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An Examination of the Temperature Measuring Accuracy of a Flowmeter System Used With Balloon-Borne Atmospheric Samplers

ROBERT H. CORDELLA, Jr., Capt, USAF

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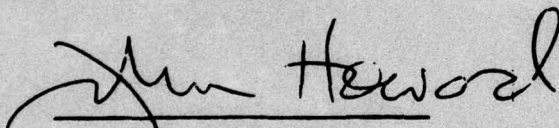


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| This report examines the temperature accuracy of a flowmeter system in two modes. Each mode is defined by the type of thermistor and its monitoring circuit. Laboratory data and flight data gathered at 15.2 to 27.4 km (50 to 90 k ft) are compared to the calculated error envelope. Agreement between the predicted and actual performance is excellent. | | | |

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Preface

This report is the result of questions raised about variations in the recorded values of temperature of air passed through balloon-borne atmospheric sampling devices. The results of this investigation provide essential information to the scientific users of the system under examination, and have implications to users of balloon-borne systems where external temperatures are a critical parameter.

The idea for this report was generated in conversations with Mr. Thomas Ashenfelter of the National Oceanic and Atmospheric Administration—Air Resources Laboratory, Mr. John Ground of New Mexico State University, and Captain J. Robert Greenlee of the Air Force Geophysics Laboratory (AFGL).

The author is indebted to his colleagues at AFGL for support and guidance in preparing this document: to Mr. George Nolan for suggesting the present format, to Mr. James Dwyer and SSgt Robert Dumont, respectively, for checking the calculus and computations, and to Mr. Ralph Cowie and Mrs. Catherine Rice for reading the initial draft and providing many thoughtful suggestions. Special thanks go to Mr. John Ground for rapidly forwarding the data in Tables 11-13, and Captain J. R. Greenlee for researching flight records and processing the large volume of data which is so succinctly presented in Table 14.

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An Examination of the Temperature Measuring Accuracy of a Flowmeter System Used With Balloon-Borne Atmospheric Samplers

I. INTRODUCTION

Every year numerous balloon missions are conducted to carry samplers to predetermined altitudes, usually between 15.2 km (60 k ft) and 36.6 km (120 k ft), to gather specimens of atmospheric constituents for various scientific groups. Motor driven fans or nitrogen driven aspirators draw air through various types of filters which remove gaseous or particulate constituents. One sensor monitors the flow rate and temperature at the inlet and another the exhaust of the sampler. This sensor is a 12.7 cm (5 in.) diameter cylinder about 15.2 cm (6 in.) in length. Temperature and flow rate are monitored independently by a thermistor and turbine driven chopper respectively. These two measurements are used to calculate the volume of air passed through the filter element. The accuracy of the volume calculation is directly proportional to the accuracy of the data.

Over the last several years interest has been growing in two characteristics of the temperature data. First, during a typical flight the measured temperature values tend to oscillate about some reference temperature. Second, a large difference in average temperature between flights at similar altitudes has been observed. The purpose of this analysis is to see if these results are being caused by the instrumentation or if the instrumentation is correctly reporting the situation.

(Received for publication 31 January 1977)

Each of these characteristics is either real or apparent. Real is defined as an actual change in air temperature; apparent is defined as no actual air temperature change. Change is defined as variations of the temperature indicated by one system, or the difference in average temperature between two systems. This analysis will explore the mechanisms which can cause apparent temperature changes.

Causes of apparent temperature changes are either internal or external to the system. Internal causes are the manufacturing tolerances of the system components. These tolerances result in the overall system accuracy which corresponds to the error envelope of the data, and the precision of an individual piece of equipment. The only external cause for apparent temperature change which has been identified, is radio frequency energy from the onboard data transmitter. Laboratory testing has verified that as the thermistor resistance increases to the 1 megohm region, energy radiated from the transmitter can affect the temperature data. The original thermistor has a resistance characteristic which exceeds 1 megohm at about -60° Celsius.

Reflecting on the above facts in light of the availability of curve-matched thermistors having lower resistance and smaller mass, the author decided to test a different thermistor while critically examining the original thermistor circuit. The following paragraphs document the preliminary calculations, laboratory tests, and flight data on which the conclusions are based.

2. THE FLOWMETER SYSTEM

The PR-3 Flowmeter System,¹ was purchased by the Department of the Air Force at Goodfellow AFB, Texas in June 1969. Temperature is sensed by a thermistor located in the air flow and recorded incrementally as a varying direct current from zero to 100 μ A.

In this report the term "original system" pertains to the original PR-3 circuit with the Fenwal rod thermistor QB41J3; the term "modified system" pertains to the author's circuit as described below with the Fenwal bead thermistor UUB31J1.

1. PR-3 Flowmeter System Technical Handbook (1969) ASD document No. 3330 by the Applied Science Division of Litton Systems, Inc., for the Dept. of the Air Force under Contract No. F41616-69-R-0442.

2.1 The Original Circuit

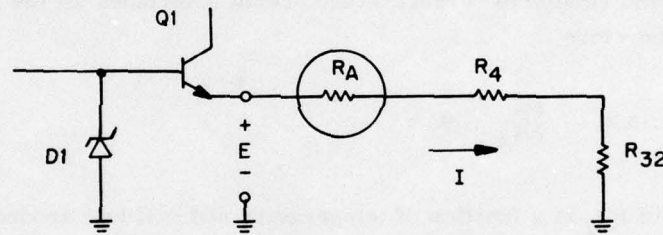
2.1.1 ACCURACY

Figure 1 portrays the critical parts of the circuit under discussion. Wire and contact resistances are small enough to be negligible. From Ohm's law,

$$I_t = \frac{E}{R_A + R_4 + R_{32}} \quad (1)$$

where the subscript t denotes the theoretical current which is dependent upon the values of ideal resistors and an ideal source E. If the components are allowed to vary according to the manufacturers specifications, this same expression can be used to define the real current I_r , where

$$I_r = \frac{E}{R_A + R_4 + R_{32}} \quad (2)$$



KEY

D1 1N4736A, 6.8V \pm 5%

Q1 2N1308

R_A 4600 ohms, assumed \pm 0% see K

R_4 60.4k ohms \pm 1%

R_{32} thermistor QB41J3 10k ohms \pm 1% at 25°C

K ammeter accuracy \pm 2% of full scale

Figure 1. Original Temperature Sensing Circuit*

* See PR-3 Flowmeter System Technical Handbook, drawing number D-17788-236465, page 37.

