EVALUATION OF A TEMPERATURE COMPENSATED THERMISTOR ANEMOMETER

by

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Chapter 1

DEVELOPMENT OF A THERMISTOR ANEMOMETER

Introduction

This thesis investigates the performance of a previously designed and tested instrument and attempts to explain and to consequently eliminate inadequacies uncovered by the initial investigation of the instrument's performance. The instrument under scrutiny is a temperature-compensated thermistor anemometer that evolved out of a thesis entitled, "A Thermistor Anemometer For Measurement of Air Velocity" by Mr. William A. Flanders (1).

The main purpose for the construction of this type of an anemometer is to measure air speed in unrestricted spaces, or more specifically in living quarters such as offices, public meeting places, and homes and apartments. Air speed measurements in these types of spaces require that the instrument must be portable, must accurately perform in temperature ranges comparable to those encountered by humans in various types of living conditions, and must be capable of measuring air speeds comparable to those experienced in ventilation and airconditioning of these spaces. Mr. Flanders, in his thesis, used an ambient temperature range of 40°F to 110°F as a basis for his design calculations. A velocity range of 10 to 1000 feet per minute was determined to be adequate for fully covering all feasible air speeds encountered in the field. As far as being portable, the final instrument could be easily hand-held while taking measurements.

Another desirable feature that should be incorporated in the design of such an anemometer is insensitivity to changes in the direction of air flow. Non-directional behavior of the anemometer is desirable because a point measurement is desired in a space. The air speed at this point is being affected by a large number of variables. Placement of supply and return ducts, movement of the occupants, and temperature gradients in the space all combine to affect air currents. If non-directional qualities are designed into the anemometer then it becomes unnecessary to evaluate these variables. Measurements of air speed should not be encumbered by always worrying about the orientation of the anemometer. Preliminary studies of this subject by Mr. Flanders indicated that the problem of directional sensitivity was minimal. This thesis will not attempt to delve into this area for two reasons. First, there seems to be no unsolvable problems associated with the present probe configuration although this is not an excellent reason by itself. Secondly, major problems have appeared in other areas whose solution must be found before the temperature-compensated anemometer can perform properly.

In the final evaluation of the anemometer, success can only be realized when it can be determined that the anemometer is ready for manufacturing. This conclusion is inevitably reached each time the purpose for undertaking the research, design, and construction of the anemometer is examined. An inexpensive (relatively), temperature-compensated, self-balancing, non-directional, fast read-out, portable anemometer is not commercially available.

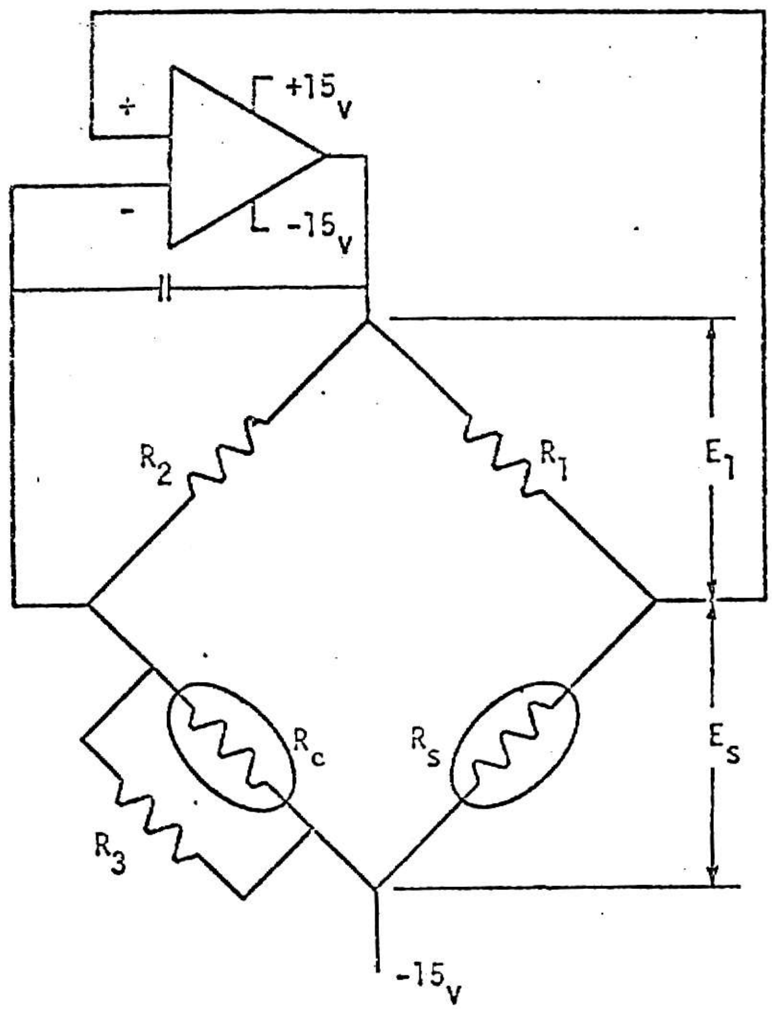
To analyze the feasibility of manufacturing the anemometer the sensitivity of the error in the air speed with respect to the error in the individual circuit components was considered to be the crucial factor. If this sensitivity was unreasonably high, construction of the anemometer on anything other than a limited, custom-built basis would have to be ruled out. The objectives of this thesis are rooted in developing a component and system error analysis.

The major objective of this thesis is the evaluation of the feasibility of manufacturing the proposed temperature-compensated thermistor anemometer. The secondary objectives that must be accomplished before the major objective can be adequately analysed are:

1. Development of a component and system error analysis
2. Improvement of the method of component sizing
3. Determination of an appropriate self-heat
4. Investigation of required thermistor performance; determination of "ideal" temperature-resistance curves
5. Evaluation of the instrument on the basis of allowable and/or reasonable component error
6. Re-evaluation of the validity of the describing heat transfer equation based on new experimental observations.

Background

The thermistor anemometer was designed to measure air speeds from 10 feet per minute up to 1000 feet per minute in an environmental temperature of approximately 50° F to 100°F. The measuring circuit for this device consisted of a 4-leg resistance bridge in the feedback circuit of an operational amplifier. The circuit for the anemometer is shown in Figure 1. The sensing thermistor and the temperature-compensating thermistor are mounted on a probe that is placed in the air stream. The fixed resistances, R_1, R_2, and R_3, are designed to cause self-heating of the sensing thermistor to a temperature above the ambient air temperature. Air flow across the



R_s - Sensing thermistor

R_c - Temperature compensating thermistor

R_3 - Temperature compensating resistor

E_1 - Voltage across resistor R_1

E_s - Voltage across the sensing thermistor

FIGURE 1

ANEMOMETER CIRCUIT

sensing thermistor bead causes heat to be dissipated at a rate proportional to the air speed across the probe. However, the bridge is automatically held at a predetermined balance point, forcing the sensing thermistor to maintain a constant temperature elevation regardless of the heat loss to the air stream. The I^2R power required to maintain this temperature is, therefore, an indicator of the air speed. The compensating thermistor in the opposite leg of the bridge provides temperature compensation for changes in the ambient temperature of the air stream by maintaining a constant power dissipation in the sensing thermistor for a specific velocity regardless of the changes in the ambient temperature.

To improve the overall accuracy of the anemometer, two subdivisions of the original velocity range were deemed necessary. The resistor, R_1, was held constant for both ranges at 2500 ohms while the resistors R_2 and R_3 were sized for the low range and the high range on a separate basis to improve the accuracy of the anemometer. The low range circuit was designed to measure air speeds in the range of 10 feet per minute to 100 feet per minute. The high range circuit was designed to measure air speeds between 100 feet per minute and 1000 feet per minute. The following resistance values were used in each circuit:

Low Range	High Range
R_2 = 18,677.5 ohms	R_2 = 18,707.5 ohms
R_3 = 149,460 ohms	R_3 = 154,790 ohms

The power dissipated by the sensing thermistor was calculated using,

$$P = E_1 E_s / R_1 . \quad [1]$$

The voltage across the resistor R_1 is designated E_1 and the voltage across the sensing thermistor is designated E_s. Measurements of the power dissipation were taken by Mr. Flanders at ambient temperatures of 65°F, 80°F, and 100°F. Reference air velocities were provided by an induced draft wind tunnel. Figure 2 graphically indicates how the error between the predicted and the experimental values is distributed throughout the instrument's range. Figures 3 and 4 compare the experimental results and theoretical results for low and high speed ranges. It should be noted at this point that the sensing

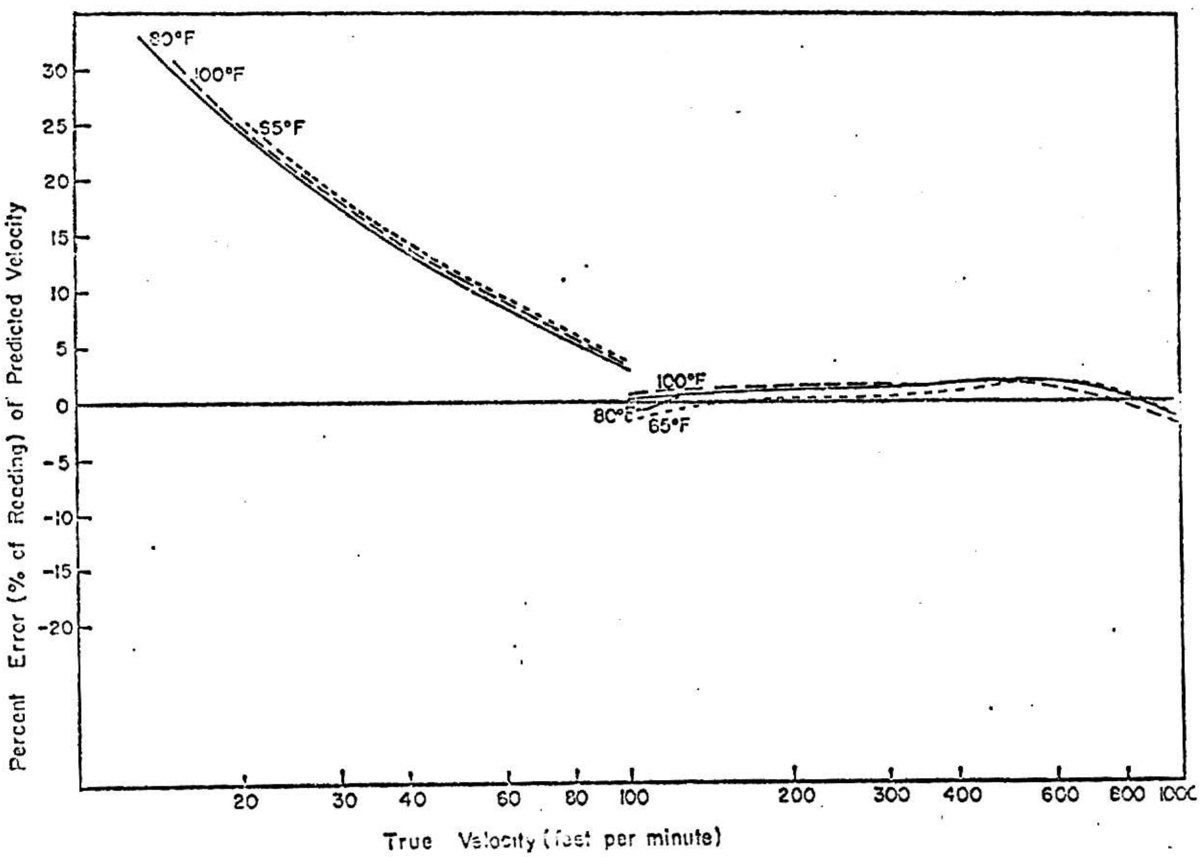


Figure 2

Errors in Predicted Velocity

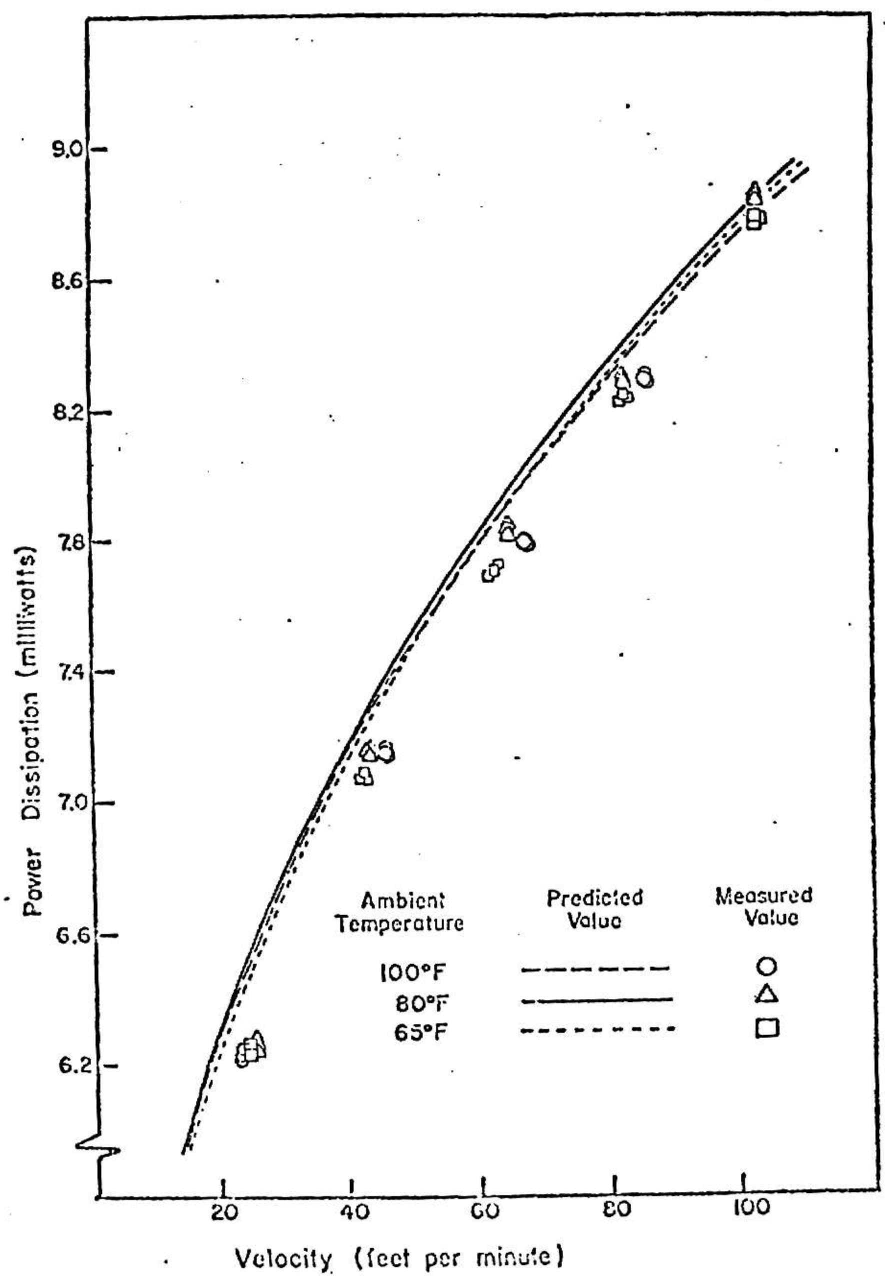


Figure 3

Experimental Results for the Low Range

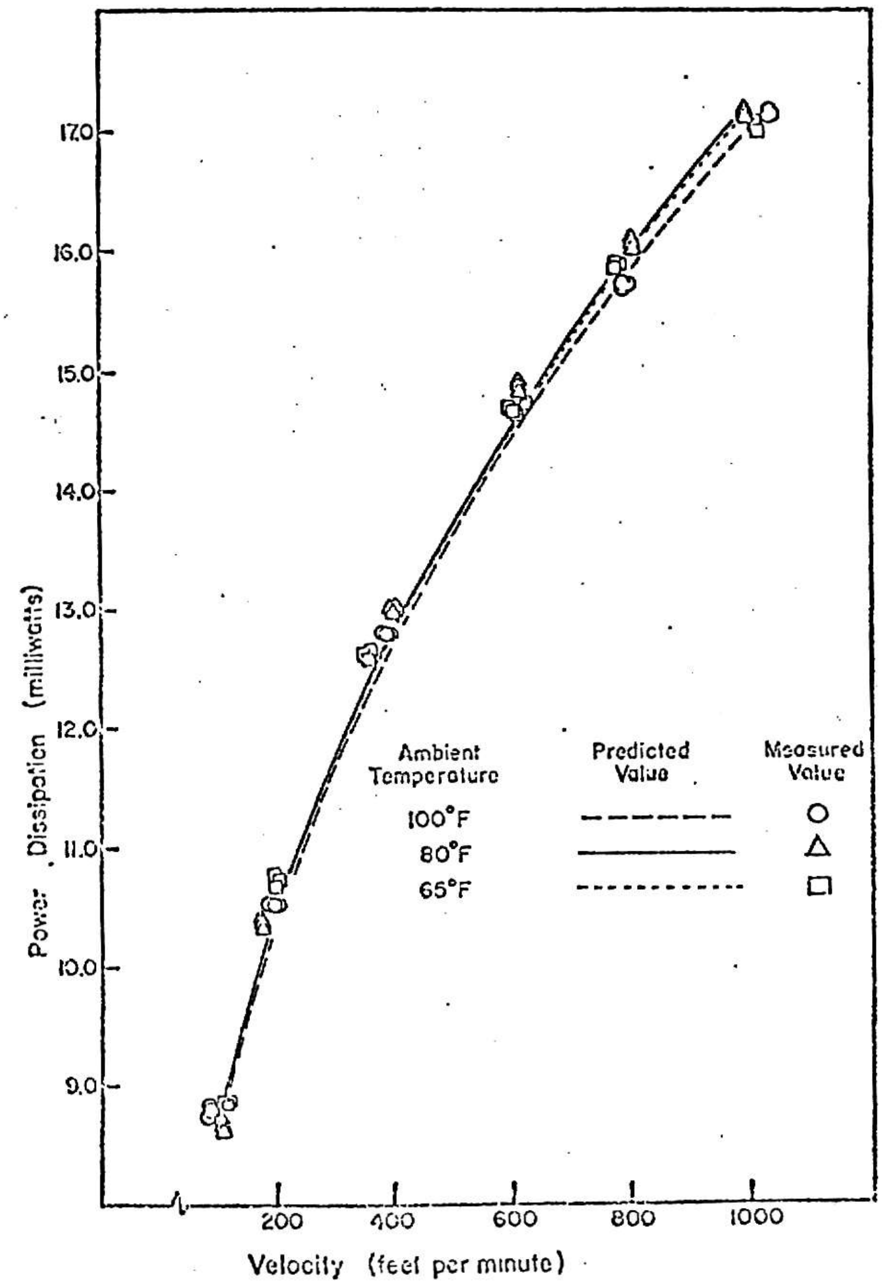


Figure 4

Experimental Results for the High Range

thermistor's temperature above ambient is approximately 20°F. Mr. Flanders reports a maximum error between measured and predicted velocities of approximately 2% in the high speed range and approximately 31% at 20 feet per minute in the low speed range. The large errors encountered in the low velocity range were attributed to the inability of the mathematical model to predict the power dissipation of the sensing thermistor.

Chapter 2

THE THEORY OF OPERATION

Introduction

To predict the performance of the anemometer, and consequently to size the circuit components, a mathematical model of the thermistor anemometer was developed. The power dissipation of the sensing thermistor bead to the air stream had to be accurately modeled. A describing heat transfer equation had to be derived to predict the heat transfer from the sensing bead to its environment by means of radiation, conduction, and convection. Also, the describing equation for the circuit had to be accounted for at the same time. The basic derivations appear in Mr. Flanders thesis. They will, however, be presented in this chapter and will be briefly reviewed. This will facilitate the discussions concerning the error analysis. A basic understanding of these equations is necessary to comprehend the relationships between the errors in the air speed and the errors in the circuit components.

The Describing Heat Transfer Equation

The sensing thermistor is shown in Figure 5. The first step in the development of the mathematical model is to perform an energy balance on the sensing thermistor. An energy balance yields the following equation:

$$P = I^2R_s = Q_{cond} + Q_{rad} + C\,\frac{dT_s}{d\theta} + Q_{conv}, \qquad [2]$$

where,

P-Power dissipated by sensing thermistor

I-Current through the sensing thermistor

R_s-Resistance of the sensing thermistor

Q_{cond}-Conductive heat loss

Q_{conv}-Convective heat loss

Q_{rad}-Radiative heat loss

C-Specific heat of the sensing thermistor

T_s-Temperature of the sensing thermistor

θ-Time

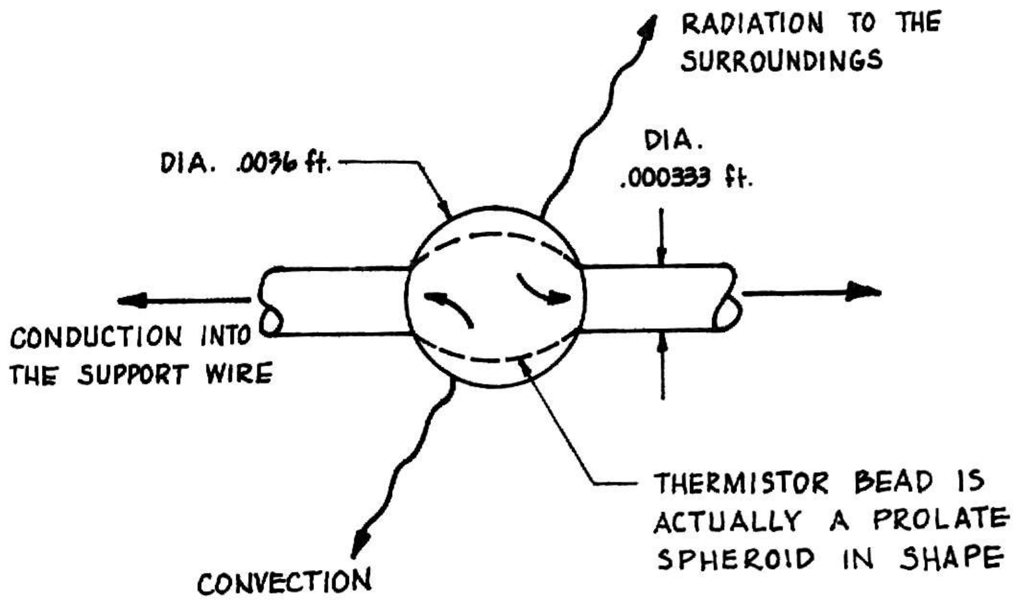


Figure 5

Means of Heat Transfer from the Sensing Thermistor to its Environment

Since the power readings are taken after steady-state has been reached, $dT_s/d\theta = 0$.

The conductive heat loss by the thermistor will be dissipated into the support wire. The support wire will then dissipate this energy by convection and radiation to the surroundings. The loss from the support wire can be expressed as,

$$Q_{cond} = Q_{c,w} + Q_{r,w}, \qquad [3]$$

where,

Q_{cond} - total heat dissipated into the wire by the thermistor bead

$Q_{c,w}$ - convective heat loss by wire

$Q_{r,w}$ - radiative heat loss by wire.

An energy balance on a differential element (see Fig. 6) of the support wire yields,

$$\frac{d^2T}{dx^2} = \frac{4h_w}{k_w D_w}(T-T_a) + \frac{4\varepsilon_w \sigma}{k_w D_w}(T^4-T_a{}^4). \qquad [4]$$

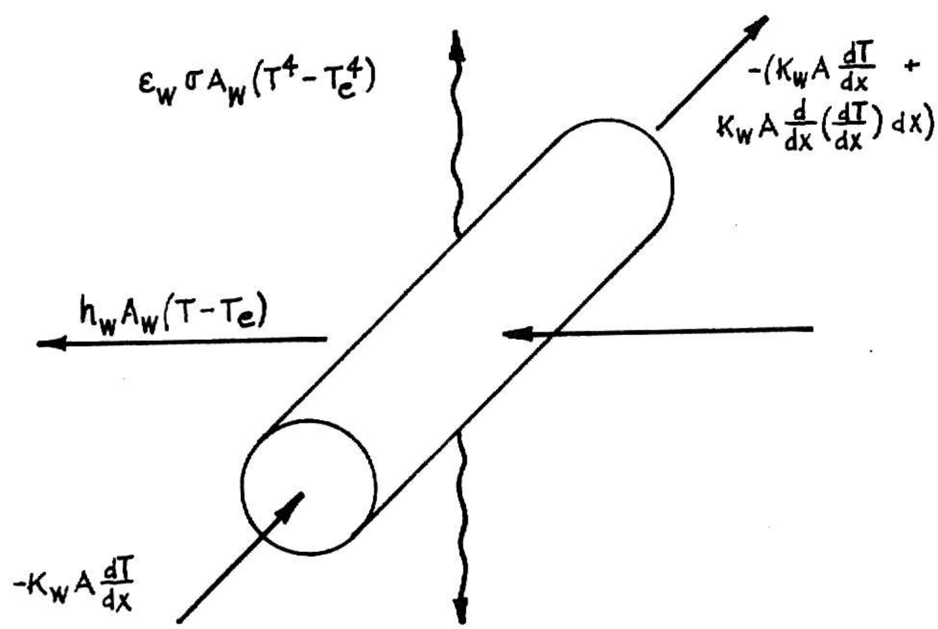


Figure 6

Means of Heat Transfer From
a Differential Element
of the Support Wire

This differential equation can be solved for the temperature distribution along the wire. The solution is,

$$T = T_a + (T_s-T_a)e^{-\beta x}.$$

where,

$$\beta^2 = \frac{4}{k_w D_w}(h_w + 4\varepsilon\sigma T_f^3). \qquad [5]$$

The energy loss from the wire can be found by evaluating,

$$Q = -k_w A_c \frac{dT}{dx}\bigg|_{x=0} , \qquad [6]$$

where,

$$A_c = \frac{\pi}{4} D_w^2.$$

Q is the total energy flux into the support wire from the thermistor. Evaluating $dT/dx|_{x=0}$ yields,

$$\frac{dT}{dx}\bigg|_{x=0} = -\beta(T_s - T_a). \qquad [7]$$

The total energy flux into the support wire can now be expressed as,

$$Q_{cond} = 2k_w \frac{\pi}{4} D_w^2 \beta(T_s - T_a). \qquad [8]$$

Substituting Eq. [5] for β and noting that there are two support wires, Eq. [8] becomes,

$$Q_{cond} = \pi[k_w D_w^3 (h_w + 4\varepsilon\sigma T_f^3)]^{\frac{1}{2}}(T_s - T_a). \qquad [9]$$

The following equation was used to evaluate the convective heat transfer coefficient for $0.02 < Re_f < 44.0$,

$$h_w = \frac{k_a}{D_w} (T_f/T_a)^{0.17}(0.24 + 0.56Re_f^{0.45}). \qquad [10]$$

Summarizing, the expression for the conduction term in the energy balance equation becomes,

$$Q_{cond} = \pi[k_w D_w^3 (\frac{k_a}{D_w}(T_f/T_a)^{0.17}(0.24 + 0.56Re_f^{0.45}) + 4\varepsilon\sigma T_f^3]^{\frac{1}{2}}(T_s - T_a). [11]$$

The radiative heat loss from the thermistor bead was calculated by,

$$Q_{rad} = \varepsilon\sigma A_w(T_s^4 - T_a^4) \simeq 4\varepsilon\sigma A_s T_f^3 (T_s - T_a), \quad [12]$$

where,

$$A_s = \frac{\pi}{4} D_s^2,$$

and the convective heat loss from the thermistor bead was found to be,

$$Q_{conv} = h_s A_s (T_s - T_a), \quad [13]$$

where the convective heat transfer coefficient, h_s, is computed by,

$$h_s = \frac{k_a}{D_s}[2 + 0.5(Re_f^2 + \frac{4}{3}Gr_f)^{0.25}], \quad [13]$$

for,

$$0.3 < Re_f < 3000.$$

The convective heat loss equation then becomes,

$$Q_{conv} = [\frac{k_a A_s}{D_s} (2 + 0.5(Re_f^2 + \frac{4}{3}Gr_f)^{0.25}](T_s - T_a). \quad [15]$$

The describing heat transfer is derived by substitution of Eqs. [11], [12], and [15] into Eq. [2].

$$P = \pi[k_w D_w^3[(\frac{k_a}{D_w}(T_f/T_a)^{0.17}(0.24 + 0.56Re_f^{0.45}) + 4\varepsilon\sigma T_f^3]^{\frac{1}{2}} + 4\varepsilon\sigma A_s T_f^3 + \frac{k_a A_s}{D_s} [2 + 0.5(Re_f^2 + \frac{4}{3}Gr_f)^{0.25}]](T_s - T_a). \quad [16]$$

This equation describes all the modes of heat transfer from the sensing thermistor. This is the mathematical model of the sensing thermistor used to design the circuit and also to compute the power curve of the anemometer.

The Circuit and its Describing Equation

Figure 7a shows the bridge circuit of the anemometer. Figure 7b shows the same circuit but with the parallel resistances R_c and R_3 replaced by an equivalent resistance, R_x. The relationship that must hold for a null or balanced bridge is,

$$\frac{R_1}{R_s} = \frac{R_2}{R_x} \quad . \tag{17}$$

Since

$$R_x = \frac{R_c R_3}{R_c + R_3} \tag{18}$$

then,

$$\frac{R_1}{R_s} = R_2/(\frac{R_c R_3}{R_c + R_3}) \ . \tag{19}$$

Solving for R_s yields,

$$R_s = \frac{R_1}{R_2} (\frac{R_c R_3}{R_c + R_3}) \ . \tag{20}$$

Beta is then defined as,

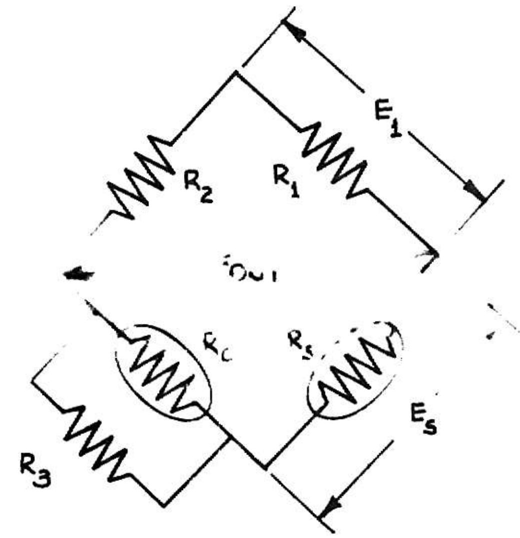
$$\text{Beta} = \frac{R_1}{R_2} \ . \tag{21}$$

And so Eq. [20] becomes,

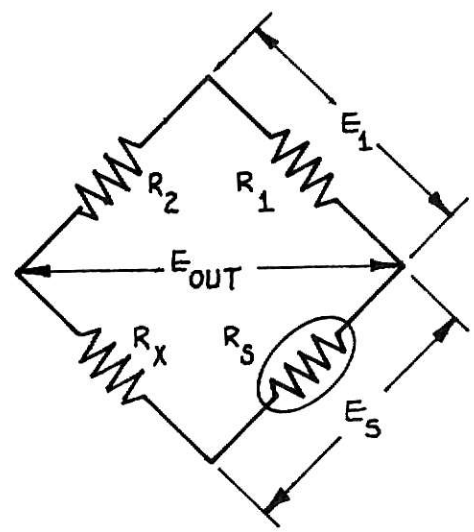
$$R_s = \text{Beta}(\frac{R_c R_3}{R_c + R_3}) \ . \tag{22}$$

This is the describing equation for the circuit.

In Figure 7a the output voltage, E_{out}, remains zero so long as the bridge is balanced. An imbalance can be introduced to the bridge by either the compensating thermistor or the sensing thermistor or both simultaneously. The output voltage, no longer zero, is amplified by the operational amplifier and the bridge exicitation is changed so that a null bridge can be achieved at the new conditions. During these transient conditions the bridge equation, Eq. [22], does not apply. However, power measurements will be made only when balance has again been achieved. A Fairchild operational amplifier, MA741, was used. This op amp has a rise time on the order of .5 microseconds



7a



7b

Figure 7

The Bridge Circuit of the Anemometer

so the taking of measurements when the bridge is unbalanced is eliminated.

The capacitance in the circuit does not affect the balance equation during steady-state null conditions. However, transient response to changes in the thermistors' resistances is affected by the fact that the capacitance is used to damp out fluctuations (or "gusts") in the air speed.

Theoretical Operation of the Complete Model

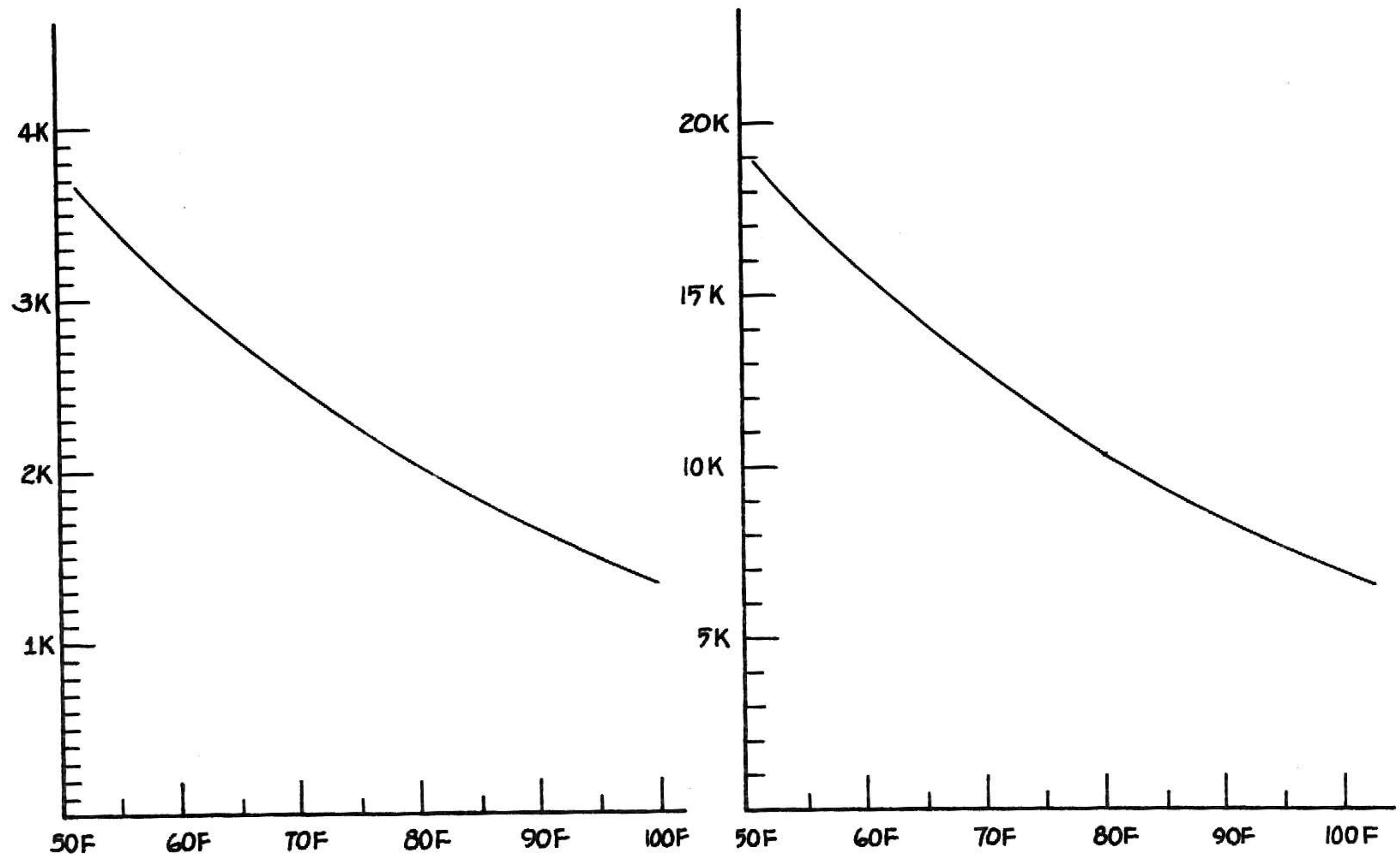
To avoid later confusion some basic terms relevant to the theoretical operation of the thermistor bridge circuit need to be defined.

Self-heat is the temperature differential, in Fahrenheit degrees, between the ambient temperature and the temperature of the sensing thermistor. This differential is always positive and is caused by purposely imposing I^2R heating of the sensing thermistor.

The reference temperature is an ambient temperature at which a specific self-heat is designated to occur. The self-heat will usually be specified in multiples of 5°F. Thus, the reference temperature will normally correspond to an interger value of self-heat.

The term "power curve" will be defined as the curve resulting from plotting the power dissipated (in milliwatts) by the sensing thermistor on the ordinate and the corresponding air apeed (in feet per minute) on the absissa. As will be illustrated later, a power curve can also be defined in terms of self-heat and reference temperature.

The heart of the bridge circuit is the thermistor. A thermistor has a negative temperature coefficient as is illustrated in Figure 8 by a plot of the sensing and compensating thermistor's temperature-resistance curves. The sensing thermistor's operating point on its particular temperature-resistance curve is subject to simultaneous regulation by the describing bridge equation and by the describing heat transfer equation. The operating point for the temperature compensating thermistor is regulated only by the ambient temperature.



SENSING THERMISTOR

COMPENSATING THERMISTOR

Figure 8

Temperature-resistance Curves for the Sensing and Compensating Thermistors

To begin an analysis a power curve is needed to uniquely relate power dissipation to velocity. By examining the describing heat transfer equation (Eq. [16]) it is evident that power dissipation is a function of air speed, V, ambient temperature, T_a, and the temperature of the sensing thermistor, T_s. This can be expressed in function form as

$$P = f(V, T_a, T_s) \qquad [23]$$

By definition,

$$\text{Reference Temperature} = T_a{}^* \qquad [24]$$

$$\text{Self-heat} = T_s - T_a \qquad [25]$$

where $T_a{}^*$ is used to indicate that the reference temperature corresponds to a specific ambient temperature. If the self-heat is also specified, Eq. [23] can be rewritten as,

$$P^* = f(V, \text{Reference Temperature, Self-heat}), \qquad [26]$$

where P* indicates that the power dissipation varies only with V since the reference temperature and the self-heat are now fixed. This leads to the conclusion that,

$$\text{Power Curve} = f(\text{Reference Temperature, Self-heat}) \qquad [27]$$

This means that the operation of the system can be defined by specifying a self-heat and a reference temperature. Computer Program I (see Appendix C) was used to generate the power dissipation values of the sensing thermistor for nineteen velocities throughout the 10 to 1000 feet per minute range. For illustration purposes, a self-heat of 20°F was specified to occur at any ambient temperature. The results of the computer program are presented in Table 1. For a specific velocity a number of different power dissipation values are seen to occur. Of course, this is undesirable. Each

TABLE 1

POWER DISSIPATION AT VARIOUS AMBIENT TEMPERATURES FOR A CONSTANT SELF-HEAT OF 20 DEGREES FAHRENHEIT

AIR SPEED (FPM)	POWER DISSIPATION (MILLIWATTS) AT 50F	60F	70F	80F	90F	100F
10	5.46	5.51	5.56	5.61	5.66	5.71
20	6.09	6.14	6.19	6.24	6.29	6.34
30	6.56	6.61	6.65	6.70	6.75	6.80
40	6.95	6.99	7.04	7.09	7.13	7.18
50	7.28	7.32	7.37	7.42	7.47	7.51
60	7.58	7.62	7.67	7.71	7.76	7.81
70	7.84	7.89	7.93	7.98	8.03	8.08
80	8.09	8.14	8.18	8.23	8.28	8.33
90	8.32	8.37	8.41	8.46	8.51	8.56
100	8.54	8.59	8.63	8.68	8.72	8.77
200	10.25	10.29	10.33	10.38	10.42	10.47
300	11.51	11.55	11.59	11.64	11.68	11.73
400	12.56	12.60	12.64	12.68	12.73	12.77
500	13.47	13.50	13.54	13.59	13.63	13.68
600	14.28	14.31	14.35	14.39	14.44	14.49
700	15.02	15.05	15.09	15.13	15.18	15.22
800	15.70	15.73	15.77	15.81	15.86	15.91
900	16.34	16.37	16.41	16.45	16.49	16.54
1000	16.94	16.97	17.01	17.05	17.09	17.14

velocity, independent of ambient temperature, must have a unique value of power dissipation associated with it.

