.0052	.0102	8
121	1.1584	4.2890	7.2273	.1181	.0374	.0045	.0079	8
122	1.6714	6.0736	6.6358	.1158	.0168	.0021	.0042	1
123	1.2536	5.0097	7.4250	.1152	.0180	.0021	.0052	9
124	1.0405	3.9214	7.6467	.1178	.0372	.0043	.0064	7
125	.9070	3.9048	7.6827	.1167	.0337	.0039	.0074	9
126	1.1102	4.2548	7.4156	.1243	.0345	.0041	.0075	7
127	.9209	3.6510	7.6247	.1044	.0469	.0056	.0095	8
128	.7584	3.2186	7.6401	.1097	.0435	.0053	.0103	9
129	1.4650	6.1382	7.4933	.1081	.0254	.0029	.0062	10
130	1.1959	6.4251	7.7082	.1076	.0266	.0030	.0070	10
131	.6262	7.1170	7.6535	.0757	.0157	.0019	-.0054	4
132	.8169	8.2584	7.4610	.0719	.0074	.0009	-.0014	8
133	.9183	8.4321	7.4467	.0654	.0076	.0009	.0026	10
134	1.0276	7.8224	7.3590	.0685	.0092	.0011	.0027	1
135	.9647	7.1862	7.5868	.0662	.0090	.0011	.0021	10
136	.8863	7.4427	7.6384	.0637	.0074	.0009	.0025	10
137	1.0532	6.2617	7.4754	.0758	.0135	.0016	-.0027	2
138	.9565	6.4448	7.5554	.0718	.0099	.0012	.0022	1
139	1.0659	6.8751	7.3713	.0733	.0080	.0010	.0021	10
140	1.0693	6.6147	7.3611	.0738	.0137	.0016	.0040	10
141	.8299	4.8217	7.8307	.0878	.0321	.0037	.0060	10
142	.9919	5.4383	7.6242	.0806	.0230	.0027	-.0045	4

† WW1, WW3, S, and SM are in volts.