To include the effect of the ammeter which displays and records the current, measured current is expressed as:

$$I_m = I_r + K = \frac{E}{R_A + R_4 + R_{32}} + K \quad (3)$$

where K is the full-scale error of the meter and recorder (Stout²).

The absolute error (U. S. Department of Commerce³) of I_m is $\Delta I_m = I_m - I_t$. Taking I_m as the dependent variable, ΔI_m is given by:

$$\Delta I_m \approx \frac{\partial I_m}{\partial K} \Delta K + \frac{\partial I_m}{\partial E} \Delta E + \frac{\partial I_m}{\partial R_A} \Delta R_A + \frac{\partial I_m}{\partial R_4} \Delta R_4 + \frac{\partial I_m}{\partial R_{32}} \Delta R_{32} \quad (4)$$

This analysis initially will express percent error of current over a temperature range. Terms E, R_A , and R_4 are independent variables. Resistor R_{32} is a function of temperature, and K is the meter accuracy which is defined by the manufacturer as ± 2 percent of full scale. The effect of K will be considered independent of R_{32} and related to current later. Term K includes all the meter inaccuracies; therefore,

$$\Delta R_A = 0 \quad \text{and} \quad \frac{\partial K}{\partial R_A} = 0 \quad (5)$$

The error of R_{32} is a function of temperature and will be introduced when numerical values are calculated. Equation (3) will be differentiated to obtain the terms necessary for Eq. (4).

$$\frac{\partial I_m}{\partial K} = \frac{\partial}{\partial K} \left\{ \frac{E}{R_A + R_4 + R_{32}} + K \right\} \quad (6)$$

$$= \frac{\partial}{\partial K} \cdot \frac{E}{R_A + R_4 + R_{32}} + \frac{\partial K}{\partial K} \quad (7)$$

$$= 0 + 1 \quad (8)$$

$$= 1 \quad (9)$$

2. Stout, M. B. (1950) Electrical Measurements, Prentice Hall, Inc. Pages 405 to 408 have a good discussion on errors in electrical indicating instruments.
3. U. S. Department of Commerce (1967) Handbook of Mathematical Functions, NBS/Applied Mathematics Series No. 55, page 14, for a discussion of error analysis.

And for the regulated voltage, E

$$\frac{\partial I_m}{\partial E} = \frac{\partial}{\partial E} \left\{ \frac{E}{R_A + R_4 + R_{32}} + K \right\} \quad (10)$$

$$= \frac{\partial}{\partial E} \cdot \frac{E}{R_A + R_4 + R_{32}} + \frac{\partial K}{\partial E} \quad (11)$$

$$= \frac{1}{R_A + R_4 + R_{32}} + 0 \quad (12)$$

$$= \frac{1}{R_A + R_4 + R_{32}} \quad (13)$$

For the first of the resistors,

$$\frac{\partial I_m}{\partial R_A} = \frac{\partial}{\partial R_A} \left\{ \frac{E}{R_A + R_4 + R_{32}} + K \right\} \quad (14)$$

$$= \frac{\partial}{\partial R_A} \cdot \frac{E}{R_A + R_4 + R_{32}} + \frac{\partial K}{\partial R_A} \quad (15)$$

$$= \frac{0 - E \cdot 1}{(R_A + R_4 + R_{32})^2} + 0 \quad (16)$$

$$= \frac{-E}{(R_A + R_4 + R_{32})^2} \quad (17)$$

Similarly for the other 2 resistors,

$$\frac{\partial I_m}{\partial R_4} = \frac{\partial I_m}{\partial R_{32}} = \frac{-E}{(R_A + R_4 + R_{32})^2} \quad (18)$$

Substituting the partial derivative equivalents in Eqs. (9), (13), (17), and (18) into Eq. (4) yields

$$\begin{aligned} \Delta I_m \approx & \Delta K + \frac{1}{R_A + R_4 + R_{32}} \Delta E - \frac{E}{(R_A + R_4 + R_{32})^2} \Delta R_A \\ & - \frac{E}{(R_A + R_4 + R_{32})^2} \Delta R_4 - \frac{E}{(R_A + R_4 + R_{32})^2} \Delta R_{32} \end{aligned} \quad (19)$$

Recall that $\Delta R_A = 0$. Then, the relative error δI is found by dividing the absolute error by the true value

$$\delta I = \frac{\Delta I_m}{I_t} \quad (20)$$

Therefore, dividing and simplifying:

$$\frac{\Delta I_m}{I_t} = \frac{\Delta K}{I_t} + \frac{\Delta E}{E} - \frac{\Delta R_4}{R_A + R_4 + R_{32}} - \frac{\Delta R_{32}}{R_A + R_4 + R_{32}} \quad (21)$$

The exact combination of deltas will not be known, but the maximum relative error can be expressed as

$$\left| \frac{\Delta I_m}{I_t} \right| \leq \left| \frac{\Delta K}{I_t} \right| + \left| \frac{\Delta E}{E} \right| + \left| \frac{\Delta R_4}{R_A + R_4 + R_{32}} \right| + \left| \frac{\Delta R_{32}}{R_A + R_4 + R_{32}} \right| \quad (22)$$

To obtain numerical values for $|\delta I|$ in Eq. (22), thermistor R_{32} was varied proportionally with temperature increasing in increments of 10 degrees Celsius. Values of all deltas were taken from manufacturers specifications. I_t was calculated from Eq. (1) so the value of the first term on the right side of the equation can be found.

The resistance and voltage values are listed on Figure 1. The voltage E is nominally 6.5 volts as derived from a 6.8 volt ± 5 percent zener diode D1 and the base - emitter voltage drop of Q1. The combined error of D1 and Q1 will be taken as 5 percent for a ΔE of 0.325 volt. For the remaining component errors, $\Delta R_4 = 0.604$ k ohms and $\Delta K = 2.0 \mu A$. Fenwal Electronics thermistor manual EMC-6 pages 24 and 29 characterizes a QB41J3 standard curve as listed in Table 1.