The solution to this problem is to choose a value for self-heat and then specify a reference temperature somewhere in the ambient temperature range of the anemometer. The power dissipation is calculated at the specified self-heat and reference temperature for each velocity. The resulting power curve is to be used at all other ambient temperatures, so it is necessary that the self-heat be a variable so that at different ambient temperatures the power dissipation remains the same for each velocity.

The results of Computer Program II for a self-heat of 5°F occurring at 50, 75, and 100°F reference temperatures are presented in Tables 2, 3, and 4, respectively. Examination of these tables shows that when the ambient temperature changed the self-heat had to change slightly to maintain the same power dissipation for a given velocity. For the power dissipation to have a unique value for any velocity throughout the temperature range, the temperature, and therefore, the resistance of the sensing thermistor must be changed to compensate for the change in the ambient temperature. The rate of change of the sensing thermistor's resistance is not the same as the rate of change of the compensating thermistor's resistance. Hence, a temperature differential of exactly 5°F cannot be maintained between these thermistors throughout the temperature range of the instrument.

A typical power curve was generated by Computer Program III and is presented in Table 5. This power curve represents the power dissipation-velocity relationship for a self-heat of 5°F at a reference temperature of 100°F. For purposes of explanation, assume that the velocity to be measured is exactly 50 feet per minute. The measured power dissipation should be 1.8685

TABLE 2

SELF-HEATS REQUIRED TO MAINTAIN A CONSTANT POWER DISSIPATION WHEN THE SELF-HEAT IS 5 DEGREES FAHRENHEIT AND THE REFERENCE TEMPERATURE IS 50 DEGREES FAHRENHEIT

AIR SPEED	SELF-HEATS (DEGREES FAHRENHEIT) AT										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	5.000	4.978	4.956	4.935	4.913	4.892	4.870	4.848	4.826	4.805	4.783
20	5.000	4.981	4.962	4.943	4.924	4.905	4.886	4.867	4.848	4.829	4.809
30	5.000	4.983	4.966	4.948	4.931	4.913	4.896	4.878	4.861	4.843	4.825
40	5.000	4.984	4.968	4.952	4.936	4.919	4.903	4.886	4.870	4.853	4.836
50	5.000	4.985	4.970	4.955	4.939	4.924	4.908	4.892	4.877	4.861	4.845
60	5.000	4.986	4.972	4.957	4.942	4.928	4.913	4.898	4.883	4.867	4.852
70	5.000	4.987	4.973	4.959	4.945	4.931	4.916	4.902	4.887	4.873	4.858
80	5.000	4.987	4.974	4.960	4.947	4.933	4.919	4.905	4.891	4.877	4.863
90	5.000	4.987	4.975	4.962	4.949	4.936	4.922	4.909	4.895	4.881	4.867
100	5.000	4.988	4.975	4.963	4.950	4.937	4.925	4.911	4.898	4.885	4.871
200	5.000	4.991	4.981	4.971	4.961	4.950	4.940	4.929	4.919	4.907	4.896
300	5.000	4.992	4.984	4.975	4.967	4.958	4.948	4.939	4.930	4.920	4.910
400	5.000	4.993	4.986	4.978	4.970	4.962	4.954	4.946	4.937	4.928	4.919
500	5.000	4.994	4.987	4.980	4.973	4.966	4.958	4.950	4.942	4.934	4.926
600	5.000	4.994	4.988	4.982	4.975	4.969	4.961	4.954	4.947	4.939	4.931
700	5.000	4.995	4.989	4.983	4.977	4.971	4.964	4.957	4.950	4.943	4.935
800	5.000	4.995	4.990	4.985	4.979	4.973	4.966	4.960	4.953	4.946	4.939
900	5.000	4.995	4.990	4.985	4.980	4.974	4.968	4.962	4.956	4.949	4.942
1000	5.000	4.996	4.991	4.986	4.981	4.976	4.970	4.964	4.958	4.951	4.945

TABLE 3

SELF-HEATS REQUIRED TO MAINTAIN A CONSTANT POWER DISSIPATION
WHEN THE SELF-HEAT IS 5 DEGREES FAHRENHEIT AND THE
REFERENCE TEMPERATURE IS 75 DEGREES FAHRENHEIT

AIR SPEED	SELF-HEATS (DEGREES FAHRENHEIT) AT										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	5.111	5.089	5.066	5.044	5.022	5.000	4.978	4.956	4.934	4.911	4.889
20	5.097	5.077	5.058	5.039	5.020	5.000	4.980	4.961	4.941	4.922	4.902
30	5.088	5.070	5.053	5.035	5.018	5.000	4.982	4.964	4.946	4.928	4.910
40	5.082	5.066	5.049	5.033	5.016	5.000	4.984	4.966	4.950	4.933	4.915
50	5.077	5.062	5.047	5.031	5.016	5.000	4.984	4.968	4.952	4.936	4.920
60	5.074	5.059	5.045	5.030	5.015	5.000	4.985	4.970	4.954	4.939	4.923
70	5.070	5.057	5.043	5.029	5.014	5.000	4.985	4.971	4.956	4.941	4.926
80	5.068	5.054	5.041	5.028	5.014	5.000	4.986	4.972	4.957	4.943	4.929
90	5.065	5.053	5.040	5.027	5.013	5.000	4.987	4.973	4.959	4.945	4.931
100	5.063	5.051	5.038	5.026	5.013	5.000	4.987	4.974	4.960	4.946	4.933
200	5.050	5.040	5.031	5.021	5.010	5.000	4.989	4.978	4.968	4.957	4.945
300	5.043	5.035	5.027	5.018	5.009	5.000	4.991	4.981	4.972	4.962	4.952
400	5.038	5.031	5.023	5.016	5.008	5.000	4.992	4.983	4.974	4.965	4.956
500	5.034	5.028	5.022	5.015	5.007	5.000	4.992	4.985	4.976	4.968	4.960
600	5.032	5.026	5.020	5.014	5.007	5.000	4.993	4.986	4.978	4.970	4.962
700	5.029	5.024	5.019	5.013	5.007	5.000	4.993	4.986	4.979	4.972	4.964
800	5.027	5.023	5.017	5.012	5.006	5.000	4.994	4.987	4.980	4.973	4.966
900	5.026	5.021	5.016	5.011	5.006	5.000	4.994	4.988	4.981	4.975	4.968
1000	5.025	5.020	5.016	5.011	5.005	5.000	4.994	4.988	4.982	4.976	4.969

TABLE 4

SELF-HEATS REQUIRED TO MAINTAIN A CONSTANT POWER DISSIPATICN WHEN THE SELF-HEAT IS 5 DEGREES FAHRENHEIT AND THE REFERENCE TEMPERATURE IS 100 DEGREES FAHRENHEIT

AIR SPEED	SELF-HEATS (DEGREES FAHRENHEIT) AT										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	5.227	5.204	5.181	5.158	5.135	5.113	5.090	5.068	5.045	5.023	5.000
20	5.198	5.179	5.159	5.139	5.119	5.100	5.080	5.060	5.040	5.020	5.000
30	5.182	5.164	5.146	5.128	5.110	5.092	5.074	5.055	5.037	5.018	5.000
40	5.169	5.153	5.136	5.120	5.103	5.086	5.069	5.052	5.034	5.017	5.000
50	5.160	5.145	5.129	5.113	5.097	5.082	5.065	5.049	5.033	5.016	5.000
60	5.153	5.138	5.123	5.108	5.093	5.078	5.062	5.047	5.031	5.016	5.000
70	5.146	5.132	5.118	5.104	5.090	5.075	5.060	5.045	5.030	5.015	5.000
80	5.141	5.128	5.114	5.100	5.086	5.072	5.058	5.044	5.029	5.015	5.000
90	5.136	5.124	5.110	5.097	5.084	5.070	5.056	5.043	5.028	5.014	5.000
100	5.132	5.120	5.107	5.094	5.081	5.068	5.055	5.041	5.028	5.014	5.000
200	5.106	5.096	5.086	5.076	5.066	5.056	5.045	5.034	5.023	5.012	5.000
300	5.092	5.084	5.075	5.067	5.058	5.049	5.039	5.030	5.020	5.010	5.000
400	5.082	5.075	5.068	5.060	5.052	5.044	5.036	5.027	5.018	5.009	5.000
500	5.076	5.069	5.062	5.055	5.048	5.041	5.033	5.025	5.017	5.008	5.000
600	5.070	5.064	5.058	5.052	5.045	5.038	5.031	5.023	5.016	5.008	5.000
700	5.066	5.060	5.055	5.049	5.042	5.036	5.029	5.022	5.015	5.008	5.000
800	5.062	5.057	5.052	5.046	5.040	5.034	5.028	5.021	5.014	5.007	5.000
900	5.059	5.054	5.049	5.044	5.038	5.033	5.027	5.020	5.014	5.007	5.000
1000	5.056	5.052	5.047	5.042	5.037	5.031	5.025	5.019	5.013	5.007	5.000

milliwatts. Further, assume that the ambient temperature is 80°F. The self-heat, therefore, should be 5.065°F as can be seen by consulting Table 4. The temperature of the sensing thermistor is 80 + 5.065 or 85.065°F.

TABLE 5

The Power Curve in Tabular Form for a Self-heat of 5°F at a Reference Temperature of 100°F

Air Speed (FPM)	Power Dissipated by Sensing Thermistor (Milliwatts)
10	1.4164
20	1.5738
30	1.6901
40	1.7857
50	1.8685
60	1.9423
70	2.0094
80	2.0713
90	2.1289
100	2.1830
200	2.6077
300	2.9229
400	3.1833
500	3.4093
600	3.6115
700	3.7957
800	3.9659
900	4.1247
1000	4.2741

Suppose the ambient temperature drops to 50°F. The power dissipation must still be 1.8685 milliwatts, but the self-heat must be changed. Again consulting Table 4 the self-heat at 50 feet per minute and 50°F is found to be 5.160°F. The new temperature of the sensing thermistor is 50 + 5.160 or 55.160°F.

The previous example illustrates the ideal operation of the anemometer as predicted by the describing heat transfer equation, Eq. [16]. The operation of the actual circuit has not yet been described. Equation [22], the describing circuit equation, must yield the same results for power dissipation throughout the ambient temperature range. To accomplish this the circuit components must be sized properly. The performance of the compensating and sensing thermistors are already known as shown in Figure 8 (see page 18). The resistor R_3 and the resistor ratio Beta must be sized to correctly provide the required values for power dissipation throughout the entire range of possible temperature-velocity combinations.

For the present assume that R_3 and Beta are properly sized so that the circuit should perform as described by the describing heat transfer equation. It is not possible to obtain a resistor that is exactly equal to some specified value. Currently, resistor tolerances better than .005% are not generally available. If R_3 is, for example, .005% greater than what is needed an error is introduced that is proportional, but not equal in magnitude to a .005% error in the measurement of the air speed. This error will affect the required value of 1.8685 milliwatts for the power dissipation at 50 feet per minute as well as all other points on the power curve in Table 5. The same problem is encountered with resistance values for Beta, R_C, and R_S. The effect of these errors in the circuit components upon the calculated air speeds is examined in detail in the following chapters.

Chapter 3

DEVELOPMENT OF THE ERROR ANALYSIS

Introduction

The following error analysis is classified as a "common sense" error analysis. Errors in the circuit components are incorporated directly into the appropriate equations and a value calculated. This value is compared with a "true" value obtained by not imposing an error in the equations. An analytical error analysis, alternatively, requires computing a partial differential with respect to the variable of interest. Due to the length, non-linearity, and graphical relationships (i.e. the thermistor curves) encountered in the modeling equations this approach is not efficient. Instead, the computer was used to calculated the magnitude of error in the variable of interest. The relative error analysis illustrates the fact that the "common sense" method, in effect is a method of computing the partial differential.

It is common knowledge that the sensitivity of a variable to uncertainty is computed by,

$$S_x = \frac{(\partial X/\partial Z)\, X}{Z} ,$$

where Z is the variable that is a function X and any other number of variables. The "common sense" method used computes the error in Z exclusively with respect to a given error in X. If the percentage error in Z is normalized by dividing by the percentage error in X, the partial differential, $\frac{\partial X}{\partial Z}$, has been effectively evaluated at this point.

The following discussion outlines the steps in developing a circuit component error analysis. The errors arising from the circuit components and, also, the errors arising from circumstances not yet defined are ultimately related to errors in the calculation of the air speed. However, before the error analysis is presented, the technique used in sizing the circuit components is presented. This systematic sizing technique was developed first because it was the basis of the ensuing error analysis as will presently become apparent.

Sizing of the Circuit Components

The resistance characteristics of the sensing thermistor and the compensating thermistor have been set. On this basis there are two unknown resistances left in Eq. [22] which is the describing circuit equation. These unknown resistances are R_3, the resistance in parallel with the temperature compensating thermistor, and Beta, which is the ratio R_1/R_2. The basic procedure was to determine optimum values for R_3 and Beta that yielded minimum errors in the air speed. Then, using Eq. [1], a value was calculated for R_1 such that the voltages E_1 and E_s would be large enough to be conveniently measured. The resistance R_2 was then calculated using the fact that $R_2 = R_1/\text{Beta}$. A sizing program for the Beta and R_3 circuit components was written. This sizing program is referred to as Computer Program IV.

There are five parameters that need to be supplied to the program. These are a self-heat, a reference temperature, an ambient temperature, a velocity, and a value for R_3. From this information a value for Beta can be calculated. The major problem comes in determining the optimum values for R_3 and Beta. Before this optimization problem is discussed, an explanation is forthcoming concerning the method for obtaining values for Beta.

Equation [22] can be solved for Beta yielding

$$\text{Beta} = R_s\left(\frac{R_3 + R_c}{R_3 R_c}\right) \qquad [23]$$

Figure 9 illustrates a simplified flow-chart for Program IV. A value for R_3 is provided to the program leaving two unknown resistances to be calculated as is evident from Eq. [23]. The value of R_c can be readily calculated since an ambient temperature is directly provided. This leaves the resistance R_s as the remaining unknown in the equation. The subroutine PDISS is used to calculate a resistance for R_s. Figure 10 shows a detailed flowchart for this subroutine.

Appropriate self-heat and reference temperature are provided to the subroutine. As explained previously, this is adequate information to completely specify a power curve for the anemometer. A function designated POWER calculates the power dissipation for any desired velocity using Eq. [16] and returns this value, in milliwatts, to the subroutine. The temperature of the sensing thermistor is varied (iterated) subject to the describing heat transfer equation until agreement (within .0001 milliwatt) is found with the power curve (e.g. the value returned by the function POWER). This iterated temperature is then converted into a resistance for the sensing thermistor by using the function RTF. The resistance value for R_s is then returned to the main program and Beta is then calculated. This process is repeated for eleven ambient temperatures ranging from 50°F to 100°F in increments of 5°F and for any number of air speeds up to nineteen.

It should be that, for every temperature-velocity combination between 10 to 100 feet per minute and 50 to 100°F, a constant value

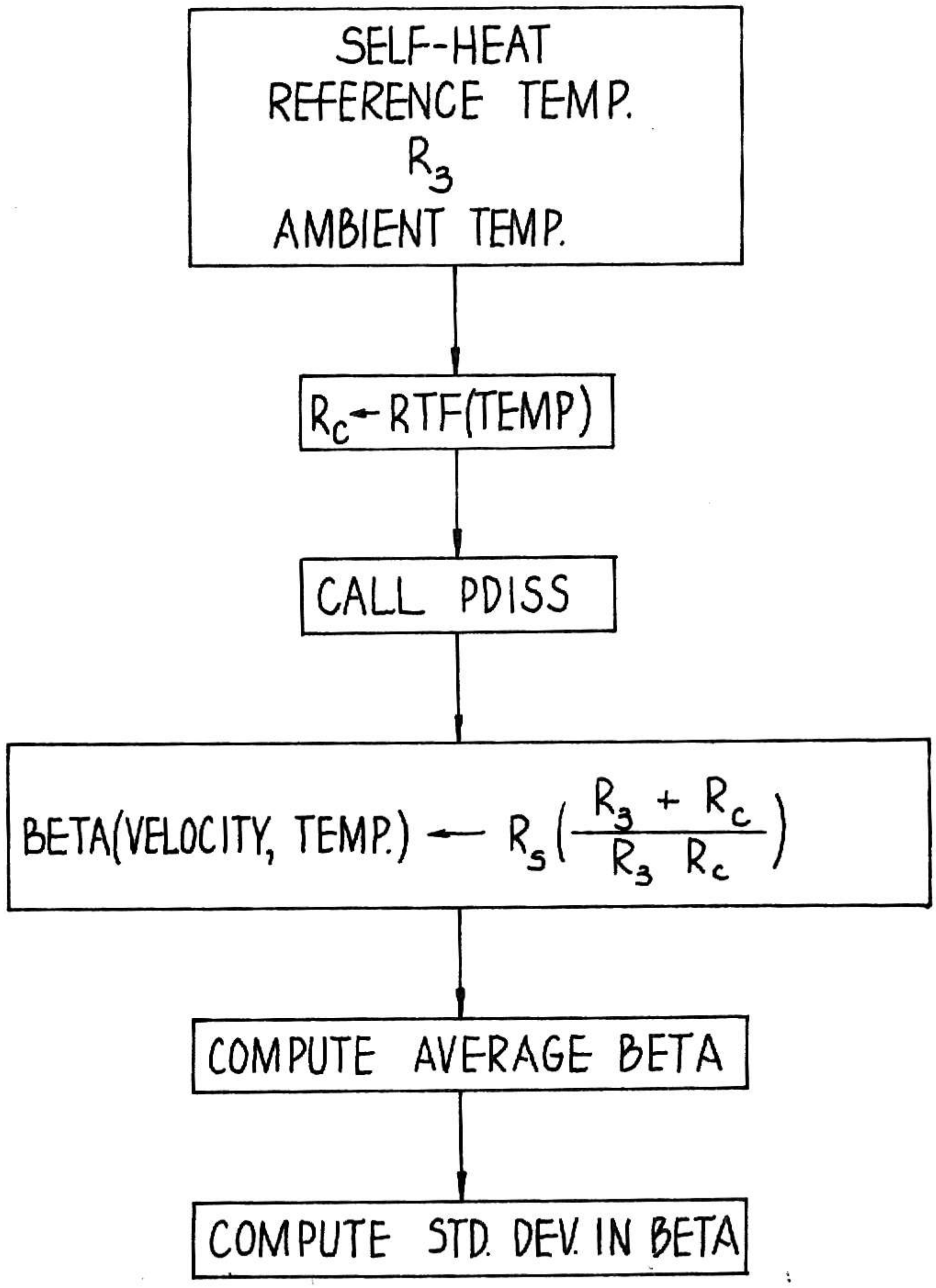


Figure 9

Simplified Flowchart for Computer Program IV

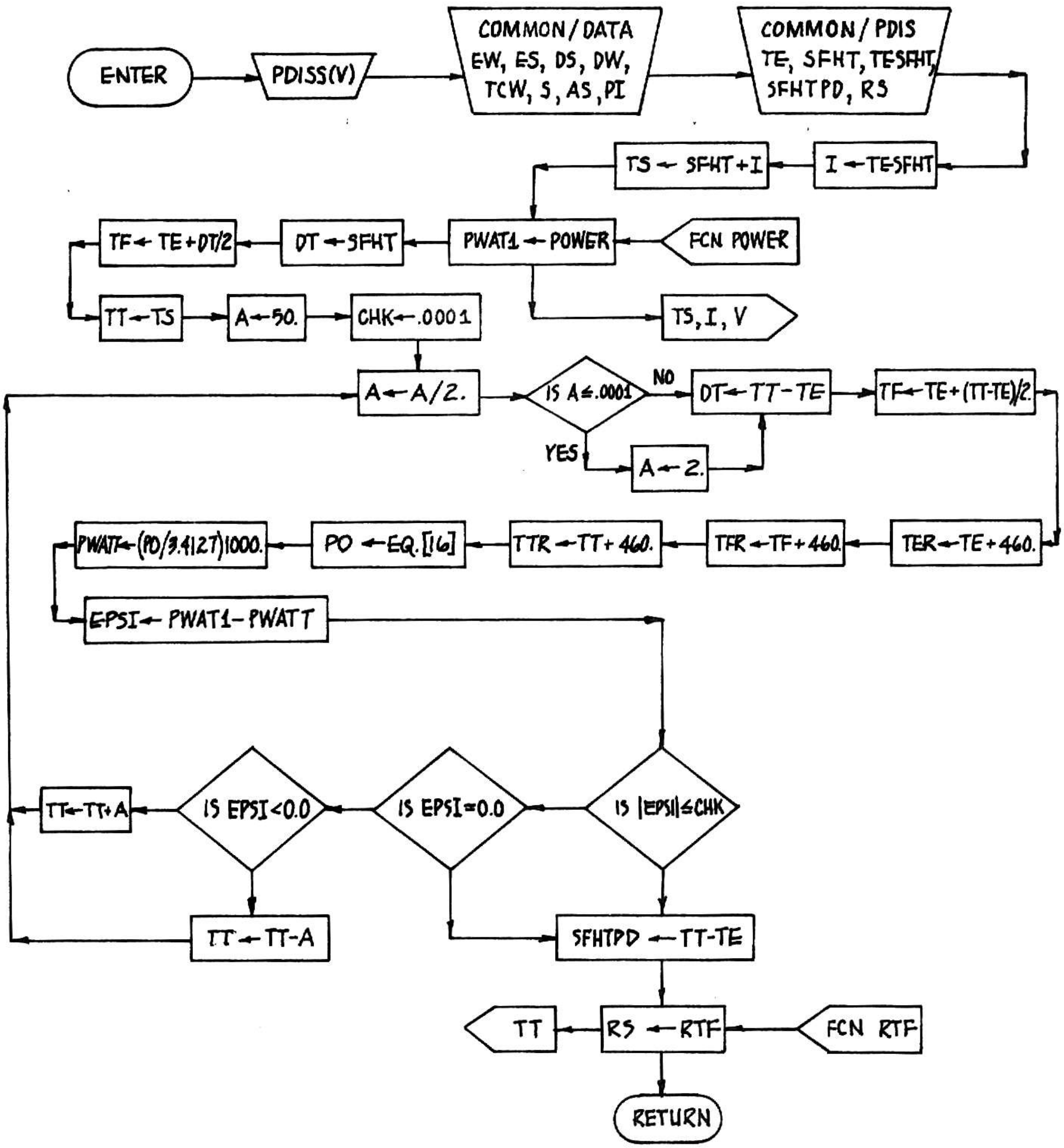


Figure 10

Flowchart for Subroutine PDISS

of Beta is maintained for a given R_3. The reason for this obvious. R_1 and R_2 can each have only one value at a time and, therefore, so can Beta. However, it was observed that the optimum value of Beta is not constant over the desired temperature-velocity range. To rectify this problem the air speed measurement capability can be divided into a reasonable number of ranges, say three or four, without too much difficulty to compensate for deviations in Beta, but deviations in Beta with respect to ambient temperature cannot be dealt with in this manner. Attempting to subdivide the temperature range defeats the purpose of constructing an anemometer that is temperature compensating. Table 6 was computed using the program just described to illustrate this variance in Beta.

To pick the best combination of R_3 and Beta, it was necessary to minmize the variance in Beta. For a given value of R_3 values for Beta were calculated for eleven temperatures and nineteen velocities. The standard deviation of Beta was computed for this eleven by nineteen matrix using ,

$$s_{Beta} = \sqrt{\frac{\sum(Beta - \overline{Beta})^2}{(11x19 - 1)}} \quad . \qquad [24]$$

The standard deviation for Beta was plotted versus R_3 for a number of power curves. Each power curve had some minimum value for the standard deviation of Beta. Figure 11 shows one of the typical curves that was obtained during the course of analysis and illustrates the fact that these curves do possess a minimum value.

The value of R_3 occurring at the minimum point of the standard deviation curve is the optimum value of R_3 for that particular power curve. The value used for Beta at this point is the average Beta for the matrix computed by

$$Beta = \left. \frac{\sum_{i=10}^{i=1000} \sum_{j=50}^{j=100} Beta_{ij}}{11 \times 19} \right|_{s_{Beta}=min} \qquad [25]$$

where i represents air speed and j represents ambient temperature.

TABLE 6

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT
POWER DISSIPATION ACROSS THE AMBIENT
TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 50 DEGREES FAHRENHEIT
R3 = 450000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17564	0.17547	0.17538	0.17537	0.17511	0.17495	0.17559	0.17566	0.17586	0.17582	0.17575
20	0.17564	0.17546	0.17536	0.17534	0.17507	0.17490	0.17553	0.17559	0.17579	0.17573	0.17565
30	0.17564	0.17545	0.17535	0.17532	0.17504	0.17487	0.17550	0.17555	0.17574	0.17568	0.17560
40	0.17564	0.17545	0.17534	0.17530	0.17502	0.17485	0.17547	0.17552	0.17571	0.17565	0.17556
50	0.17564	0.17544	0.17533	0.17529	0.17501	0.17484	0.17545	0.17550	0.17568	0.17562	0.17553
60	0.17564	0.17544	0.17533	0.17529	0.17500	0.17482	0.17543	0.17548	0.17566	0.17560	0.17550
70	0.17564	0.17544	0.17532	0.17528	0.17499	0.17481	0.17542	0.17546	0.17564	0.17558	0.17548
80	0.17564	0.17544	0.17532	0.17527	0.17498	0.17480	0.17541	0.17545	0.17563	0.17556	0.17547
90	0.17564	0.17544	0.17532	0.17527	0.17497	0.17479	0.17540	0.17544	0.17562	0.17555	0.17545
100	0.17564	0.17543	0.17531	0.17526	0.17496	0.17479	0.17539	0.17543	0.17560	0.17554	0.17544
200	0.17564	0.17542	0.17529	0.17523	0.17493	0.17474	0.17534	0.17536	0.17553	0.17546	0.17535
300	0.17564	0.17542	0.17528	0.17522	0.17490	0.17471	0.17531	0.17533	0.17549	0.17541	0.17530
400	0.17564	0.17541	0.17527	0.17521	0.17489	0.17470	0.17528	0.17531	0.17547	0.17538	0.17527
500	0.17564	0.17541	0.17527	0.17520	0.17488	0.17469	0.17527	0.17529	0.17545	0.17536	0.17525
600	0.17564	0.17541	0.17526	0.17519	0.17487	0.17467	0.17526	0.17528	0.17543	0.17535	0.17523
700	0.17564	0.17541	0.17526	0.17519	0.17486	0.17467	0.17525	0.17526	0.17542	0.17533	0.17521
800	0.17564	0.17541	0.17526	0.17518	0.17486	0.17466	0.17524	0.17526	0.17541	0.17532	0.17520
900	0.17564	0.17541	0.17526	0.17518	0.17485	0.17466	0.17523	0.17525	0.17540	0.17531	0.17519
1000	0.17564	0.17540	0.17525	0.17518	0.17485	0.17465	0.17523	0.17524	0.17539	0.17530	0.17518

AVERAGE BETA =0.17532 STD. DEVIATION =0.000269

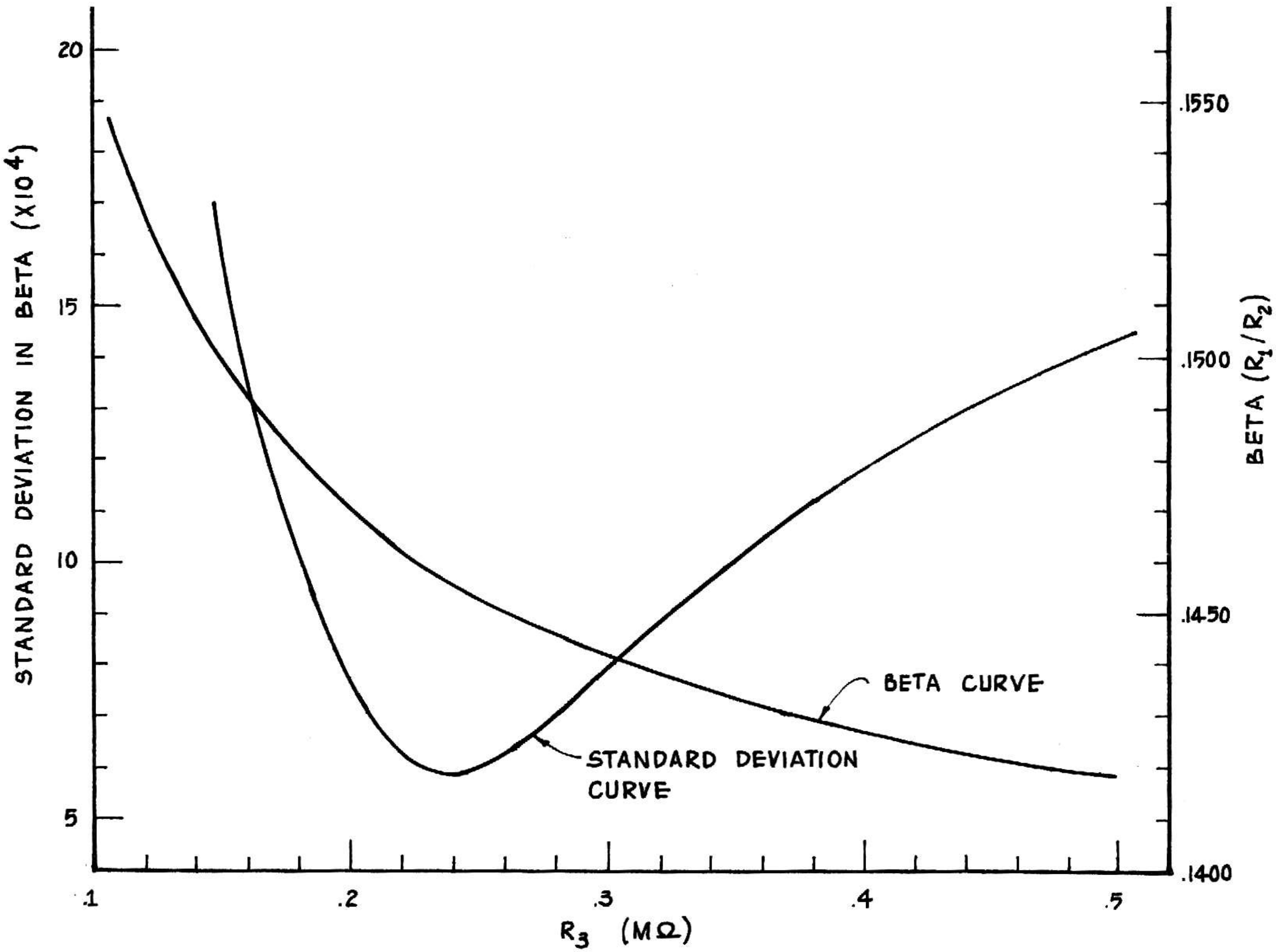


Figure 11

Illustration of the Minimum Standard Deviation in Beta

A study was made, using Program IV, concerning determination of R_3 and Beta at a reference temperature of 75°F for self-heats ranging from 5 to 15°F. For each self-heat the minimum standard deviation versus R_3 was plotted on one graph for comparison purposes. This graph is illustrated in Figure 12.

The conclusion that can be drawn from this plot is that the standard deviation of Beta decreases (actually approaches zero) as the self-heat decreases. This means that the operation of the anemometer should be restricted to lower self-heats. Mr. Flanders incorporated a self-heat of 20°F with a reference temperature of 100°F in his anemometer where, for example, a self-heat of 5, 10, or 15°F and a reference temperature of 100°F would have resulted in smaller value for the minimum standard deviation in Beta.

Deviations from the average value of Beta, consequently will cause errors to be present between the actual and predicted values of power dissipation. This will alter the power curve and, therefore, cause errors in measurement of air speeds by the anemometer. The following section will depict the method used to evaluate the magnitude of these errors and explain their cause.

Absolute Error Analysis

To evaluate the magnitude and sign of the error in the air speed that is contributed by Beta, Computer Program V was developed. The error in the air speed was computed on the basis that all the components had zero error with regard to their specific values and hence the phraseology absolute error analysis was adopted. A self-heat of 5°F and a reference temperature of 100°F were used since these values yielded a small value for the minimum standard deviation in Beta.

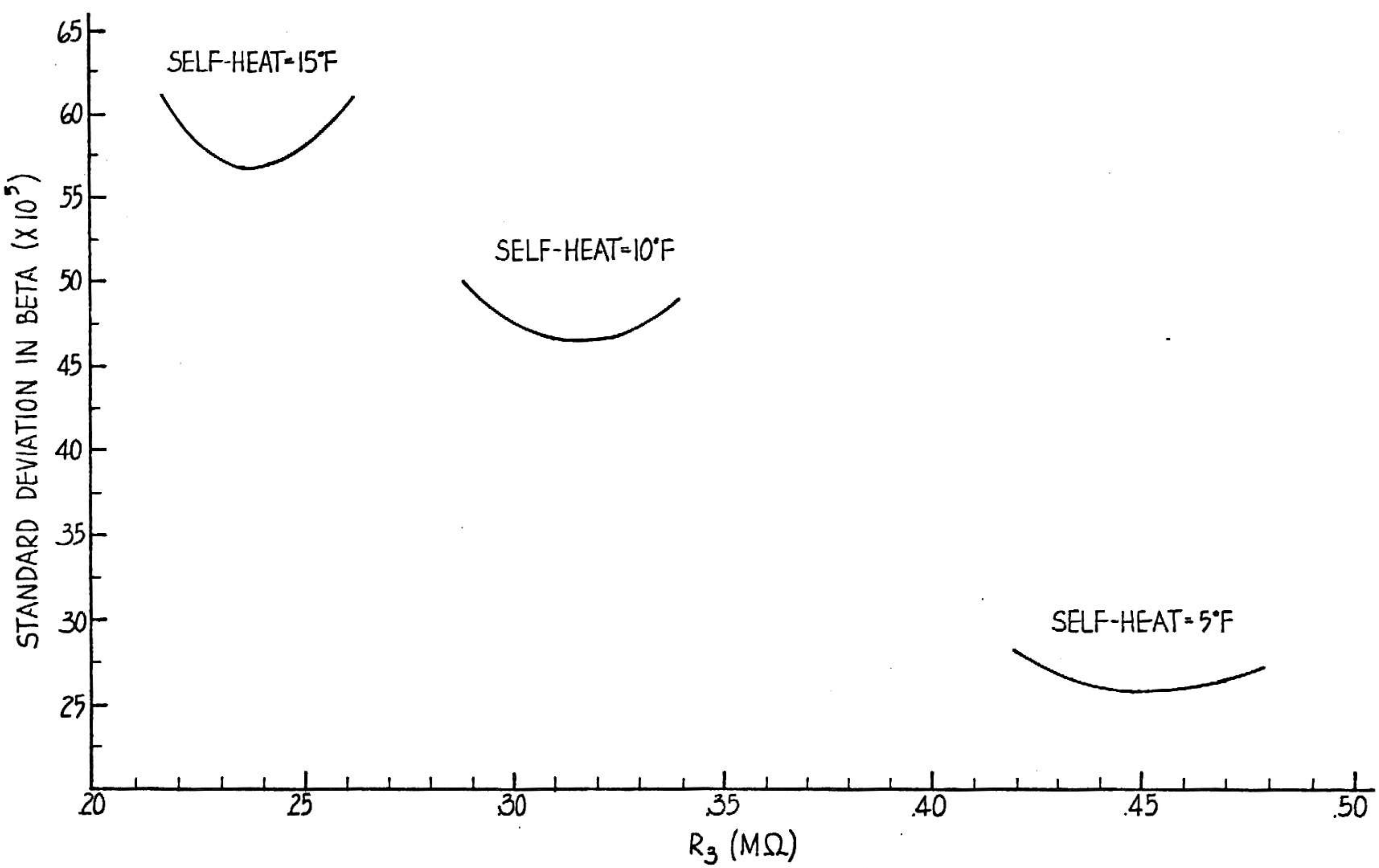


Figure 12

Illustration of the Minimum Standard Deviation in Beta for Three Self-heats

The basic equation used in this program was,

$$R_s = Beta * R_x, \quad [26]$$

where,

$$R_x = (R_3 * RTC) / (R_3 + RTC), \quad [27]$$

and,

RTC = Resistance of the compensating thermistor.

This sizing program for R_3 and Beta was run and the resulting standard deviations in Beta were plotted versus R_3 as depicted in Figure 13 to find optimum values for R_3 and Beta to use in the absolute error analysis. The best values were found to be:

$$R_3 = 450{,}000 \text{ ohms}$$

$$Beta = .17488$$

for,

$$s_{Beta} = .000275 .$$

The sizing program was then run again at R_3 = 450,000 ohms so that the actual variations in Beta could be observed. The results of this computer run are shown in Table 7. Using these values for R_3 and Beta the absolute error analysis program was run. The results can be found in Table 8.

It should be emphasized that the results depicted in Table 8 are the best obtainable using the particular compensating and sensing thermistors. Even so, a maximum error of -25.7% is seen to occur at an ambient temperature of 75°F and a velocity of 10 feet per minute. It should be emphasized that component errors have yet to be considered.