TABLE 11.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE RMS †

RUN	RR1	RR2	RR3	RR4	S	SM	D	DL	L
1	227.02	-257.22	-49.15	-12.05	8.46	4.53	.1466	.2680	1
2	206.04	-232.54	-43.66	-9.13	6.17	1.98	.0884	-.1362	6
3	211.43	-235.15	-44.10	-9.93	6.44	2.92	.1025	-.1432	6
4	219.48	-244.16	-45.95	-10.08	10.11	6.40	.1850	.4623	1
5	273.51	-309.20	-62.38	-15.69	9.50	5.04	.1630	.3503	3
6	291.75	-327.26	-59.36	-11.86	8.61	3.23	.0977	.1627	8
7	337.23	-368.98	-61.97	-13.68	8.21	3.17	.0640	-.1355	3
8	423.21	-475.55	-89.89	-20.83	12.05	5.58	.1291	-.2335	5
9	66.28	-68.03	-9.33	-3.29	6.79	1.57	.1272	-.1837	8
10	69.06	-71.58	-11.06	-4.19	6.55	1.49	.1107	.1798	10
11	47.79	-50.72	-6.48	-2.04	5.38	.59	.1007	-.1382	4
12	74.32	-83.53	-14.74	-5.01	7.09	1.84	.3800	.8914	3
13	256.89	-294.36	-62.20	-16.49	9.30	5.38	.2157	.3302	1
14	220.17	-249.59	-51.11	-13.31	7.12	3.27	.1545	-.2401	6
15	104.84	-113.28	-17.82	-4.66	9.68	3.09	.1839	.4076	3
16	90.59	-96.85	-15.18	-5.42	8.48	1.81	.1349	.2804	4
17	99.36	-107.98	-16.49	-4.49	8.92	2.34	.1693	.2553	8
18	77.29	-80.31	-9.59	-1.84	8.30	1.59	.1333	-.2819	7
19	138.15	-155.65	-29.93	-10.12	9.03	1.85	.1775	-.4233	5
20	120.29	-133.31	-22.50	-5.98	8.62	2.52	.1682	-.3320	6
21	64.37	-68.74	-9.90	-2.95	7.16	.89	.0950	-.1679	6
22	66.86	-71.80	-9.75	-2.35	7.22	1.63	.1223	-.2278	5
23	90.71	-93.20	-12.19	-3.19	8.68	1.96	.0936	-.1493	9
24	86.82	-89.29	-12.93	-3.71	7.09	.95	.0515	-.0937	2
25	80.23	-82.08	-10.65	-3.30	8.34	2.45	.1270	.2099	2
26	77.59	-78.21	-9.81	-2.55	7.66	.96	.0568	-.0955	8
27	100.51	-101.23	-12.99	-4.66	7.80	1.34	.0813	.1415	4
28	116.39	-119.98	-18.56	-6.63	9.11	3.78	.1637	.2191	1
29	88.49	-80.99	-4.99	-.43	7.82	1.66	.0518	.0873	3
30	77.95	-69.13	-2.19	-1.21	7.57	1.37	.0523	-.1047	9
31	89.48	-94.28	-11.93	-2.29	7.50	.91	.0572	-.0942	3
32	96.66	-102.39	-14.73	-4.48	8.40	2.17	.0973	.1815	1
33	198.84	-223.68	-44.99	-10.17	6.18	1.75	.0973	-.1896	3
34	199.08	-222.76	-39.74	-6.49	8.59	2.73	.0746	-.1721	2
35	204.16	-231.00	-40.69	-7.14	6.94	1.92	.0825	-.1724	4
36	240.46	-274.71	-52.80	-10.76	8.69	4.04	.1240	-.2311	8
37	131.85	-136.49	-18.16	-5.73	9.60	3.46	.1892	.3636	3
38	113.69	-114.46	-12.92	-3.70	7.87	1.45	.0697	.1264	7
39	130.74	-134.04	-17.09	-6.11	7.85	1.79	.0742	.1455	8
40	121.94	-123.02	-13.64	-3.96	8.31	2.12	.1049	.1985	3
41	117.13	-115.96	-12.13	-3.26	9.29	2.62	.0841	-.1573	6
42	115.10	-110.89	-7.25	-1.02	8.55	2.44	.1006	.1603	7
43	123.67	-131.66	-19.85	-7.53	7.19	1.47	.0899	-.2140	6
44	102.19	-105.62	-11.10	-1.54	7.66	3.09	.1873	.4025	3
45	213.39	-243.24	-49.57	-12.96	8.97	3.48	.1607	.2848	3
46	172.42	-192.87	-37.16	-9.44	7.16	1.96	.1174	-.1820	6
47	236.32	-263.64	-51.81	-12.74	7.05	2.54	.0996	.1882	8
48	299.23	-341.80	-71.90	-18.57	9.78	3.29	.1263	-.2075	5