Table 1. Thermistor QB41J3 Data

| True Temperature (°C) | Resistance (ohms $\times 10^3$) | Accuracy (\pm percent ^{**}) | ΔR (ohms $\times 10^3$) |
|--------------------------|-------------------------------------|---|-------------------------------------|
| -80 | 2576.* | 14.6 | 376.1 |
| -70 | 1032.* | 12.5 | 129.0 |
| -60 | 730.4 | 10.7 | 78.2 |
| -50 | 389.5 | 9.2 | 35.8 |
| -40 | 215.1 | 7.8 | 16.8 |
| -30 | 123.3 | 6.6 | 8.14 |
| -20 | 73.07 | 5.4 | 3.95 |
| -10 | 44.76 | 4.3 | 1.93 |
| 0 | 28.25 | 3.3 | 0.932 |
| 10 | 18.30 | 2.2 | 0.403 |
| 20 | 12.16 | 1.3 | 0.158 |

Notes: * These two points were calculated from empirical data recorded on 21 February 1974. The data is within +4 percent of the Fenwal values except at the coldest temperature where it was +6.7 percent in error.

** See Fenwal Electronics manual EMC-6 (copyright 1974) page 27, curve No. 10 resistance deviation due to beta tolerance table and the explanation below it. The points for -80° and -70° Celsius were extrapolated.

Time Constant: Still air, 20 sec.

Dissipation Constant: Still air at 25°C, 2.5 mW/°C.

Table 2 shows the contributions of the terms of Eq. (22) to $|\delta I|$. Multiplication of the last column by 100 yields \pm percent error of the current.

Table 3 correlates the relative current error, degrees Celsius error, and the overall percent error of the measurement. The degrees Celsius error for any temperature was calculated as the product of the following three terms: temperature rate of change with current, the ideal meter current I_t , and the relative error. The first 2 terms are from Table 4 and the last term is from Table 2.

Although the relative error in Table 2 is indeed enormous, especially at the lowest temperatures, it must be remembered that this is the maximum error possible with the given component tolerances. The major contributor at the low temperatures is the recorder ammeter. A telephone call to the manufacturer verified that the instrument's accuracy is ± 2 percent of full scale. The galvanometer is purchased to ± 1 percent of full scale and when the total recorder is

Table 2. Calculation of Maximum Relative Current Error Versus Temperature for the Original System

| Temperature (°C) | $\frac{\Delta K^*}{I_t}$ | $\frac{\Delta E}{E}$ | $\frac{\Delta R_4}{R_A + R_4 + R_{32}}$ | $\frac{\Delta R_{32}}{R_A + R_4 + R_{32}}$ | $\frac{\Delta I_m}{I_t}$ |
|---------------------|--------------------------|----------------------|---|--|--------------------------|
| -70 | 0.500 | 0.05 | 0.001 | 0.118 | 0.669 |
| -60 | 0.267 | 0.05 | 0.001 | 0.098 | 0.416 |
| -50 | 0.148 | 0.05 | 0.001 | 0.079 | 0.278 |
| -40 | 0.087 | 0.05 | 0.002 | 0.060 | 0.199 |
| -30 | 0.057 | 0.05 | 0.003 | 0.043 | 0.153 |
| -20 | 0.043 | 0.05 | 0.004 | 0.029 | 0.126 |
| -10 | 0.034 | 0.05 | 0.006 | 0.018 | 0.108 |
| 0 | 0.029 | 0.05 | 0.006 | 0.010 | 0.095 |
| 10 | 0.025 | 0.05 | 0.007 | 0.005 | 0.087 |
| 20 | 0.024 | 0.05 | 0.008 | 0.002 | 0.084 |

Note: * Based on I_t values from Table 3 (which are extracted from the table used to process the recorded data).

Table 3. Temperature Error of the Original System

| Temperature (°C) | Maximum error (± °C) | Percent error* (± percent) |
|---------------------|-------------------------|-------------------------------|
| -70 | 8.0 | 3.9 |
| -60 | 6.5 | 3.1 |
| -50 | 5.8 | 2.6 |
| -40 | 3.7 | 1.6 |
| -30 | 4.5 | 1.9 |
| -20 | 4.7 | 1.9 |
| -10 | 5.1 | 1.9 |
| 0 | 6.7 | 2.5 |
| 10 | 9.6 | 3.4 |
| 20 | 13.5 | 4.6 |

Note: * Based on degrees Kelvin.

Table 4. Current Versus Temperature for the Original System

| Temperature (°C) | Current: I_t (μA) | Rate (°C/ μA) |
|---------------------|-------------------------------|------------------------|
| -70 | 4.0 | 3.0 |
| -60 | 7.8 | 2.0 |
| -50 | 13.8 | 1.5 |
| -40 | 23.0 | 0.85 |
| -30 | 34.8 | 0.85 |
| -20 | 47.0 | 0.80 |
| -10 | 59.3 | 0.80 |
| 0 | 70.0 | 1.0 |
| 10 | 78.5 | 1.4 |
| 20 | 84.6 | 1.9 |

considered in terms of linearity, temperature, function and ohmic resistance, it is accurate to ± 2 percent FS (full scale).

Determination of the probability of any error in the envelope defined by Eq. (22) would necessitate knowledge of the error distribution of each of the components. This information is not available.

One point which should be touched upon is the thermistor self-heating. Using the thermistor dissipation constant, listed in Table 1, temperature errors of $0.05^\circ C$ take place at full scale readings, and significantly smaller errors take place at the temperatures discussed in this report. Because this effect is so much smaller than the calculated error, it has been ignored.

2.1.2 THE SELF CALIBRATION

The manufacturer's procedure for reducing the data from the recorder tapes involves zero and $75 \mu A$ reference currents. According to the recorder manufacturer, the zero current indication should never be more than $0.25 \mu A$ from the zero current line of the chart paper. Major deviations would indicate that the device is in need of repair. The high current reference is obtained when R_4 and R_{32} are switched out and replaced with R_2 ($= 82.5 K \pm 1$ percent) to derive a $75 \mu A$ current from the 6.5 volt reference voltage. However, the current I produced by applying 6.5 volts to R_2 is:

$$\begin{aligned}
I &= E/R_2 \\
&= 6.5 \text{ volts}/82.5 \text{ k ohms} \\
&= 78.79 \mu\text{A} .
\end{aligned}$$

The meter has an accuracy of ± 2.7 percent at $75 \mu\text{A}$.