It was realized beforehand that there was a direct correlation between the deviations in Beta from the average Beta and in the absolute error in air speed. This can be confirmed by observing Tables 7 and 8. In Table 7

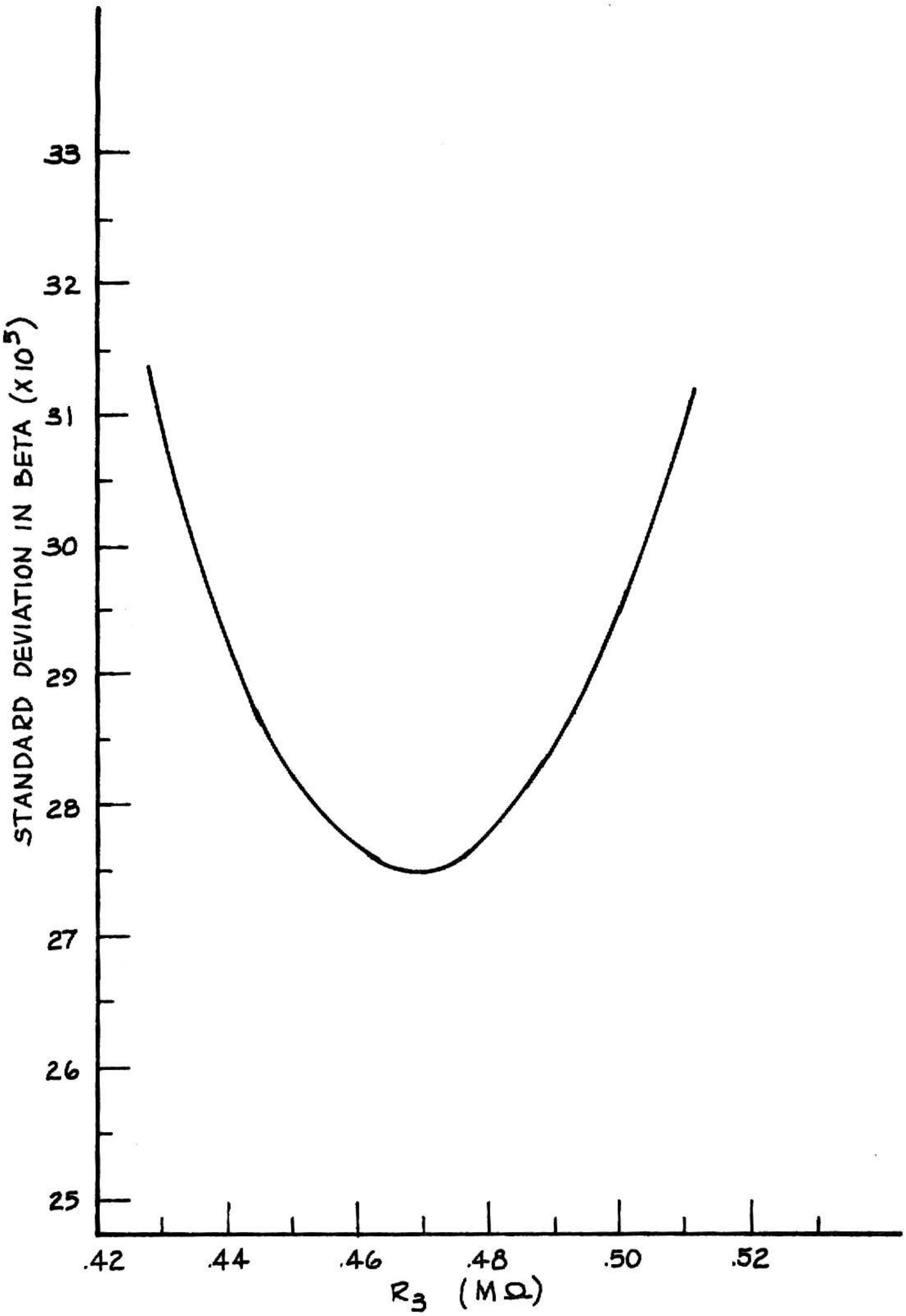


Figure 13

Standard Deviation Curve for 5°F Self-heat @ 100°F

TABLE 7

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT
POWER DISSIPATION ACROSS THE AMBIENT
TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 450000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17478	0.17462	0.17454	0.17453	0.17425	0.17416	0.17479	0.17487	0.17508	0.17505	0.17499
20	0.17489	0.17472	0.17462	0.17460	0.17432	0.17420	0.17483	0.17490	0.17510	0.17506	0.17499
30	0.17495	0.17477	0.17467	0.17464	0.17435	0.17423	0.17485	0.17491	0.17511	0.17507	0.17499
40	0.17500	0.17481	0.17471	0.17467	0.17438	0.17425	0.17487	0.17493	0.17511	0.17507	0.17499
50	0.17503	0.17484	0.17473	0.17470	0.17440	0.17427	0.17488	0.17493	0.17512	0.17507	0.17499
60	0.17506	0.17487	0.17476	0.17472	0.17442	0.17428	0.17489	0.17494	0.17513	0.17508	0.17499
70	0.17508	0.17489	0.17478	0.17473	0.17443	0.17429	0.17490	0.17495	0.17513	0.17508	0.17499
80	0.17510	0.17491	0.17479	0.17475	0.17444	0.17430	0.17491	0.17495	0.17513	0.17508	0.17499
90	0.17512	0.17492	0.17480	0.17476	0.17445	0.17431	0.17491	0.17496	0.17514	0.17508	0.17499
100	0.17514	0.17494	0.17482	0.17477	0.17446	0.17432	0.17492	0.17496	0.17514	0.17508	0.17499
200	0.17524	0.17502	0.17489	0.17484	0.17452	0.17436	0.17496	0.17499	0.17516	0.17509	0.17499
300	0.17529	0.17507	0.17494	0.17487	0.17455	0.17439	0.17498	0.17500	0.17517	0.17510	0.17499
400	0.17533	0.17510	0.17496	0.17490	0.17457	0.17440	0.17499	0.17501	0.17517	0.17510	0.17499
500	0.17535	0.17513	0.17498	0.17492	0.17459	0.17441	0.17500	0.17502	0.17518	0.17510	0.17499
600	0.17537	0.17515	0.17500	0.17493	0.17460	0.17442	0.17501	0.17503	0.17518	0.17510	0.17499
700	0.17539	0.17516	0.17501	0.17494	0.17461	0.17443	0.17501	0.17503	0.17518	0.17510	0.17499
800	0.17540	0.17517	0.17502	0.17495	0.17462	0.17444	0.17502	0.17504	0.17519	0.17510	0.17499
900	0.17541	0.17518	0.17503	0.17496	0.17463	0.17444	0.17502	0.17504	0.17519	0.17511	0.17499
1000	0.17542	0.17519	0.17504	0.17497	0.17463	0.17445	0.17503	0.17504	0.17519	0.17511	0.17499

AVERAGE BETA =0.17488 STD. DEVIATION =0.000275

TABLE 8

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 45000C. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	-3.4	-9.0	-11.9	-12.3	-21.0	-25.7	-3.4	-0.4	8.1	7.2	4.4
20	0.3	-4.8	-7.6	-8.2	-16.0	-20.4	-1.6	0.5	7.3	6.2	3.7
30	2.0	-2.9	-5.5	-6.3	-13.6	-17.7	-0.8	1.0	6.9	5.8	3.3
40	3.0	-1.7	-4.4	-5.2	-12.1	-16.2	-0.3	1.3	6.7	5.5	3.1
50	3.7	-0.8	-3.5	-4.4	-11.2	-15.1	0.1	1.4	6.5	5.3	2.9
60	4.2	-0.3	-2.9	-3.8	-10.4	-14.2	0.3	1.6	6.4	5.2	2.8
70	4.6	0.2	-2.3	-3.3	-9.8	-13.6	0.5	1.7	6.3	5.1	2.7
80	5.0	0.6	-2.0	-2.9	-9.3	-13.0	0.7	1.8	6.2	5.0	2.7
90	5.3	0.9	-1.6	-2.6	-8.9	-12.6	0.8	1.9	6.1	4.9	2.6
100	5.5	1.2	-1.3	-2.3	-8.5	-12.2	0.9	1.9	6.1	4.8	2.5
200	6.8	2.7	0.3	-0.8	-6.6	-10.0	1.5	2.3	5.7	4.4	2.3
300	7.3	3.4	1.0	-0.1	-5.6	-9.0	1.8	2.4	5.6	4.3	2.1
400	7.7	3.8	1.4	0.3	-5.1	-8.4	2.0	2.5	5.4	4.1	2.0
500	7.9	4.1	1.7	0.6	-4.7	-8.0	2.1	2.5	5.4	4.1	2.0
600	8.1	4.3	2.0	0.8	-4.4	-7.6	2.2	2.6	5.3	4.0	1.9
700	8.2	4.5	2.1	1.0	-4.2	-7.4	2.3	2.6	5.3	3.9	1.9
800	8.3	4.6	2.3	1.1	-4.0	-7.1	2.3	2.6	5.2	3.9	1.8
900	8.4	4.8	2.4	1.2	-3.8	-7.0	2.3	2.6	5.2	3.9	1.8
1000	8.5	4.8	2.5	1.3	-3.7	-6.8	2.4	2.7	5.2	3.8	1.8

for a velocity of 50 feet per minute and an ambient temperature of 80°F the calculated Beta is equal to the average Beta. In Table 8 for the same velocity-temperature combination, the error in air speed is essentially zero as it should be. Going back to Table 7 for a velocity of 80 feet per minute and a temperature of 50°F, the calculated Beta is greater than the average Beta and the result is a positive error in air speed. This relationship occurs without exception for all cases. So the problem becomes discovering the cause or causes for the deviation in Beta.

Figure 14 shows the anemometer circuit with the compensating thermistor and R_3 replaced by some unknown equivalent resistance. Computer Program VI was written to compute the value of this equivalent resistance needed when R_3 = 450,000 ohms and Beta = .17488. The equation used to calculate this equivalent resistance, designated R_x is,

$$R_x = R_s/\text{Beta}. \qquad [28]$$

The effect of R_c and R_3 is not present and, thereby, the value for R_x is independent of the particular compensating thermistor and parallel resistance. Thus, R_x is the value of resistance that must be provided by the parallel combination of R_3 and R_c to yield zero absolute error throughout the range of the anemometer.

The results of this program, for a velocity of 10 feet per minute and a self-heat of 5°F at a reference temperature of 100°F are presented in Table 9. The results indicate that a maximum difference between the actual and ideal resistance occurred at 72°F. Going back to Table 7 for a velocity of 10 feet per minute the deviation in Beta from the average Beta suspiciously occurs at what appears to be approximately the same ambient temperature. Consequently, the same observation can be made for the error in the air speed in Table 8.

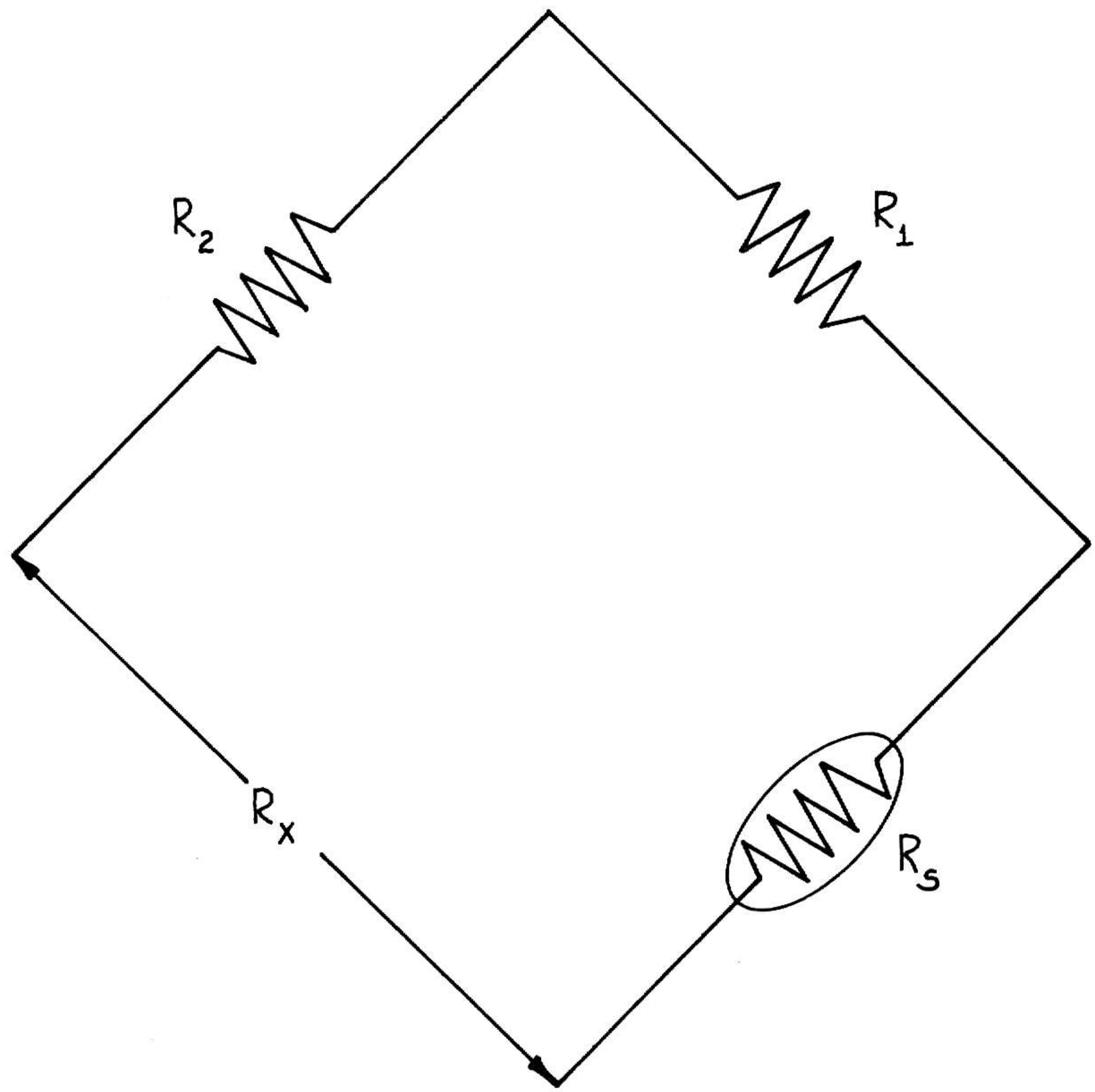


Figure 14

The Anemometer Bridge Circuit with an Equivalent Resistance Subtituted for R_3 and R_c

Table 9

Comparison of the Actual and Ideal Resistances for R_x

Ambient Temperature	Ideal R_x	Actual R_x	Error in Ohms	Error in Percent of Ideal R_x
50	19391.230	19382.250	-8.988	-0.046
52	18578.890	18579.320	0.434	0.002
54	17800.290	17808.220	7.934	0.045
56	17054.460	17067.820	13.355	0.078
58	16339.880	16356.970	17.090	0.105
60	15655.110	15674.640	19.527	0.125
62	14999.290	15019.720	20.426	0.136
64	14370.700	14391.250	20.543	0.143
66	13768.690	13788.190	19.496	0.142
68	13179.280	13209.630	30.352	0.230
70	12615.230	12654.590	39.355	0.312
72	12075.140	12136.090	60.949	0.505
74	11566.100	11622.640	56.531	0.489
76	11100.410	11130.350	29.941	0.270
78	10653.560	10658.370	4.816	0.045
80	10224.690	10227.080	2.391	0.023
82	9813.016	9813.137	0.121	0.001
84	9413.621	9415.566	1.945	0.021
86	9037.883	9033.758	-4.125	-0.046
88	8677.270	8667.117	-10.152	-0.117
90	8330.918	8320.641	-10.277	-0.123
92	8004.336	7995.480	-8.855	-0.111
94	7690.867	7682.793	-8.074	-0.105
96	7389.559	7384.113	-5.445	-0.074
98	7100.160	7097.609	-2.551	-0.036
100	6826.094	6822.051	-4.043	-0.059

The values in this table were calculated for:

Velocity = 10 fpm
Beta = 0.17488
R_3 = 450,000 ohms
Self-heat = 5°F @ 100°F.

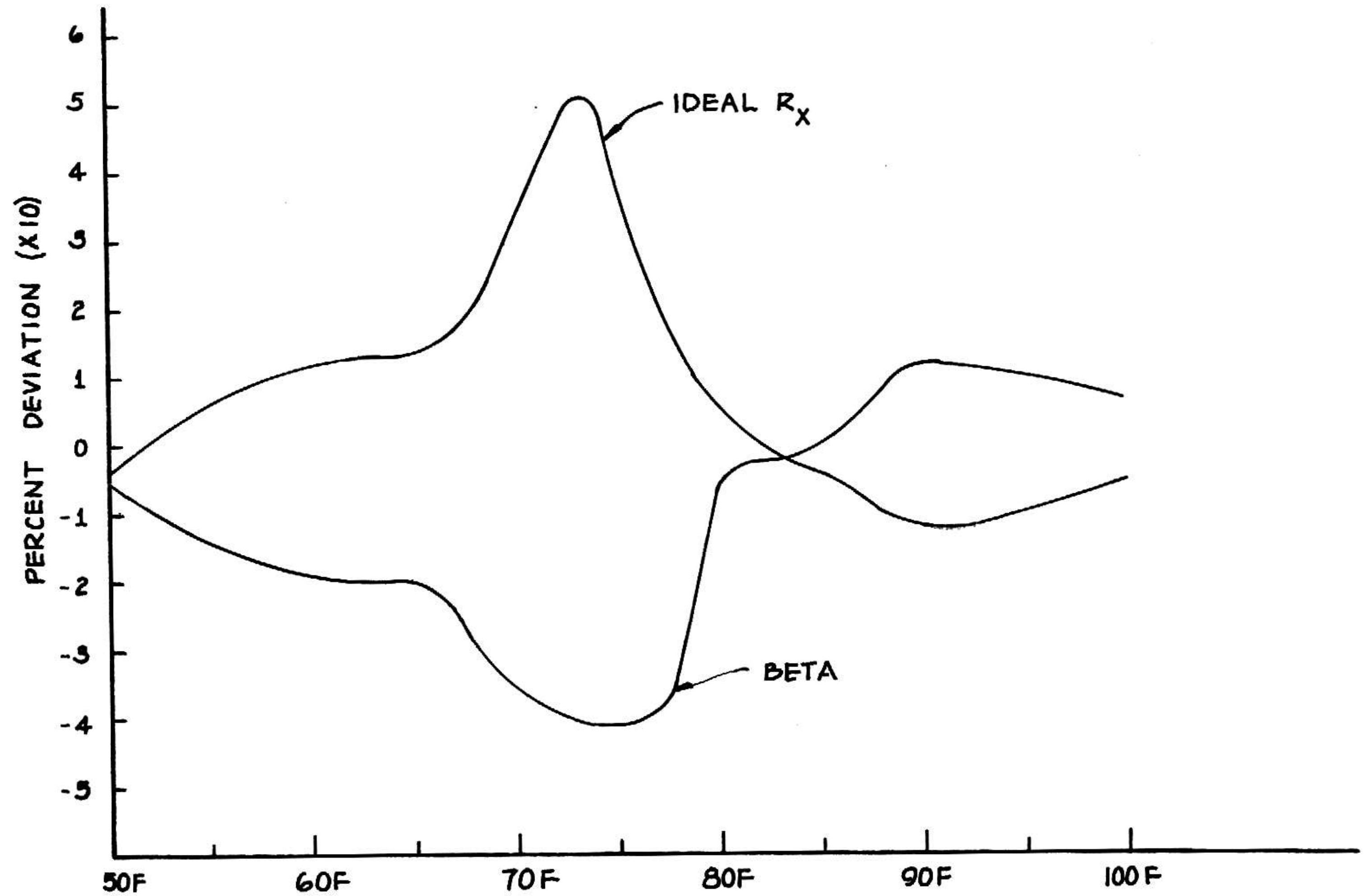


Figure 15

Illustration of the Absolute Error Dependency on R_3 and R_c

An attempt was made to correlate the percent errors in Table 9 with the error in Table 7 for a velocity of 10 feet per minute. The percent deviation from the average Beta was computed throughout the temperature range at a velocity of 10 feet per minute. These percentages are presented in Table 10. A graph was plotted using the percentage values in Table 10 and the percentage values in Table 9 versus the ambient temperature. This graph appears in Figure 15.

The results are conclusive and show beyond a doubt that the deviation in Beta and, therefore, the error in the air speed can be contributed to the fact that the ideal curve cannot be exactly fitted by the parallel combination of R_3 and R_c. It is emphazied that the best fit possible was obtained to begin with, because values for R_3 and Beta were taken at the minimum of the standard deviation curve.

Figure 16 shows an exaggerated graph of the ideal equivalent resistance and the actual "best" curve that resulted from the parallel combination of R_3 and R_c. The most pertinent fact is that an error of .312% in the curve fit caused an error of -21% in the air speed. This represents a sensitivity of better than -67 at this point.

Relative Error Analysis for the Circuit Components

In addition to the absolute error analysis a study was made concerning the effects the errors in the specific circuit components, R_3 , Beta, R_c, and R_s, have upon the error in the air speed. A relative error analysis was performed on each individual component and a final analysis was made that evaluated the effect of simultaneous errors occurring in the combined components. Air speeds of 20, 80, 200, 400, 600, and 1000 feet per minute were used as criteria for comparision of the errors.

Table 10

Percentage Deviation in Beta

Ambient Temperature	Percentage Deviation from Average Beta (.17488)
50	-.057
55	-.149
60	-.194
65	-.200
70	-.360
75	-.412
80	-.051
85	-.006
90	.114
95	.097
100	.063

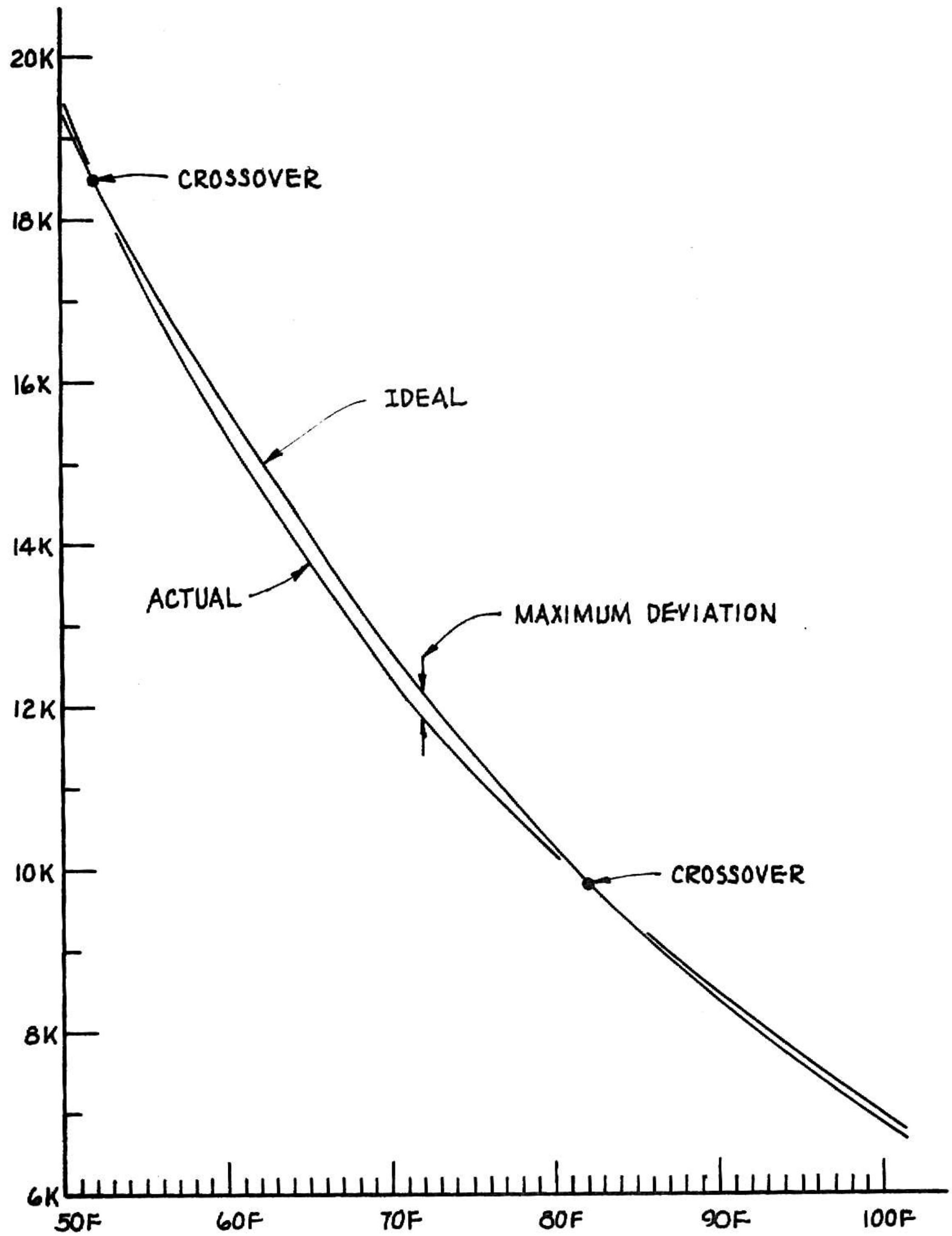


Figure 16

Comparison of Ideal Resistance with the Actual Resistance Obtained from the Parallel Combination of R_3 and R_c

The terminology, relative error analysis, was coined to emphasize the fact that a quantitative analysis was not made. The reason for this was that the absolute errors encountered were of such large magnitude that it would be difficult to observe and evaluate the effects of the additional errors contributed by the circuit components. Instead, an ideal resistance was generated for each of the six air speeds previously mentioned to replace the resistance characteristics of the compensating thermistor. This was done in a similar manner to the procedure for generating R_x in the previous section. Computer Program VII evaluates the relative errors for each circuit component separately and also computes the effect of equal errors occurring simultaneously in all the components.

To compute an ideal resistance to replace the one actually obtainable, an imaginary thermistor was created whose resistance values were described by

$$R_c = \frac{R_s}{\text{Beta} - (R_s/R_3)} \ . \qquad [29]$$

This equation forces R_c to take on a resistance that always is exactly the correct value for the bridge to be balanced. The temperature-resistance curve for R_c is not used in the relative error analysis programs, instead, Eq. [29] is used. The same temperature-resistance curve for the sensing thermistor is still used to compute the values for R_s once a temperature of the sensing thermistor is known.

To incorporate an error into the mathematical model for the system, the following relative component error equations are used:

For R_3,

$$R_s = \text{Beta}\frac{(R_3 \pm (R_3{*}PCT)){*}R_c}{(R_3 \pm (R_3{*}PCT)) + R_c} \ , \qquad [30]$$

For Beta,

$$R_s = \text{Beta} \pm (\text{Beta*PCT}) \frac{R_3 R_c}{R_3 + R_c}, \qquad [31]$$

For R_c,

$$R_s = \text{Beta} \frac{R_3 * (R_c \pm * \text{PCT}))}{R_3 + (R_c \pm R_c * \text{PCT}))}, \qquad [32]$$

For R_s

$$R_s = \text{Beta} \frac{R_3 R_c}{R_3 + R_c}, \qquad [33]$$

and,

$$R_{ss} = R_s \pm (R_s * \text{Beta}), \qquad [34]$$

where R_{ss} is the actual error equation for R_s.

For the combined components,

$$R_s = (\text{Beta} \pm (\text{Beta*PCT}) \frac{(R_3 \pm R_3 * \text{PCT})(R_c \pm R_c * \text{PCT})}{(R_3 \pm R_c * \text{PCT}) + (R_c \pm R_c * \text{PCT})}, \qquad [35]$$

$$R_{ss} = \text{Beta} \frac{R_3 R_c}{R_3 + R_c}, \qquad [36]$$

$$\text{ERRR}_{ss} = R_{ss} \pm \text{PCT}, \qquad [37]$$

$$R_{sss} = R_s + \text{ERRR}_{ss}, \qquad [38]$$

where Eq. [38] is the total relative error equation for the system. It should be noted that Eqs. [36] and [37] were necessary because an error in R_s is independent of errors in the other components. If the error for R_s were to be calculated as a percentage of Eq. [35], dependency upon errors in R_3, R_c, and Beta would result.

It should also be obvious that R_s is always the quantity being calculated. The reason for this is that this resistance is the only vehicle available to get to the describing heat transfer equation. The relative error programs determine the value of resistance for R_s first and then the temperature of the thermistor is calculated. With this temperature the power dissipation is calculated and then an air speed is determined from the amount of power dissipated. This air speed is then compared to what the true air speed should be for a zero error in all the components.

Tables 11 through 15 are the results of a relative error analysis computer run for a component error of 0.1%. The correct way to interpret these tables is to realize that each component must be compared at the same velocity since ideal resistance for the compensating thermistor is the same only for identical velocities and changes as the velocity changes. Also, the errors in the components represent the sensitivity and not the quantitative error. If these errors are divided by 0.1%, the sensitivity in the air speed with respect to the particular component is found. To illustrate this occurrence Table 16 was compiled at an ambient temperature of 100°F and a self-heat of 5°F for each component and for the complete system at an air speed of 20 feet per minute. The sensitivities were computed by dividing the errors in Tables 11 through 15 by 0.1%.

TABLE 11

RELATIVE ERROR ANALYSIS FOR THE

R3 CIRCUIT COMPONENT

R3 = 450000. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	SIGN OF COMPONENT ERROR	A 0.100 % ERROR IN THE CIRCUIT COMPONENT YIELDS THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED										
		50 F	55 F	60 F	65 F	70 F	75 F	80 F	85 F	90 F	95 F	100 F
20	+	-0.196	-0.196	-0.196	-0.196	-0.131	-0.131	-0.131	-0.131	-0.131	-0.131	-0.065
20	-	0.196	0.196	0.196	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.065
80	+	-0.163	-0.163	-0.131	-0.131	-0.098	-0.098	-0.098	-0.066	-0.066	-0.066	-0.066
80	-	0.163	0.130	0.130	0.130	0.097	0.097	0.097	0.097	0.065	0.065	0.065
200	+	-0.131	-0.131	-0.114	-0.098	-0.098	-0.098	-0.082	-0.065	-0.065	-0.065	-0.065
200	-	0.130	0.130	0.114	0.098	0.098	0.098	0.065	0.065	0.065	0.065	0.065
400	+	-0.131	-0.114	-0.098	-0.098	-0.082	-0.082	-0.065	-0.065	-0.065	-0.065	-0.049
400	-	0.130	0.114	0.098	0.098	0.082	0.082	0.065	0.065	0.065	0.065	0.049
600	+	-0.131	-0.114	-0.098	-0.082	-0.082	-0.082	-0.065	-0.065	-0.049	-0.049	-0.049
600	-	0.114	0.114	0.098	0.098	0.082	0.065	0.065	0.065	0.049	0.049	0.049
1000	+	-0.114	-0.098	-0.098	-0.082	-0.082	-0.065	-0.065	-0.065	-0.049	-0.049	-0.049
1000	-	0.114	0.098	0.098	0.081	0.073	0.065	0.065	0.057	0.049	0.049	0.049

TABLE 12

RELATIVE ERROR ANALYSIS FOR THE

BETA CIRCUIT COMPONENT

R3 = 450000. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	SIGN OF COMPONENT ERROR	A 0.100 % ERROR IN THE CIRCUIT COMPONENT YIELDS THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED										
		50 F	55 F	60 F	65 F	70 F	75 F	80 F	85 F	90 F	95 F	100 F
20	+	-5.088	-5.088	-5.154	-5.154	-5.088	-5.480	-5.545	-5.610	-5.675	-5.806	-5.871
20	-	5.219	5.219	5.284	5.349	5.284	5.675	5.741	5.806	5.871	6.001	6.132
80	+	-3.784	-3.784	-3.816	-3.849	-3.784	-4.045	-4.045	-4.110	-4.143	-4.241	-4.306
80	-	3.848	3.881	3.914	3.914	3.848	4.142	4.175	4.240	4.240	4.370	4.403
200	+	-3.229	-3.262	-3.262	-3.262	-3.229	-3.441	-3.458	-3.523	-3.523	-3.604	-3.637
200	-	3.294	3.310	3.327	3.343	3.294	3.523	3.523	3.588	3.588	3.686	3.718
400	+	-2.936	-2.952	-2.968	-2.968	-2.919	-3.115	-3.131	-3.164	-3.180	-3.246	-3.278
400	-	2.984	3.001	3.001	3.017	2.968	3.164	3.180	3.229	3.245	3.311	3.343
600	+	-2.805	-2.805	-2.805	-2.821	-2.773	-2.952	-2.968	-3.001	-3.017	-3.082	-3.099
600	-	2.838	2.854	2.870	2.870	2.821	3.017	3.017	3.066	3.066	3.131	3.164
1000	+	-2.650	-2.658	-2.658	-2.666	-2.618	-2.789	-2.805	-2.838	-2.838	-2.903	-2.919
1000	-	2.691	2.691	2.707	2.707	2.658	2.838	2.854	2.887	2.887	2.952	2.968

TABLE 13

RELATIVE ERROR ANALYSIS FOR THE

COMPENSATING THERMISTOR

R3 = 45000C. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	SIGN OF COMPONENT ERROR	A 0.100 % ERROR IN THE CIRCUIT COMPONENT YIELDS THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED										
		50 F	55 F	60 F	65 F	70 F	75 F	80 F	85 F	90 F	95 F	100 F
20	+	-4.827	-4.893	-4.958	-5.023	-4.958	-5.349	-5.415	-5.545	-5.610	-5.741	-5.806
20	-	4.958	5.023	5.088	5.153	5.088	5.545	5.610	5.675	5.741	5.936	6.001
80	+	-3.588	-3.653	-3.686	-3.719	-3.653	-3.947	-3.980	-4.045	-4.077	-4.175	-4.241
80	-	3.685	3.718	3.750	3.783	3.750	4.044	4.077	4.142	4.175	4.305	4.338
200	+	-3.099	-3.131	-3.164	-3.164	-3.131	-3.360	-3.392	-3.425	-3.458	-3.555	-3.588
200	-	3.164	3.180	3.196	3.229	3.196	3.425	3.457	3.490	3.523	3.620	3.653
400	+	-2.805	-2.838	-2.854	-2.870	-2.838	-3.033	-3.050	-3.099	-3.115	-3.197	-3.229
400	-	2.854	2.887	2.903	2.935	2.887	3.099	3.115	3.164	3.180	3.262	3.294
600	+	-2.675	-2.691	-2.724	-2.740	-2.691	-2.887	-2.903	-2.952	-2.952	-3.033	-3.050
600	-	2.723	2.740	2.756	2.789	2.740	2.936	2.952	3.001	3.017	3.082	3.115
1000	+	-2.536	-2.552	-2.577	-2.585	-2.544	-2.724	-2.740	-2.772	-2.789	-2.854	-2.879
1000	-	2.577	2.593	2.609	2.626	2.585	2.764	2.789	2.821	2.838	2.903	2.927

TABLE 14

RELATIVE ERROR ANALYSIS FOR THE

SENSING THERMISTOR

R3 = 450000. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	SIGN OF COMPONENT ERROR	A 0.100 % ERROR IN THE CIRCUIT COMPONENT YIELDS THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED										
		50 F	55 F	60 F	65 F	70 F	75 F	80 F	85 F	90 F	95 F	100 F
20	+	-5.088	-5.088	-5.154	-5.219	-5.088	-5.480	-5.545	-5.610	-5.675	-5.871	-5.871
20	-	5.219	5.219	5.284	5.349	5.284	5.675	5.741	5.806	5.871	6.001	6.132
80	+	-3.784	-3.784	-3.816	-3.849	-3.784	-4.045	-4.045	-4.110	-4.143	-4.241	-4.306
80	-	3.848	3.881	3.914	3.914	3.848	4.142	4.175	4.240	4.240	4.370	4.403
200	+	-3.229	-3.262	-3.262	-3.278	-3.229	-3.441	-3.458	-3.523	-3.523	-3.604	-3.637
200	-	3.294	3.310	3.327	3.343	3.294	3.523	3.523	3.588	3.588	3.686	3.718
400	+	-2.936	-2.952	-2.968	-2.968	-2.919	-3.115	-3.131	-3.164	-3.180	-3.262	-3.278
400	-	2.984	3.001	3.001	3.017	2.968	3.164	3.196	3.229	3.245	3.311	3.343
600	+	-2.805	-2.805	-2.821	-2.821	-2.773	-2.952	-2.968	-3.001	-3.017	-3.082	-3.099
600	-	2.838	2.854	2.870	2.870	2.821	3.017	3.017	3.066	3.066	3.131	3.164
1000	+	-2.650	-2.658	-2.658	-2.666	-2.618	-2.789	-2.805	-2.838	-2.838	-2.903	-2.919
1000	-	2.691	2.699	2.707	2.707	2.658	2.838	2.854	2.887	2.887	2.952	2.968

TABLE 15

RELATIVE ERROR ANALYSIS FOR THE

COMBINED CIRCUIT COMPONENTS

R3 = 450000. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	SIGN OF COMPONENT ERROR	A 0.100 % ERROR IN THE CIRCUIT COMPONENT YIELDS THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED										
		50 F	55 F	60 F	65 F	70 F	75 F	80 F	85 F	90 F	95 F	100 F
20	+	-14.678	-14.808	-14.939	-15.069	-14.873	-15.917	-16.048	-16.309	-16.439	-16.896	-17.091
20	-	16.113	16.243	16.374	16.569	16.309	17.548	17.744	18.070	18.200	18.787	18.983
80	+	-11.025	-11.090	-11.155	-11.221	-11.058	-11.840	-11.906	-12.069	-12.134	-12.460	-12.558
80	-	11.807	11.872	11.970	12.035	11.840	12.720	12.786	12.981	13.079	13.438	13.569
200	+	-9.508	-9.557	-9.590	-9.639	-9.492	-10.111	-10.177	-10.307	-10.340	-10.601	-10.682
200	-	10.079	10.111	10.176	10.209	10.046	10.764	10.812	10.959	11.024	11.285	11.383
400	+	-8.660	-8.693	-8.725	-8.758	-8.595	-9.166	-9.198	-9.329	-9.361	-9.557	-9.638
400	-	9.116	9.149	9.198	9.231	9.051	9.687	9.720	9.850	9.899	10.128	10.209
600	+	-8.252	-8.285	-8.301	-8.334	-8.171	-8.725	-8.741	-8.856	-8.888	-9.084	-9.149
600	-	8.676	8.692	8.725	8.758	8.595	9.198	9.214	9.328	9.361	9.589	9.655
1000	+	-7.828	-7.844	-7.861	-7.877	-7.730	-8.252	-8.268	-8.358	-8.383	-8.562	-8.619
1000	-	8.195	8.219	8.236	8.260	8.089	8.660	8.676	8.790	8.807	9.002	9.067

Table 16

Maximum Sensitivities for an Air Speed of 20 fpm

Circuit Component	Ambient Temperature 50	55	60	65	70	75	80	85	90	95	100
R_3	-2.44	-2.03	-1.63	-1.63	-1.63	-1.63	-1.63	-.81	-.81	-.81	-.81
Beta	-52.08	-52.49	-52.90	-53.71	-52.90	-56.97	-56.97	-58.89	-58.59	-60.22	-61.04
Compensating Thermistor	-49.48	-50.78	-50.78	-52.08	-51.43	-55.34	-55.99	-57.29	-57.29	-59.24	-59.90
Sensing Thermistor	-52.08	-52.73	-52.73	-53.39	-52.73	-56.64	-57.29	-58.59	-58.59	-60.55	-61.20
Combined	-160.81	-162.76	-164.06	-165.36	-162.76	-175.28	-177.08	-180.34	-182.29	-187.50	-190.10

Chapter 4

FINAL DESIGN CONSIDERATIONS

Introduction

Until now the theory behind sizing the components has been presented. In this chapter the theory will be used to obtain resistance values for R_1, R_2, and R_3 that represent the best possible values as far as minimizing the errors in air speed contributed by the circuit (see Fig. 1). In addition a comparision will be made between the values Flanders obtained for the circuit resistances and the ones obtained using the procedures discussed in this thesis. In addition the required performance of the compensating thermistor is examined and compared with its actual performance for both designs.

Component Sizing Procedure

The first step was to choose an appropriate power curve. To specify the power curve a self-heat and a reference temperature had to be determined. The reference temperature was not a critical parameter. Once a self-heat was choosen, the difference between a reference temperature of 50°F and 100°F amounted to a slight increase in the power dissipation for all velocities. The self-heat, on the other hand, had a marked effect on the performance of the the anemometer. It was determined in Chapter 3 that lower self-heats caused a decrease in the minimum standard deviation in Beta throughout the temperature-velocity range of the anemometer. On this basis, a self-heat of

5°F it was chosen to begin a preliminary investigation. Before the final sizing calculations were performed, a check was made to see if the sensitivity between changes in the air speed versus changes in the power dissipation was large enough to be adequately measured (see Appendix A). The values to be measured were the two voltages E_1 and E_s in Eq. [1]. It was concluded that accurate measurements could be made with available digital multimeters. Therefore, the anemometer was designed on a basis of using a self-heat of 5°F and a reference temperature of 100°F. The resulting power curve is illustrated in Table 17.

Table 17

The Power Curve in Tabular Form for a Self-heat of 5°F at a Reference Temperature of 100°F

Air Speed (FPM)	Power Dissipated by Sensing Thermistor (Milliwatts)
10	1.4164
20	1.5738
30	1.6901
40	1.7857
50	1.8685
60	1.9423
70	2.0094
80	2.0713
90	2.1289
100	2.1830
200	2.6077
300	2.9229
400	3.1833
500	3.4093
600	3.6115
700	3.7957
800	3.9659
900	4.1247
1000	4.2741

The next step was to determine the value of R_3 at which the standard deviation in Beta was minimum. The approximate range of the minimum standard deviation in Beta was narrowed down to between 400,000 ohms and 500,000 ohms for R_3. The sizing program, Program IV, was run for the following values of R_3:

400,000 ohms
420,000 ohms
440,000 ohms
460,000 ohms
480,000 ohms
500,000 ohms

The results of these runs appear in Tables 18 through 23, respectively. The resulting standard deviations were plotted versus the corresponding resistance for R_3 in Fig. 17. The minimum of this curve was found to occur at R_3 = 450,000 ohms. The sizing program was then run again for this value of R_3 and the results are shown in Table 24. A value of 0.17488 for Beta was calculated.