TABLE 11, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE RMS

RUN	RR1	RR2	RR3	RR4	S	SM	D	DL	L
49	371.41	-426.10	-88.83	-22.68	12.43	6.34	.1833	-.2972	8
50	305.68	-346.48	-71.98	-19.12	7.94	2.88	.0987	-.1529	6
51	282.68	-317.70	-64.92	-17.20	10.92	3.29	.1432	-.2539	5
52	329.23	-372.20	-72.99	-17.79	9.12	3.76	.1023	-.1846	6
53	338.26	-382.25	-75.35	-15.94	11.71	7.39	.1744	.3302	10
54	273.68	-307.23	-62.00	-15.70	8.97	2.86	.1299	.2328	7
55	86.21	-80.56	-4.60	-.50	7.93	1.60	.1044	.2947	3
56	97.00	-93.29	-8.48	-4.48	7.85	1.27	.0813	.1387	7
57	45.43	-28.01	6.88	1.74	7.92	2.12	.0903	.1916	6
58	125.16	-121.97	-14.44	-6.10	8.22	1.55	.0494	-.0867	6
59	116.23	-118.95	-17.46	-5.89	7.00	1.48	.0625	.1088	8
60	115.76	-117.98	-15.77	-4.28	7.99	1.94	.0726	-.1402	8
61	97.91	-96.78	-12.17	-3.27	7.02	.95	.0287	-.0435	1
62	106.22	-107.38	-15.96	-4.61	10.29	6.99	.3357	.6318	1
63	123.45	-126.95	-18.55	-6.25	8.58	1.81	.0844	-.1446	7
64	97.64	-94.24	-9.51	-3.15	7.74	1.57	.0506	.0908	10
65	137.11	-142.27	-22.12	-6.81	8.28	2.40	.0815	-.1238	2
66	123.57	-125.31	-17.64	-6.16	8.24	3.21	.1450	.2553	4
67	62.00	-52.89	1.54	.33	6.97	2.33	.0840	-.1319	9
68	95.60	-95.44	-10.97	-3.26	6.90	1.83	.1324	.2764	3
69	425.82	-420.71	-23.44	15.80	21.24	14.38	.1171	-.2174	7
70	412.58	-403.47	-15.84	16.92	14.70	6.78	.0909	.1740	6
71	57.82	-51.95	-1.11	-.20	7.58	2.19	.1151	.2225	4
72	83.90	-84.75	-10.72	-4.04	7.53	2.48	.1553	.2508	4
73	188.36	-214.09	-41.30	-9.02	6.77	2.75	.1083	.1768	1
74	156.61	-175.69	-34.16	-7.60	5.15	1.63	.1180	-.2006	9
75	249.78	-281.63	-56.68	-15.80	8.06	2.97	.1246	.2224	4
76	226.03	-253.26	-50.36	-12.87	8.55	2.47	.1126	.1911	7
77	89.03	-78.80	-1.80	-.76	8.44	3.14	.1164	-.2153	7
78	98.86	-92.87	-5.47	-2.02	7.95	.82	.0414	-.0841	6
79	57.24	-62.66	-10.00	-2.54	6.35	.56	.1030	-.2189	5
80	50.50	-53.62	-6.30	-.98	6.61	.67	.0705	-.1397	8
81	448.93	-463.77	-52.00	-2.09	13.10	6.41	.0883	-.1340	8
82	404.97	-416.72	-44.04	.11	13.27	8.07	.0721	.1381	1
83	96.83	-88.38	-7.79	-4.86	7.99	1.99	.0817	.1642	7
84	88.93	-78.88	-4.75	-2.08	8.30	3.32	.1024	.2055	1
85	54.50	-42.15	4.93	2.40	7.99	1.45	.0966	-.2163	5
86	76.65	-70.30	-2.35	-1.34	7.59	1.32	.0694	.1208	4
87	204.45	-231.95	-47.68	-11.94	7.63	1.73	.1091	-.2103	5
88	146.60	-160.71	-29.97	-6.00	6.09	1.47	.0860	.1962	4
89	233.23	-257.94	-43.80	-8.45	7.41	1.67	.0630	.1000	4
90	237.21	-262.37	-46.32	-10.18	7.56	1.45	.0814	-.1612	5
91	242.24	-260.96	-36.85	-5.35	9.20	1.36	.0252	-.0522	1
92	247.43	-268.26	-40.41	-4.99	8.25	1.71	.0567	-.1019	3
93	246.30	-270.98	-48.33	-9.00	7.57	2.45	.0982	.1993	8
94	261.26	-288.65	-51.74	-11.01	9.84	5.86	.1161	.2734	1
95	70.41	-72.89	-11.01	-3.43	8.49	2.47	.1812	.3642	3
96	50.92	-48.72	-5.27	-1.58	7.43	.95	.0747	.1736	4

TABLE 11, CONTINUED.