This calibration is useful in the range of the current measured but, since the majority of measurements are accomplished at much lower currents, this technique is not valid because the meter error K has ever increasing significance as current decreases.

2.1.3 PRECISION

The precision, the degree of repeatability of a measurement regardless of its accuracy, is not defined in the flowmeter system literature. However, enough data has been compiled over years of operational use to define the system precision as $\pm 0.35 \mu\text{A}$. This can be converted to degrees Celsius at a specified temperature by referring to Table 4. For example, at -30°C the rate of change of temperature is $0.85^\circ\text{C}/\mu\text{A}$. Multiplying by the precision of $\pm 0.35 \mu\text{A}$ results in a product of $\pm 0.3^\circ\text{C}$ for the temperature precision.

2.2 The Modified Circuit

2.2.1 ACCURACY

The circuit under discussion is shown in Figure 2. It is very similar to the standard circuit and the same constraints hold for both circuits. From Ohm's law it can be shown that

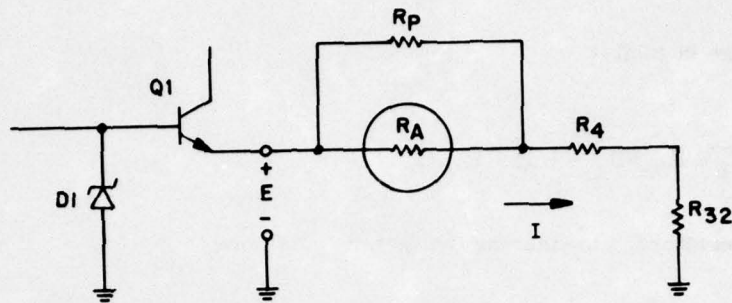
$$E = I \left\{ \frac{R_A R_P}{R_A + R_P} + R_4 + R_{32} \right\} \quad (23)$$

or, rearranging the terms

$$I = E \cdot \frac{1}{R_A R_P / (R_A + R_P) + R_4 + R_{32}} \quad (24)$$

The ammeter current is

$$I_t = E \cdot \frac{R_P}{R_A + R_P} \cdot \frac{1}{R_A R_P / (R_A + R_P) + R_4 + R_{32}} \quad (25)$$



KEY

| | | | | |
|----------------|-----------|--------------------------|-----------------|---|
| D1 | 1N4736A | 68.V ± 5% | R ₄ | 16.0k ohms ± 1% |
| Q1 | 2N1308 | | R ₃₂ | thermistor UUB31J1 1k ohms ± 1% at 25°C |
| R _A | 4600 ohms | error accounted for by K | K | ammeter accuracy ± 2% of full scale |
| R _P | 1.8k ohms | ± 1% | | |

Figure 2. Modified Temperature Sensing Circuit

where the I_t denotes theoretical current based on ideal components. If the components are allowed to vary according to manufacturer specifications, then the same expression can define the real meter current for any set of components. However, we are interested in the current as recorded on the tape. The measured current is

$$I_m = I_r + K = E \cdot \frac{R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} + K \quad (26)$$

where K is the meter accuracy as defined in Figure 2.

The absolute error of I_m is $\Delta I_m = I_m - I_t$. As a function of the terms in Eq. (26)

$$\Delta I_m \approx \frac{\partial I_m}{\partial K} \Delta K + \frac{\partial I_m}{\partial E} \Delta E + \frac{\partial I_m}{\partial R_A} \Delta R_A + \frac{\partial I_m}{\partial R_P} \Delta R_P + \frac{\partial I_m}{\partial R_4} \Delta R_4 + \frac{\partial I_m}{\partial R_{32}} \Delta R_{32} \quad (27)$$

Differentiating Eq. (26) for the various partials yields

$$\frac{\partial I_m}{\partial K} = 1 \quad (28)$$

For the voltage regulator

$$\frac{\partial I_m}{\partial E} = \frac{R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \quad (29)$$

And for the resistors, considering the meter resistance,

$$\frac{\partial I_m}{\partial R_A} = E \frac{\partial}{\partial R_A} \left\{ \frac{R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \right\} \quad (30)$$

$$= - \frac{E \cdot R_P (R_4 + R_{32} + R_P)}{[(R_4 + R_{32})(R_A + R_P) + R_A R_P]^2} \quad (31)$$

and the parallel resistance

$$\frac{\partial I_m}{\partial R_P} = E \frac{\partial}{\partial R_P} \left\{ \frac{R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \right\} \quad (32)$$

$$= \frac{E \cdot R_A (R_4 + R_{32})}{[(R_4 + R_{32})(R_A + R_P) + R_A R_P]^2} \quad (33)$$

For R_4

$$\frac{\partial I_m}{\partial R_4} = E \cdot \frac{\partial}{\partial R_4} \left\{ \frac{R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \right\} \quad (34)$$

$$= - \frac{E \cdot R_P (R_A + R_P)}{[(R_4 + R_{32})(R_A + R_P) + R_A R_P]^2} \quad (35)$$

Because of the similarity in the positioning of R_{32} and R_4 , it can be written by inspection that

$$\frac{\partial I_m}{\partial R_{32}} = - \frac{E \cdot R_P (R_A + R_P)}{[(R_4 + R_{32})(R_A + R_P) + R_A R_P]^2} \quad (36)$$

This completes the calculation of the 6 partial derivatives for I_m . The substitution into Eq. (27) and subsequent division by I_t to obtain δI , the relative error of I_m results in

$$\begin{aligned} \delta I = \frac{\Delta I_m}{I_t} = & \frac{\Delta K}{I_t} + \frac{\Delta E}{E} - \frac{R_4 + R_{32} + R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \cdot \Delta R_A \\ & + \frac{R_A(R_4 + R_{32})}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \cdot \frac{\Delta R_P}{R_P} \\ & - \frac{R_A + R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \Delta R_4 \\ & - \frac{R_A + R_P}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \Delta R_{32} \end{aligned} \quad (37)$$