The next step was to determine the magnitude of the absolute errors occurring throughout the entire operating range for R_3 = 450,000 ohms and Beta = 0.17488. The absolute error program, Program V, was run. The results appear in Table 25. A maximum error of -25.7% occurs at an ambient temperature of 75°F and an air speed of 10 feet per minute. The errors at several other air speeds are, accordingly, quite large.

In an attempt to reduce these errors, the air speed was divided into three ranges, 10 to 100 feet per minute, 100 to 500 feet per minute, and 500 to 1000 feet per minute. The sizing program was run for each of these ranges to determine the minimum standard deviation in Beta. The final results are presented in Table 26.

The absolute error program was run for each range. Tables 27 through 29 show the results. The maximum error in the low range was -23.7% and occurr at 10 feet per minute and 75°F. The maximum error in the medium range was -13.2% and occurred at 100 feet per minute and 75°F. The maximum error for the

TABLE 18

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT POWER DISSIPATION ACROSS THE AMBIENT TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 400000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT										
	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17573	0.17547	0.17530	0.17521	0.17487	0.17471	0.17529	0.17532	0.17548	0.17542	0.17532
20	0.17583	0.17556	0.17538	0.17529	0.17493	0.17475	0.17533	0.17534	0.17550	0.17543	0.17532
30	0.17590	0.17562	0.17543	0.17533	0.17497	0.17478	0.17535	0.17536	0.17551	0.17543	0.17532
40	0.17594	0.17566	0.17547	0.17536	0.17499	0.17480	0.17537	0.17537	0.17552	0.17544	0.17532
50	0.17598	0.17569	0.17550	0.17538	0.17501	0.17482	0.17538	0.17538	0.17553	0.17544	0.17532
60	0.17601	0.17572	0.17552	0.17540	0.17503	0.17483	0.17539	0.17539	0.17553	0.17544	0.17532
70	0.17603	0.17574	0.17554	0.17542	0.17504	0.17484	0.17540	0.17540	0.17553	0.17544	0.17532
80	0.17605	0.17576	0.17555	0.17543	0.17506	0.17485	0.17541	0.17540	0.17554	0.17545	0.17532
90	0.17607	0.17577	0.17557	0.17544	0.17507	0.17486	0.17541	0.17541	0.17554	0.17545	0.17532
100	0.17608	0.17579	0.17558	0.17545	0.17508	0.17487	0.17542	0.17541	0.17554	0.17545	0.17532
200	0.17618	0.17587	0.17566	0.17552	0.17514	0.17491	0.17545	0.17544	0.17556	0.17546	0.17532
300	0.17623	0.17592	0.17570	0.17556	0.17517	0.17494	0.17547	0.17545	0.17557	0.17546	0.17532
400	0.17627	0.17595	0.17573	0.17558	0.17519	0.17495	0.17549	0.17546	0.17558	0.17546	0.17532
500	0.17630	0.17598	0.17575	0.17560	0.17520	0.17497	0.17550	0.17547	0.17558	0.17547	0.17532
600	0.17632	0.17599	0.17576	0.17561	0.17522	0.17498	0.17550	0.17548	0.17559	0.17547	0.17532
700	0.17633	0.17601	0.17578	0.17563	0.17523	0.17498	0.17551	0.17548	0.17559	0.17547	0.17532
800	0.17635	0.17602	0.17579	0.17564	0.17523	0.17499	0.17552	0.17548	0.17559	0.17547	0.17532
900	0.17636	0.17603	0.17580	0.17564	0.17524	0.17500	0.17552	0.17549	0.17559	0.17547	0.17532
1000	0.17637	0.17604	0.17581	0.17565	0.17525	0.17500	0.17552	0.17549	0.17560	0.17547	0.17532

AVERAGE BETA =0.17547 , STD. DEVIATION =0.000333

TABLE 19

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT
POWER DISSIPATION ACROSS THE AMBIENT
TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 42000C. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17532	0.17510	0.17497	0.17492	0.17461	0.17447	0.17508	0.17513	0.17531	0.17526	0.17518
20	0.17543	0.17520	0.17506	0.17499	0.17467	0.17452	0.17512	0.17515	0.17533	0.17527	0.17518
30	0.17549	0.17526	0.17511	0.17504	0.17470	0.17455	0.17514	0.17517	0.17534	0.17528	0.17518
40	0.17554	0.17530	0.17514	0.17506	0.17473	0.17457	0.17515	0.17518	0.17535	0.17528	0.17518
50	0.17557	0.17533	0.17517	0.17509	0.17475	0.17458	0.17517	0.17519	0.17535	0.17528	0.17518
60	0.17560	0.17535	0.17519	0.17511	0.17477	0.17460	0.17518	0.17520	0.17536	0.17528	0.17518
70	0.17562	0.17537	0.17521	0.17512	0.17478	0.17461	0.17519	0.17521	0.17536	0.17529	0.17518
80	0.17564	0.17539	0.17523	0.17514	0.17479	0.17462	0.17519	0.17521	0.17537	0.17529	0.17518
90	0.17566	0.17541	0.17524	0.17515	0.17480	0.17462	0.17520	0.17522	0.17537	0.17529	0.17518
100	0.17568	0.17542	0.17525	0.17516	0.17481	0.17463	0.17520	0.17522	0.17537	0.17529	0.17518
200	0.17578	0.17551	0.17533	0.17523	0.17487	0.17468	0.17524	0.17525	0.17539	0.17530	0.17518
300	0.17583	0.17556	0.17537	0.17526	0.17490	0.17470	0.17526	0.17526	0.17540	0.17530	0.17518
400	0.17587	0.17559	0.17540	0.17529	0.17492	0.17472	0.17527	0.17527	0.17540	0.17531	0.17518
500	0.17589	0.17561	0.17542	0.17531	0.17494	0.17473	0.17528	0.17528	0.17541	0.17531	0.17518
600	0.17591	0.17563	0.17544	0.17532	0.17495	0.17474	0.17529	0.17528	0.17541	0.17531	0.17518
700	0.17593	0.17565	0.17545	0.17533	0.17496	0.17475	0.17530	0.17529	0.17542	0.17531	0.17518
800	0.17594	0.17566	0.17546	0.17534	0.17497	0.17475	0.17530	0.17529	0.17542	0.17531	0.17518
900	0.17596	0.17567	0.17547	0.17535	0.17498	0.17476	0.17531	0.17530	0.17542	0.17532	0.17518
1000	0.17597	0.17568	0.17548	0.17536	0.17498	0.17476	0.17531	0.17530	0.17542	0.17532	0.17518

AVERAGE BETA =0.17522 STD. DEVIATION =0.000294

TABLE 20

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT POWER DISSIPATION ACROSS THE AMBIENT TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 440000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17495	0.17477	0.17468	0.17465	0.17437	0.17426	0.17488	0.17495	0.17515	0.17512	0.17505
20	0.17506	0.17487	0.17476	0.17473	0.17443	0.17430	0.17492	0.17498	0.17517	0.17513	0.17505
30	0.17512	0.17493	0.17481	0.17477	0.17447	0.17433	0.17494	0.17500	0.17518	0.17513	0.17505
40	0.17517	0.17497	0.17485	0.17480	0.17449	0.17435	0.17496	0.17501	0.17519	0.17514	0.17505
50	0.17520	0.17500	0.17487	0.17482	0.17451	0.17437	0.17497	0.17502	0.17519	0.17514	0.17505
60	0.17523	0.17502	0.17489	0.17484	0.17453	0.17438	0.17498	0.17502	0.17520	0.17514	0.17505
70	0.17526	0.17504	0.17491	0.17486	0.17454	0.17439	0.17499	0.17503	0.17520	0.17514	0.17505
80	0.17528	0.17506	0.17493	0.17487	0.17456	0.17440	0.17500	0.17504	0.17521	0.17515	0.17505
90	0.17529	0.17508	0.17494	0.17488	0.17457	0.17441	0.17501	0.17504	0.17521	0.17515	0.17505
100	0.17531	0.17509	0.17496	0.17489	0.17457	0.17442	0.17501	0.17504	0.17521	0.17515	0.17505
200	0.17541	0.17518	0.17503	0.17496	0.17463	0.17446	0.17505	0.17507	0.17523	0.17516	0.17505
300	0.17546	0.17523	0.17507	0.17500	0.17466	0.17449	0.17507	0.17509	0.17524	0.17516	0.17505
400	0.17550	0.17526	0.17510	0.17502	0.17469	0.17450	0.17508	0.17510	0.17525	0.17516	0.17505
500	0.17552	0.17528	0.17512	0.17504	0.17470	0.17451	0.17509	0.17510	0.17525	0.17517	0.17505
600	0.17554	0.17530	0.17514	0.17505	0.17471	0.17452	0.17510	0.17511	0.17526	0.17517	0.17505
700	0.17556	0.17532	0.17515	0.17507	0.17472	0.17453	0.17510	0.17511	0.17526	0.17517	0.17505
800	0.17557	0.17533	0.17516	0.17508	0.17473	0.17454	0.17511	0.17512	0.17526	0.17517	0.17505
900	0.17559	0.17534	0.17517	0.17508	0.17474	0.17454	0.17511	0.17512	0.17526	0.17517	0.17505
1000	0.17560	0.17535	0.17518	0.17509	0.17474	0.17455	0.17512	0.17512	0.17527	0.17517	0.17505

AVERAGE BETA =0.17499 STD. DEVIATION =0.000277

TABLE 21

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT POWER DISSIPATION ACROSS THE AMBIENT TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 460000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17462	0.17447	0.17441	0.17441	0.17415	0.17406	0.17471	0.17479	0.17501	0.17499	0.17493
20	0.17473	0.17457	0.17449	0.17448	0.17421	0.17411	0.17474	0.17482	0.17503	0.17500	0.17493
30	0.17479	0.17462	0.17454	0.17453	0.17425	0.17414	0.17477	0.17484	0.17504	0.17500	0.17493
40	0.17483	0.17466	0.17457	0.17455	0.17427	0.17416	0.17478	0.17485	0.17504	0.17501	0.17493
50	0.17487	0.17470	0.17460	0.17458	0.17429	0.17417	0.17480	0.17486	0.17505	0.17501	0.17493
60	0.17490	0.17472	0.17462	0.17460	0.17431	0.17419	0.17481	0.17486	0.17506	0.17501	0.17493
70	0.17492	0.17474	0.17464	0.17461	0.17432	0.17420	0.17481	0.17487	0.17506	0.17501	0.17493
80	0.17494	0.17476	0.17466	0.17463	0.17434	0.17420	0.17482	0.17488	0.17506	0.17502	0.17493
90	0.17496	0.17478	0.17467	0.17464	0.17435	0.17421	0.17483	0.17488	0.17507	0.17502	0.17493
100	0.17497	0.17479	0.17468	0.17465	0.17436	0.17422	0.17483	0.17489	0.17507	0.17502	0.17493
200	0.17507	0.17488	0.17476	0.17472	0.17441	0.17427	0.17487	0.17491	0.17509	0.17503	0.17493
300	0.17513	0.17492	0.17480	0.17475	0.17445	0.17429	0.17489	0.17493	0.17510	0.17503	0.17493
400	0.17516	0.17496	0.17483	0.17478	0.17447	0.17431	0.17490	0.17494	0.17510	0.17503	0.17493
500	0.17519	0.17498	0.17485	0.17480	0.17448	0.17432	0.17491	0.17494	0.17511	0.17504	0.17493
600	0.17521	0.17500	0.17487	0.17481	0.17449	0.17433	0.17492	0.17495	0.17511	0.17504	0.17493
700	0.17522	0.17501	0.17488	0.17482	0.17450	0.17434	0.17493	0.17495	0.17511	0.17504	0.17493
800	0.17524	0.17503	0.17489	0.17483	0.17451	0.17434	0.17493	0.17496	0.17512	0.17504	0.17493
900	0.17525	0.17504	0.17490	0.17484	0.17452	0.17435	0.17494	0.17496	0.17512	0.17504	0.17493
1000	0.17526	0.17504	0.17491	0.17485	0.17453	0.17435	0.17494	0.17496	0.17512	0.17504	0.17493

AVERAGE BETA =0.17478 STD. DEVIATION =0.000278

TABLE 22

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT POWER DISSIPATION ACROSS THE AMBIENT TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 480000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17431	0.17420	0.17416	0.17419	0.17395	0.17388	0.17454	0.17464	0.17487	0.17487	0.17482
20	0.17442	0.17429	0.17424	0.17426	0.17401	0.17393	0.17458	0.17467	0.17489	0.17488	0.17482
30	0.17448	0.17435	0.17429	0.17430	0.17405	0.17396	0.17460	0.17469	0.17490	0.17488	0.17482
40	0.17453	0.17439	0.17433	0.17433	0.17407	0.17398	0.17462	0.17470	0.17491	0.17489	0.17482
50	0.17456	0.17442	0.17435	0.17436	0.17409	0.17399	0.17463	0.17471	0.17492	0.17489	0.17482
60	0.17459	0.17444	0.17437	0.17437	0.17411	0.17401	0.17464	0.17472	0.17492	0.17489	0.17482
70	0.17461	0.17447	0.17439	0.17439	0.17412	0.17402	0.17465	0.17473	0.17493	0.17489	0.17482
80	0.17463	0.17448	0.17441	0.17441	0.17414	0.17403	0.17466	0.17473	0.17493	0.17490	0.17482
90	0.17465	0.17450	0.17442	0.17442	0.17415	0.17403	0.17467	0.17473	0.17493	0.17490	0.17482
100	0.17467	0.17451	0.17444	0.17443	0.17416	0.17404	0.17467	0.17474	0.17494	0.17490	0.17482
200	0.17476	0.17460	0.17451	0.17449	0.17421	0.17409	0.17471	0.17477	0.17495	0.17491	0.17482
300	0.17482	0.17465	0.17455	0.17453	0.17425	0.17411	0.17473	0.17478	0.17496	0.17491	0.17482
400	0.17485	0.17468	0.17458	0.17455	0.17427	0.17413	0.17474	0.17479	0.17497	0.17491	0.17482
500	0.17488	0.17470	0.17460	0.17457	0.17428	0.17414	0.17475	0.17480	0.17498	0.17492	0.17482
600	0.17490	0.17472	0.17462	0.17459	0.17429	0.17415	0.17476	0.17480	0.17498	0.17492	0.17482
700	0.17492	0.17474	0.17463	0.17460	0.17430	0.17416	0.17476	0.17481	0.17498	0.17492	0.17482
800	0.17493	0.17475	0.17464	0.17461	0.17431	0.17416	0.17477	0.17481	0.17498	0.17492	0.17482
900	0.17494	0.17476	0.17465	0.17462	0.17432	0.17417	0.17477	0.17481	0.17499	0.17492	0.17482
1000	0.17495	0.17477	0.17466	0.17462	0.17433	0.17417	0.17478	0.17482	0.17499	0.17492	0.17482

AVERAGE BETA =0.17459 STD. DEVIATION =0.000294

TABLE 23

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT
POWER DISSIPATION ACROSS THE AMBIENT
TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 500000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17403	0.17394	0.17393	0.17398	0.17376	0.17371	0.17439	0.17451	0.17475	0.17476	0.17472
20	0.17413	0.17404	0.17401	0.17405	0.17383	0.17376	0.17443	0.17454	0.17477	0.17477	0.17472
30	0.17420	0.17409	0.17406	0.17410	0.17386	0.17379	0.17446	0.17456	0.17478	0.17477	0.17472
40	0.17424	0.17413	0.17410	0.17413	0.17389	0.17381	0.17447	0.17457	0.17479	0.17478	0.17472
50	0.17428	0.17417	0.17412	0.17415	0.17391	0.17383	0.17449	0.17458	0.17480	0.17478	0.17472
60	0.17431	0.17419	0.17415	0.17417	0.17393	0.17384	0.17450	0.17458	0.17480	0.17478	0.17472
70	0.17433	0.17421	0.17417	0.17419	0.17394	0.17385	0.17450	0.17459	0.17481	0.17478	0.17472
80	0.17435	0.17423	0.17418	0.17420	0.17395	0.17386	0.17451	0.17460	0.17481	0.17479	0.17472
90	0.17437	0.17424	0.17419	0.17421	0.17396	0.17387	0.17452	0.17460	0.17481	0.17479	0.17472
100	0.17438	0.17426	0.17421	0.17422	0.17397	0.17388	0.17452	0.17460	0.17482	0.17479	0.17472
200	0.17448	0.17435	0.17428	0.17429	0.17403	0.17392	0.17456	0.17463	0.17483	0.17480	0.17472
300	0.17453	0.17439	0.17433	0.17432	0.17406	0.17394	0.17458	0.17465	0.17484	0.17480	0.17472
400	0.17457	0.17442	0.17435	0.17435	0.17408	0.17396	0.17459	0.17466	0.17485	0.17480	0.17472
500	0.17460	0.17445	0.17437	0.17437	0.17410	0.17397	0.17460	0.17466	0.17485	0.17481	0.17472
600	0.17462	0.17447	0.17439	0.17438	0.17411	0.17398	0.17461	0.17467	0.17486	0.17481	0.17472
700	0.17463	0.17448	0.17440	0.17439	0.17412	0.17399	0.17461	0.17467	0.17486	0.17481	0.17472
800	0.17465	0.17449	0.17441	0.17440	0.17413	0.17400	0.17462	0.17468	0.17486	0.17481	0.17472
900	0.17466	0.17450	0.17442	0.17441	0.17414	0.17400	0.17462	0.17468	0.17487	0.17481	0.17472
1000	0.17467	0.17451	0.17443	0.17442	0.17414	0.17401	0.17463	0.17468	0.17487	0.17481	0.17472

AVERAGE BETA =0.17441 STD. DEVIATION =0.000319

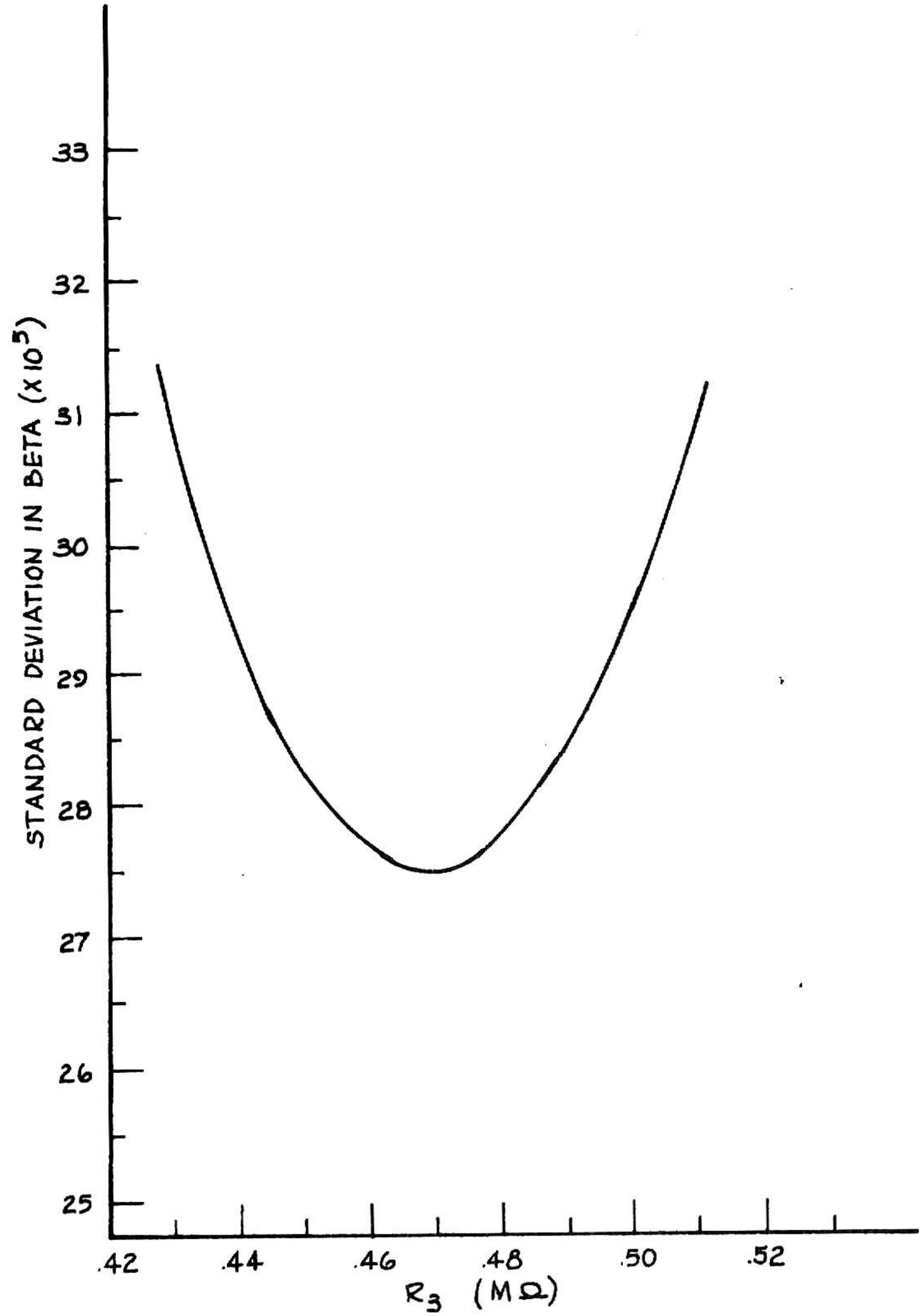


Figure 17

Final Design Results of the Standard Deviation
Curve for 5°F Self-heat @ 100°F

TABLE 24

REQUIRED VALUES OF BETA (R1/R2) FOR CONSTANT
POWER DISSIPATION ACROSS THE AMBIENT
TEMPERATURE RANGE OF 50 F TO 100 F

SELF-HEAT = 5 DEGREES FAHRENHEIT
REFERENCE TEMPERATURE = 100 DEGREES FAHRENHEIT
R3 = 450000. OHMS

AIR SPEED (FPM)	REQUIRED VALUES OF BETA AT 50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	0.17478	0.17462	0.17454	0.17453	0.17425	0.17416	0.17479	0.17487	0.17508	0.17505	0.17499
20	0.17489	0.17472	0.17462	0.17460	0.17432	0.17420	0.17483	0.17490	0.17510	0.17506	0.17499
30	0.17495	0.17477	0.17467	0.17464	0.17435	0.17423	0.17485	0.17491	0.17511	0.17507	0.17499
40	0.17500	0.17481	0.17471	0.17467	0.17438	0.17425	0.17487	0.17493	0.17511	0.17507	0.17499
50	0.17503	0.17484	0.17473	0.17470	0.17440	0.17427	0.17488	0.17493	0.17512	0.17507	0.17499
60	0.17506	0.17487	0.17476	0.17472	0.17442	0.17428	0.17489	0.17494	0.17513	0.17508	0.17499
70	0.17508	0.17489	0.17478	0.17473	0.17443	0.17429	0.17490	0.17495	0.17513	0.17508	0.17499
80	0.17510	0.17491	0.17479	0.17475	0.17444	0.17430	0.17491	0.17495	0.17513	0.17508	0.17499
90	0.17512	0.17492	0.17480	0.17476	0.17445	0.17431	0.17491	0.17496	0.17514	0.17508	0.17499
100	0.17514	0.17494	0.17482	0.17477	0.17446	0.17432	0.17492	0.17496	0.17514	0.17508	0.17499
200	0.17524	0.17502	0.17489	0.17484	0.17452	0.17436	0.17496	0.17499	0.17516	0.17509	0.17499
300	0.17529	0.17507	0.17494	0.17487	0.17455	0.17439	0.17498	0.17500	0.17517	0.17510	0.17499
400	0.17533	0.17510	0.17496	0.17490	0.17457	0.17440	0.17499	0.17501	0.17517	0.17510	0.17499
500	0.17535	0.17513	0.17498	0.17492	0.17459	0.17441	0.17500	0.17502	0.17518	0.17510	0.17499
600	0.17537	0.17515	0.17500	0.17493	0.17460	0.17442	0.17501	0.17503	0.17518	0.17510	0.17499
700	0.17539	0.17516	0.17501	0.17494	0.17461	0.17443	0.17501	0.17503	0.17518	0.17510	0.17499
800	0.17540	0.17517	0.17502	0.17495	0.17462	0.17444	0.17502	0.17504	0.17519	0.17510	0.17499
900	0.17541	0.17518	0.17503	0.17496	0.17463	0.17444	0.17502	0.17504	0.17519	0.17511	0.17499
1000	0.17542	0.17519	0.17504	0.17497	0.17463	0.17445	0.17503	0.17504	0.17519	0.17511	0.17499

AVERAGE BETA =0.17488 STD. DEVIATION =0.000275

TABLE 25

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 45000C. OHMS
BETA = 0.17488
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	-3.4	-9.0	-11.9	-12.3	-21.0	-25.7	-3.4	-0.4	8.1	7.2	4.4
20	0.3	-4.8	-7.6	-8.2	-16.0	-20.4	-1.6	0.5	7.3	6.2	3.7
30	2.0	-2.9	-5.5	-6.3	-13.6	-17.7	-0.8	1.0	6.9	5.8	3.3
40	2.0	-1.7	-4.4	-5.2	-12.1	-16.2	-0.3	1.3	6.7	5.5	3.1
50	3.7	-0.8	-3.5	-4.4	-11.2	-15.1	0.1	1.4	6.5	5.3	2.9
60	4.2	-0.3	-2.9	-3.8	-10.4	-14.2	0.3	1.6	6.4	5.2	2.8
70	4.6	0.2	-2.3	-3.3	-9.8	-13.6	0.5	1.7	6.3	5.1	2.7
80	5.0	0.6	-2.0	-2.9	-9.3	-13.0	0.7	1.8	6.2	5.0	2.7
90	5.3	0.9	-1.6	-2.6	-8.9	-12.6	0.8	1.9	6.1	4.9	2.6
100	5.5	1.2	-1.3	-2.3	-8.5	-12.2	0.9	1.9	6.1	4.8	2.5
200	6.8	2.7	0.3	-0.8	-6.6	-10.0	1.5	2.3	5.7	4.4	2.3
300	7.3	3.4	1.0	-0.1	-5.6	-9.0	1.8	2.4	5.6	4.3	2.1
400	7.7	3.8	1.4	0.3	-5.1	-8.4	2.0	2.5	5.4	4.1	2.0
500	7.9	4.1	1.7	0.6	-4.7	-8.0	2.1	2.5	5.4	4.1	2.0
600	8.1	4.3	2.0	0.8	-4.4	-7.6	2.2	2.6	5.3	4.0	1.9
700	8.2	4.5	2.1	1.0	-4.2	-7.4	2.3	2.6	5.3	3.9	1.9
800	8.3	4.6	2.3	1.1	-4.0	-7.1	2.3	2.6	5.2	3.9	1.8
900	8.4	4.8	2.4	1.2	-3.8	-7.0	2.3	2.6	5.2	3.9	1.8
1000	8.5	4.8	2.5	1.3	-3.7	-6.8	2.4	2.7	5.2	3.8	1.8

Table 26

Resistance Values for R_3 and Beta for the Low, Medium, and High Ranges

Low Range 10-100 fpm
R_3 = 434,000 ohms
Beta = .17498

Medium Range 100-500 fpm
R_3 = 460,000 ohms
Beta = .17483

High Range 500-1000 fpm
R_3 = 470,000 ohms
Beta = .17479

TABLE 27

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 434000. OHMS
BETA = 0.17498
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED (FPM)	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	2.9	-3.8	-7.6	-8.8	-18.4	-23.7	-1.6	0.8	8.9	7.6	4.4
20	5.6	-0.5	-4.0	-5.2	-13.8	-18.6	-0.1	1.6	8.0	6.5	3.6
30	6.8	1.1	-2.2	-3.6	-11.5	-16.1	0.6	2.0	7.5	6.1	3.3
40	7.6	2.1	-1.2	-2.7	-10.2	-14.6	1.0	2.2	7.2	5.7	3.0
50	8.1	2.7	-0.5	-2.0	-9.3	-13.6	1.3	2.3	7.0	5.5	2.9
60	8.5	3.2	0.0	-1.4	-8.6	-12.8	1.5	2.4	6.9	5.4	2.7
70	8.7	3.6	0.5	-1.0	-8.1	-12.2	1.6	2.5	6.8	5.3	2.7
80	9.0	3.9	0.7	-0.7	-7.6	-11.7	1.8	2.6	6.7	5.2	2.6
90	9.2	4.2	1.0	-0.4	-7.2	-11.3	1.9	2.6	6.6	5.1	2.5
100	9.4	4.4	1.3	-0.2	-6.9	-10.9	2.0	2.6	6.5	5.0	2.5

TABLE 28

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 460000. OHMS
BETA = 0.17483
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
100	3.1	-0.8	-3.1	-3.8	-9.7	-13.1	0.1	1.3	5.6	4.5	2.3
200	4.6	0.9	-1.3	-2.1	-7.6	-10.9	0.8	1.7	5.3	4.1	2.1
300	5.3	1.7	-0.5	-1.4	-6.6	-9.8	1.1	1.9	5.2	4.0	2.0
400	5.7	2.2	0.0	-0.9	-6.0	-9.2	1.3	2.0	5.1	3.9	1.9
500	6.0	2.5	0.4	-0.6	-5.6	-8.7	1.5	2.0	5.0	3.8	1.8

TABLE 29

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 47COOC. OHMS
BETA = 0.17479
SELF-HEAT = 5 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
500	4.0	0.8	-1.1	-1.8	-6.6	-9.6	0.7	1.4	4.5	3.4	1.5
600	4.2	1.1	-0.8	-1.5	-6.2	-9.2	0.8	1.5	4.5	3.4	1.5
700	4.4	1.3	-0.6	-1.3	-6.0	-8.9	0.9	1.5	4.4	3.3	1.5
800	4.6	1.5	-0.4	-1.1	-5.8	-8.7	1.0	1.6	4.4	3.3	1.4
900	4.7	1.6	-0.2	-1.0	-5.6	-8.5	1.0	1.6	4.4	3.3	1.4
1000	4.8	1.7	-0.1	-0.9	-5.4	-8.3	1.1	1.6	4.4	3.2	1.4

high range occurred at 500 feet per minute and 75°F and was equal to -9.6%. A resistance of 10,000 ohms was chosen for R_1 for all three ranges (see Appendix A). Table 30 shows resistances used in construction of the anemometer circuit.

Table 30

Resistance Values Used in Construction of the Final Circuit

Low Range:

R_1 = 10,000 ohms

R_2 = 57,150 ohms

R_3 = 434,000 ohms

Middle Range:

R_1 = 10,000 ohms

R_2 = 57,200 ohms

R_3 = 460,000 ohms

High Range:

R_1 = 10,000 ohms

R_2 = 57,212 ohms

R_3 = 470,000 ohms

A comparison was made between the maximum absolute errors occurring for the full range using the results of Table 25 and for the low, medium, and high ranges using the results from Tables 27 through 29. Between 10 and 100 feet per minute the full range exhibited a maximum error of -25.7%. This is 2.0% greater than for the low range. Between 100 and 500 feet per minute, the full range had a maximum error of -12.2% which is 2.6% larger than for the middle range. Between 500 and 1000 feet per minute, the full range had a maximum error of 8.0% and the high range had a maximum error of -9.6%.

However, when the rest of the values in the middle and high range are examined the average error is an improvement over the average error for the comparable range of the full range.

Another comparison was made between the absolute errors obtained for the low, medium, and high ranges and those occurring using Mr. Flanders values. Flanders used a self-heat of 20°F and a reference temperature of 100°F in his instrument. The air speed was divided into two ranges: 10 to 100 feet per minute and 100 to 1000 feet per minute. For the low range, Flanders used R_1 = 2500 ohms, R_2 = 18,677.5 ohms, and R_3 = 149,460.0 ohms resulting in a value of 0.13385 for Beta. For the high range R_1 = 2500 ohms, R_2 = 18,707.5 ohms, and R_3 = 154,790.0 ohms resulting in a value of 0.13364 for Beta. The absolute error program was run using these values for each range. The results are presented in Tables 31 and 32. For Flanders' low range (Table 31) the maximum absolute error occurs at 10 feet per minute and 50°F and remains nearly constant at approximately 20% up to 100 feet per minute. As the temperature increases the errors drop rapidly to nearly zero.

To more clearly evaluate Flanders' choice of resistance size the sizing program, Program IV, was run for the low and high range. Beta versus R_3 was plotted to find the optimum values for Beta and R_3 at 20°F and a reference temperature of 100°F. The plot for the low range is illustrated in Figure 18 and the plot for the high range is illustrated in Figure 19. The operating point of Flanders' circuit for each range is plotted as indicated by the small circle on the curves. It is evident that for each range the operating point is removed from the optimum condition which is located at the minimum of the standard deviation curve for each case. Therefore, the resistors Mr. Flanders used to construct his circuit were not the "best" combination for obtaining 20°F self-heat at a reference temperature of 100°F.

If the magnitude of the absolute errors in Table 31 are compared to Table 27, the overall errors are smaller for 20°F self-heat (4.2%) than for 5°F self-heat (5.38%). It was assumed in Chapter 3 that smaller standard deviations in Beta should yield smaller absolute errors. The standard deviation in Beta is .000750 for 20°F self-heat and .000275 for 5°F self-heat yet the absolute error average is about 1% greater for 5°F self-heat. The reason must be that the sensitivity of the air speed to the deviation from the average Beta decreases as the self-heat increases. It will be recommended that subsequent investigations into this effect be carried out.

TABLE 31

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 149460. OHMS
BETA = 0.13385
SELF-HEAT = 20 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
10	21.2	5.1	-4.3	-6.0	-6.6	-5.1	0.1	2.3	4.2	0.8	-0.1
20	20.9	7.0	-1.2	-3.0	-3.7	-2.7	1.3	2.9	4.0	1.0	-0.1
30	20.7	7.9	0.2	-1.5	-2.4	-1.7	1.9	3.1	4.0	1.1	-0.1
40	20.6	8.5	1.1	-0.7	-1.6	-1.0	2.2	3.2	3.9	1.1	-0.1
50	20.5	8.8	1.7	-0.1	-1.0	-0.6	2.4	3.3	3.9	1.1	-0.1
60	20.4	9.1	2.2	0.4	-0.6	-0.2	2.6	3.4	3.9	1.1	-0.1
70	20.3	9.3	2.5	0.7	-0.3	0.0	2.7	3.4	3.8	1.2	-0.1
80	20.2	9.5	2.8	1.0	-0.0	0.3	2.8	3.4	3.8	1.2	-0.1
90	20.2	9.6	3.0	1.2	0.2	0.4	2.9	3.5	3.8	1.2	-0.1
100	20.1	9.7	3.2	1.4	0.4	0.6	2.9	3.5	3.8	1.2	-0.1

TABLE 32

ABSOLUTE ERROR ANALYSIS

THE PERCENT ERRORS IN THE AIR SPEED LISTED IN THE TABLE BELOW WERE CALCULATED WITH THE FOLLOWING RESTRICTIONS:

R3 = 154790. OHMS
BETA = 0.13364
SELF-HEAT = 20 F
REFERENCE TEMPERATURE = 100 F

AIR SPEED	PERCENTAGE ERROR IN THE INDICATED AIR SPEED AT ELEVEN DIFFERENT AMBIENT TEMPERATURES										
(FPM)	50F	55F	60F	65F	70F	75F	80F	85F	90F	95F	100F
100	17.6	7.6	1.5	-0.0	-0.8	-0.3	2.2	3.0	3.5	1.1	-0.0
200	17.6	8.5	2.7	1.2	0.4	0.6	2.7	3.2	3.4	1.1	-0.0
300	17.5	8.8	3.3	1.8	0.9	1.0	2.9	3.3	3.4	1.1	-0.0
400	17.5	9.0	3.7	2.2	1.2	1.3	3.0	3.3	3.4	1.2	-0.0
500	17.4	9.2	3.9	2.4	1.4	1.4	3.1	3.3	3.4	1.2	-0.0
600	17.4	9.3	4.1	2.6	1.6	1.6	3.2	3.4	3.4	1.2	-0.0
700	17.3	9.4	4.2	2.7	1.7	1.7	3.2	3.4	3.3	1.2	-0.0
800	17.3	9.4	4.3	2.8	1.8	1.7	3.2	3.4	3.3	1.2	-0.0
900	17.3	9.5	4.4	2.9	1.9	1.8	3.3	3.4	3.3	1.2	-0.0
1000	17.2	9.5	4.5	3.0	2.0	1.9	3.3	3.4	3.3	1.2	-0.0

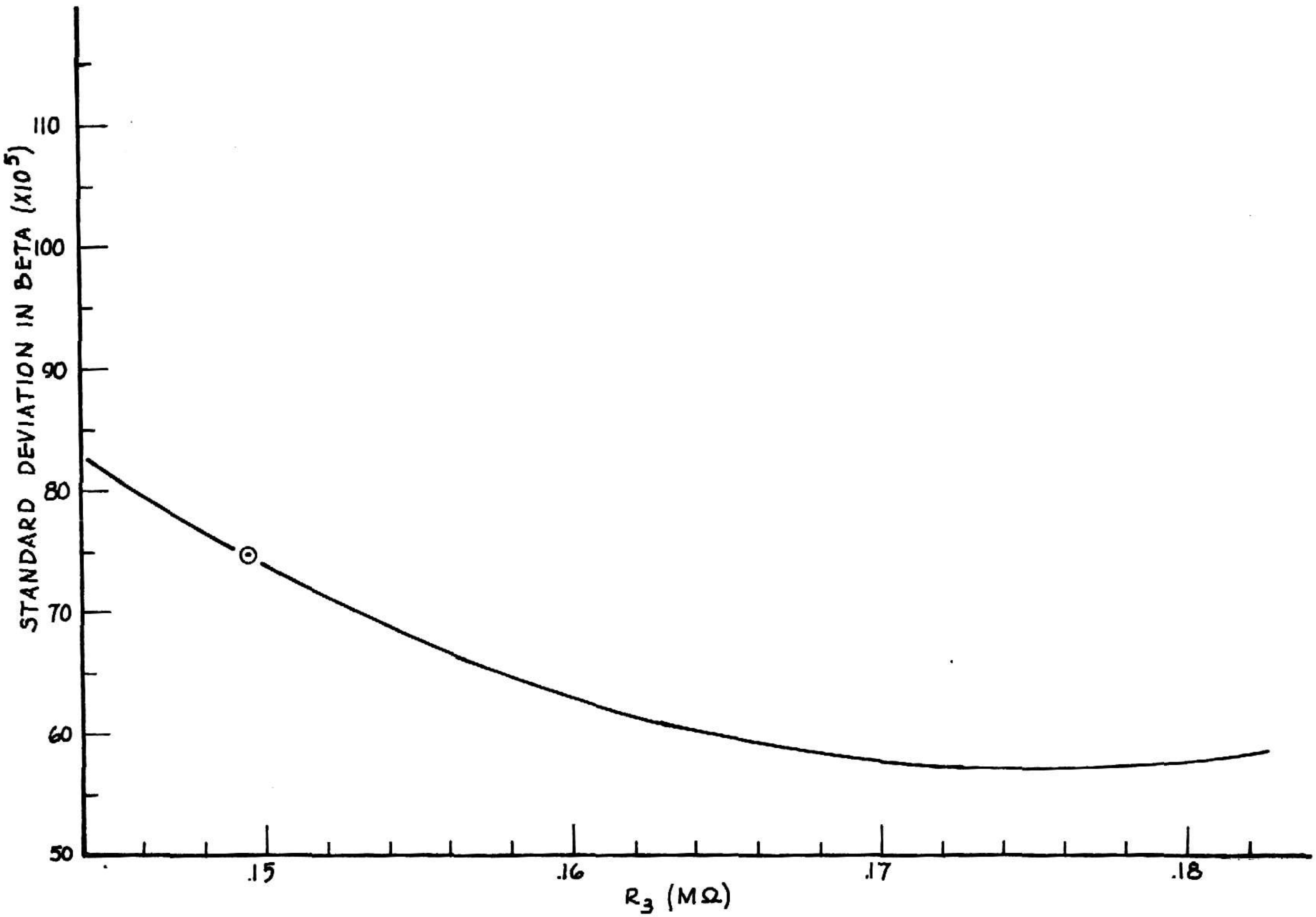


Figure 18

Comparison of Flanders' Resistance Values for Beta and R_3
with the Optimum Resistance Values - Low Range