PARAMETERS OF EMPIRICAL EQUATION OF HOTWIRE RMS

RUN	RR1	RR2	RR3	RR4	S	SM	D	DL	L
97	71.12	-73.75	-9.60	-2.41	7.72	1.69	.1072	-.1923	5
98	70.98	-73.61	-10.36	-2.59	8.70	1.74	.1074	.2180	1
99	60.18	-57.17	-5.03	-1.42	9.05	1.64	.1006	-.1449	4
100	81.61	-83.56	-10.36	-2.82	9.77	2.36	.1822	.4308	4
101	90.38	-94.72	-13.52	-4.18	8.05	1.80	.1026	.1440	1
102	74.93	-74.73	-8.43	-2.70	6.79	1.35	.0719	-.1241	4
103	79.86	-81.64	-11.16	-4.18	6.63	1.23	.0862	.1817	3
104	82.50	-85.42	-12.45	-4.39	6.76	1.07	.0798	-.1531	6
105	110.74	-110.35	-13.31	-4.14	7.77	2.38	.1045	.1559	3
106	106.89	-103.32	-8.39	-2.43	8.01	1.42	.0713	.1425	8
107	133.59	-137.44	-19.73	-5.91	8.44	1.97	.0809	.1680	3
108	90.30	-84.86	-5.97	-1.88	7.10	1.98	.0688	.1027	5
109	327.04	-375.67	-81.06	-22.20	9.74	4.31	.1679	.2934	3
110	244.30	-273.83	-53.23	-14.08	7.49	2.54	.1212	-.2163	6
111	291.88	-333.23	-71.85	-20.83	9.97	3.41	.1770	-.3035	5
112	303.08	-345.44	-68.10	-16.03	7.65	3.59	.1143	-.1740	6
113	301.83	-344.27	-69.43	-14.97	11.00	5.68	.1714	.3092	3
114	258.66	-291.57	-59.32	-14.97	7.30	2.43	.1065	.2032	4
115	90.41	-84.62	-4.29	.17	8.35	1.94	.0839	-.1614	4
116	100.42	-96.33	-6.54	-.62	8.22	2.72	.1304	.2063	3
117	216.01	-230.53	-30.89	-1.19	12.81	2.11	.0587	.0928	5
118	221.95	-238.49	-34.00	-4.50	12.22	2.08	.0505	-.0907	7
119	163.97	-167.85	-20.40	-1.44	12.16	1.78	.0358	.0693	9
120	176.28	-182.57	-23.56	-1.94	11.87	1.58	.0469	-.1353	4
121	213.10	-230.54	-35.07	-5.50	13.97	1.27	.0638	.1247	4
122	237.03	-257.66	-39.39	-4.38	14.34	4.24	.0972	-.1816	4
123	206.07	-220.18	-29.87	-3.48	12.03	1.68	.0458	.0797	6
124	219.72	-239.45	-37.88	-6.12	13.16	1.45	.0359	.0601	8
125	194.77	-207.79	-31.57	-4.32	11.11	1.36	.0541	-.1313	4
126	185.99	-194.04	-23.21	-.65	12.31	2.02	.0435	-.0691	3
127	159.00	-174.52	-24.23	-1.57	9.86	2.29	.1232	-.2358	3
128	167.22	-181.88	-23.95	-2.44	10.48	1.50	.0683	-.1536	8
129	185.38	-201.05	-29.65	-3.48	11.11	1.65	.0464	-.0992	8
130	179.62	-193.40	-29.62	-4.46	10.46	1.65	.0691	-.1165	6
131	98.04	-114.70	-23.92	-6.69	8.46	1.20	.3372	.6806	3
132	103.74	-121.06	-24.56	-5.97	7.08	1.13	.1716	-.3592	6
133	308.66	-351.85	-72.69	-19.65	8.57	3.99	.1548	.2357	3
134	292.46	-331.28	-65.48	-15.69	7.26	2.53	.1066	-.1848	6
135	255.82	-288.31	-51.00	-9.14	8.07	2.75	.0829	.1687	7
136	262.25	-298.23	-58.45	-14.05	7.89	2.72	.1290	-.2041	5
137	298.25	-326.76	-52.55	-8.70	8.96	3.02	.0816	-.1394	9
138	302.53	-336.03	-58.81	-12.60	8.51	2.82	.0800	-.1635	2
139	298.96	-328.20	-52.73	-9.85	9.15	2.02	.0331	.0582	6
140	312.22	-342.81	-54.70	-7.26	8.33	2.62	.0789	-.1705	8
141	369.90	-397.60	-53.08	-3.74	10.55	4.31	.0887	-.1805	8
142	317.52	-336.51	-43.49	-2.41	9.65	3.07	.0472	-.0979	7

† RR1, RR2, RR3, RR4, S, and SM are in millivolts.

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