This shows that the absolute errors of the meter and the voltage source, ΔK and ΔE respectively, contribute directly to the overall relative error. However, the contributions of the resistance errors are not so straightforward. Since R_A was taken as zero because it is covered by K , the first resistive term is zero. Considering the second resistive term

$$\frac{R_A(R_4 + R_{32})}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \cdot \frac{\Delta R_P}{R_P} \quad (38)$$

dividing numerator and denominator by $R_A(R_4 + R_{32})$ yields

$$\frac{1}{\frac{R_A + R_P}{R_A} + \frac{R_P}{R_4 + R_{32}}} \cdot \frac{\Delta R_P}{R_P} \quad (39)$$

or

$$\frac{1}{1 + \frac{R_P}{R_A} + \frac{R_P}{R_4 + R_{32}}} \cdot \frac{\Delta R_P}{R_P} \quad (40)$$

which, as temperature decreases and

$$R_{32} \gg R_P \quad (41)$$

will simplify to

$$\frac{1}{1 + R_P/R_A} \cdot \frac{\Delta R_P}{R_P} \quad (42)$$

Considering the third resistive term

$$\frac{(R_A + R_P) \Delta R_4}{(R_4 + R_{32})(R_A + R_P) + R_A R_P} \quad (43)$$

dividing numerator and denominator by $R_A + R_P$ yields

$$\frac{\Delta R_4}{R_4 + R_{32} + R_A R_P / (R_A + R_P)} \quad (44)$$

which shows that at cold temperature where

$$R_{32} \gg R_4 + R_A R_P / (R_A + R_P) \quad (45)$$

the contribution of ΔR_4 approaches zero.

The last term is similar to the third. By inspection, it is seen that it will reduce to

$$\frac{\Delta R_{32}}{R_4 + R_{32} + R_A R_P / (R_A + R_P)} \quad (46)$$

However, ΔR_{32} is a function of temperature and rises approximately linearly. Even though the denominator will become dominated by R_{32} , Eq. (46) should be calculated for a thorough investigation because

$$R_{32} \gg R_4 + R_A R_P / (R_A + R_P) \quad (47)$$

only below -75°C .

To calculate the worst case error, take the absolute value of both sides of Eq. (37), recalling that there is zero contribution from ΔR_A

$$\left| \frac{\Delta I_m}{I_t} \right| \leq \left| \frac{\Delta K}{I_t} \right| + \left| \frac{\Delta E}{E} \right| + \frac{1}{D} \left\{ \left| \frac{R_A(R_4 + R_{32}) \cdot \Delta R_P}{R_P} \right| + |(R_A + R_P) \Delta R_4| + |(R_A + R_P) \Delta R_{32}| \right\} \quad (48)$$

where

$$D = (R_4 + R_{32})(R_A + R_P) + R_A R_P \quad (49)$$

Calculating the deltas from the accuracies of the components yields $\Delta E = \pm 0.325$ volt, $\Delta R_P = \pm 0.18$ k ohm, $\Delta R_4 = \pm 0.16$ k ohm and, $\Delta K = \pm 2 \mu A$. The absolute error of R_{32} is a function of temperature (see Table 5).

Table 5. Thermistor UUB31J1 Data

| Temperature (°C) | Resistance (ohms $\times 10^3$) | Accuracy (\pm percent) | ΔR (ohms $\times 10^3$) |
|---------------------|-------------------------------------|------------------------------|-------------------------------------|
| -80 | 229.0 | 10.0 | 22.9 |
| -70 | 114.3 | 7.2 | 8.230 |
| -60 | 59.77 | 5.6 | 3.347 |
| -50 | 32.64 | 4.4 | 1.436 |
| -40 | 18.55 | 3.4 | 0.631 |
| -30 | 10.92 | 2.5 | 0.273 |
| -20 | 6.649 | 1.7 | 0.113 |
| -10 | 4.172 | 1.2 | 0.050 |
| 0 | 2.691 | 1.0 | 0.027 |
| 10 | 1.779 | 0.9 | 0.016 |
| 20 | 1.204 | 0.8 | 0.010 |

Notes: This table is based on data in Fenwal Electronics' Uni-Curve Thermistor Manual L-6A (reference number 10M-5-874-MBP) pages 5 and 6.

Time Constant: Still air, 10 sec maximum
Stirred oil bath, 1 sec maximum

Dissipation Constant: Still air, 1 mW/°C.

Table 6 shows the contributions of the terms of Eq. (48) to $|\delta I|$. Multiplication of the last column by 100 yields \pm percent error of current.

Table 6. Calculation of Maximum Relative Current Error Versus Temperature for the Modified System

| Temperature (°C) | $\frac{\Delta K}{I_t}$ | $\frac{\Delta E}{E}$ | T3 | T4 | T5 | $\frac{\Delta I_m}{I_t}$ |
|---------------------|------------------------|----------------------|-------|-------|-------|--------------------------|
| -80 | 0.269 | 0.05 | 0.007 | 0.001 | 0.093 | 0.420 |
| -70 | 0.144 | 0.05 | 0.007 | 0.001 | 0.063 | 0.265 |
| -60 | 0.084 | 0.05 | 0.007 | 0.002 | 0.043 | 0.186 |
| -50 | 0.055 | 0.05 | 0.007 | 0.003 | 0.029 | 0.144 |
| -40 | 0.039 | 0.05 | 0.007 | 0.004 | 0.018 | 0.118 |
| -30 | 0.031 | 0.05 | 0.007 | 0.006 | 0.010 | 0.104 |
| -20 | 0.026 | 0.05 | 0.007 | 0.007 | 0.005 | 0.095 |
| -10 | 0.023 | 0.05 | 0.007 | 0.007 | 0.002 | 0.089 |
| 0 | 0.022 | 0.05 | 0.007 | 0.008 | 0.001 | 0.088 |
| 10 | 0.021 | 0.05 | 0.007 | 0.008 | 0.001 | 0.087 |
| 20 | 0.020 | 0.05 | 0.007 | 0.009 | 0.001 | 0.087 |

Notes:

References
From Text

$$\text{where: } T3 = \frac{1}{1 + R_P/R_A + R_P/(R_4 + R_{32})} \cdot \frac{\Delta R_P}{R_P} \quad (40)$$

$$T4 = \frac{\Delta R_4}{R_4 + R_{32} + R_A R_P / (R_A + R_P)} \quad (44)$$

$$T5 = \frac{\Delta R_{32}}{R_4 + R_{32} + R_A R_P / (R_A + R_P)} \quad (46)$$

Table 7 correlates the relative current error, degrees Celsius error, and overall percent error based upon degrees Kelvin. The degrees Celsius error for a given temperature was computed as the product of the rate of change, the ideal current, and the relative error. The first two terms are from Table 8 and the last term is from Table 6.