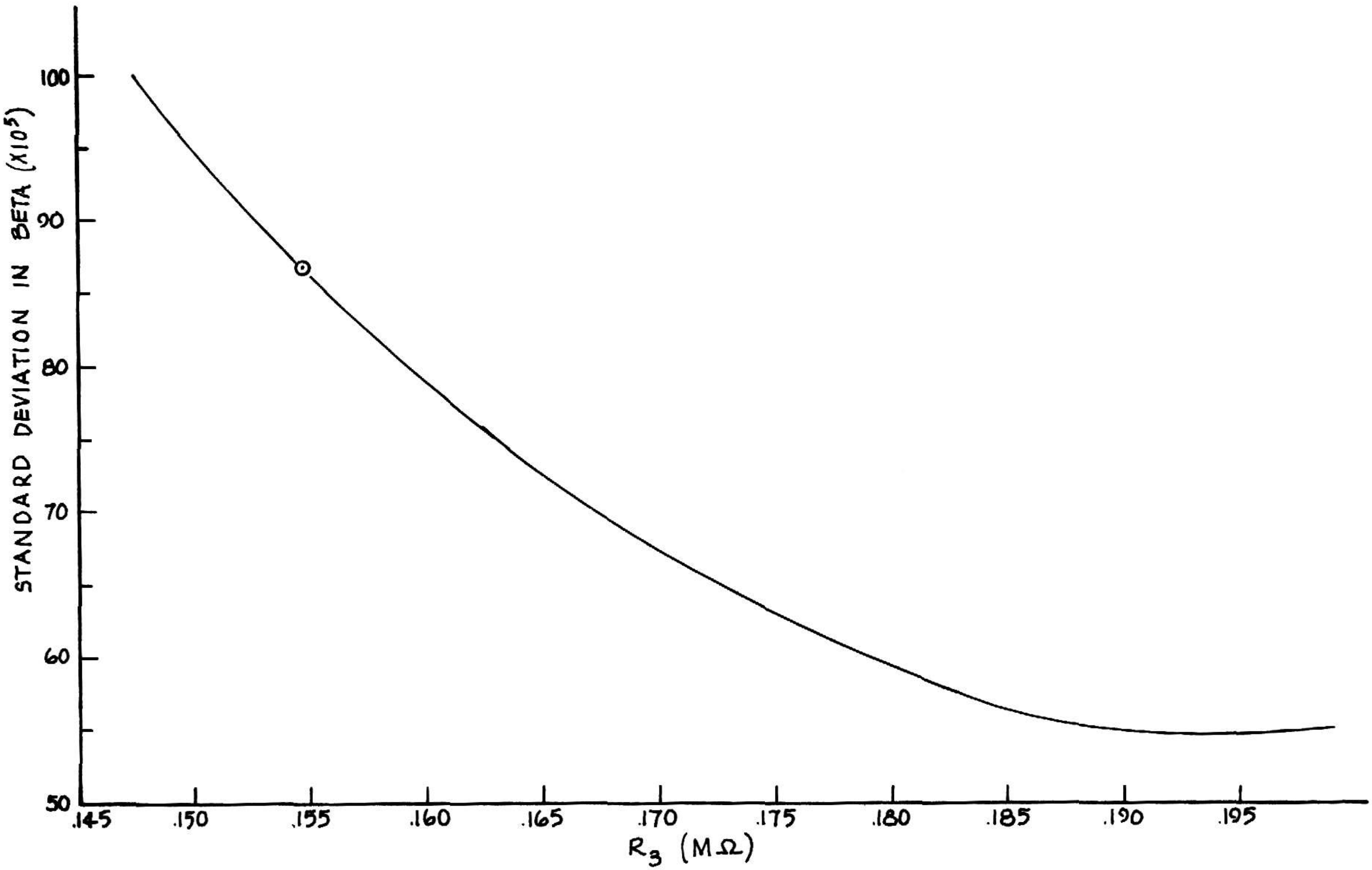


Figure 19

Comparison of Flanders' Resistance Values for Beta and R_3 with the Optimum Resistance Values - High Range

Chapter 5

EXPERIMENTAL RESULTS

Introduction

Using the calculated resistance values from Chapter 4 the circuit was constructed. A range control switch was incorporated to conveniently select the proper air speed range and output jacks were installed to provide for hook-up of two digital multimeters to monitor the voltage across resistors R_1 and R_s. Figure 20 displays the complete circuit diagram. The sensing and compensating thermistor were mounted together on a probe so that they would be

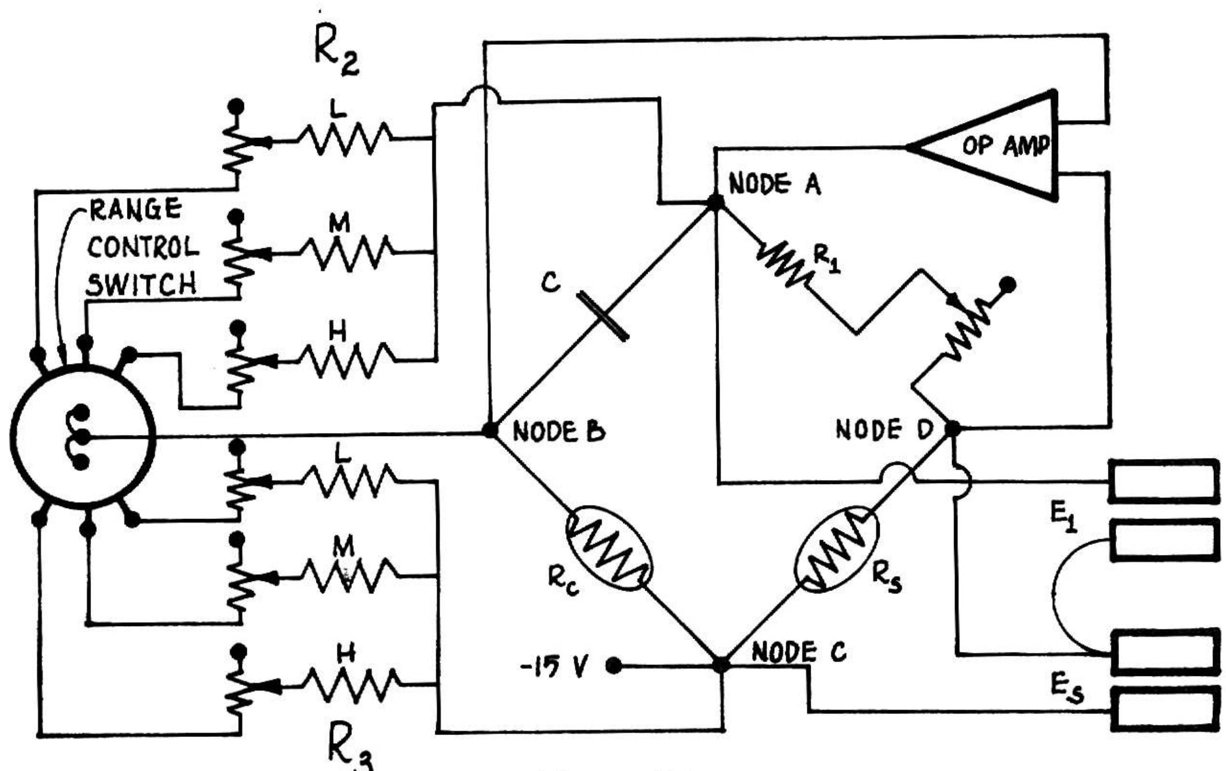


Figure 20

Final Circuit Diagram

simultaneously subjected to the same environment. Figure 21 shows the probe configuration. Metal film resistors were selected that were approximately equal to the desired values and were connected in series to trim pots as indicated in the circuit diagram. The trim pots were adjusted until the exact calculated resistances were obtained. A 10μF non-polar capacitor was used. This value for the capacitance was chosen on a trial and error basis with the criteria being to provide a reasonably quick response to change in velocity while keeping fluctuations in voltages E_1 and E_s to a minimum over the air speed range of the anemometer.

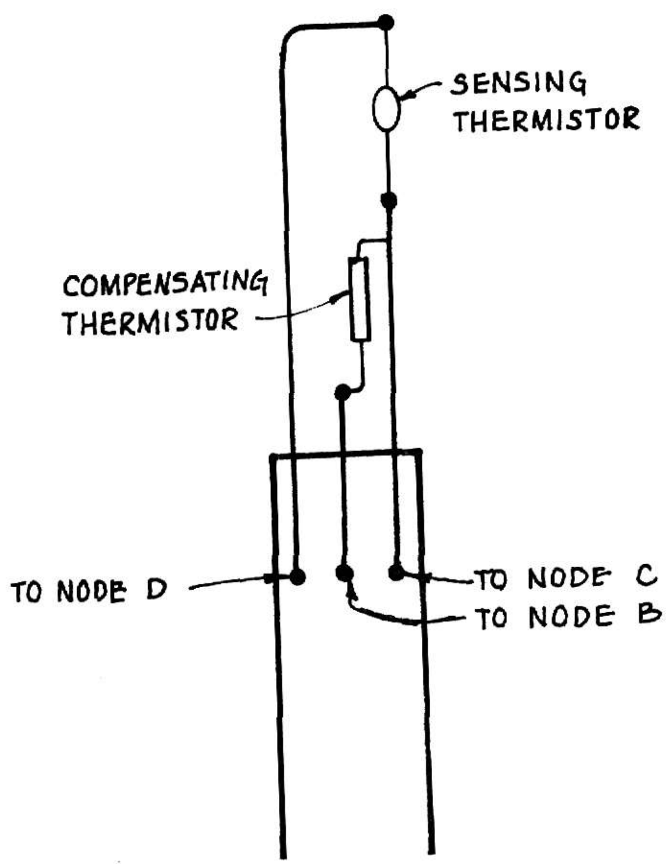


Figure 21

Probe Configuration

Before any data were taken, the instrument was bench tested to see if it was performing properly and supplying the appropriate self-heat. Using digital multimeters, the current and voltage were monitored through both the sensing and compensating thermistors while different velocities were supplied. The output voltage across the bridge was also monitored. The resistance of the thermistors could be calculated from R = E/I and, using Flanders' thermistor calibration curves, the thermistor's temperatures could be calculated while in operation.

Preliminary testing indicated that the desired self-heats (between 5 and 5.5 °F) were not being achieved. The bridge was coming to balance since less than .00005 volts was measured across Nodes B and D (see Fig. 20). Further investigation led to suspicion of the validity of the calibrated thermistor resistance-temperature curves, so it was decided to recheck the calibration of both thermistors. A Sargent Oil Viscometer was used to provide a constant temperature medium for the thermistors. The temperature of the oil bath was monitored with precision mercury thermometers with smallest divisions of 0.2°F. A 4 1/2 digit Fluke multimeter was used to monitor the thermistors' resistance. Figure 22 shows the test setup used for the recalibration.

The temperature of the oil bath was varied from 46°F to 102°F and the resistance values were measured simultaneously for both thermistors at approximately 4°F intervals. The data were then plotted on semilog paper with temperature on the linear scale and resistance on the log scale. The results were compared with the previous (Flanders) calibration curve. Figures 23 and 24 illustrate these results.

Excellent agreement was found for the compensating thermistor. However, the new sensing thermistor calibration indicated disagreement with its former

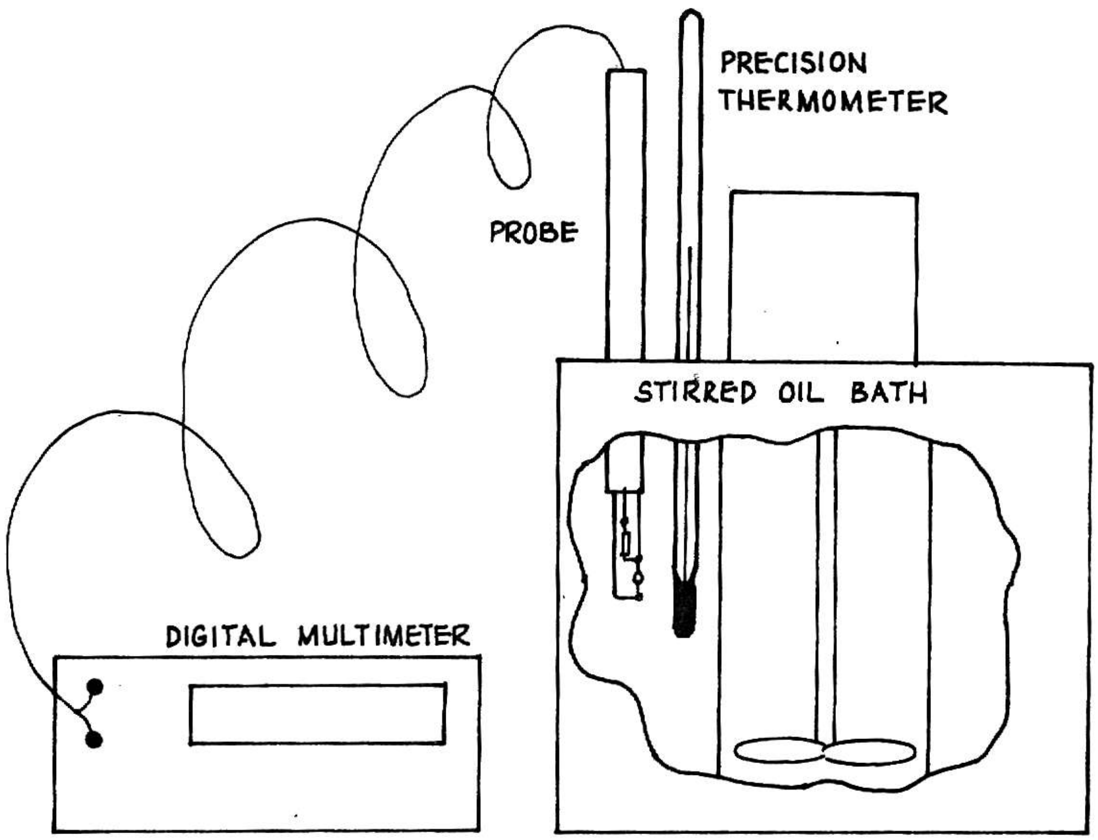


Figure 22

Thermistor Recalibration Test Setup

curve. As much as 4°F difference was discovered between the sensing thermistor curves. An exponential curve fit according to $R_s = Ae^{(BT_s)}$ was made and a correlation of 0.99958 resulted. The values for A and B were found to be:

$$A = 11736.13202 \text{ ohms}$$

$$B = -0.0212051 \text{ °F}^{-1}.$$

Using the previous calibration curve for the compensating thermistor and the new calibration curve for the sensing thermistor, the resistor sizing program, Program IV, was rerun for each air speed range: 10-100, 100-500, and 500-1000 feet per minute.

The results for each range appear in Tables 33, 34, and 35. For the 10-100 feet per minute range the minimum standard deviation occurred at

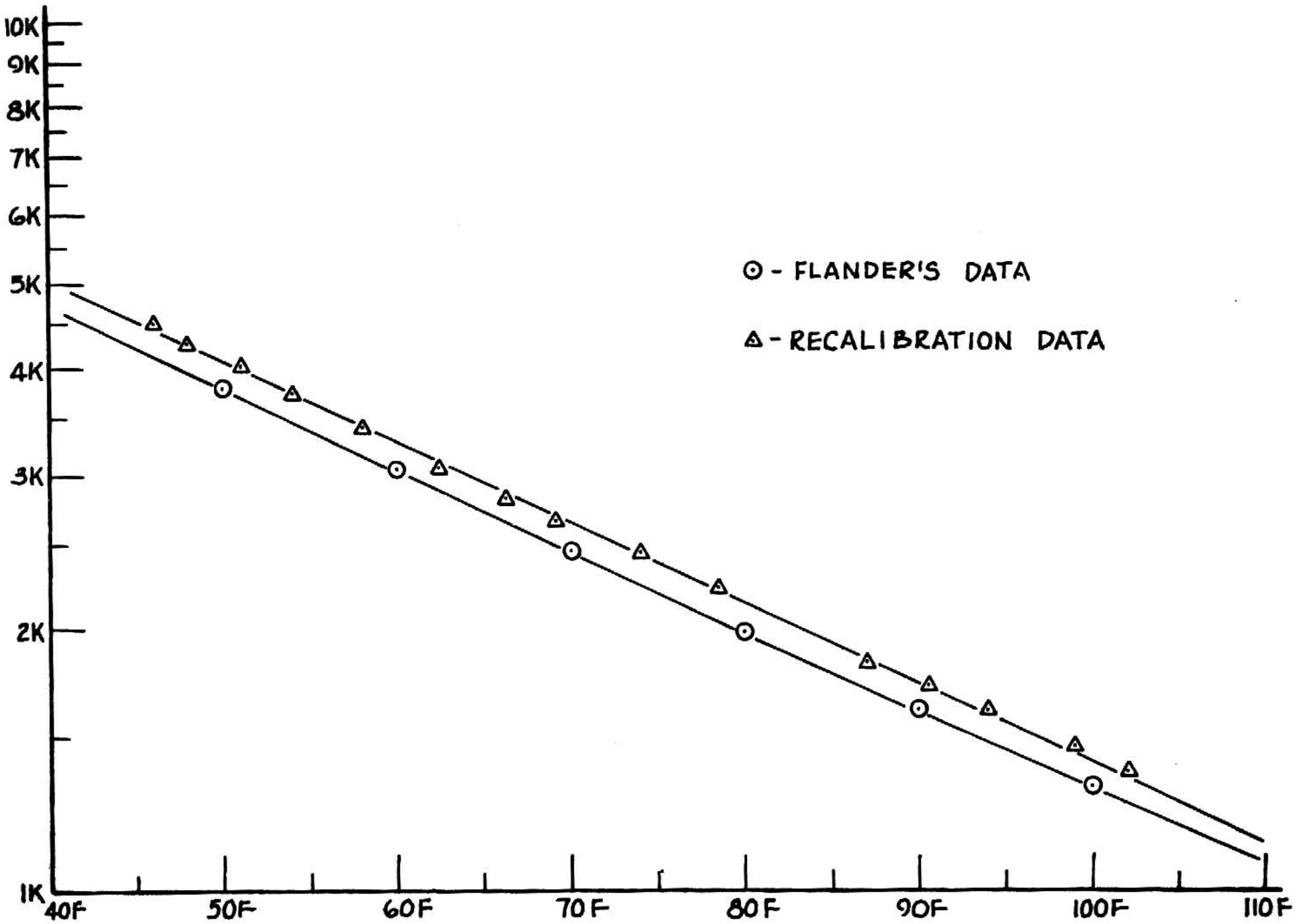


Figure 23

Sensing Thermistor Recalibration Results

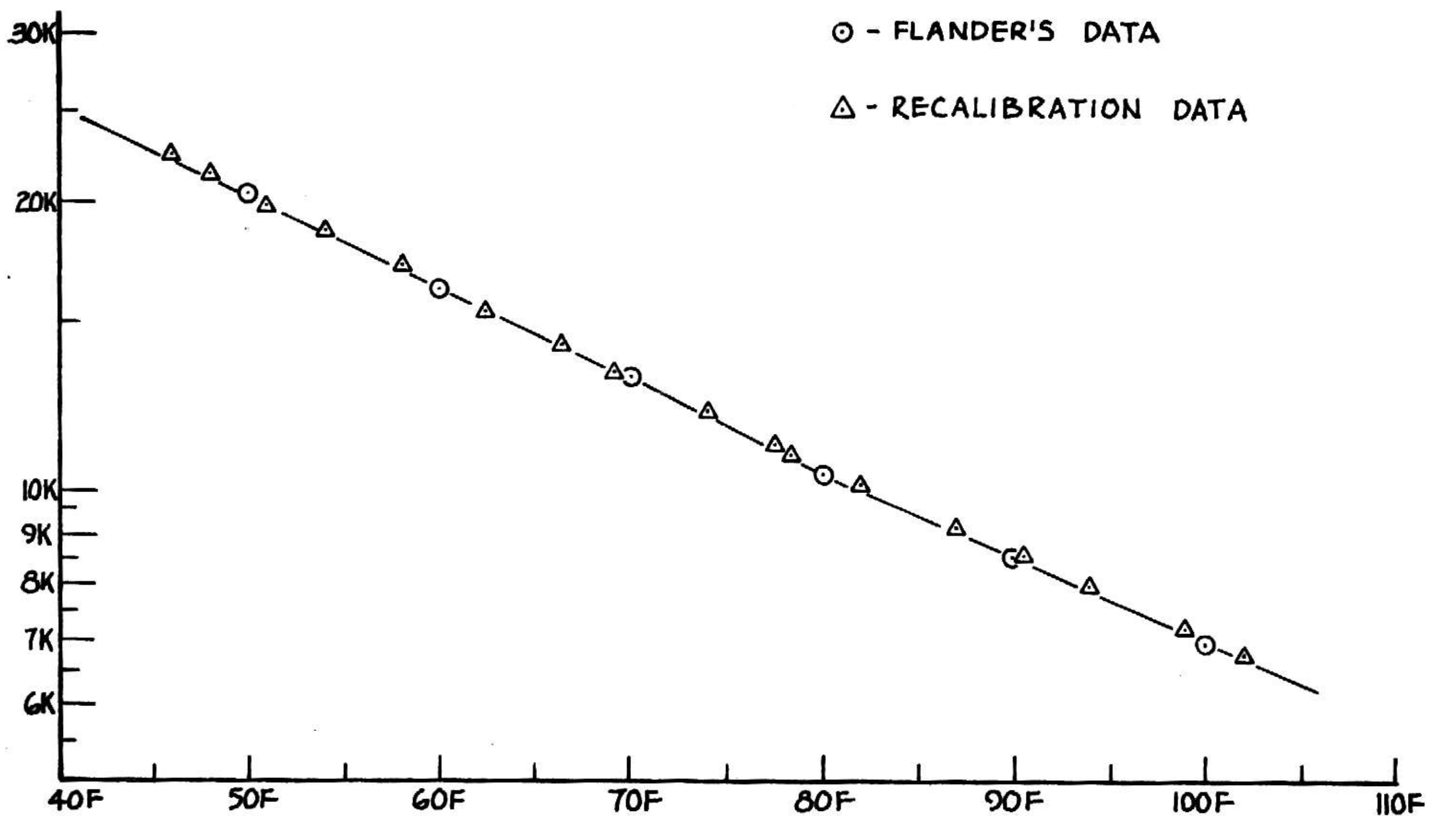


Figure 24

Compensating Thermistor Recalibration Results

Table 33

Computer Program IV Results for the Low Range

R_3 (ohms)	Beta	Standard Deviation
460,000	.18770	.000896
470,000	.18760	.000886
480,000	.18750	.000879
490,000	.18740	.000872
500,000	.18731	.000867
510,000	.18722	.000863
520,000	.18713	.000861
530,000	.18705	.000859
540,000	.18697	.000858
550,000	.18690	.000858
560,000	.18682	.000858
570,000	.18675	.000860
580,000	.18668	.000861
590,000	.18662	.000864
600,000	.18655	.000867
610,000	.18649	.000870
620,000	.18643	.000873
630,000	.18637	.000877
640,000	.18632	.000881
650,000	.18626	.000886

Table 34

Computer Program IV Results for the Middle Range

R_3 (ohms)	Beta	Standard Deviation
460,000	.18784	.000935
470,000	.18773	.000923
480,000	.18763	.000912
490,000	.18753	.000903
500,000	.18744	.000895
510,000	.18735	.000889
520,000	.18727	.000883
530,000	.18718	.000879
540,000	.18710	.000876
550,000	.18703	.000873
560,000	.18695	.000871
570,000	.18688	.000870
580,000	.18681	.000870
590,000	.18675	.000870
600,000	.18668	.000871
610,000	.18662	.000872
620,000	.18656	.000874
630,000	.18650	.000876
640,000	.18645	.000878
650,000	.18639	.000881

Table 35

Computer Program IV Results for the High Range

R_3 (ohms)	Beta	Standard Deviation
460,000	.18790	.000953
470,000	.18779	.000940
480,000	.18769	.000928
490,000	.18760	.000917
500,000	.18750	.000908
510,000	.18742	.000900
520,000	.18733	.000894
530,000	.18725	.000888
540,000	.18717	.000884
550,000	.18709	.000880
560,000	.18702	.000877
570,000	.18695	.000875
580,000	.18688	.000873
590,000	.18681	.000873
600,000	.18675	.000872
610,000	.18668	.000873
620,000	.18662	.000873
630,000	.18657	.000874
640,000	.18651	.000876
650,000	.18646	.000878

R_3 = 550,000 ohms. This value of R_3 required that Beta = 0.18683 to achieve approximately 5°F of self-heat. Keeping R_1 = 10,000 ohms this value of Beta yielded a value of 53,505 ohms for R_2. Similarly, for the middle range, a value of 580,000 ohms for R_3 and a value of 53,530 ohms for R_2 was determined For the high range optimum values of 600,000 ohms for R_3 and 53,548 ohms for R_2 were calculated.

These resistance values were incorporated into the circuit and the circuit was bench tested as before to determine if the correct self-heat was being maintained. Self-heats on the order of 5.09 to 5.62°F were obtained over the complete range for an ambient temperature ranging from 72 to 75°F. These results indicated that the instrument was ready for final testing.

Test Setup

The testing of the anemometer required application of two controlled variables. These are ambient temperature and air speed. Ambient temperature control was provided by a test chamber located in the KSU Institute for Environmental Research. An air speed was imposed on the sensing probe by a portable wind tunnel designed especially for anemometer calibration. Information concerning performance and operation details of the wind tunnel can be found in reference (2).

The test setup for the experiment is presented in Figure 25. The wind tunnel and probe are subject to the temperature environment of the test chamber. The temperature in the test chamber can be controlled remotely and a fairly constant temperature can be maintained. A thermistor probe was placed in the air stream of the wind tunnel approximately 1.5 feet above the sensing probe. The thermistor probe was connected to a data acquisition system that

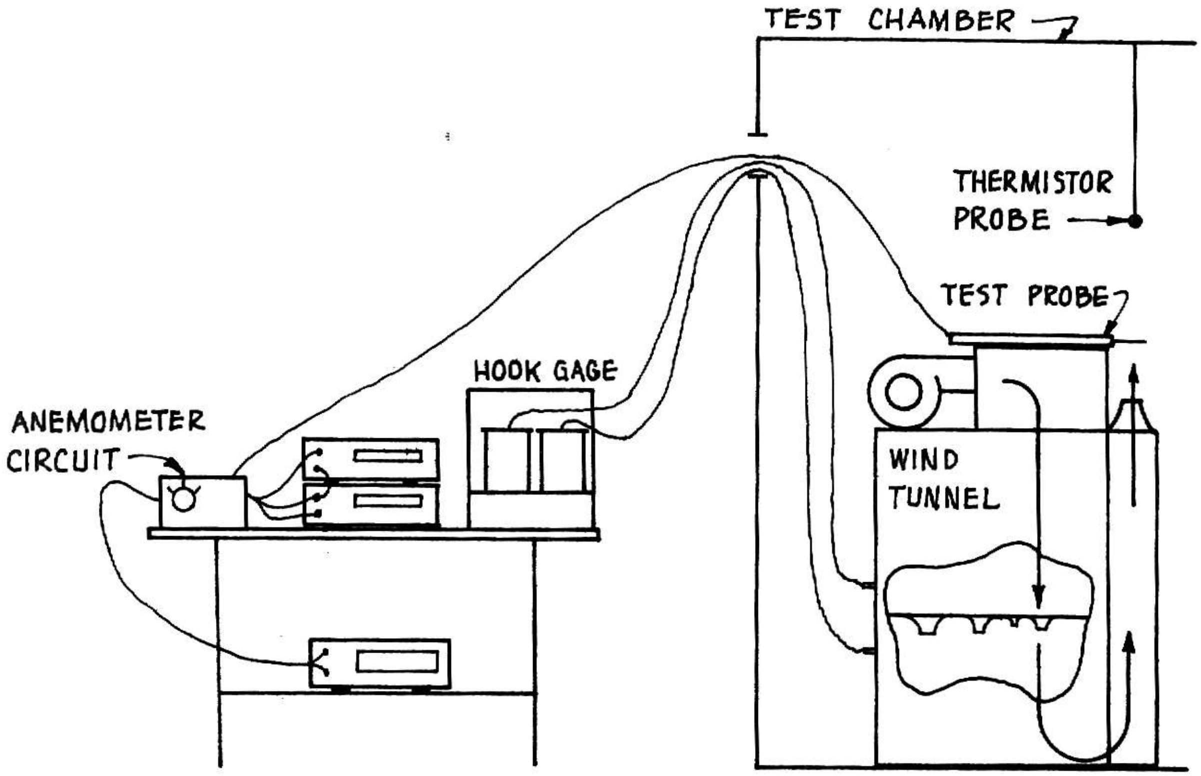


Figure 25

Test Setup

displayed a digital read-out of the temperature. The temperature in the chamber was monitored according to the read-out of this probe.

The velocity provided by the wind tunnel was calculated using a hook gage as the primary measuring instrument. The pressure differential was measured across a parallel configuration of ASME nozzles in the wind tunnel. Any combination of 4 nozzles are available. The nozzle sizes are 1/4", 1/2", 1", 1.6". The 1.6" nozzle was not used and remained plugged throughout the experiment. For centerline velocities between 15 fpm and 65 fpm the 1/4" nozzle was used. For centerline velocities between 65 fpm and 300 fpm the combination of 1/4" + 1/2" nozzles was used. For centerline velocities between 300 fpm and 1000 fpm the combination of 1/4" + 1/2" + 1" nozzles was used. Reference (2) did not directly provide a relationship between pressure drop and centerline velocity. This relationship was derived according to the information that was provided.

With all the nozzles plugged except the 1/4" nozzles, reference (2) gives the following empirical relationship relating the pressure drop, h(inches H_2O), to flowrate, q (ft^3/min),

$$h = 0.4069\ q^{1.779}, \qquad [39]$$

for,

$$0 < q \leq 1.35\ ft^3/min.$$

Solving for q yields,

$$q = (h/0.4069)^{\frac{1}{1.779}}. \qquad [40]$$

The average velocity, in ft/min, is computed by,

$$\bar{V} = q/A, \qquad [41]$$

where A is the cross-sectional area of the output nozzle which is a 2" ASME. A standard density for air of .075 lbm/ft^3 is assumed in the previous analysis. To correct $\bar{V}$ for other than standard air densities the relationship,

$$\bar{V}_r = \bar{V}\ \left(\frac{.075}{\rho_r}\right) \qquad [42]$$

is used. The air density, ρ_r, at the particular conditions is computed by,

$$\rho_r = \frac{b - e_w h + e_w \theta s}{.7538\ (t + 549.7)}, \qquad [43]$$

where,

b - barometric pressure ("Hg)

e_w - vapor pressure of H_2O at t ("Hg)

θ - relative humidity (dimensionless)

s - relative density of water vapor (dimensionless)

t - dry bulb temperature.

The relative density of water vapor is computed from,

$$s = 0.6214 + \frac{h(e_w)^{\frac{1}{1.42}}}{1130} . \quad [44]$$

The vapor pressure of water is computed from an exponential curve fit using information from Keenan and Keyes Steam Tables. The resulting curve fit used is,

$$e_w = [.03439608\ e^{.03346475\ t}]/.49115, \quad [45]$$

where division by .49115 is used to correct the units from psi to inches of mercury.

A pitot traverse of the 2" ASME output nozzle was made to determine its discharge coefficient. In reference (2) the discharge coefficient, $\bar{V}/V_{cl}$, is plotted versus flowrate for each nozzle combination. The plots were made on semilog paper and yielded straight lines. This suggests an exponential curve relating discharge coefficient to flowrate. The slope of these plots for each nozzle combination of interest was computed graphically. The results for the 1/4" nozzle are,

$$V_{cl} = \frac{6.5118\ Vr}{\ln\ (q) + 5.5661}. \quad [46]$$

Given values for h, b, e_w, θ, s, and t the centerline velocity for a 1/4" nozzle can now be computed.

For the 1/4" + 1/2" nozzle combination and the 1/4" + 1/2" + 1" nozzle combination Eqs. [39], [40], and [46] must be modified. For a 1/4" + 1/2" nozzle configuration,

$$q = (h/0.0250)^{\frac{1}{1.401}}, \quad [47]$$

and,

$$V_{cl} = \frac{69.3147\ Vr}{\ln\ (q) + 62,5067}. \quad [48]$$

For a 1/4" + 1/2" + 1" nozzle configuration,

$$q = (h/.001556)^{\frac{1}{1.982}} , \qquad [49]$$

and,

$$V_{cl} = \frac{13.5911\ Vr}{\ln (q) + 10.3915} . \qquad [50]$$

The voltages across the sensing thermistor and the compensating thermistor were measured using two Fluke digital multimeters. The bridge output, the voltage across nodes B and D (see Fig. 20), was measured using a 4 1/2 digit Fluke multimeter. This voltage was kept at less than 0.00005 volts, if possible, by adjusting the trim pot in the null circuit of the Fairchild amplifier. The null circuit is illustrated in Figure 26.

Power and velocity measurements were taken at ambient temperatures of approximately 60°F, 75°F, and 90°F.

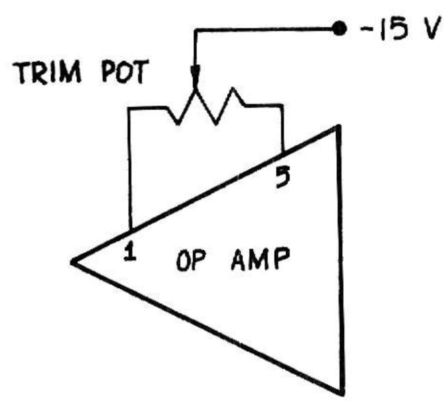


Figure 26

Null Circuit

For each ambient temperature eight calibration velocities were provided to the measuring circuit by the wind tunnel. Table 36 shows the original data. The experimental results appear in Table 37. Computer Program VIII was used

Table 36

Experimental Data

Run No.	Pressure drop ("H_2O)	Nozzle Configuration*	Instrument Range Setting**	EMF Across Rl (Volts)	EMF Across Rs (Volts)	Relative Humidity	Barometric Pressure ("Hg)
1	.200	1	1	8.98	1.88	.50	28.97
2	.513	1	1	9.23	1.95	.50	28.97
3	.069	2	1	9.67	2.04	.50	28.97
4	.381	2	2	10.43	2.23	.50	28.97
5	.106	3	2	11.70	2.50	.50	28.97
6	.258	3	3	12.77	2.70	.50	28.97
7	.452	3	3	13.42	2.83	.50	28.97
8	.567	3	3	13.80	2.90	.50	28.97
9	.2015	1	1	11.88	1.88	.50	28.97
10	.4145	1	1	12.40	1.97	.50	28.97
11	.080	2	1	13.22	2.13	.50	28.97
12	.260	2	2	13.94	2.26	.50	28.97
13	.121	3	2	15.49	2.52	.50	28.97
14	.210	3	3	15.99	2.62	.50	28.97
15	.341	3	3	16.28	2.69	.50	28.97
16	.567	3	3	16.40	2.78	.50	28.97
17	.200	1	1	8.23	2.33	.50	28.97
18	.444	1	1	6.75	1.90	.50	28.97
19	.050	2	1	6.71	1.82	.50	28.97
20	.550	2	2	7.54	2.04	.50	28.97
21	.100	3	2	9.01	2.45	.50	28.97
22	.246	3	3	10.20	2.80	.50	28.97
23	.4345	3	3	11.07	3.02	.50	28.97
24	.6475	3	3	12.01	3.27	.50	28.97

* 1 indicates the 1/4" nozzle, 2 indicates the 1/4" + 1/2" nozzle configuration, and 3 indicates the 1/4" + 1/2" + 1" nozzle configuration.
** 1 indicates the low range, 2 indicates the middle range, and 3 indicates the high range.

Table 37

Experimental Results

Run	Instrument Reading		Calculated Thermistor Temperatures			Calculated Instrument Performance		Centerline Velocity
No.	EMF Across R1 (Volts)	EMF Across Rs (Volts)	Compensating (°F)	Sensing (°F)	Self-heat (°F)	Power Dissipation (Milliwatts)	Air Speed (fpm)	(fpm)
1	8.98	1.88	75.9	81.3	5.4	1.69	22	40.74
2	9.23	1.95	75.5	80.9	5.4	1.80	32	62.70
3	9.67	2.04	75.6	80.9	5.4	1.97	50	90.32
4	10.43	2.23	75.0	80.3	5.3	2.33	106	218.51
5	11.70	2.50	75.0	80.3	5.3	2.93	251	439.26
6	12.77	2.70	75.5	80.8	5.3	3.45	436	664.95
7	13.42	2.83	75.6	81.0	5.3	3.80	591	863.75
8	13.80	2.90	75.8	81.1	5.3	4.00	693	960.44
9	11.88	1.88	88.8	94.5	5.7	2.23	65	42.00
10	12.40	1.97	88.6	94.3	5.7	2.44	96	58.39
11	13,22	2.13	88.0	93.6	5.7	2.82	171	100.07
12	13.94	2.26	87.7	93.3	5.6	3.15	260	184.10
13	15.49	2.52	87.5	93.2	5.6	3.90	531	479.47
14	15.99	2.62	87.2	92.8	5.6	4.19	669	619.13
15	16.28	2.69	86.8	92.5	5.6	4.38	770	775.31
16	16.40	2.78	85.7	91.2	5.6	4.56	885	980.39
17	8.23	2.33	59.8	67.1	7.3	1.92	7	39.42
18	6.75	1.90	60.1	67.3	7.3	1.28	0	55.50
19	6.71	1.82	61.9	69.1	7.1	1.22	0	72.50
20	7.54	2.04	62.1	69.2	7.1	1.54	1	257.40
21	9.01	2.45	61.9	69.0	7.1	2.21	22	416.19
22	10,20	2.80	61.4	68.5	7.1	2.86	77	631.86
23	11.07	3.02	61.7	68.8	7.1	3.34	146	824.19
24	12.01	3.27	61.8	68.9	7.1	3.93	263	993.05

to reduce the experimental data.

In Table 37 the calculated thermistor temperatures were arrived at by using the formula, E = IR, and the measured values for the voltage across $R_1(V_1)$ and $R_s(V_s)$. The current through the sensing thermistor is computed by,

$$I_s = \frac{V_1}{R_1} \,. \tag{51}$$

The resistance of the sensing thermistor is then calculated by,

$$R_s = \frac{V_s}{I_s} = \frac{(V_s)(R_s)}{V_1} \,. \tag{52}$$

The temperature of the sensing thermistor is computed from its temperature-resistance calibration curve. The current through the parallel resistance of R_3 and R_c is calculated by,

$$I_{3,c} = \frac{V_1}{R_2} \,. \tag{53}$$

The current through R_c is computed from,

$$R_x = \frac{V_s}{I_{3,c}} = \frac{R_3\ R_c}{R_3+R_c} \,. \tag{54}$$

Solving Eq. [54] for R_c yields,

$$R_c = \frac{\frac{V_s}{I_{3,c}}\ R_3}{R_3 - V_s/I_{3,c}} \,,$$

or,

$$R_c = \frac{V_s\ R_3}{I_{3,c}\ R_3 - V_s} \,. \tag{55}$$

Substituting Eq. [53] for $I_{3,c}$,

$$R_c = \frac{V_s\ R_3}{(\frac{V_1}{R_2})\ R_3 - V_s} \,,$$

finally,

$$R_c = \frac{V_s R_3 R_2}{V_1 R_3 - V_s R_2} . \qquad [56]$$

The temperature of the compensating thermistor can be computed from its temperature-resistance curve. This temperature is the ambient temperature. The difference between the sensing thermistor's temperature and the compensating thermistor's temperature is the self-heat. The power dissipation is calculated using Eq. [1] where $E_1 = V_1$ and $E_s = V_s$. The predicted air speed is calculated by iterating the heat transfer equation with velocity as the variable until the power dissipation is equal to the measured power dissipation. The ambient temperature and the self-heat used in the iteration are taken from Table 37. The centerline velocity is calculated from h, θ, and b using equations [41] through [50].

The uncertainties in the experimental results are derived in Appendix B. Using these relationships values for the uncertainties in the results are presented in Table 38.

Two graphs were plotted from the experimental results. The first graph (see Figure 27) plots the calculated velocity versus the centerline velocity for each ambient temperature range. This graph compares the observed instrument performance to ideal performance. The second graph (see Figure 28) plots the measured power dissipation versus centerline velocity provided by the wind tunnel for the three ambient temperature ranges. The power curve for a self-heat of 5°F at a reference temperature of 100°F is plotted for comparison purposes. This graph, while comparing actual performance to predicted performance also serves as a calibration chart for the anemometer.

Very large errors between predicted performance and actual performance are evident for each ambient temperature range. Also, the anemometer appears

Table 38

Uncertainties

Run No.	V_1 (± %)	V_s (± %)	Comp. Therm. Temperature (± %)	Sensing Therm. Temperature (± %)	Self-heat (± %)	Power Diss. (± %)	Calculated Air Speed (%)	Centerline Velocity (± %)
1	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	5.00
2	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	5.00
3	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	5.00
4	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	2.00
5	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	2.00
6	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	2.00
7	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	2.00
8	0.25	0.65	0.811	1.568	25.33	0.70	-55.86, +154.81	2.00
9	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	5.00
10	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	5.00
11	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	5.00
12	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	2.00
13	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	2.00
14	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	2.00
15	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	2.00
16	0.25	0.65	0.838	1.478	18.94	0.70	-22.21, +31.25	2.00
17	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	5.00
18	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	5.00
19	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	5.00
20	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	2.00
21	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	2.00
22	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	2.00
23	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	2.00
24	0.25	0.65	3.55	1.568	33.92	0.70	-75.26, +367.54	2.00

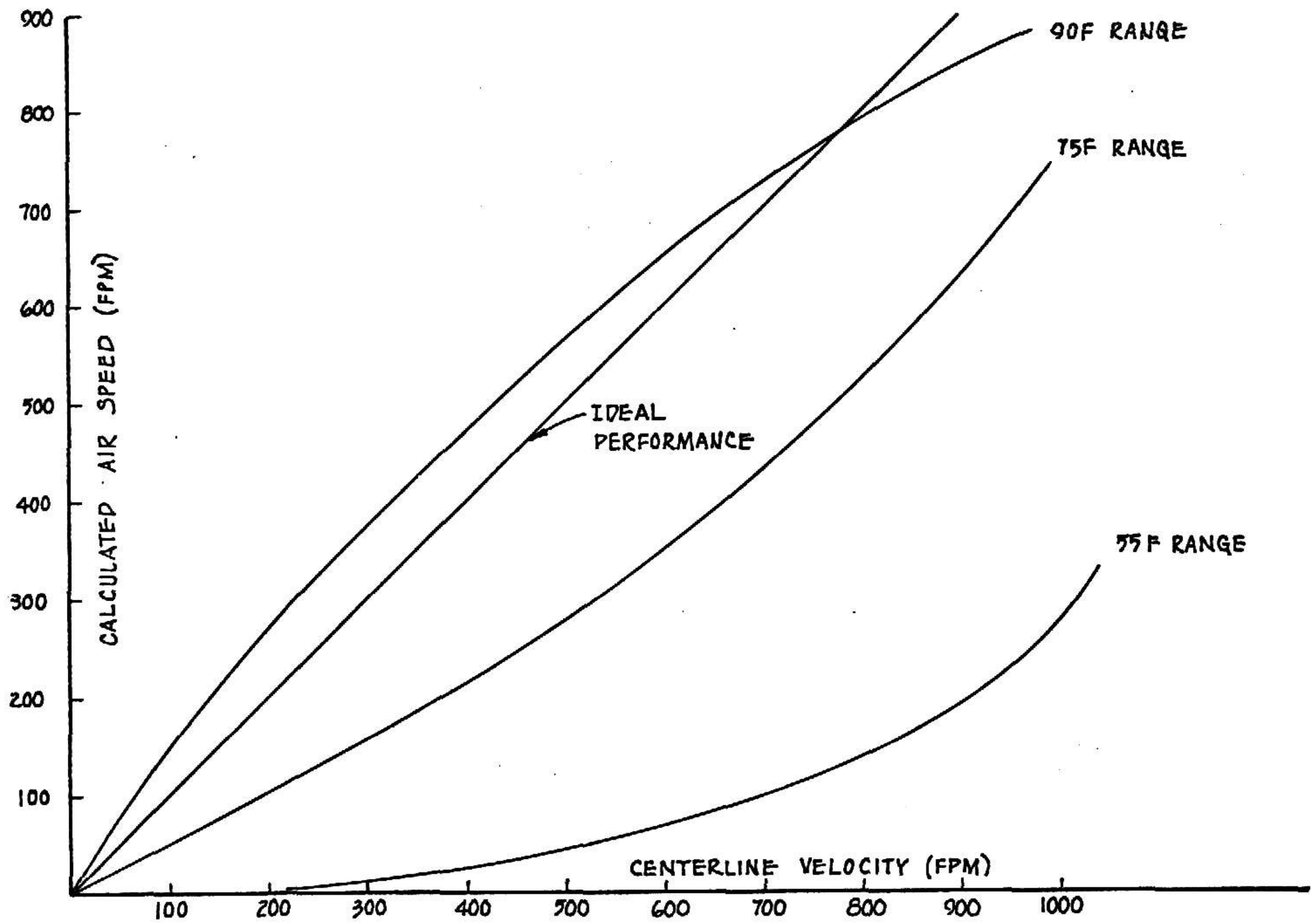


Figure 27

Instrument Performance Curves

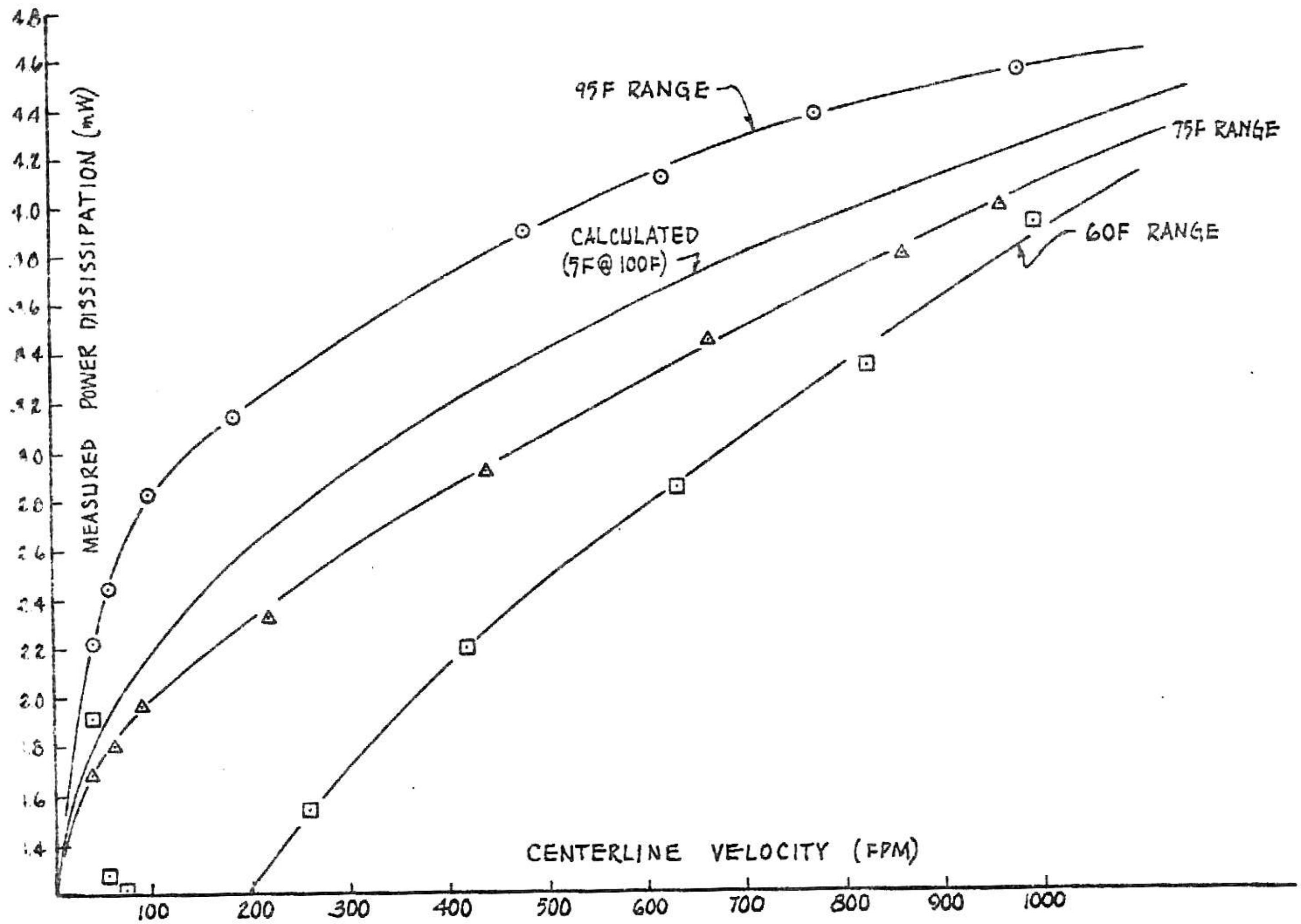


Figure 28

Instrument Calibration Curves

to exhibit temperature dependency. For nearly any velocity the power dissipation varies widely for each ambient temperature range. In the next chapter a hypothesis will be presented to account for these results.

Chapter 6

EVALUATION

Introduction

The major objective of the thesis was to evaluate the feasibility of manufacturing the anemometer. At the present point of development, an attempt to discuss the pros and cons of manufacturing the instrument would be fruitless. The large uncertainties (Table 38) coupled with the large spread in the data (see Figs. 27 and 28) lead to the obvious conclusion that, in its present state, the thermistor anemometer is not yet ready to be manufactured. Instead, the attention will be focused on presenting an explanation of the observed performance in regard to the predicted performance.

Conclusions

Referring to Fig. 27, the data points for a "perfect anemometer" should fall along the 45° line labeled "ideal curve". This curve describes a perfectly linear instrument having the characteristics of perfect linearity, perfect temperature compensation, and no zero offset. The three curves for the actual instrument obviously differ from the ideal. It is observed that the instrument is non-linear but, more importantly, it is not temperature compensating. The curves, however, indicate that no appreciable zero offset occurs since all three curves pass through the zero centerline velocity point for a zero calculated air speed. Another observation can be made for the 60°F curve. The instrument sensitivity (3) is defined by,

$$\text{sensitivity} = \frac{\text{change in measured variable}}{\text{change in indicated variable}} \,. \qquad [57]$$

The sensitivity for the ideal curve is 1.0, but the sensitivity for the "flat" portion of the 60°F curve is approximately 0.17. This low sensitivity is an indication that it will be difficult to obtain accurate measurements in the low temperature ranges. It should be noted that the uncertainties (see Table 38) associated with each of the curves is very large especially for the 60°F curve. This is due mainly to large uncertainties in the self-heat. If the indicated velocities for the 60°F curve were increased by 367.5%, the sensitivity of the "flat" portion of the curve would be increased to about 0.83. Much better results than were indicated could be achieved with this higher sensitivity. Therefore, the anemometer could be operating much better than the data indicates.

Calibration curves (see Fig. 28) for each ambient temperature were generated by plotting the measured power dissipation versus the measured centerline velocity. It would seem that the large uncertainties affecting the curves in Fig. 27 would not allow the instrument to be calibrated with any degree of accuracy. This is not the case because the errors in the indicated air speed do not affect the measured power or the measured centerline velocity. The uncertainty (see Table 38) in the measured power dissipation is only ± 0.7% for the complete range. For calibration tunnel centerline velocities less than 100 fpm the uncertainty (see Appendix B) is ± 5% and for centerline velocities greater than 100 fpm the uncertainty is ± 2%. These uncertainties are small enough to permit good accuracy in the calibration curves. The only problem that could be encountered in using the instrument and the calibration curves is the low instrument sensitivity that occurs at lower ambient temperatures. However, the uncertainties in instrument sensitivity for the low temperature ranges as well as for the higher temperature ranges are too large to draw any valid conclusions about the actual sensitivity. Therefore, it is concluded that the thermistor anemometer must be further modified before it is made available for laboratory uses. The direction that these modifications should take is presented in the next section.

Before proceeding to the next section, the heat transfer equation will be evaluated to comply with the secondary objective mentioned in Chapter 1. This evaluation will compare the predicted power dissipation (see Eq. [16]) to the measured power dissipation using data from run numbers 6, 12, and 23. (The data from these runs will be consider typical of the other data in the respective temperature ranges.).

It was shown earlier that $P = f(V, T_s, T_a)$. This is equivalent to,

$$P = f(V_{cl}, T_c, \text{self-heat}) \qquad [58]$$

V_{cl} - centerline velocity

T_c - compensating thermistor temperature

when computing the power dissipation from the data. The resulting calculated power dissipation will be subject to uncertainties in V_{cl}, T_c and the self-heat. The nominal power dissipation was computed using the data from Table 37. The uncertainty was then assigned to the nominal power dissipation by changing the self-heat by the percentages indicated in Table 38, recalculating the power dissipation, and expressing this new power dissipation as a percentage of the nominal power dissipation. Since the uncertainty in the self-heat was much larger than uncertainties in T_c and V_{cl}, the affects of these uncertainties will be ignored. The results calculated by this procedure are presented in Table 39 and compared with the measured power dissipation from Table 37. The measured power dissipation for runs 6 and 12 (ambient temperature is equal to 75.5°F and 87.7°F respectively) is within the possible ranges of power

Table 39

Evaluation of the Heat Transfer Model

Run No.	Measured		Predicted		
	Power Dissipation (Milliwatts)	Uncertainty (±%)	Power Dissipation (Milliwatts)	Uncertainty (%)	Possible Range of Power Dissipation (Milliwatts)
6	3.448	0.70	3.943	+25.357 -25.346	4.943 2.943
12	3.150	0.70	2.862	+18.973 -18.962	3.405 2.379
23	3.343	0.70	5.622	+33.964 -33.942	7.531 3.713

Note: Computer Program X (see Appendix C) was used to compute the uncertainties in Predicted Power Dissipation.

dissipation calculated by the heat transfer equation (equation [16]). The measured power dissipation for run 23 (ambient temperature = 61.7°F is below the range calculated. However, due to the large uncertainties, an accurate evaluation of the heat transfer is not possible. The only valid conclusion that can be drawn from Table 39 is that there is a good chance that the heat transfer model is valid for the middle and upper ambient temperature ranges and it is probably predicting too high of a power dissipation for the low temperature range. To be more specific then this would be misleading.

Recommendations

There is an apparent conflict between what the analytical models (circuit and heat transfer) say should happen and what actually happens. The models indicate that, as the self-heat is decreased, the anemometer (combined models) should more closely predict actual performance. This was brought out in the absolute error analysis in Chapter 3. The experimental results, however, do not show this to be true. This is evident by comparing the experimental results Mr. Flanders obtained using 20°F self-heat with the results obtained in this thesis for 5°F self-heat.

The rather disappointing performance of the anemometer at low self-heats can be attributed to the large (20% - 35%) uncertainties in the self-heat. If these uncertainties can be reduced to a reasonable level, for example, less than ± 5%, the performance of the anemometer can be more closely predicted and the accuracy of the heat transfer model can be evaluated more effectively. It is hypothesized that decreasing the uncertainty in the self-heat will virtually eliminate the observed temperature dependency and, additionally, the instrument will follow the predicted performance very closely.

The variables having the greatest effect on the uncertainty in the self-heat are the sensitivity in the sensing thermistor temperature, S_{T_s}, and the sensitivity in the compensating thermistor temperature, S_{T_c}. The sensitivity equations for S_{T_s} and S_{T_c} are (see Appendix B, Eqs. [60] and [61]),

$$S_{T_s} = \frac{T_s}{T_s - T_c}, \quad [59]$$

$$S_{T_c} = \frac{-T_c}{T_s - T_c}, \quad [60]$$

where,

T_c - compensating thermistor temperature

T_s - sensing thermistor temperature.

To decrease S_{T_s} and S_{T_c} the temperature difference, $T_s - T_c$, must be increased. Since,

$$\text{self-heat} = T_s - T_c, \quad [61]$$

then the self-heat must be increased to reduce its uncertainty.

Two other factors effect the uncertainty in the self-heat. These factors are the uncertainty in the oil bath calibration and the ability to accurately curve fit the data obtained in the oil bath calibration (see Uncertainty in the Compensating Thermistor Temperature, Appendix B). The major source of error is in curve fitting the data. An exponential curve fit using

$$R_{therm} = Ae^{B(T_{therm})} \quad [62]$$

has been determined to be the best. However, experimental results indicated that the thermistors exhibit a small but measurable sinusoidal fluctuation about a "true" exponential curve. To obtain satisfactory results the exponential curve fit must be reapplied at least every 5°F. To do this effectively, measurements with the oil bath should be performed every degree. Since the anemometer was designed to operate over a range of 50°F this means that

50 points are required for the calibration. Experience indicated that approximately 30 minutes are required for the oil bath to stablize once its temperature has been changed. Therefore, approximately 25 hours are required to perform the necessary thermistor calibration. Of course, this is not practical. Therefore, the only alternative is to decrease S_{T_s} and S_{T_c}. This means increasing the self-heat.

To solve this problem, a compromise must be made between Eqs. [59] and [60] and the absolute error analysis regarding the self-heat. This thesis recommends that future investigations be guided in this direction.

It was pointed out in the latter part of Chapter 4 that, as the self-heat increased, there was a decrease in the sensitivity of the absolute error in the indicated air speed with respect to the deviations in Beta. This was illustrated numerically by comparing absolute errors for 20°F self-heat and 5°F self-heat. It is recommended that, in future studies, the effect of decreasing sensitivity with increasing self-heat be investigated. If this effect is confirmed, as is strongly indicated, then another argument for increasing the self-heat becomes evident.

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Appendix A

Sizing Calculations for R_1

A check was made to determine if a resistance value of 10,000 ohms for R_1 would create adequately large voltages for E_1 and E_s. A resistance of 10,000 ohms was chosen to allow ease in computing the power dissipation since,

$$P = \frac{E_1 E_s}{R_1} . \qquad [1]$$

The lowest values for P will occur at 50°F and 10 fpm. This should also result in the lowest values for E_1 and E_s. At 50°F and 10 fpm the value of P is equal to 1.4164 (see Table 5). The voltage, E_s, can be computed from,

$$i = \sqrt{\frac{P}{R_s}} , \qquad [2]$$

where R_s is the sensing thermistor's resistance at 50°F. This was calculated to be 4065 ohms using the thermistor's calibration curve. The current through the bridge leg using Eq. [2] was determined to be .590 mA. Using $E_s = iR_s$ yields a value of 2.4 volts for E_s. Since the current through R_1 will also be .590 mA, E_1 can be computed by $E_1 = iR_1$ or E_1 = (.590mA)(10000 ohms) = 5.90 volts. The voltages can be easily and accurately measured using available Fluke digital multimeters.

APPENDIX B

UNCERTAINTY ANALYSIS

Introduction

The following uncertainty analysis assigns uncertainties to the experimental results in Table 37. Uncertainty occurs in the following variables:

V_1 - voltage drop across R_1 (measured)

V_s - voltage drop across R_s (measured)

T_a - ambient temperature as measured by the compensating thermistor (calculated)

T_s - temperature of the sensing thermistor (calculated)

SFHT - self-heat (calculated)

P_m - power dissipation (calculated)

V_m - measured air speed (calculated)

V_{cl} - centerline velocity (measured).

The voltage drop across R_s was measured with a 8000A digital Fluke multimeter. The uncertainty of the multimeter is expressed by,

$$\text{Uncertainty} = \pm\ (0.1\%\ \text{of reading} + 1\ \text{digit}). \qquad [1]$$

A typical value measured (see Table 36) is 1.82 volts. The uncertainty of this measurement is,

$$\lambda_{V_s} = \pm \frac{[\ (.001)(1.82v) + .01v]}{1.82v} = \pm\ 0.65\%. \qquad [2]$$

The voltage across R_1 was also measured with an 8000A multimeter. A typical value (see Table 36) is 6.71 volts. The uncertainty of the measurement is,

$$\lambda_{V_1} = \pm \frac{[\ (.001)(6.71v) + .01v]}{6.71v} = \pm\ 0.25\%. \qquad [3]$$

The uncertainty varies for different measured voltages for both V_1 and V_s. However, the results obtained in Eqs. [2] and [3] will be considered typical.

These values represent a good estimate for the complete range of the measured voltages.

Uncertainty in Measured Power Dissipation

The power dissipation was calculated using,

$$P_m = \frac{V_1 V_s}{R_1}. \qquad [4]$$

The uncertainty equation for P_m is,

$$\lambda_{P_m} = \pm [(S_{V_1} \lambda_{V_1})^2 + (S_{V_s} \lambda_{V_s})^2 + (S_{R_1} \lambda_{R_1})^2]^{\frac{1}{2}}. \qquad [5]$$

The senitivities for V_1, V_s, and R_1 are computed as,

$$S_{V_1} = \frac{(\partial P_m/\partial V_1)V_1}{P_m} = 1.0, \qquad [6]$$

$$S_{V_s} = \frac{(\partial P_m/\partial V_s)V_s}{P_m} = 1.0, \qquad [7]$$

$$S_{R_1} = \frac{(\partial P_m/\partial R_1)R_1}{P_m} = 1.0. \qquad [8]$$

The resistance of R_1 was measured with an 8100A digital Fluke multimeter. The uncertainty in the 8100A is expressed as,

$$\text{Uncertainty} = \pm\ (0.05\%\ \text{of input} + 0.01\%\ \text{of range}). \qquad [9]$$

For a nomimal resistance of 10,000 ohms for R_1 the uncertainty is equal to,

$$\lambda_{R_1} = \pm \frac{[\ (.0005)(10000) + (.0001)(10000)\ ]}{10000} = \pm\ .06\%. \qquad [10]$$

Equation [5] can now be evaluated,

$$\lambda_{P_m} = \pm [\ [(1.0)(.25\%)]^2 + [(1.0)(.65\%)]^2 + [(-1.0)(.06\%)]^2]^{\frac{1}{2}}$$

$$\lambda_{P_m} = \pm 0.70\%. \qquad [11]$$

This uncertainty will be assigned to all measured power dissipation values.

Uncertainty in the Compensating Thermistor Temperature (Ambient Temperature)

The equation used to compute the resistance for the compensating thermistor, R_c, is,

$$R_c = \frac{V_s\, R_3\, R_2}{V_1 R_3 - V_s R_2} \qquad [12]$$

The resistances, R_2 and R_3, were measured with an 8100A multimeter. These resistances have different nomimal values for each of the three instrument ranges. V_s and V_1 also have different values. However, the uncertainty in R_c is effected very little by these changes. Hence, a good estimate of the uncertainty in R_c can be made using the following nomimal values,

$$R_2 = 53{,}505 \text{ ohms}$$

$$R_3 = 550{,}000 \text{ ohms}$$

$$V_s{}^* = 1.90 \text{ v}$$

$$V_1{}^* = 6.75 \text{ v}$$

* see Table 36.

The sensitivities of the variables in Eq. [12] are computed as,

$$S_{R_2} = \frac{(\partial R_c/\partial R_2)R_2}{R_c} = 1 + \frac{V_s R_2}{V_1 R_3 - V_s R_2} = 1.03, \qquad [13]$$

$$S_{R_3} = \frac{(\partial R_c/\partial R_3)R_3}{R_c} = 1 + \frac{R_2 V_s}{V_1 R_3 - V_s R_2} = 1.03, \qquad [14]$$

$$S_{V_s} = \frac{(\partial R_c/\partial V_s)V_s}{R_c} = 1 + \frac{R_2 V_s}{V_1 R_3 - V_s R_2} = 1.03, \qquad [15]$$

$$S_{V_1} = \frac{(\partial R_c/\partial V_1)V_1}{R_c} = \frac{-R_3 V_1}{V_1 R_3 - V_s R_2} = -1.03. \qquad [16]$$

The uncertainties for R_2 and R_3 are computed using Eq. [9] as,

$$\lambda_{R_2} = \frac{\pm[(.0005)(53505) + (.0001)(100000)]}{53505} = \pm .07\%, \qquad [17]$$

$$\lambda_{R_3} = \frac{\pm[(.0005)(550000) + (.0001)(10000000)]}{550000} = \pm .23\%. \qquad [18]$$

The uncertainty in R_c is evaluated as,

$$\lambda_{R_c} = \pm[(S_{V_1}\lambda_{V_1})^2 + (S_{V_s}\lambda_{V_s})^2 + (S_{R_2}\lambda_{R_c})^2 + (S_{R_3}\lambda_{R_3})^2]^{\frac{1}{2}}$$

$$= \pm[[(1.03)(.25\%)]^2 + [(1.03)(.65\%)]^2 + [(1.03)(.07\%)]^2 + [(1.03)(.23\%)]^2]^{\frac{1}{2}}$$

$$= \pm 0.76\%. \qquad [19]$$

An error in measurement of R_c for all data of $\pm$ 0.76% will be used.

Now that the uncertainty in R_c has been evaluated this must be incorporated into an uncertainty in the calculated ambient temperature by use of the temperature-resistance calibration curve. The following equation relates the resistance to the temperature for the appropriate ambient temperature range. For 60°F,

$$T_a = -49.697 (\ln R_c - 10.856). \qquad [20]$$

For 75°F,

$$T_a = -45.205 (\ln R_c - 11.0239). \qquad [21]$$

For 90°F,

$$T_a = -47.287 (\ln R_c - 10.948). \qquad [22]$$

The uncertainty at 60°F is,

$$\lambda_{T_{60}} = \pm [(S_{T_{60}}\lambda_{R_c})^2]^{\frac{1}{2}}, \qquad [23]$$

where,

$$S_{T_{60}} = \left.\frac{(\partial T_a/\partial R_c)R_c}{T_a}\right|_{T_a=60} = \left.\frac{-49.67}{T_a}\right|_{T_a=60} = -.828. \qquad [24]$$

Therefore,

$$\lambda_{T_{60}} = \pm\ [(-.828)(.76\%)^2]^{\frac{1}{2}} = \pm\ 0.63\%. \qquad [25]$$

The uncertainty at 75°F is,

$$\lambda_{T_{75}} = \pm\ [(S_{T_{75}}\ \lambda R_c)^2]^{\frac{1}{2}}\ , \qquad [26]$$

where,

$$S_{T_{75}} = \left.\frac{(\partial T_a/\partial R_c)R_c}{T_a}\right|_{T_a=75} = \left.\frac{-45.205}{T_a}\right|_{T_a=75} = -.603. \qquad [27]$$

Therefore,

$$\lambda_{T_{75}} = \pm\ [(-.603)(.76\%)^2]^{\frac{1}{2}} = \pm\ .46\%. \qquad [28]$$

The uncertainty at 90°F is,

$$\lambda_{T_{90}} = \pm\ [(S_{T_{90}}\lambda_{R_c})^2]^{\frac{1}{2}}\ ,$$

where,

$$S_{T_{90}} = \left.\frac{(\partial T_a/\partial R_c)\ R_c}{T_a}\right|_{T_a=90} = \left.\frac{-47.287}{T_a}\right|_{T_a=90} = -.525. \qquad [29]$$

Therefore,

$$\lambda_{T_{90}} = \pm\ [(-.525)(.76\%)^2]^{\frac{1}{2}} = \pm\ .40\%. \qquad [30]$$

In summary the uncertainties in the measurement of the ambient temperature are,

$$\lambda_{T_{60}} = \pm\ 0.63\%$$

$$\lambda_{T_{75}} = \pm\ 0.46\%$$

$$\lambda_{T_{90}} = \pm\ 0.40\%.$$

Before the uncertainty analysis is complete two other independent uncertainties must be evaluated. First, uncertainties in the temperature-resistance measurements will be analyzed. These uncertainties were incurred when the thermistor was calibrated in the oil bath. Secondly, uncertainties in the exponential curve fit with respect to the measured data will be accounted for. These errors will then be combined with the previously determined uncertainty in the measurement of the ambient temperature by,

$$\lambda_{T_{T_a}} = \pm [\lambda_{T_a}^2 + \lambda_{oil\ bath}^2 + \lambda_{curve}^2]^{\frac{1}{2}} . \qquad [31]$$

The value of $\lambda_{T_{Ta}}$ will be the overall uncertainty in the ambient temperature.

For the oil bath calibration two independent errors occur,

1. Resistance mesurement with the 8100A
2. Temperature measurement with a set of calibrated, precision mercury thermometers.

The uncertainty in the thermometer is calculated by assuming that the accuracy is equal to the resolution and both the resolution and the accuracy are independent. The smallest division on the thermometer is .2°F. Therefore,

$$\text{resolution} = \lambda_r = \tfrac{1}{2}(.2°F) = .1°F \qquad [32]$$

so,

$$\text{accuracy} = \lambda_a = \lambda_r = .1°F. \qquad [33]$$

The uncertainty in measurements made with the thermometer becomes,

$$\lambda_T = \pm (\lambda_r^2 + \lambda_a^2)^{\frac{1}{2}} = \pm .141°F. \qquad [34]$$

Normalizing with respect to temperature yields,

$$\lambda_T = \pm \frac{.141}{T_a}. \qquad [35]$$

The resistance values for R_c will typically be in the 10k range of the 8100A. The uncertainty can be computed from Eq. [9] as,

$$\lambda_R = \frac{\pm[(.0005)(10{,}000) + (.0001)(10{,}000)]}{10{,}000} = \pm .06\%. \quad [36]$$

The uncertainty in the temperature due to uncertainty in the resistance measurement is calculated by,

$$\lambda_{T_a} = \pm[(S_R \lambda_R)^2]^{\frac{1}{2}} , \quad [37]$$

where eq. [24], [27], and [29] are used to determine S_R. The following uncertainties for λ_{T_a} were determined:

$$\lambda_{60} = \pm .05\%$$

$$\lambda_{75} = \pm .036\%$$

$$\lambda_{90} = \pm .032\%.$$

The uncertainty in the resistance due to uncertainty in the temperature measurement is calculated by,

$$\lambda_{R_c}\Big|_{T_a} = \pm[(S_{T_a} \lambda_T)^2]^{\frac{1}{2}} \quad [38]$$

where,

$$S_{T_a}\Big|_{60} = \frac{(\partial R_c/\partial T_a)\ T_a}{T_a}\Big|_{60} = \frac{T_a}{-49.67}\Big|_{60} = -1.349 \quad [39]$$

$$S_{T_a}\Big|_{75} = \frac{T_a}{-45.205}\Big|_{75} = -1.659 \quad [40]$$

$$S_{T_a}\Big|_{90} = \frac{T_a}{-47.287}\Big|_{90} = -1.903 . \quad [41]$$

Therefore,

$$\lambda_{R_c}\Big|_{60} = \pm[(-1.349)(.06\%)^2]^{\frac{1}{2}} = \pm .081\% \quad [42]$$

$$\lambda_{R_c}\Big|_{75} = \pm[(-1.659)(.06\%)^2]^{\frac{1}{2}} = \pm .100\% \quad [43]$$

$$\lambda_{R_c}\Big|_{90} = [(-1.903)(.06\%)^2]^{\frac{1}{2}} = \pm .114\%. \qquad [44]$$

The total uncertainty in the oil bath calibration can now be computed by,

$$\lambda_{\text{oil bath}}\Big|_{T_a} = (\lambda_{R_s}\Big|_{T_a}^{2} + \lambda_{T_a}\Big|_{T_a}^{2})^{\frac{1}{2}} . \qquad [45]$$

This results in,

$$\lambda_{\text{oil bath}}\Big|_{60} = (.081\%^2 + .05\%^2)^{\frac{1}{2}} = \pm .095\% \qquad [46]$$

$$\lambda_{\text{oil bath}}\Big|_{75} = (.100\%^2 + .036\%^2)^{\frac{1}{2}} = \pm .106\% \qquad [47]$$

$$\lambda_{\text{oil bath}}\Big|_{90} = (.114\%^2 + .032\%^2)^{\frac{1}{2}} = \pm .118\%. \qquad [48]$$

The final step considers the uncertainty in the curve fit to the data. It should be mentioned again that this error is independent and unrelated to the error in the data that the curve is attempting to fit. Figure 29 shows some imaginary curve fit and an associated point that was determined experimentally. The uncertainty along only one axis will be considered. Since the resistance of the compensating thermistor is measured and the temperature is computed, the error will be computed along the temperature axis. The expression used (See Figure 29) is,

$$\lambda_{\text{curve}}\Big|_{T_2} = \frac{T_1 - T_2}{T_2} , \qquad [49]$$

where T_2 is calculated using the curve fit equation and R. T_1 is the temperature measured at R. The actual data points are needed to complete the calculations. The data were taken in the ambient temperature ranges of 60°F, 75°F, and 90°F. For each of these ranges the closest data points were,

62.4°F - 15,410 ohms

74.0°F - 12,060 ohms

90.5°F - 8,505 ohms.

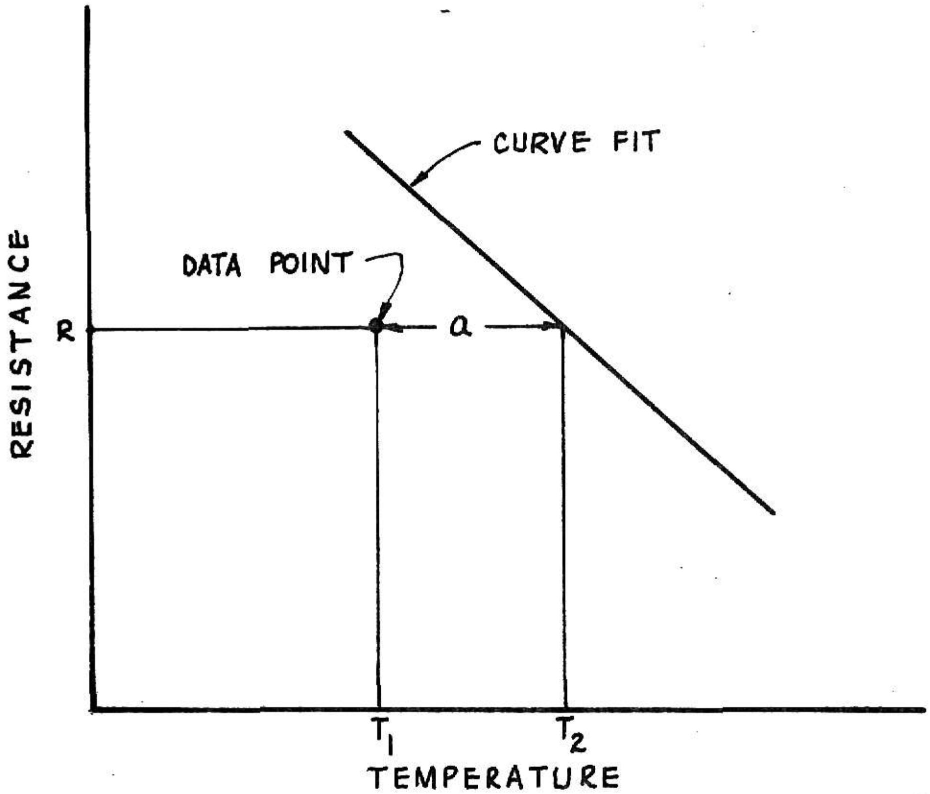

Figure 29

Illustration of the Curve Fit Error

Using Eq. [49] for these points yields,

$$\lambda_{curve}\Big|_{60} = \pm 3.49\%$$

$$\lambda_{curve}\Big|_{75} = \pm .66\%$$

$$\lambda_{curve}\Big|_{90} = \pm .727\%.$$

The total uncertainty in the ambient temperature can now be computed using Eq. [31]:

$$\lambda_{T_{60}} = \pm[.63\%^2 + .095\%^2 + 3.49\%^2]^{\frac{1}{2}} = \pm 3.55\%$$

$$\lambda_{T_{75}} = \pm[.46\%^2 + .106\%^2 + .66\%^2]^{\frac{1}{2}} = \pm .811\%$$

$$\lambda_{T_{90}} = \pm[.40\%^2 + .118\%^2 + .727\%^2]^{\frac{1}{2}} = \pm .838\% .$$

Uncertainty in the Sensing Thermistor Temperature

The uncertainty analysis for the sensing thermistor is very similar to that for the compensating thermistor. Again, three primary uncertainties occur due to measurement of R_s, the oil bath calibration, and the curve fit. The equation used to compute R_s from the measured variables, V_1 and V_s, is different from the equation used to compute R_c. Hence, a new uncertainty analysis will be presented to compute the measurement uncertainty. The arguments and calculations presented in the previous section for the oil bath calibration and curve fit are still valid. Therefore, only the necessary calculations and results will be presented for these uncertainties.

The equation used to calculated R_s is,

$$R_s = \frac{V_s R_1}{V_1} . \qquad [50]$$

The measurement uncertainty can be expressed by,

$$\lambda_{R_s} = \pm[(S_{V_s}\lambda_{V_s})^2 + (S_{V_1}\lambda_{V_1})^2 + (S_{R_1}\lambda_{R_1})^2]^{\frac{1}{2}} , \qquad [51]$$

where,

$$S_{V_s} = \frac{(\partial R_s/\partial V_s)V_s}{R_s} = 1.0, \qquad [52]$$

$$S_{V_1} = \frac{(\partial R_s/\partial R_1)R_1}{R_s} = -1.0, \qquad [53]$$

$$S_{R_1} = \frac{(\partial R_s/\partial R_1)R_1}{R_s} = 1.0, \qquad [54]$$

and, from Eq. [2], [3], and [10],

$$\lambda_{V_s} = \pm\ 0.65\%,$$

$$\lambda_{V_1} = \pm\ 0.25\%,$$

$$\lambda_{R_1} = \pm\ 0.06\%.$$

The measurement uncertainty results are,

$$\lambda_{R_s} = \pm[(1.0)(0.65\%)^2 + (1.0)(0.25\%)^2 + (-1.0)(0.06\%)^2]^{\frac{1}{2}}$$

$$\lambda_{R_s} = \pm\ 0.70\%.$$

The uncertainty due to the oil bath calibration is calculated for ambient temperatures of 67°F, 81°F, and 93°F and a nominal resistance of 2800 ohms. Using Eqs. [9] and [35],

$$\lambda_{T_{67}} = \pm\ 0.210\%$$

$$\lambda_{T_{81}} = \pm\ 0.174\%$$

$$\lambda_{T_{93}} = \pm\ 0.152\%$$

and,

$$\lambda_{R_s} = \pm\ .085\%.$$

Equations [39], [40], and [41] were used to compute the temperature sensitivities and Eqs. [24], [27], and [29] were used to compute the resistance senitivities. The results are,

$$S_{T_{67}} = -1.349$$

$$S_{T_{81}} = -1.792$$

$$S_{T_{93}} = -1.967$$

and,

$$S_{R_{67}} = .741$$

$$S_{R_{81}} = .558$$

$$S_{T_{93}} = .508.$$

The uncertainties in temperature measurement and in resistance measurement are computed using Eq. [37] and [38]:

For temperature,

$$\lambda_{67} = \pm .283\%$$

$$\lambda_{81} = \pm .312\%$$

$$\lambda_{93} = \pm .299\%$$

For resistance,

$$\lambda_{R_c}\Big|_{67} = \pm .063\%$$

$$\lambda_{R_c}\Big|_{81} = \pm .047\%$$

$$\lambda_{R_c}\Big|_{93} = \pm .043\%.$$

The total uncertainty in the results of the oil bath calibration computed by Eq. [45] are,

$$\lambda_{\text{oil bath}}\Big|_{67} = \pm .290\%$$

$$\lambda_{\text{oil bath}}\Big|_{81} = \pm .316\%$$

$$\lambda_{\text{oil bath}}\Big|_{93} = \pm .302\% .$$

Finally, the uncertainty in the curve fit is calculated at the following data points,

66.4°F - 2816 ohms,

77.6°F - 2311 ohms,

94°F - 1607 ohms.