Table 7. Temperature Error of the Modified System

| Temperature (°C) | Maximum Error (±°C) | Percent Error* (± percent) |
|---------------------|------------------------|-------------------------------|
| -80 | 6.2 | 3.2 |
| -70 | 4.4 | 2.2 |
| -60 | 3.5 | 1.6 |
| -50 | 3.7 | 1.7 |
| -40 | 4.2 | 1.8 |
| -30 | 4.7 | 1.9 |
| -20 | 7.3 | 2.8 |
| -10 | 9.9 | 3.8 |
| 0 | 15.3 | 5.6 |
| 10 | 22.5 | 7.9 |
| 20 | 33.5 | 11.4 |

Note: * Based on degrees Kelvin.

Table 8. Current Versus Temperature for the Modified System

| Temperature (°C) | Current (μA) | Rate (°C/μA) |
|---------------------|-----------------|-----------------|
| -80 | 7.4 | 2.0 |
| -70 | 13.9 | 1.2 |
| -60 | 23.7 | 0.8 |
| -50 | 36.6 | 0.7 |
| -40 | 51.0 | 0.7 |
| -30 | 64.8 | 0.8 |
| -20 | 76.4 | 1.0 |
| -10 | 85.2 | 1.3 |
| 0 | 91.5 | 1.9 |
| 10 | 95.9 | 2.7 |
| 20 | 98.8 | 3.9 |

The calculated temperature rise due to self-heating of this thermistor under maximum current conditions, using the dissipation constant for still air listed in Table 5, is about 0.01°C . This effect decreases rapidly as the current decreases at colder temperatures. Its effect is so small that it will not be considered.

Resistors R_P and R_4 were chosen to shift the region of best accuracy for the new thermistor into the temperature region where most of the data is gathered. Table 3 shows the least error occurring between -10°C and -40°C for the original circuit, while Table 7 shows that the modified circuit has the least error occurring between -30°C and -60°C . This will improve the accuracy of most of the volume computations.

2.2.2 PRECISION

The precision of the modified flow sensor is the same as that of the original flow sensor (see Section 2.1.3). In each case, the parameter is controlled by the meter movement of the recorder. Precision can be expressed in degrees Celsius by referring to Table 8.

2.2.3 LABORATORY TEST AND DATA

A laboratory test of the modified PR-3 flow sensor was conducted to verify circuit performance prior to implementing a balloon-borne test. Simulating the thermistor with a switchable resistance precluded the errors inherent in the thermistor and a temperature controlled chamber. Eleven values of resistance corresponding to 10 degree steps from -80°C to $+20^{\circ}\text{C}$ were set with an impedance bridge to an accuracy of better than 0.1 percent. This device is effectively an ideal UUB31J1 thermistor for the preset temperatures. Table 9 shows the results of 5 data runs with the ideal thermistor and PR-3 serial number 068AB.

The relative error (Table 9, column four) is well within the tolerances calculated in Table 6. This is very reasonable since all the data is gathered using one sensor with no error introduced by the ideal thermistor. It is worth noting that the precision is within the limits mentioned in Section 2.1.3. The next step was to compare the 2 thermistors in their respective circuits during a balloon-borne sampling mission.

Table 9. Data From Laboratory Test of Modified System

| T_t (°C) | I_t (μA) | \bar{I} (μA) | $\frac{\Delta I}{I_t}$ | Test Data | | | | |
|---------------|----------------------|--------------------------|------------------------|------------------|------------------|------------------|------------------|------------------|
| | | | | 1 (μA) | 2 (μA) | 3 (μA) | 4 (μA) | 5 (μA) |
| -80 | 7.42 | 7.31 | -0.015 | 7.45 | 7.19 | 7.45 | 7.22 | 7.24 |
| -70 | 13.89 | 13.75 | -0.010 | 13.7 | 13.4 | 13.9 | 13.9 | 13.9 |
| -60 | 23.72 | 23.50 | -0.009 | 23.3 | 23.4 | 23.4 | 23.6 | 23.7 |
| -50 | 36.61 | 36.50 | -0.003 | 36.6 | 36.2 | 36.7 | 36.5 | 36.5 |
| -40 | 51.00 | 51.05 | 0.001 | 50.9 | 50.9 | 51.1 | 51.1 | 51.3 |
| -30 | 64.80 | 65.37 | 0.009 | 65.2 | 65.2 | 65.5 | 65.5 | 65.5 |
| -20 | 76.35 | 77.18 | 0.011 | 77.1 | 77.1 | 77.3 | 77.1 | 77.3 |
| -10 | 85.17 | 85.94 | 0.009 | 85.8 | 86.1 | 86.0 | 85.8 | 86.0 |
| 0 | 91.48 | 92.38 | 0.010 | 92.5 | 92.2 | 92.5 | 92.2 | 92.5 |
| +10 | 95.85 | 96.87 | 0.011 | 96.8 | 96.8 | 97.1 | 96.8 | 96.8 |
| +20 | 98.83 | 100.12 | 0.013 | 100.0 | 100.0 | 100.3 | 100.2 | 100.2 |

3. COMPARISON OF THE TWO THERMISTOR CIRCUITS

3.1 Experimental Circuit

Physical construction of the PR-3 flow sensor system provides for monitoring 2 thermistors. A commutator switches each thermistor into the circuit, thereby utilizing the same voltage regulator and recorder for each. This is schematically drawn in Figure 3.