Equation [49] is used to determine the uncertainties. The results are,

$$\lambda_{curve}\Big|_{67} = \pm 1.373\%$$

$$\lambda_{curve}\Big|_{81} = \pm 1.263\%$$

$$\lambda_{curve}\Big|_{93} = \pm .250\%.$$

Equation [31] is used to compute the combined error in the sensing temperature due to λ_{R_s}, $\lambda_{oil\ bath}$, and λ_{curve}. The results are,

$$\lambda_{T_{67}} = \pm[.70\%^2 + .29\%^2 + 1.373\%^2]^{\frac{1}{2}} = \pm 1.568\% \quad [55]$$

$$\lambda_{T_{81}} = \pm[.70\%^2 + .316\%^2 + 1.263\%^2]^{\frac{1}{2}} = \pm 1.478\% \quad [56]$$

$$\lambda_{T_{93}} = \pm[.70\%^2 + .302\%^2 + .250\%^2]^{\frac{1}{2}} = \pm .802\%. \quad [57]$$

Uncertainty in the Self-heat

The self-heat of the sensing thermistor is computed by,

$$SFHT = T_s - T_c \quad [58]$$

where,

λ_{SFHT} = self-heat,

T_s = temperature of sensing thermistor,

T_c = temperature of compensating thermistor.

The uncertainty in SFHT is computed by,

$$\lambda_{SFHT} = [(S_{T_s}\lambda_{T_{T_s}})^2 + (S_{T_c}\lambda_{T_{T_c}})^2]^{\frac{1}{2}} , \quad [59]$$

where,

$$S_{T_s} = \frac{(\partial SFHT/\partial T_s)T_s}{SFHT} = \frac{T_s}{T_s - T_c} , \quad [60]$$

and,

$$S_{T_c} = \frac{(\partial SFHT/\partial T_c)T_c}{SFHT} = \frac{-T_c}{T_s - T_c} . \quad [61]$$

For the ambient temperature range of 60°F,

$$S_{T_s} = \frac{67}{7.0} = 9.57,$$

$$S_{T_c} = \frac{60}{7.0} = -8.57.$$

Therefore,

$$\lambda_{SFHT}\Big|_{60} = \pm[(9.57)(1.568\%)^2 + (-8.57)(3.55\%)^2]^{\frac{1}{2}} = \pm 33.92\%. \quad [62]$$

For the ambient temperature range of 75°F,

$$S_{T_s} = \frac{81}{5.3} = 15.28,$$

$$S_{T_c} = \frac{75}{5.3} = -14.15.$$

Therefore,

$$\lambda_{SFHT}\Big|_{75} = \pm[(15.28)(1.478\%)^2 + (-14.15)(.811\%)^2]^{\frac{1}{2}} = \pm 25.33\%. \quad [63]$$

For the ambient temperature range of 90°F,

$$S_{T_s} = \frac{93}{5.6} = 16.61,$$

$$S_{T_c} = \frac{90}{5.6} = -16.07.$$

Therefore,

$$\lambda_{SFHT}\Big|_{90} = \pm[(16.61)(.802\%)^2 + (-16.07)(.838\%)^2]^{\frac{1}{2}} = \pm 18.94\%. \quad [64]$$

Summarizing, the uncertainties in the self-heat for the ambient temperature ranges of 60°F, 75°F, and 90°F were found to be,

$$\lambda_{SFHT}\Big|_{60} = \pm 33.92\%$$

$$\lambda_{SFHT}\Big|_{75} = \pm 25.33\%$$

$$\lambda_{SFHT}\Big|_{90} = \pm 18.94\%.$$

Uncertainty in the Calculated Air Speed

The uncertainty in the air speed was not calculated directly due to the complexity of the equations involved. Instead, Computer Program IX was used to directly incorporate the appropriate uncertainties. The effect of the uncertainties was determined by observing the magnitude and direction of the associated change in calculated velocities that were caused by imposing these uncertainties.

The uncertainties were contributed by the self-heat and the power dissipation. The following method was used to calculate the uncertainty in the calculated air speed.

1. Run numbers 5, 13, and 22 were chosen to represent each ambient temperature range (see Table 37).

2. The compensating thermistor temperature, the self-heat, and the power dissipation from each run was used to calculate the air speed. However, using results from the previous uncertainty analysis, the self-heat and the power dissipation values were changed before the air speed was calculated. For run 5 the self-heat was increased by 25.33% and the power dissipation was increased by 0.70%.

3. The air speed was calculated and the change was expressed as a percentage of the air speed obtained initially.

4. The self-heat and the power dissipation were decreased by the same percentages and the air speed was again calculated and expressed as a percentage of the initial value.

5. Steps 2 through 4 were repeated for runs 13 and 22 using the appropriate uncertainties for the self-heat and power dissipation. The compensating thermistor temperature uncertainty was already incorporated into the self-heat uncertainty and was, therefore, ignored.

The results from Computer Program IX are presented in Table 40.

Table 40

Computed Uncertainties in
Air Speed

Uncertainty in Air Speed Computed from Data for Run No.	Typical for Runs	Sign of Uncertainty	Percentage Error in Calculated Air Speed
5	1 - 8	+	-55.86%
		-	+154.81%
13	9 - 16	+	-22.21%
		-	+31.25%
22	17 - 24	+	-75.26%
		-	+367.54%

Uncertainty in the
Centerline Velocity

The uncertainty in the centerline velocity produced by the portable wind tunnel was obtained from a thesis entitled, "The Design, Construction, and Calibration of a Low Velocity Anemometer Calibrator" by Mr. Rodney Gene Keif (2). The uncertainty analysis for the centerline velocity was not completed in currently available copies of this thesis. The uncertainties in the centerline velocities were obtained by directly contacting Mr. Keif. For centerline velocities less than 100 fpm Mr. Keif reported an uncertainty of ± 5% and for centerline velocities greater than 100 fpm Mr. Keif reported an uncertainty of ± 2%.

APPENDIX C

Computer Programs

Appendix C is a list of all the computer programs used in this thesis. The values for the various constants used in the programs (see describing heat transfer equation, Eq. [16] of the text) were obtained from Mr. William Flanders. These constants and their symbols are:

EW (Thermal emittance of the support wire) = 0.90.

ES (Thermal emittance of the sensing thermistor) = 0.60.

DS (Diameter of the sensing thermistor) = .0036 ft.

DW (Diameter of the support wire) = .000333 ft.