The similarity between Figure 3 and Figures 1 and 2 is obvious. The switch represents the commutator and the subscript T denotes components of the circuit under test. If they are removed, the original circuit remains. Component values are the same as in Figure 2 for those with the T subscript and as in Figure 1 for the remainder.

3.2 Accuracy

The accuracy of the circuit in Figure 3 can be computed from the preceding information. The total error (\pm °C) will be the sum of the error for each thermistor circuit, and will be computed that way because the different currents produced in the 2 circuits at the same temperature preclude the summing of relative errors.

Since the same voltage regulator is used for both circuits, the effect of its component tolerances should cancel out. However, since there is the difference in

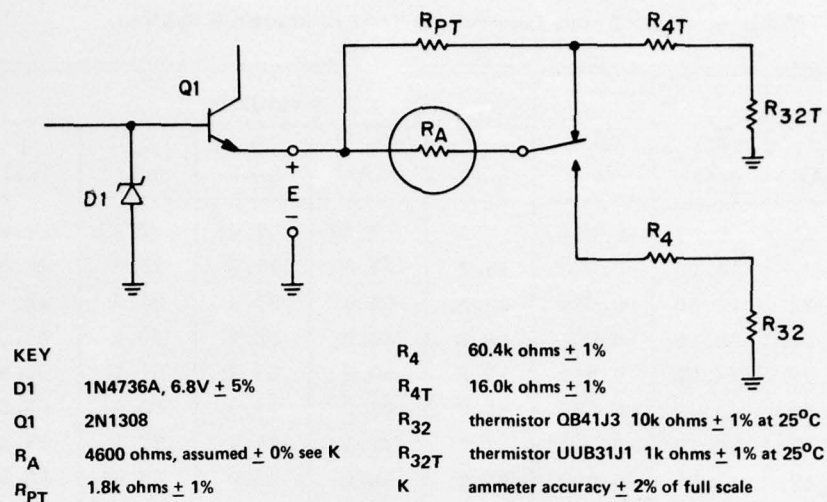


Figure 3. Test Circuit

circuit resistance at the same temperature, it doesn't quite drop out. The error introduced by assuming it does, is small and computable. For example, at -30°C the original circuit has a maximum relative current error of ± 0.153 corresponding to $\pm 4.5^{\circ}\text{C}$, while the modified circuit has a maximum error of ± 0.104 corresponding to $\pm 4.7^{\circ}\text{C}$. If the contribution of the voltage source relative accuracy, ± 0.05 , is computed the relative current errors are $\pm 1.5^{\circ}\text{C}$ and $\pm 2.3^{\circ}\text{C}$ respectively. If the error in the voltage supply is maximum, then the maximum error generated by our assumption is 0.8°C . Should the regulator error be nonexistent, then the error from our assumption is 0°C . The function is linear in the region between the examples mentioned.

Ammeter accuracy is treated the same way since it is unknown, but common to the 2 sections of the test circuit. In each case at -30°C , the meter contributes approximately 30 percent of the uncertainty. Therefore, if the meter is at its maximum error the error generated by our assumption is less than 0.5°C .

Errors for the remaining components are as listed in Table 2 and Table 6, respectively. Computation of the maximum error $^{\circ}\text{C}$ was accomplished as described above. Table 10a is the error for the original circuit, and, Table 10b is the error for the modified circuit. Table 10c is the sum of the preceding 2 tables and is the maximum possible error.

Table 10a. Maximum Error Contribution of the Original Part of the Test Circuit

| Temperature (°C) | $\frac{\Delta R_4}{D_1}$ | $\frac{\Delta R_{32}}{D_1}$ | $\frac{\Delta I_m}{I_t}$ | Maximum Error (±°C) |
|------------------|--------------------------|-----------------------------|--------------------------|---------------------|
| -70 | 0.001 | 0.118 | 0.119 | 1.4 |
| -60 | 0.001 | 0.098 | 0.099 | 1.5 |
| -50 | 0.001 | 0.079 | 0.080 | 1.7 |
| -40 | 0.002 | 0.060 | 0.062 | 1.2 |
| -30 | 0.003 | 0.043 | 0.046 | 1.4 |
| -20 | 0.004 | 0.029 | 0.033 | 1.2 |
| -10 | 0.006 | 0.018 | 0.024 | 1.1 |
| 0 | 0.006 | 0.010 | 0.016 | 1.1 |
| 10 | 0.007 | 0.005 | 0.012 | 1.3 |
| 20 | 0.008 | 0.002 | 0.010 | 1.6 |

Note: $D_1 = R_A + R_4 + R_{32}$.

Table 10b. Maximum Error Contribution of the Modified Part of the Test Circuit

| Temperature (°C) | T3 | T4 | T5 | $\frac{\Delta I_m}{\Delta I_t}$ | Maximum Error (±°C) |
|------------------|-------|-------|-------|---------------------------------|---------------------|
| -70 | 0.007 | 0.001 | 0.063 | 0.071 | 1.2 |
| -60 | 0.007 | 0.002 | 0.043 | 0.052 | 1.0 |
| -50 | 0.007 | 0.003 | 0.029 | 0.039 | 1.0 |
| -40 | 0.007 | 0.004 | 0.018 | 0.029 | 1.0 |
| -30 | 0.007 | 0.006 | 0.010 | 0.023 | 1.2 |
| -20 | 0.007 | 0.007 | 0.005 | 0.019 | 1.5 |
| -10 | 0.007 | 0.007 | 0.002 | 0.016 | 1.8 |
| 0 | 0.007 | 0.008 | 0.001 | 0.016 | 2.8 |
| 10 | 0.007 | 0.008 | 0.001 | 0.016 | 4.1 |
| 20 | 0.007 | 0.009 | 0.001 | 0.017 | 6.6 |

Note: Terms T3, T4, and T5 are defined in Table 6.

Table 10c. Maximum Error of the Test Circuit*

| Temperature (°C) | Error (± °C) |
|------------------|--------------|
| -70 | 2.6 |
| -60 | 2.5 |
| -50 | 2.7 |
| -40 | 2.2 |
| -30 | 2.6 |
| -20 | 2.7 |
| -10 | 2.9 |
| 0 | 3.9 |
| 10 | 5.4 |
| 20 | 8.2 |

*Under the constraints mentioned in the text.