TCW (Thermal conductivity of the support wire) = 17.92 Btu/HR-FT-F.

```
C                              PROGRAM I
C
C
C                   POWER DISSIPATION AT VARIOUS AMBIENT
C                   TEMPERATURES FOR CONSTANT SELF-HEAT
C
C
C
C             THIS PROGRAM COMPUTES THE POWER DISSIPATIONS FOR THE
C       FULL RANGE OF THE ANEMOMETER FOR A CONSTANT SELF-HEAT THROUGHOUT
C       THE RANGE.
C
C
      DIMENSION P(6)
   99 FORMAT(5F16.6)
  100 FORMAT('1',////,63X,'TABLE 1',//,40X,'POWER DISSIPATION AT VARIOUS
     1 AMBIENT TEMPERATURES FOR',/,46X,'A CONSTANT SELF-HEAT OF ',I2,
     1' DEGREES FAHRENHEIT',//)
  101 FORMAT(34X,65(1H-),/,35X,'AIR SPEED  |',10X,'POWER DISSIPATION (MI
     1LLIWATTS) AT',/,37X,'(FPM)     |',5X,'50F',5X,'60F',5X,'70F',5X,'80
     1F',5X,'90F',4X,'100F',/,34X,65(1H-))
  102 FORMAT('0',38X,I4,3X,'|',6(3X,F5.2))
      READ(5,99) EW,ES,DS,DW,TCW
C
C     EW-THERMAL EMITTANCE OF SUPPORT WIRE
C     ES-THERMAL EMITTANCE OF SENSING THERMISTOR
C     DS-DIAMETER OF THE SENSING THERMISTOR IN FEET
C     DW-DIAMETER OF SUPPORT WIRE IN FEET
C     TCW-THERMAL CONDUCTIVITY OF SUPPORT WIRE IN BTU/HR-FT-F
C
      PI=3.14159
      S=0.1714E-08
C     THE SURFACE AREA OF THE SENSING THERMISTER IS
      AS=PI*DS**2
C     THE POWER DISSIPATION OF THE SENSING THERMISTOR IS NOW CALCULATED.
C     DO- LOOP 10 VARIES THE TEMPERATURE ELEVATION OF THE SENSING THERMISTOR
C     WHILE DO-LOOP 20 CHANGES THE AIR VELOCITY AND DO-LOOP 30 VARIES THE
C     AMBIENT TEMPERATURE
      DO 10 JDT=20,20,5
C     THE SENSING THERMISTOR'S TEMPERATURE ELEVATION IS
      DT=JDT
      WRITE(6,100) JDT
      WRITE(6,101)
      DO 10  I=10,190,10
C     THE AIR VELOCITY IS
      IVEL=I
```

```
      IF(IVEL.GT.100)  IVEL=10*(I-90)
      DO 30  K=1,6
C     THE VELOCITY IN FT/HR IS
      V=IVEL*60.0
C     THE AMBIENT TEMP. (F) IS
      TE=50.0 + 10.0*(K-1)
C     THE FILM TEMP. IS
      TF=TE + DT/2.0
C     THE TEMP. OF THE SENSING THERMISTOR IS
      TT=TE + DT
C     CONVERTING DEGREES FAHRENHEIT TO DEGREES RANKINE
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
C     THE KINEMATIC VISCOSITY OF THE AIR IS
      VA=.00198*(TFR-460.) + 0.461
C     THE THERMAL CONDUCTIVITY OF THE AIR IS
      XKA=.0000233*(TFR-460.0) + 0.01317
C     THE REYNOLDS NUMBER FOR THE SENSING THERMISTOR IS
      RES=(V*DS)/VA
C     THE GRASHOFF NO. FOR THE SENSING THERMISTOR IS
      GR=((DS**3.0)*32.174*DT)/(TER*VA**2.0)
C     THE REYNOLDS NUMBER FOR THE SUPPORT WIRE IS
      REW=(V*DW)/VA
C     THE SURFACE HT. TRANS. COEFF. OF THE SENSING THERMISTOR IS
      HS=(XKA/DS)*(2.0+0.5*(RES**2.0+(4.0/3.0)*GR)**.25)
C     THE SURFACE HT. TRANS. COEFF. OF THE SUPPORT WIRE IS
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
C     CALCULATION OF POWER DISSIPATION
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      P(K)=(PO/3.4127)*1000.0
   30 CONTINUE
      WRITE(6,102)  IVEL, (P(K), K=1,6)
   10 CONTINUE
      WRITE(6,100)
      STOP
      END
```

```
C                                   PROGRAM II
C
C
C                    SELF-HEATS FCR CCNSTANT POWER
C                               DISSIPATION
C
C
C
C            THIS PRCGRAM COMPUTES THE VALUES OF SELF-HEATS REQUIRED
C      FOR CCNSTANT POWER DISSIPATICN THRCUGHOUT THE AMBIENT TEMPER-
C      ATURE RANGE FOR EACH VELOCITY.  A SELF-HEAT (SFHT) AND A
C      REFERENCE TEMPERATURE (TESFHT) MUST BE SPECIFIED.
C
C
      DIMENSICN SS(11)
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      CCMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
   98 FCRMAT(I1)
   99 FORMAT(5F16.6)
  100 FORMAT(2F10.2)
  101 FORMAT('1',////////,63X,'TABLE ',I1,//,37X,'SELF-HEATS REQUIRED TO
     1 MAINTAIN A CONSTANT POWER DISSIPATICN',/,42X,'WHEN THE SELF-HEAT
     1IS',I2,' DEGREES FAHRENHEIT AND THE',/,44X,'REFERENCE TEMPERATURE
     1IS ',I3, ' DEGREES FAHRENHEIT',//22X,89(1H-))
  102 FORMAT(23X,'AIR SPEED |',20X,'SELF-HEATS (DEGREES FAHRENHEIT) AT',
     1/,25X,'(FPM)    |',3X,'50F',4X,'55F',4X,'60F',4X,'65F',4X,'70F',4X,
     1'75F',4X,'80F',4X,'85F',4X,'90F',4X,'95F',4X,'100F',/,22X,89(1H-))
  103 FORMAT(25X,I4,4X,'|',11(2X,F5.3))
      READ(5,99)  EW,ES,DS,DW,TCW
      READ(5,98)  NUM
      DC 50  III=1,NUM
      READ(5,100)  SFHT,TESFHT
      N=III+1
      NS=SFHT
      NT=TESFHT
      WRITE(6,101)  N,NS,NT
      WRITE(6,102)
      S=0.1714E-C8
      PI=3.14159
      AS=PI*DS**2
      DO 50  IV=10,190,10
      NV=IV
      IF(IV.GE.100)  NV=(IV-90)*10
      VEL=NV*60.0
      DC 40  ITE=50,100,5
      N=(ITE-45)/5
```

```
      TE=ITE
      CALL PDISS(VEL)
      SS(N)=SFHTPD
   40 CONTINUE
      WRITE(6,103)  NV,(SS(I),I=1,11)
   50 CONTINUE
      WRITE(6,101)  N
      STOP
      END
```

```
      FUNCTION POWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELOCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      DT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PO/3.4127)*1000.0
      RETURN
      END
```

```
      SUBROUTINE PDISS(V)
C
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF SELF-HEAT NECESSARY FOR
C     CONSTANT POWER DISSIPATION AT ANY VELOCITY-AMBIENT TEMPERATURE
C     COMBINATION ONCE A POWER-VELOCITY CURVE IS INITIALLY SPECIFIED BY
C     A CERTAIN SELF-HEAT (SFHT) OCCURING AT A SPECIFIC AMBIENT TEMPERA-
C     TURE (TESFHT).  THIS NEW SELF-HEAT IS DESIGNATED SFHTPD.  ALSO A
C     VALUE FOR THE SENSING RESISTOR IN OHMS IS CALCULATED AT THIS NEW
C     SELF-HEAT (I.E. NEW SENSING THERMISTOR TEMPERATURE).
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/POIS/TE,SFHT,TESFHT,SFHTPD,RS
      I=TESFHT
      TS=SFHT+I
C
C     PWAT1 IS THE POWER DISSIPATION IN MILLIWATTS AT THE GIVEN SELF-
C     HEAT OCCURING AT THE SPECIFIED AMBIENT TEMPERATURE.
C
      PWAT1=POWER(TS,I,V)
      DT=SFHT
      TF=TE+DT/2.
      TT=TS
C
C     A IS TWICE THE INITIAL INCREMENT USED TO INITIATE THE ITERATION PRO-
C     CEDURE.  CHK IS THE VALUE IN MILLIWATTS THAT SERVES AS AN ITERATION
C     CRITERIA THAT MUST BE MET BEFORE THE ITERATION IS TERMINATED.
C
      NUM=0
      A=50.
      CHK=.0001
   53 A=A/2.
      NUM=NUM+1
      IF(A.LE..0000001)  A=2.0
      DT=TT-TE
      TF=TE+(TT-TE)/2.0
      TER=TE+460.
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
```

```
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
C
C     PWATT IS THE POWER DISSIPATION IN MILLIWATTS THAT MUST BE ALTERED
C     BY VARYING THE SENSING THERMISTORS TEMPERATURE.  THE DIFFERENCE BE-
C     TWEEN PWATT AND PWAT1 IS MINIMIZED BY CHANGING TT, WHICH IS THE
C     TEMPERATURE OF THE SENSING THERMISTOR, UNTIL THE ABSOLUTE VALUE OF
C     THIS DIFFERENCE, ABS(EPSI), IS LESS THAN OR EQUAL TO CHK.
C
      PWATT=(PO/3.4127)*1000.0
      EPSI=PWAT1-PWATT
      IF(ABS(EPSI).LE.CHK)  GOTO60
      IF(EPSI)  50,60,52
   50 TT=TT-A
      GOTO53
   52 TT=TT+A
      GOTO53
C
C     THE NEW SELF-HEAT IS CALCULATED USING ITERATED VALUES OF TT AND
C     THE VALUE OF TE WHICH WAS INTIALLY USED TO ENTER THE SUBROUTINE.
C
   60 SFHTPO=TT-TE
      RETURN
      END
```

```
C                               PROGRAM III
C
C
C                    POWER CURVE GENERATION PROGRAM
C
C
C
C               THIS PROGRAM GENERATES VALUES OF POWER DISSIPATION
C       FOR EACH VELOCITY GIVEN A REFERENCE TEMPERATURE (TNT) AND A
C       SELF-HEAT (ITT).  THE DESCRIBING HEAT TRANSFER EQUATION (SEE
C       EQ. 16 OF THE TEXT) IS USED TO COMPUTE THE POWER DISSIPATION OF
C       THE SENSING THERMISTOR.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
  100 FORMAT(6F10.6)
  101 FORMAT('1',//////    ,62X,'TABLE ',I2,//,42X,'THE POWER CURVE IN TA
     1BULAR FORM FOR A SELF-HEAT',/,46X,'OF ',I2,' DEGREES FAHRENHEIT AT
     1 A REFERENCE',/,47X,'TEMPERATURE OF ',I3,' DEGREES FAHRENHEIT',//,
     134X,65(1H-),/,39X,'AIR SPEED',5X,'|',4X,'POWER DISSIPATED BY SENSI
     1NG THERMISTOR',/,41X,'(FPM)',7X,'|',16X,'(MILLIWATTS)',/,34X,65(1H
     1-),/,53X,'|')
  102 FORMAT(41X,I4,8X,'|',20X,F7.4,/,53X,'|')
  103 FORMAT(I1)
  104 FORMAT(I2,I2)
      READ(5,100)  EW,ES,DS,DW,TCW,TNT
      READ(5,103)  NUM
      S=0.1714E-08
      PI=3.14159
      AS=PI*DS**2
      NT=TNT
      DO 200 I=1,NUM
      READ(5,104)  NTABLE,ITT
      WRITE(6,101)  NTABLE,ITT,NT
      TT=ITT+TNT
      DO 200  IV=10,190,10
      NV=IV
      IF(IV.GE.100)  NV=10*(IV-90)
      V=60.0*NV
      P=POWER(TT,NT,V)
      WRITE(6,102)  NV,P
  200 CONTINUE
      WRITE(6,101)  NTABLE,ITT,NT
      STOP
      END
```

```
      FUNCTION POWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELOCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      CT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/CW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PC/3.4127)*1000.0
      RETURN
      END
```

```
C                                 PROGRAM  IV
C
C
C                  SIMULTANEOUS SIZING PROGRAM FOR THE
C                     BETA AND R3 CIRCUIT COMPONENTS
C
C
C
C          IN ORDER TO MINIMIZE THE INSTRUMENT ERROR IN RECORDING THE
C      TRUE AIR SPEED THE RESISTOR, R3, IN PARALLEL WITH THE TEMPERATURE
C      COMPENSATING RESISTOR MUST BE CHOSEN SO THE RESISTOR RATIO BETA,
C      R1/R2, IS A CONSTANT (IDEALLY) THROUGHOUT THE VELOCITY RANGE 10 FPM
C      TO 1000 FPM AND THROUGHOUT THE TEMPERATURE RANGE 50F TO 100F.
C          THIS PROGRAM DOES NOT AUTOMATICALLY SELECT THE OPTIMUM VALUE
C      OF R3 AND THE CORRESPONDING VALUE OF BETA.  INSTEAD, A PRINTOUT OF
C      ALL THE VALUES OF BETA AT  19 DIFFERENT VELOCITIES AND  11 AMBIENT
C      TEMPERATURES IS MADE FOR EACH VALUE OF R3.  THE AVERAGE BETA
C      AND THE STANDARD DEVIATION IN BETA ARE THEN CALCULATED AND PRINTED
C      OUT.
C            TO FIND OPTIMUM VALUES FOR BETA AND R3 THIS PROGRAM
C      MUST BE RUN FOR A NUMBER OF R3 VALUES AND EACH RESULTING STANDARD
C      DEVIATION PLOTTED VERSUS R3 UNTIL A MINIMUM STANDARD DEVIATION
C      IS FOUND.
C
C
      COMMON/SDEV/BETA(19,11)
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
C
C          THE VARIABLES IN THE COMMON LOCATIONS ARE DEFINED AS FOLLOWS:
C                EW=THERMAL EMITTANCE OF THE SUPPORT WIRE
C                ES=THERMAL EMITTANCE OF THE SENSING THERMISTOR
C                DS=DIAMETER OF THE SENSING THERMISTOR IN FEET
C                DW=THERMAL CONDUCTIVITY OF THE SUPPORT WIRE
C                   IN BTU/HR-FT-F
C                S=STEFAN-BOLTZMANN CONSTANT
C                PI=PI
C                AS=SURFACE AREA OF THE SENSING THERMISTOR
C                TE=AMBIENT AIR TEMPERATURE
C                SFHT=THE SELF-HEAT AT A GIVEN REFERENCE TEMPERATURE
C                TESFHT=REFERENCE TEMPERATURE
C                SFHTPD=THE SELF-HEAT AT ANY AMBIENT TEMPERATURE
C               RS=RESISTANCE IN OHMS OF THE SENSING THERMISTOR
C
  101 FORMAT(14X,I4,6X,'|',11(2X,F7.5),/,24X,'|')
  102 FORMAT('1',//              ,63X,'TABLE ',I2,//,44X,'REQUIRED VALUES
```

```
     1 OF BETA (R1/R2) FOR CONSTANT',/,48X,'POWER DISSIPATION ACROSS THE
     1 AMBIENT',/,49X,'TEMPERATURE RANGE OF 50 F TO 100 F',//)
 103 FORMAT(22X,'SELF-HEAT = ',I2,' DEGREES FAHRENHEIT',/,22X,'REFERENC
     1E TEMPERATURE = ',I3,' DEGREES FAHRENHEIT',/,22X,'R3 = ',F7.0,' OH
     1MS',//,10X,115(1H-),/,11X,'AIR SPEED',4X,'|',37X,'REQUIRED VALUES
     1OF BETA AT',/,13X,'(FPM)',6X,'|',4X,'50F',6X,'55F',6X,'60F',6X,'65
     1F',6X,'70F',6X,'75F',6X,'80F',6X,'85F',6X,'90F',6X,'95F',6X,'100F'
     1,/,10X,115(1H-),/,24X,'|')
 104 FORMAT(5F16.6)
 105 FORMAT(I2,5F10.1)
 106 FORMAT(2I3)
     READ(5,104) EW,ES,DS,DW,TCW
     READ(5,105)  NDATA
     S=.1714E-08
     PI=3.14159
     AS=PI*DS**2
     DO 300  NN=1,NDATA
     READ(5,105)  NTABLE
     READ(5,104)  TESFHT
     NTT=TESFHT
     READ(5,105)  NUMR
     READ(5,106)  ILV,IHV
     DO 50  III=1,19
     DO 50  INN=1,11
     BETA(III,INN)=0.0
  50 CONTINUE
     READ(5,105)  ISHT,R11,R12,R13,R14,R15
     SFHT=ISHT
     DO 200  IR3=1,NUMR
     WRITE(6,102)  NTABLE
C
C    THIS COMPUTED GOTO SETS THE VALUES OF R3 THAT ARE OF INTEREST.
C
     GOTO(1,2,3,4,5),IR3
   1 R3=R11
     GOTO6
   2 R3=R12
     GOTO6
   3 R3=R13
     GOTO6
   4 R3=R14
     GOTO6
   5 R3=R15
   6 WRITE(6,103) ISHT,NTT,R3
C
C    THIS LOOP PARAMETER IS VELOCITY.
```

```
C
      DC 100  NV=ILV,IHV,10
      IROWS=((IHV-ILV)/10)+1
      LL=(NV/10)-((ILV-10)/10)
      NVL=NV
      IF(NV.GE.100)  NVL=10*(NV-90)
      VEL=NVL*60.
C
C     THIS LOOP PARAMETER IS AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.
C
      DC 99  IT=50,100,5
      TE=IT
      II=(IT-45)/5
C
C     THE SUBROUTINE PDISS RETURNS THE VALUE OF RS, THE RESISTANCE OF
C     THE SENSING THERMISTOR.
C
      CALL PDISS(VEL)
C
C     THE FUNCTICN RTCF COMPUTES THE RESISTANCE,RTC, OF THE TEMPERATURE
C     COMPENSATING RESISTOR.
C
      RTC=RTCF(TE)
C
C     THIS EQUALITY MUST HOLD FCR THE BRIDGE TO BE IN BALANCE.
C
      BETA(LL,II)=RS*((R3+RTC)/(R3*RTC))
C
   99 CONTINUE
      WRITE(6,101)  NVL,(BETA(LL,I), I=1,11)
  100 CONTINUE
C
C     THE AVERAGE BETA AND THE STANCARD DEVIATION IN BETA ARE CALCULATED.
C
      CALL SDBETA(IROWS)
C
  200 CONTINUE
  300 CONTINUE
      WRITE(6,102)  NTABLE
      STOP
      END
```

```
      SUBROUTINE SDBETA(IR)
C
C
C            THIS SUBROUTINE CALCULATES THE STANDARD DEVAITION IN
C     BETA (STDEV) AND THE AVERAGE BETA (XBAR).
C
C
      COMMON/SDEV/BETA(19,11)
   10 FORMAT(44X,'AVERAGE BETA =',F7.5,10X,'STD. DEVIATION =',F8.6)
      SUMB=0.0
      SUMDEV=0.0
      AN=11.0*IR
      DO 20  N=1,IR
      DO 20  I=1,11
      SUMB=SUMB+BETA(N,I)
   20 CONTINUE
      XBAR=SUMB/AN
      DO 30  N=1,IR
      DO 30  I=1,11
      DEV=BETA(N,I)-XBAR
      SUMDEV=SUMDEV+(DEV**2)
   30 CONTINUE
      STDEV=(SUMDEV/(AN-1))**0.5
      WRITE(6,10)  XBAR,STDEV
      RETURN
      END
```

```
      FUNCTION POWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELCCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      CCMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      DT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      PCWER=(PO/3.4127)*1000.0
      RETURN
      END
```

```
C
C
C
      SUBROUTINE PDISS(V)
C
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF SELF-HEAT NECESSARY FOR
C     CONSTANT POWER DISSIPATION AT ANY VELOCITY-AMBIENT TEMPERATURE
C     COMBINATION ONCE A POWER-VELOCITY CURVE IS INITIALLY SPECIFIED BY
C     A CERTAIN SELF-HEAT (SFHT) OCCURING AT A SPECIFIC AMBIENT TEMPERA-
C     TURE (TESFHT).  THIS NEW SELF-HEAT IS DESIGNATED SFHTPD.  ALSO A
C     VALUE FOR THE SENSING RESISTOR IN OHMS IS CALCULATED AT THIS NEW
C     SELF-HEAT (I.E. NEW SENSING THERMISTOR TEMPERATURE).
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      I=TESFHT
      TS=SFHT+I
C
C     PWAT1 IS THE POWER DISSIPATION IN MILLIWATTS AT THE GIVEN SELF-
C     HEAT OCCURING AT THE SPECIFIED AMBIENT TEMPERATURE.
C
      PWAT1=POWER(TS,I,V)
      DT=SFHT
      TF=TE+DT/2.
      TT=TS
C
C     A IS TWICE THE INITIAL INCREMENT USED TO INITIATE THE ITERATION PRO-
C     CEDURE.  CHK IS THE VALUE IN MILLIWATTS THAT SERVES AS AN ITERATION
C     CRITERIA THAT MUST BE MET BEFORE THE ITERATION IS TERMINATED.
C
      NUM=0
      A=50.
      CHK=.0001
   53 A=A/2.
      NUM=NUM+1
      IF(A.LE..0001)  A=2.0
      DT=TT-TE
      TF=TE+(TT-TE)/2.0
      TER=TE+460.
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
```

```
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
C
C     PWATT IS THE POWER DISSIPATION IN MILLIWATTS THAT MUST BE ALTERED
C     BY VARYING THE SENSING THERMISTORS TEMPERATURE.  THE DIFFERENCE BE-
C     TWEEN PWATT AND PWAT1 IS MINIMIZED BY CHANGING TT, WHICH IS THE
C     TEMPERATURE OF THE SENSING THERMISTOR, UNTIL THE ABSOLUTE VALUE OF
C     THIS DIFFERENCE, ABS(EPSI), IS LESS THAN OR EQUAL TO CHK.
C
      PWATT=(PO/3.4127)*1000.0
      EPSI=PWAT1-PWATT
      IF(ABS(EPSI).LE.CHK)  GOTO60
      IF(EPSI)  50,60,52
   50 TT=TT-A
      GOTO53
   52 TT=TT+A
      GOTO53
C
C     THE NEW SELF-HEAT IS CALCULATED USING ITERATED VALUES OF TT AND
C     THE VALUE OF TE WHICH WAS INTIALLY USED TO ENTER THE SUBROUTINE.
C
   60 SFHTPD=TT-TE
C
C     RS, THE SENSING THERMISTOR'S RESISTANCE IN OHMS, IS CALCULATED BY
C     CALLING THE FUNCTION RTF AND ENTERING IT WITH THE NEWLY ITERATED
C     SENSING THERMISTOR TEMPERATURE, TT.
C
      RS=RTF(TT)
      RETURN
      END
```

```
      FUNCTION RTCF(A)
C
C
C     THIS FUNCTION APPROXIMATES THE TEMPERATURE-RESISTANCE CURVE FOR A
C     FENWAL MODEL   QB41J1  10K    TEMPERATURE COMPENSATING THERMISTOR
C     USING THE RELATICNSHIP RTCF=AA*EXP(B*T) WHICH IS ACCURATE TO WITHIN
C     0.03% OF THE MEASURED VALLES.  GIVEN A TEMPERATURE, A, OF THE TEMP-
C     RATURE COMPENSATING RESISTOR A VALUE OF RESISTANCE, RTCF, IS
C     CALCULATED (IN OHMS).
C
C
      IF (A.LT.71.2) GO TO 100
      IF(A.LT.79.15) GO TO 200
      IF (A.LT.88.3) GO TO 300
      IF (A.LT.95.9) GO TO 400
      GO TO 500
 100  AA=61321.457
      B=-.02212168
      GO TO 700
 200  AA=61840.436
      B=-.02222238
      GO TO 700
 300  AA=56864.665
      B=-.02114734
      GC TC 700
 400  AA=52789.792
      B=-.02031355
      GC TC 700
 500  AA=51841.729
      B=-.02012192
      GO TO 700
 700  RTCF=AA*EXP(A*B)
      RETURN
      END
```

```
      FUNCTION RTF(A)
C
C
C     GIVEN A TEMPERATURE, A, OF THE SENSING THERMISTCR A VALUE OF RESIS-
C     TANCE, RTF, IS CALCULATED.  THIS FUNCTION APPRCXIMATES THE TEMPERA-
C     TURE-RESISTANCE CURVE FOR A FENWAL MCDEL GB32L1 2K BEAD-TYPE THER-
C     MISTOR USING THE RELATICNSHIP RTF=AA*EXP(B*T).  THIS APPROXIMATION
C     AGREES TO WITHIN 0.03% OF THE MEASURED VALUES.
C
C
      IF(A.LT.71.2) GO TO 100
      IF (A.LT.79.0) GC TO 200
      IF (A.LT.88.3) GO TO 300
      IF (A.LT.95.9) GO TO 400
      IF (A.LT.104.75) GO TO 500
      IF (A.LT.120.0) GO TO 600
      GC TO 650
  100 AA=11123.679
      B=-.0214994
      GC TC 700
  200 AA=11506.074
      B=-.02197434
      GO TO 700
  300 AA=10358.781
      B=-.02063821
      GO TO 700
  400 AA=10187.096
      B=-.02045587
      GO TO 700
  500 AA=9820.2646
      B=-.02007028
      GO TO 700
  600 AA=9746.2463
      B=-.01999251
      GC TO 700
  650 AA=7914.3419
      B=-.01824245
  700 RTF=AA*EXP(A*B)
      RETURN
      END
```

```
C                                 PROGRAM  V
C
C
C                        ABSCLUTE ERRCR CCMPUTATICN
C                                 PROGRAM
C
C
C
C          THIS PRCGRAM INCORPORATES VALUES FROM THE SIMULTANEOUS SIZING
C     PROGRAM FOR BETA AND R3 INTO THE DESCRIBING CIRCUIT EQUATION
C     TO OBTAIN A RESULTING ERRCR IN THE AIR SPEED.  THE ERROR IN AIR
C     SPEED IS CCMPUTED FOR THE TEMPERATURE RANGE OF 50F TO 100F IN
C     INCREMENTS CF 5F.
C
C
      CCMMCN/PARAM/VEL
      COMMON/XX/BETA,R3,PCTV(11),ITT
      CCMMCN/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
C
C
C          THE VARIABLES IN THE CCMMON LOCATIONS ARE DEFINED AS FOLLOWS:
C               EW=THERMAL EMITTANCE OF THE SUPPORT WIRE
C               ES=THERMAL EMITTANCE CF THE SENSING THERMISTOR
C               DS=DIAMETER OF THE SENSING THERMISTOR IN FEET
C               DW=THERMAL CCNDUCTIVITY OF THE SUPPORT WIRE
C                  IN BTU/HR-FT-F
C               S=STEFAN-BOLTZMANN CONSTANT
C               PI=PI
C               AS=SURFACE AREA OF THE SENSING THERMISTOR
C               TE=AMBIENT AIR TEMPERATURE
C               SFHT=THE SELF-HEAT AT A GIVEN REFERENCE TEMPERATURE
C               TESFHT=REFERENCE TEMPERATURE
C               SFHTPD=THE SELF-HEAT AT ANY AMBIENT TEMPERATURE
C              RS=RESISTANCE IN OHMS CF THE SENSING THERMISTOR
C
  200 FCRMAT('1',////           ,62X,'TABLE ',I2,//,55X,'ABSOLUTE ERROR A
     1NALYSIS',///,24X,'THE PERCENT ERRORS IN THE AIR SPEED',/,22X,'LIST
     1ED IN THE TABLE BELOW WERE',/,22X,'CALCULATED WITH THE FCLLOWING',
     1/,22X,'RESTRICTIONS:',/)
  201 FORMAT(37X,'R3 = ',F7.0,' OHMS',/,37X,'BETA = ',F7.5,/,37X,'SELF-H
     1EAT = ',I2,' F',/,37X,'REFERENCE TEMPERATURE = ',I3,' F',///,22X,8
     19(1H-))
  204 FCRMAT(5F16.6)
  205 FORMAT(24X,I4,3X,'|',11(2X,F5.1),/,31X,'|')
  206 FORMAT(25X,'AIR',3X,'|',17X,'PERCENTAGE ERROR IN THE INDICATED AIR
```

```
     1 SPEED',/,24X,'SPEED',2X,'|',18X,'AT ELEVEN DIFFERENT AMBIENT TEMP
     1ERATURES',/,22X, 89(1H-),/,24X,'(FPM)',2X,'|',3X,'50F',4X,'55F',4X
     1,'60F',4X,'65F',4X,'70F',4X,'75F',4X,'80F',4X,'85F',4X,'90F',4X,'9
     15F',3X,'100F',/,22X,89(1H-),/,31X,'|')
  207 FORMAT(I2)
  208 FORMAT(4I3)
  209 FORMAT(24X,I4,3X,'|',11(2X,F5.1))
      READ(5,207)  NDATA
      READ(5,204)  EW,ES,DS,DW,TCW,TESFHT
      DO 100  IO=1,NDATA
      READ(5,207) NTABLE
      READ(5,208)  ILV,IHV,ISL,ISH
      S=0.1714E-08
      PI=3.14159
      AS=PI*DS**2
      READ(5,204)  BETA,R3
      DO 100  ISFHT=ISL,ISH,5
      KEY=ISFHT/5
      SFHT=ISFHT
      ITESF=TESFHT
      WRITE(6,200)  NTABLE
      WRITE(6,201)  R3,BETA,ISFHT,ITESF
      WRITE(6,206)
C
C     THIS LOOP SETS THE VELOCITY IN FPM
C
      DO 100  NV=ILV,IHV,10
      NVEL=NV
      IF(NV.GE.100)  NVEL=10*(NV-90)
      VEL=NVEL*60.0
C
C     THIS LOOP PARAMETER IS AMBIENT TEMPERATURE
C
      DO 50  IT=50,100,5
      ITT=(IT/5)-9
      TE=IT
      CALL ABEROR
   50 CONTINUE
      IF(NTABLE.LE.25)  GOTO333
      GOTO334
  333 WRITE(6,209)  NVEL,(PCTV(II),  II=1,11)
      GOTO100
  334 WRITE(6,205)  NVEL,(PCTV(II),  II=1,11)
  100 CONTINUE
      WRITE(6,200)  NTABLE
      STOP
```

```
      SUBROUTINE ABEROR
C
C
C           THIS SUBROUTINE COMPUTES THE ABSOLUTE ERROR IN THE
C     INDICATED AIR SPEED.
C
C
      COMMON/PARAM/VEL
      COMMON/XX/BETA,R3,PCTV(11),ITT
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      I=ITT
      RTC=RTCF(TE)
      RX=(R3*RTC )/(R3 + RTC)
      RS=BETA*RX
      TTT=TTF(RS)
      CALL PDISS(VEL)
      IT=TE
      PD=POWER(TTT,IT,VEL)
      V1=SPEED(VEL,PD)
      PCTV(I)=((V1-VEL)/VEL)*100.0
      RETURN
      END
```

```
      SUBROUTINE PDISS(V)
C
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF SELF-HEAT NECESSARY FOR
C     CONSTANT POWER DISSIPATION AT ANY VELOCITY-AMBIENT TEMPERATURE
C     COMBINATION ONCE A POWER-VELOCITY CURVE IS INITIALLY SPECIFIED BY
C     A CERTAIN SELF-HEAT (SFHT) OCCURING AT A SPECIFIC AMBIENT TEMPERA-
C     TURE (TESFHT).  THIS NEW SELF-HEAT IS DESIGNATED SFHTPD.  ALSO A
C     VALUE FOR THE SENSING RESISTOR IN OHMS IS CALCULATED AT THIS NEW
C     SELF-HEAT (I.E. NEW SENSING THERMISTOR TEMPERATURE).
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      I=TESFHT
      TS=SFHT+I
C
C     PWAT1 IS THE POWER DISSIPATION IN MILLIWATTS AT THE GIVEN SELF-
C     HEAT OCCURING AT THE SPECIFIED AMBIENT TEMPERATURE.
C
      PWAT1=POWER(TS,I,V)
      DT=SFHT
      TF=TE+DT/2.
      TT=TS
C
C     A IS TWICE THE INITIAL INCREMENT USED TO INITIATE THE ITERATION PRO-
C     CEDURE.  CHK IS THE VALUE IN MILLIWATTS THAT SERVES AS AN ITERATION
C     CRITERIA THAT MUST BE MET BEFORE THE ITERATION IS TERMINATED.
C
      NUM=0
      A=50.
      CHK=.0001
   53 A=A/2.
      NUM=NUM+1
      IF(A.LE..0000001)  A=2.0
      DT=TT-TE
      TF=TE+(TT-TE)/2.0
      TER=TE+460.
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
```

```
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
C
C     PWATT IS THE POWER DISSIPATION IN MILLIWATTS THAT MUST BE ALTERED
C     BY VARYING THE SENSING THERMISTORS TEMPERATURE.  THE DIFFERENCE BE-
C     TWEEN PWATT AND PWAT1 IS MINIMIZED BY CHANGING TT, WHICH IS THE
C     TEMPERATURE OF THE SENSING THERMISTOR, UNTIL THE ABSOLUTE VALUE OF
C     THIS DIFFERENCE, ABS(EPSI), IS LESS THAN OR EQUAL TO CHK.
C
      PWATT=(PO/3.4127)*1000.0
      EPSI=PWAT1-PWATT
      IF(ABS(EPSI).LE.CHK)  GOTO60
      IF(EPSI)  50,60,52
   50 TT=TT-A
      GOTO53
   52 TT=TT+A
      GOTO53
C
C     THE NEW SELF-HEAT IS CALCULATED USING ITERATED VALUES OF TT AND
C     THE VALUE OF TE WHICH WAS INTIALLY USED TO ENTER THE SUBROUTINE.
C
   60 SFHTPD=TT-TE
      RETURN
      END
```

```
      FUNCTION SPEED(VL,P)
C
C
C     GIVEN A VALUE FOR POWER DISSIPATION, P, AND A VALUE FOR SELF-
C     HEAT, SFHTPD, THIS FUNCTION ITERATES THE HEAT TRANSFER EQUATION
C     WITH VELOCITY AS THE VARIABLE UNTIL A VELOCITY IS FOUND AT WHICH
C     THE POWER DISSIPATION IS EQUAL TO P WITHIN AN EPSILON NEIGHBORHOOD
C     EQUIVALENT TO CHK.  VL IS THE VELOCITY THAT IS USED TO START THE
C     ITERATION  AND A IS THE STARTING INCREMENT IN UNITS OF FPHR.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      V=VL
      NUM=0
      DT=SFHTPD
      TF=TE + DT/2.0
      TT=TE + DT
      A=.167*VL
      CHK=.0001
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      GOTO10
   52 A=A/2.
      IF(V.LE.0.0)  V=300.0
      NUM=NUM+1
      IF(NUM.EQ.25.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.50.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.75.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.100.AND.ABS(EPSI).GT.0.2)  A=.500*V
      IF(A.LE..000001)  A=.0167*VL
   10 RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      PWAT=(PO/3.4127)*1000.0
      EPSI=PWAT-P
      IF(ABS(EPSI).LE.CHK)   GOTO50
      IF(EPSI)  49,50,51
   49 V=V+A
```

```
      GOTO52
   51 V=V-A
      GOTO52
   50 SPEED=V
      RETURN
      END
```

```
      FUNCTION POWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELOCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      DT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PO/3.4127)*1000.0
      RETURN
      END
```

```
      FUNCTION TTF(A)
C
C
C     THIS FUNCTION IS THE INVERSE OF THE FUNCTION RTF.  GIVEN A RESISTANCE
C     FOR THE MODEL GB32L1 2K SENSING THERMISTOR A TEMPERATURE, TTF IS
C     CALCULATED.
C
C
      IF (A.GT.2406.) GO TO 100
      IF (A.GT.2020.) GO TO 200
      IF (A.GT.1675.) GO TO 300
      IF (A.GT.1430.) GO TO 400
      IF (A.GT.1210.) GO TO 500
      IF (A.GT.889.) GO TO 600
      GO TO 650
  100 AA=11123.679
      B=-.0214994
      GO TO 700
  200 AA=11506.074
      B=-.02197434
      GO TO 700
  300 AA=10358.781
      B=-.02063821
      GO TO 700
  400 AA=10187.096
      B=-.02045587
      GO TO 700
  500 AA=9820.2646
      B=-.02007028
      GO TO 700
  600 AA=9746.2463
      B=-.01999251
      GO TO 700
  650 AA=7914.3419
      B=-.01824245
  700 TTF=(ALOG(A/AA))/B
      RETURN
      END
```

```
      FUNCTION RTCF(A)
C
C
C     THIS FUNCTION APPROXIMATES THE TEMPERATURE-RESISTANCE CURVE FOR A
C     FENWAL MODEL   Q941J1  10K    TEMPERATURE COMPENSATING THERMISTOR
C     USING THE RELATIONSHIP RTCF=AA*EXP(B*T) WHICH IS ACCURATE TO WITHIN
C     0.03% OF THE MEASURED VALUES.  GIVEN A TEMPERATURE, A, OF THE TEMP-
C     RATURE COMPENSATING RESISTOR A VALUE OF RESISTANCE, RTCF, IS
C     CALCULATED (IN OHMS).
C
C
      IF (A.LT.71.2) GO TO 100
      IF(A.LT.79.15) GO TO 200
      IF (A.LT.88.3) GO TO 300
      IF (A.LT.95.9) GO TO 400
      GO TO 500
  100 AA=61321.457
      B=-.02212168
      GO TO 700
  200 AA=61840.436
      B=-.02222238
      GO TO 700
  300 AA=56864.665
      B=-.02114734
      GO TO 700
  400 AA=52789.792
      B=-.02031355
      GO TO 700
  500 AA=51841.729
      B=-.02012192
      GO TO 700
  700 RTCF=AA*EXP(A*B)
      RETURN
      END
```

```
C                             PROGRAM VI
C
C
C      THIS PROGRAM GENERATES THE VALUES OF RESISTANCE THE PARALLEL
C      RESISTANCE COMBINATICN, R3 AND RC, SHOULD HAVE TO OBTAIN ZERO
C      ERROR (ZERO ABSCLUTE ERROR) IN THE AIR SPEED.
C
C
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
  100 FORMAT(5F16.6)
  101 FORMAT(2I3,3F10.5)
  102 FORMAT('1',////////////,55X,'BETA = ',F8.6,/,55X,'SFHT = ',F4.1,'F
     1 AT ',F5.1,'F',/,55X,'VELOCITY = ',I4,' FPM',///)
  103 FORMAT(20X,I3,5X,4(5X,F10.3))
      READ(5,100)  EW,ES,DS,DW,TCW
      READ(5,101)  ILO,IHI,BETA,TESFHT,SFHT
      R3=434000.
      S=0.1714E-08
      PI=3.14159
      AS=PI*DS**2
      DO 40  IV=ILO,IHI,10
      NV=IV
      IF(IV.GE.100)  NV=(IV-90)*10
      WRITE(6,102)  BETA,SFHT,TESFHT,NV
      VEL=NV*60.0
      DO 40  ITE=50,100,2
      TE=ITE
      CALL PDISS(VEL)
      RX=RS/BETA
      RC=RTCF(TE)
      RXACT=(R3*RC)/(R3+RC)
      RXX=RXACT-RX
      PCTRX=(RXX/RX)*100.0
      WRITE(6,103)  ITE,RX,RXACT,RXX,PCTRX
   40 CONTINUE
      STOP
      END
```

```
      SUBROUTINE POISS(V)
C
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF SELF-HEAT NECESSARY FOR
C     CONSTANT POWER DISSIPATION AT ANY VELOCITY-AMBIENT TEMPERATURE
C     COMBINATION ONCE A POWER-VELOCITY CURVE IS INITIALLY SPECIFIED BY
C     A CERTAIN SELF-HEAT (SFHT) OCCURING AT A SPECIFIC AMBIENT TEMPERA-
C     TURE (TESFHT).  THIS NEW SELF-HEAT IS DESIGNATED SFHTPD.  ALSO A
C     VALUE FOR THE SENSING RESISTOR IN OHMS IS CALCULATED AT THIS NEW
C     SELF-HEAT (I.E. NEW SENSING THERMISTOR TEMPERATURE).
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/POIS/TE,SFHT,TESFHT,SFHTPD,RS
      I=TESFHT
      TS=SFHT+I
C
C     PWAT1 IS THE POWER DISSIPATION IN MILLIWATTS AT THE GIVEN SELF-
C     HEAT OCCURING AT THE SPECIFIED AMBIENT TEMPERATURE.
C
      PWAT1=POWER(TS,I,V)
      DT=SFHT
      TF=TE+DT/2.
      TT=TS
C
C     A IS TWICE THE INITIAL INCREMENT USED TO INITIATE THE ITERATION PRO-
C     CEDURE.  CHK IS THE VALUE IN MILLIWATTS THAT SERVES AS AN ITERATION
C     CRITERIA THAT MUST BE MET BEFORE THE ITERATION IS TERMINATED.
C
      NUM=0
      A=50.
      CHK=.0001
   53 A=A/2.
      NUM=NUM+1
      IF(A.LE..0000001)  A=2.0
      DT=TT-TE
      TF=TE+(TT-TE)/2.0
      TER=TE+460.
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
```

```
     1S*AS*(TFR**3))
C
C     PWATT IS THE POWER DISSIPATION IN MILLIWATTS THAT MUST BE ALTERED
C     BY VARYING THE SENSING THERMISTORS TEMPERATURE.  THE DIFFERENCE BE-
C     TWEEN PWATT AND PWAT1 IS MINIMIZED BY CHANGING TT, WHICH IS THE
C     TEMPERATURE OF THE SENSING THERMISTOR, UNTIL THE ABSOLUTE VALUE OF
C     THIS DIFFERENCE, ABS(EPSI), IS LESS THAN OR EQUAL TO CHK.
C
      PWATT=(PO/3.4127)*1000.0
      EPSI=PWAT1-PWATT
      IF(ABS(EPSI).LE.CHK)  GCTO60
      IF(EPSI)  50,60,52
   50 TT=TT-A
      GOTO53
   52 TT=TT+A
      GOTO53
C
C     THE NEW SELF-HEAT IS CALCULATED USING ITERATED VALUES OF TT AND
C     THE VALUE OF TE WHICH WAS INTIALLY USED TO ENTER THE SUBROUTINE.
C
   60 SFHTPD=TT-TE
      RETURN
      END
```

```
      FUNCTICN POWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELCCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      DT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PD=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PD/3.4127)*1000.0
      RETURN
      END
```

```
      FUNCTION RTCF(A)
C
C
C     THIS FUNCTICN APPROXIMATES THE TEMPERATURE-RESISTANCE CURVE FOR A
C     FENWAL MCDEL   QB41J1  10K    TEMPERATURE COMPENSATING THERMISTOR
C     USING THE RELATIONSHIP RTCF=AA*EXP(B*T) WHICH IS ACCURATE TO WITHIN
C     0.03% OF THE MEASURED VALUES.  GIVEN A TEMPERATURE, A, OF THE TEMP-
C     RATURE COMPENSATING RESISTOR A VALUE OF RESISTANCE, RTCF, IS
C     CALCULATED (IN OHMS).
C
C
      IF (A.LT.71.2) GO TO 100
      IF(A.LT.79.15) GO TO 200
      IF (A.LT.88.3) GO TO 300
      IF (A.LT.95.9) GO TO 400
      GO TO 500
 100  AA=61321.457
      B=-.02212168
      GO TO 700
 200  AA=61840.436
      B=-.02222238
      GO TO 700
 300  AA=56864.665
      B=-.02114734
      GO TO 700
 400  AA=52789.792
      B=-.02031355
      GO TO 700
 500  AA=51841.729
      B=-.02012192
      GO TO 700
 700  RTCF=AA*EXP(A*B)
      RETURN
      END
```

```
C                             PROGRAM VII
C
C
C                  RELATIVE ERROR PROGRAM FOR THE
C                          CIRCUIT COMPONENTS
C
C
C
C            GIVEN A SMALL   ( .1% ) COMPONENT ERROR THIS PROGRAM
C       CALCULATES THE EFFECT OF THIS ERROR ON THE INDICATED AIR SPEED
C       AND PRINTS OUT THE PERCENTAGE CHANGE FROM THE TRUE AIR SPEED.
C
C
      DIMENSION PCTV(2,11)
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
  200 FORMAT(5F16.6)
  201 FORMAT(2F5.1)
  202 FORMAT('1',/////          ,62X,'TABLE ',I2,//,51X,'RELATIVE ERROR
     1ANALYSIS FOR THE',/)
  203 FORMAT(58X,'R3 CIRCUIT COMPONENT')
  204 FORMAT(55X,'BETA CIRCUIT COMPONENT')
  205 FORMAT(55X,'COMPENSATING THERMISTOR')
  206 FORMAT(57X,'SENSING THERMISTOR')
  207 FORMAT(//,32X,'R3 = ',F7.0,' OHMS',/,32X,'BETA = ',F7.5,/,32X,'SEL
     1F-HEAT = ',I2,' F',/,32X,'REFERENCE TEMPERATURE = ',I3,' F',//,8X,
     1116(1H-))
  208 FORMAT(13X,'AIR',4X,'|',2X,'SIGN OF',2X,'|',22X,'A ',F5.3,' % ERRO
     1R IN THE CIRCUIT COMPONENT YIELDS',/,12X,'SPEED',3X,'|',1X,'COMPON
     1ENT',1X,'|',23X,'THE FOLLOWING RELATIVE ERRORS IN THE AIR SPEED',
     1/,12X,'(FPM)',3X,'|',3X,'ERROR',3X,'|',91(1H-),/,20X,'|',11X,'|',
     14X,'50 F',4X,'55 F',4X,'60 F',4X,'65 F',4X,'70 F',4X,'75 F',4X,'80
     1 F',4X,'85 F',4X,'90 F',4X,'95 F',4X,'100 F',/,8X,116(1H-),/,20X,'
     1|',11X,'|')
  209 FORMAT(13X,I4,3X,'|',5X,'+',5X,'|',11(1X,F7.3))
  210 FORMAT(13X,I4,3X,'|',5X,'-',5X,'|',11(1X,F7.3),/,20X,'|',11X,'|')
  211 FORMAT(I2)
  212 FORMAT(53X,'COMBINED CIRCUIT COMPONENTS')
      READ(5,200)  EW,ES,DS,DW,TCW
      READ(5,201)  TESFHT,SFHT
      READ(5,211)  NDATA
      DO 300  IXX=1,NDATA
      READ(5,211)  NTABLE
      READ(5,211)  NN
      BETA=.17488
      R3=450000.
```

```
      S=0.1714E-C8
      PI=3.14159
      AS=PI*DS**2
      ITST=TESFHT
      ISF=SFHT
      PCT=0.001
      PCT100=PCT*100.0
      WRITE(6,202)  NTABLE
      GOTO(144,146,148,149,151),NN
  144 WRITE(6,203)
      GOTO141
  146 WRITE(6,204)
      GOTO141
  148 WRITE(6,205)
      GOTO141
  149 WRITE(6,206)
      GOTO141
  151 WRITE(6,212)
  141 WRITE(6,207)  R3,BETA,ISF,ITST
      WRITE(6,208)  PCT100
      DO 300  I=1,6
      GOTO(10,20,30,40,50,60),I
   10 NV=20
      GOTO70
   20 NV=80
      GOTO70
   30 NV=200
      GOTO70
   40 NV=400
      GOTO70
   50 NV=600
      GOTO70
   60 NV=1000
   70 VEL=NV*60.0
      DO 150  IT=50,100,5
      ITT=(IT/5)-9
      TE=IT
      CALL PDISS(VEL)
      RTC=RS/(BETA-(RS/R3))
      DO 150  NEGPOS=1,2
C
C     THIS COMPUTED GO TO ASSIGNS APPROPRIATE ERROR EQUATIONS FOR
C     THE RELATIVE ERROR ANALYSIS (SEE EQS. 30-38 OF THE TEXT).
C
      GOTO(401,402,403,404,405),NN
  401 RS=BETA*(((R3+(R3*PCT))*RTC)/(R3+(R3*PCT)+RTC))
```

```
      FUNCTICN PCWER(TT,NT,V)
C
C
C     GIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELCCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTOR IN UNITS OF MILLIWATTS.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=NT
      CT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*CT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PO/3.4127)*1000.0
      RETURN
      END
```

```
      FUNCTION SPEEC(VL,P)
C
C
C     GIVEN A VALUE FOR POWER DISSIPATION, P, AND A VALUE FOR SELF-
C     HEAT, SFHTPD, THIS FUNCTION ITERATES THE HEAT TRANSFER EQUATION
C     WITH VELOCITY AS THE VARIABLE UNTIL A VELOCITY IS FOUND AT WHICH
C     THE POWER DISSIPATION IS EQUAL TO P WITHIN AN EPSILON NEIGHBORHOOD
C     EQUIVALENT TO CHK.  VL IS THE VELOCITY THAT IS USED TO START THE
C     ITERATION  AND A IS THE STARTING INCREMENT IN UNITS OF FPHR.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      V=VL
      NUM=0
      DT=SFHTPD
      TF=TE + DT/2.0
      TT=TE + DT
      A=.167*VL
      CHK=.0001
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      GOTO10
   52 A=A/2.
      IF(V.LE.0.0)  V=300.0
      NUM=NUM+1
      IF(NUM.EQ.25.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.50.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.75.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.100.AND.ABS(EPSI).GT.0.2)  A=.500*V
      IF(A.LE..000001)  A=.0167*VL
   10 RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PD=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      PWAT=(PD/3.4127)*1000.0
      EPSI=PWAT-P
      IF(ABS(EPSI).LE.CHK)   GOTO50
      IF(EPSI)  49,50,51
   49 V=V+A
```

```
      GOTO52
   51 V=V-A
      GOTO52
   50 SPEED=V
      RETURN
      END
```

```
      IF(NEGPOS.EQ.2)  RS=BETA*(((R3-(R3*PCT))*RTC)/(R3-(R3*PCT)+RTC))
      GOTO400
  402 RS=(BETA+(BETA*PCT))*(R3*RTC)/(R3+RTC)
      IF(NEGPOS.EQ.2)  RS=(BETA-(BETA*PCT))*(R3*RTC)/(R3+RTC)
      GOTO400
  403 RS=BETA*(R3*(RTC+(RTC*PCT)))/(R3+(RTC+(RTC*PCT)))
      IF(NEGPOS.EQ.2)  RS=BETA*(R3*(RTC-(RTC*PCT)))/(R3+(RTC-(RTC*PCT)))
      GOTO400
  404 RR=BETA*((R3*RTC)/(R3+RTC))
      RS=RR+(RR*PCT)
      IF(NEGPOS.EQ.2)  RS=RR-(RR*PCT)
      GOTO400
  405 ERS=(BETA+(BETA*PCT))*((R3+(R3*PCT))*(RTC+(RTC*PCT)))/((R3+(R3*PCT
     1))+(RTC+(RTC*PCT)))
      RSS=BETA*(R3*RTC)/(R3+RTC)
      ERSS=RSS*PCT
      IF(NEGPOS.EQ.2)  GOTO406
      RS=ERS+ERSS
      GOTO400
  406 EERS=(BETA-(BETA*PCT))*((R3-(R3*PCT))*(RTC-(RTC*PCT)))/((R3-(R3*PC
     1T))+(RTC-(RTC*PCT)))
      RS=EERS-ERSS
  400 TTT=TTF(RS)
      PD=POWER(TTT,IT,VEL)
      V1=SPEED(VEL,PD)
      PCTV(NEGPOS,ITT)=((V1-VEL)/VEL)*100.0
  150 CONTINUE
      WRITE(6,209)  NV,(PCTV(1,LL),  LL=1,11)
      WRITE(6,210)  NV,(PCTV(2,LL),  LL=1,11)
  300 CONTINUE
      WRITE(6,202) NTABLE
      STOP
      END
```

```
      SUBROUTINE POISS(V)
C
C
C     THIS SUBROUTINE CALCULATES THE AMOUNT OF SELF-HEAT NECESSARY FOR
C     CONSTANT POWER DISSIPATION AT ANY VELOCITY-AMBIENT TEMPERATURE
C     COMBINATION ONCE A POWER-VELOCITY CURVE IS INITIALLY SPECIFIED BY
C     A CERTAIN SELF-HEAT (SFHT) OCCURING AT A SPECIFIC AMBIENT TEMPERA-
C     TURE (TESFHT).  THIS NEW SELF-HEAT IS DESIGNATED SFHTPD.  ALSO A
C     VALUE FOR THE SENSING RESISTOR IN OHMS IS CALCULATED AT THIS NEW
C     SELF-HEAT (I.E. NEW SENSING THERMISTOR TEMPERATURE).
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PDIS/TE,SFHT,TESFHT,SFHTPD,RS
      I=TESFHT
      TS=SFHT+I
C
C     PWAT1 IS THE POWER DISSIPATION IN MILLIWATTS AT THE GIVEN SELF-
C     HEAT OCCURING AT THE SPECIFIED AMBIENT TEMPERATURE.
C
      PWAT1=POWER(TS,I,V)
      DT=SFHT
      TF=TE+DT/2.
      TT=TS
C
C     A IS TWICE THE INITIAL INCREMENT USED TO INITIATE THE ITERATION PRO-
C     CEDURE.  CHK IS THE VALUE IN MILLIWATTS THAT SERVES AS AN ITERATION
C     CRITERIA THAT MUST BE MET BEFORE THE ITERATION IS TERMINATED.
C
      NUM=0
      A=50.
      CHK=.0001
   53 A=A/2.
      NUM=NUM+1
      IF(A.LE..0000001)  A=2.0
      DT=TT-TE
      TF=TE+(TT-TE)/2.0
      TER=TE+460.
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
```

```
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
C
C     PWATT IS THE POWER DISSIPATION IN MILLIWATTS THAT MUST BE ALTERED
C     BY VARYING THE SENSING THERMISTORS TEMPERATURE.  THE DIFFERENCE BE-
C     TWEEN PWATT AND PWAT1 IS MINIMIZED BY CHANGING TT, WHICH IS THE
C     TEMPERATURE OF THE SENSING THERMISTOR, UNTIL THE ABSOLUTE VALUE OF
C     THIS DIFFERENCE, ABS(EPSI), IS LESS THAN OR EQUAL TO CHK.
C
      PWATT=(PO/3.4127)*1000.0
      EPSI=PWAT1-PWATT
      IF(ABS(EPSI).LE.CHK)  GOTO60
      IF(EPSI)  50,60,52
   50 TT=TT-A
      GOTO53
   52 TT=TT+A
      GOTO53
C
C     THE NEW SELF-HEAT IS CALCULATED USING ITERATED VALUES OF TT AND
C     THE VALUE OF TE WHICH WAS INTIALLY USED TO ENTER THE SUBROUTINE.
C
   60 SFHTPD=TT-TE
C
C     RS, THE SENSING THERMISTOR'S RESISTANCE IN OHMS, IS CALCULATED BY
C     CALLING THE FUNCTION RTF AND ENTERING IT WITH THE NEWLY ITERATED
C     SENSING THERMISTOR TEMPERATURE, TT.
C
      RS=RTF(TT)
C
      RETURN
      END
```

```
      FUNCTION TTF(A)
C
C
C     THIS FUNCTION IS THE INVERSE OF THE FUNCTION RTF.  GIVEN A RESISTANCE
C     FOR THE MODEL GB32L1 2K SENSING THERMISTOR A TEMPERATURE, TTF IS
C     CALCULATED.
C
C
      IF (A.GT.2406.) GO TO 100
      IF (A.GT.2020.) GO TO 200
      IF (A.GT.1675.) GO TO 300
      IF (A.GT.1430.) GO TO 400
      IF (A.GT.1210.) GO TO 500
      IF (A.GT.889.) GO TO 600
      GO TO 650
  100 AA=11123.679
      B=-.0214994
      GO TO 700
  200 AA=11506.074
      B=-.02197434
      GO TO 700
  300 AA=10358.781
      B=-.02063821
      GO TO 700
  400 AA=10187.096
      B=-.02045587
      GO TO 700
  500 AA=9820.2646
      B=-.02007028
      GO TO 700
  600 AA=9746.2463
      B=-.01999251
      GO TO 700
  650 AA=7914.3419
      B=-.01824245
  700 TTF=(ALOG(A/AA))/B
      RETURN
      END
```

```
      FUNCTION RTF(A)
C
C
C     GIVEN A TEMPERATURE, A, OF THE SENSING THERMISTCR A VALUE OF RESIS-
C     TANCE, RTF, IS CALCULATED.  THIS FUNCTION APPROXIMATES THE TEMPERA-
C     TURE-RESISTANCE CURVE FOR A FENWAL MCDEL GB32L1 2K BEAD-TYPE THER-
C     MISTOR USING THE RELATICNSHIP RTF=AA*EXP(B*T).  THIS APPROXIMATION
C     AGREES TC WITHIN 0.03% OF THE MEASURED VALUES.
C
C
      IF(A.LT.71.2) GO TO 100
      IF (A.LT.79.0) GO TO 200
      IF (A.LT.88.3) GO TO 300
      IF (A.LT.95.9) GO TO 400
      IF (A.LT.104.75) GO TO 500
      IF (A.LT.120.0) GO TO 600
      GO TO 650
  100 AA=11123.679
      B=-.0214994
      GO TO 700
  200 AA=11506.C74
      B=-.02197434
      GO TO 700
  300 AA=10358.781
      B=-.02063821
      GO TO 700
  400 AA=10187.096
      B=-.02045587
      GO TO 700
  500 AA=9820.2646
      B=-.02007028
      GC TO 700
  600 AA=9746.2463
      B=-.01999251
      GC TO 700
  650 AA=7914.3419
      B=-.01824245
  700 RTF=AA*EXP(A*B)
      RETURN
      END
```

```
C                             PROGRAM VIII
C
C
C
C                    DATA REDUCTION PROGRAM
C
C
      COMMON/REF/VCL
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMCN/PPP/SFHTPD,TE,NRANGE
      COMMON/VAL/H,BAR,REL,NOZ
  100 FORMAT(6F10.2,I2)
  101 FORMAT(5F10.3,2I1)
  102 FORMAT('1',53X,'DATA REDUCTION',///,10X,'R1 VOLT. DROP',3X,
     1 'RS VCLT. CROP',3X,'CCMP. TEMP.',3X,'SENSING TEMP.',3X,'SELF-HEAT
     1',3X,'MEA.POWER DISS.',3X,'MEA. AIR SPEED',7X,'VCL',//)
  103 FORMAT(14X,F6.3,10X,F6.3,8X,F7.3,8X,F7.3,8X,F6.3,9X,F6.3,11X,F7.2,
     1  5X,F7.2)
  104 FORMAT(5F16.6)
      READ(5,100)  R2L,R2M,R2H,R3L,R3M,R3H,NDATA
      READ(5,104)  EW,ES,DS,DW,TCW
      S=0.1714E-08
      PI=3.14159
      AS=PI*DS**2
      R1=10000.
      WRITE(6,102)
      CO 1000  I=1,NDATA
      READ(5,101)  H,V1,VS,BAR,REL,NOZ,NRANGE
      GOTO(10,20,30),NRANGE
   10 R2=R2L
      R3=R3L
      GOTO40
   20 R2=R2M
      R3=R3M
      GOTO40
   30 R2=R2H
      R3=R3H
   40 RS=(VS*R1)/V1
      RC=(R2*VS*R3)/(V1*R3 - VS*R2)
      TS=TTF(RS)
      TC=TRCF(RC)
      TE=TC
      SFHTPD=TS-TC
      PMEA=(V1*VS)/10.
      GUESS=POLY(PMEA)
      VMEA=SPEEC(GUESS,PMEA)/60.0
      CALL REFV
      WRITE(6,103)  V1,VS,TC,TS,SFHTPD,PMEA,VMEA,VCL
```

```
1000 CONTINUE
     WRITE(6,102)
     STOP
     END
```

```
      SUBROUTINE REFV
C
C
C           THIS SUBROUTINE CALCULATES THE CENTERLINE VELOCITY (VCL)
C     PROVIDED BY THE PORTABLE WIND TUNNEL.  THE DATA THAT  MUST BE
C     PROVIDEC ARE:
                 H-HEAD LOSS (IN. WATER)
C                BAR-BARCMETRIC PRESSURE (IN. MERCURY)
C                REL-RELATIVE HUMIDITY
C                NOZ-NOZZLE CONFIGURATION (SEE TABLE 36 IN THE
C                    TEXT FOR THE KEY USED TO INDICATE WHICH
C                    NOZZLES ARE BEING USED)
C
C
      COMMON/VAL/H,BAR,REL,NOZ
      COMMON/REF/VCL
      COMMON/PPP/SFHTPD,TE,NRANGE
      TA=TE
      T=0.03346475*TA
      VP=(0.03439608*EXP(T))/0.49115
      S1=0.6214 + ((REL*(VP**0.7042))/1130.0)
      RO=(BAR-(VP*REL) + (VP*REL*S1))/(0.7538*(TA + 459.7))
      A=2.181662E-02
      GOTO(10,20,30),NOZ
   10 Q=(H/0.4069)**(1/1.779)
      VBS=Q/A
      VBT=VBS*(0.0750/RO)
      VCL=(6.5118*VBT)/(ALOG(Q) + 5.5661)
      GOTO40
   20 C=(H/0.0250)**(1/1.901)
      VBS=Q/A
      VBT=VBS*(0.C750/RO)
      VCL=(69.3147*VBT)/(ALOG(Q) + 62.5067)
      GOTO40
   30 Q=(H/0.001556)**(1/1.982)
      VBS=Q/A
      VBT=VBS*(0.C750/RO)
      VCL=(13.5911*VBT)/(ALOG(Q) + 10.3915)
   40 CONTINUE
      RETURN
      END
```

```
      FUNCTICN TRCF(A)
C
C
C             GIVEN A RESISTANCE (A) OF THE COMPENSATING THERMISTOR
C     ITS TEMPERATURE (IN F) IS CCMPUTED.
C
C
      IF(A.LT.12693.2)  GOTO100
      IF(A.LT.10651.02)  GOTO200
      IF(A.LT.8787.80)  GOTO300
      IF(A.LT.7525.13)  GOTO400
      GO TO 500
 100  AA=61321.457
      B=-.02212168
      GO TO 700
 200  AA=61840.436
      B=-.02222238
      GO TO 700
 300  AA=56864.665
      B=-.02114734
      GO TO 700
 400  AA=52789.792
      B=-.02031355
      GO TO 700
 500  AA=51841.729
      B=-.02012192
      GO TO 700
  700 TRCF=(ALOG(A/AA))/B
      RETURN
      END
```

```
      FUNCTION TTF(A)
C
C
C     THIS FUNCTICN IS THE INVERSE OF THE FUNCTION RTF.  GIVEN A RESISTANCE
C     FOR THE MODEL GB32L1 2K SENSING THERMISTOR A TEMPERATURE, TTF IS
C     CALCULATED.
C
C
      AA=11736.13202
      B=-0.0212051
      TTF=(ALOG(A/AA))/B
      RETURN
      END
```

```
      FUNCTION PCLY(P)
C
C
C             A 5TH ORDER FIT TO THE 5F (SELF-HEAT AT 100F) POWER
C     CURVE IS USED AS A GUESS FOR THE TRUE AIR SPEED TO START THE
C     ITERATICN PROCEDURE.
C
C
      VELO=41.59272 - 50.9203*P - 17.9615*(P**2) + 31.7372*(P**3) -
     1 3.8031*(P**4) + 0.2036*(P**5)
   40 PCLY=60.0*VELO
      RETURN
      END
```

```
      FUNCTION SPEED(VL,P)
C
C
C     GIVEN A VALUE FOR POWER DISSIPATION, P, AND A VALUE FOR SELF-
C     HEAT, SFHTPD, THIS FUNCTION ITERATES THE HEAT TRANSFER EQUATION
C     WITH VELOCITY AS THE VARIABLE UNTIL A VELOCITY IS FOUND AT WHICH
C     THE POWER DISSIPATION IS EQUAL TO P WITHIN AN EPSILON NEIGHBORHOOD
C     EQUIVALENT TO CHK.  VL IS THE VELOCITY THAT IS USED TO START THE
C     ITERATION  AND A IS THE STARTING INCREMENT IN UNITS OF FPHR.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PPP/SFHTPD,TE
      V=VL
      NUM=0
      DT=SFHTPD
      TF=TE + DT/2.0
      TT=TE + DT
      A=.167*VL
      CHK=.0001
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      GOTO10
   52 A=A/2.
      IF(V.LE.0.0)  V=300.0
      NUM=NUM+1
      IF(NUM.EQ.25.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.50.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.75.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.100.AND.ABS(EPSI).GT.0.2)  A=.500*V
      IF(A.LE..000001)  A=.0167*VL
   10 RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PD=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      PWAT=(PD/3.4127)*1000.0
      EPSI=PWAT-P
      IF(ABS(EPSI).LE.CHK)   GOTO50
      IF(EPSI)  49,50,51
   49 V=V+A
      GOTO52
   51 V=V-A
```

```
      GOTO52
   50 SPEED=V
      RETURN
      END
```

```
C                                   PROGRAM IX
C
C
C                      UNCERTAINTY IN CALCULATED AIR SPEED
C
C
C
C           THIS PROGRAM IS USED TO GENERATE TABLE 40 IN APPENDIX B.
C
C
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PPP/SFHTPD,TE
  100 FORMAT(5F16.6)
  101 FORMAT('1',20X,4(5X,F7.3))
      READ(5,100)  EW,ES,DS,DW,TCW
      PI=3.14159
      S=0.1714E-08
      AS=PI*DS**2
      DO 500  I=1,3
      READ(5,100)  TE,ST,P,G,US
      DO 500  II=1,2
      GOTO(10,20),II
   10 SFHTPD=ST + (ST*US/100.)
      PO=P + (P*.007)
      GOTO30
   20 SFHTPD=ST - (ST*US/100.)
      PO=P - (P*.007)
   30 V=SPEED(G,PO)
      PCT=((V-G)/G)*100.
  500 WRITE(6,101)  TE,ST,SFHTPD,PCT
      STOP
      END
```

```
      FUNCTICN SPEEC(VL,P)
C
C
C  .  GIVEN A VALUE FCR PCWER DISSIPATION, P, ANC A VALUE FOR SELF-
C     FEAT, SFHTPC, THIS FUNCTION ITERATES THE HEAT TRANSFER EQUATION
C     WITH VELCCITY AS THE VARIABLE UNTIL A VELOCITY IS FOUND AT WHICH
C     THE POWER DISSIPATION IS EQUAL TO P WITHIN AN EPSILCN NEIGHBORHOOD
C     EQUIVALENT TO CHK.  VL IS THE VELOCITY THAT IS USED TO START THE
C     ITERATICN  AND A IS THE STARTING INCREMENT IN UNITS OF FPHR.
C
C
      COMMON/CATA/EW,ES,DS,DW,TCW,S,AS,PI
      COMMON/PPP/SFHTPD,TE
      V=VL
      NUM=0
      DT=SFHTPD
      TF=TE + DT/2.0
      TT=TE + DT
      A=.167*VL
      CHK=.0001
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      GOTO10
   52 A=A/2.
      IF(V.LE.0.0)  V=300.0
      NUM=NUM+1
      IF(NUM.EQ.25.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.50.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.75.AND.ABS(EPSI).GT.0.2)  A=.250*V
      IF(NUM.EQ.100.AND.ABS(EPSI).GT.0.2)  A=.500*V
      IF(A.LE..000001)  A=.0167*VL
   10 RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      PWAT=(PO/3.4127)*1000.0
      EPSI=PWAT-P
      IF(ABS(EPSI).LE.CHK)   GOTO50
      IF(EPSI)  49,50,51
   49 V=V+A
      GOTO52
   51 V=V-A
```

```
      GOTO52
   50 SPEED=V
      RETURN
      END
```

```
C                                   PROGRAM X
C
C
C                         UNCERTAINTY IN MEASURED POWER
C                                 DISSIPATION
C
C
C
C           THIS PROGRAM IS USED TO GENERATE THE UNCERTAINTIES IN
C     THE PREDICTED POWER DISSIPATION PRESENTED IN TABLE 39 OF THE TEXT.
C
C
      DIMENSION P(3),PCT(3)
      COMMON/DATA/EW,ES,DS,DW,TCW,S,AS,PI
  100 FORMAT(5F16.6)
  102 FORMAT(4F10.3)
  103 FORMAT(30X,3(5X,F7.3))
      READ(5,100)  EW,ES,DS,DW,TCW
      PI=3.14159
      S=0.1714E-08
      AS=PI*DS**2
      DO 500  I=1,3
      READ(5,102)  TC,VCL,SHT,USS
      US=USS/100.
      VH=60.*VCL
      DO 501  II=1,3
      GOTO(10,20,30),II
   10 TS=TC+SHT
      GOTO40
   20 SS=SHT+(US*SHT)
      TS=TC+SS
      GOTO40
   30 SS=SHT-(US*SHT)
      TS=TC+SS
   40 P(II)=POWER(TS,TC,VH)
      PCT(II)=((P(II)-P(1))/P(1))*100.
  501 CONTINUE
      WRITE(6,103)  P(1),(PCT(K),  K=2,3)
  500 CONTINUE
      STOP
      END
```

```
      FUNCTICN PCWER(TT,TA,V)
C
C
C     CIVEN A TEMPERATURE OF THE SENSING THERMISTOR, TT, AN AMBIENT
C     TEMPERATURE, NT, AND A VELCCITY, V, THIS FUNCTION USES THE GOVERN-
C     ING HEAT TRANSFER EQUATION TO CALCULATE THE POWER DISSIPATED BY
C     THE SENSING THERMISTCR IN UNITS OF MILLIWATTS.
C
C
      COMMCN/DATA/EW,ES,DS,DW,TCW,S,AS,PI
      TE=TA
      DT=TT-TE
      TF=TE + DT/2.0
      TER=TE + 460.0
      TFR=TF + 460.0
      TTR=TT + 460.0
      VA=.00198*(TFR-460.) + 0.451
      XKA=.0000233*(TFR-460.0) + 0.01317
      RES=(V*DS)/VA
      GR=((DS**3)*32.174*DT)/(TER*VA**2)
      REW=(V*DW)/VA
      HS=(XKA/DS)*(2.0+0.5*(RES**2+(4.0/3.0)*GR)**.25)
      HW=(XKA/DW)*(TFR/TER)**0.17*(0.24+0.56*REW**0.45)
      PO=DT*((HS*AS)+PI*((TCW*(DW**3)*(HW+4.*EW*S*(TFR**3)))**.5)+4.*ES*
     1S*AS*(TFR**3))
      POWER=(PO/3.4127)*1000.0
      RETURN
      END
```

VITA

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Master of Science

Thesis: EVALUATION OF A TEMPERATURE-COMPENSATED THERMISTOR ANEMOMETER

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EVALUATION OF A TEMPERATURE COMPENSATED THERMISTOR ANEMOMETER

by

JON B. MILLIKEN

B.S., Kansas State University, 1974

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

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Manhattan, Kansas

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This thesis investigates the performance of a previously designed and tested instrument and attempts to explain and to consequently eliminate inadequacies uncovered by the initial investigation of the instrument's performance. The instrument under scrutiny is a temperature-compensated thermistor anemometer that evolved out of a thesis entitled, "A Thermistor Anemometer For Measurement of Air Velocity", by Mr. William A. Flanders. The main purpose for the construction of this type of an anemometer is to measure air speed in unrestricted spaces, or more specifically in living quarters such as offices, public meeting places, and homes and apartments.

The basic anemometer circuit was composed of a wheatstone bridge with a bead-type sensing thermistor in one leg of the bridge and a rod-type temperature compensating thermistor in the opposing leg of the bridge. The temperature compensating thermistor indicated the particular environmental temperature. By proper choice of fixed resistors the wheatstone bridge maintained a constant temperature differential between the sensing thermistor's temperature and the environmental temperature. This temperature differential caused heat transfer to take place between the thermistor and the environment. A describing heat transfer equation was used to predict the resulting heat transfer. The describing equation was expressed as a function of air speed across the sensing thermistor and the power dissipation of the sensing thermistor. By measuring the power dissipation of the sensing thermistor the corresponding air speed could be calculated from the describing heat transfer equation.

A systematic procedure for sizing the resistance components of the anemometer circuit was developed. Using this procedure an error analysis was derived relating uncertainties in the circuit components to uncertainties in the measured air speed. The error analysis indicated that the best performance of the anemometer would occur at lower temperature differentials between the sensing thermistor and its environment.

The anemometer was designed and tested for a temperature differential of 5°F. The results of the experiment indicated that, as the temperature differential became smaller, the uncertainties in the measured temperature differential became very large (20% - 35%). Hence, the resulting air speed measurements using a temperature differential of 5°F reflected a large uncertainty and could not be meaningfully interpreted. It was recommended that future investigations be made to find a temperature differential that will result in good anemometer performance, and at the same time, yield small uncertainties in the measured temperature differential.