3.3 Experimental Data

Data was gathered by modifying the circuitry in a PR-3 Data Recorder so that it corresponds to Figure 3. Resistors R_{PT} and R_{4T} were added to Recorder serial number 077AB, and R_{32T} , and the UUB31J1 thermistor was mounted in a Flow Sensor next to the standard thermistor.

Here, the exact mounting is described. The flow sensor interior is radially divided into 8 sections, by 8 evenly spaced "flow straightening vanes." Mounts for the bead thermistor are one vane, so that the thermistor leads are parallel to the radial dimension of the vane and the bead is in the center of the section about 0.5 in. (~1.3 cm) from any surface. The rod thermistor is secured to mounts located along the circumference of the cylinder on the opposite side of the same vane. The mounts are located so that the flow is across the axis of the thermistor which is also about a 0.5 in. (~1.3 cm) from any surface. The distance from thermistor to thermistor measured as a cord projected on the plane defined by the outward facing end of the sensor is about 1.3 in. (~3.2 cm). Measuring into the sensor from this plane, the rod thermistor is back about 1 in. (2.54 cm) and the bead thermistor is back about 1.7 in. (4.3 cm). This equipment was subsequently used on 3 atmospheric sampling missions to monitor the exhaust port of a motor driven sampler. The procedure in each case was to allow the balloon to rise to its

float altitude, then to activate the samplers while the balloon altitude remained within a nominal envelope to ± 1.5 km (5 kft). Data were taken while air was flowing over the thermistors. Temperatures were derived directly from the chart recorder data in microamperes. No corrections have been applied.

3.3.1 FIRST TEST FLIGHT, H76-7/H-78X, 13 FEBRUARY 1976

Data were recorded at an altitude of 32.2 km ± 0.15 km (105.5 k ft ± 0.5 k ft) for 280 min (see Table 11). It is important to remember that the data are commutated so the temperatures listed for a given time were recorded about 20 sec apart. Delta (Δ) is defined as the temperature from the original system minus the temperature from the modified system. The average temperature from the original system is -21.4°C , and from the modified system -22.3°C . The difference of 0.9°C is well within the error envelope of the test circuit.

3.3.2 SECOND TEST FLIGHT, H76-12/H-83X, 26 FEBRUARY 1976

This balloon floated at an altitude of 30.8 km ± 0.24 km (101.1 k ft ± 0.8 k ft) and the data were recorded for 330 min (see Table 12). The average temperature from the original system is -23.3°C , while the average temperature from the modified system is -20.6 for an average difference of -2.6°C . This average difference is also within the computed error envelope.

3.3.3 THIRD TEST FLIGHT, H76-48/H-93, 25 AUGUST 1976

Data were recorded at an altitude of 21.5 km ± 0.03 km (70.8 k ft ± 0.1 k ft) for 180 min (see Table 13). The average temperature from the original system is -37.6°C , and -37.2°C for the modified system. Once again the difference of -0.4°C is well within the allowable envelope.

3.4 Data Evaluation

Data from 3 dual thermistor flights described in the preceding paragraphs of Section 3 will be used to evaluate the first characteristic mentioned in the introduction; that is, data exhibiting an oscillation about some reference temperature. Data in Tables 11, 12 and 13 definitely have oscillations and both thermistors track very well in all cases. Tables 11 and 12 exhibit 2 1/2 cycles, while Table 13 has 2 complete cycles.

There is no common frequency of oscillation. Also, in each case the difference between the maximum and minimum temperature values for each thermistor is about the same - that is, 9°C , 21°C , and 5°C respectively for the three flights. The maximum variation in temperature due to the circuit would have to be based on the circuit precision. Allowing for $\pm 1/4^{\circ}\text{C}$ per thermistor circuit, the maximum difference from this cause would be $1/2^{\circ}$ Celsius.

Table 11. Data From the First Flight Test

| Time (Min) | Original Part | | Modified Part | |
|---------------|-----------------------|--------------------------------|-----------------------|--------------------------------|
| | Current (μ A) | Temperature ($^{\circ}$ C) | Current (μ A) | Temperature ($^{\circ}$ C) |
| 0 | 43.0 | -23.2 | 70.0 | -25.8 |
| 10 | 42.0 | -24.0 | 71.0 | -24.9 |
| 20 | 41.0 | -24.8 | 71.0 | -24.9 |
| 30 | 41.0 | -24.8 | 69.0 | -26.6 |
| 40 | 43.0 | -23.2 | 75.0 | -21.3 |
| 50 | 41.0 | -24.8 | 70.0 | -25.8 |
| 60 | 47.0 | -24.0 | 70.0 | -25.8 |
| 70 | 48.0 | -19.2 | 71.5 | -24.5 |
| 80 | 51.0 | -16.8 | 76.5 | -19.9 |
| 90 | 53.0 | -15.1 | 78.0 | -18.4 |
| 100 | 53.0 | -15.1 | 79.0 | -17.3 |
| 110 | 53.0 | -15.1 | 78.0 | -18.4 |
| 120 | 46.0 | -20.8 | 76.0 | -20.4 |
| 130 | 43.0 | -23.2 | 73.0 | -23.2 |
| 140 | 43.5 | -22.9 | 74.0 | -22.2 |
| 150 | 44.5 | -22.1 | 74.5 | -21.7 |
| 160 | 45.0 | -21.7 | 73.5 | -22.7 |
| 170 | 43.5 | -22.9 | 74.0 | -22.2 |
| 180 | 49.5 | -18.0 | 78.0 | -18.4 |
| 190 | 48.5 | -18.8 | 75.0 | -21.3 |
| 200 | 43.5 | -22.9 | 72.5 | -23.7 |
| 210 | 42.0 | -24.0 | 72.0 | -24.1 |
| 220 | 41.0 | -24.8 | 68.5 | -27.0 |
| 230 | 42.0 | -24.0 | 70.5 | -25.3 |
| 240 | 40.0 | -25.7 | 70.0 | -25.8 |
| 250 | 44.0 | -22.5 | 76.0 | -20.4 |
| 260 | 48.5 | -18.8 | 78.5 | -17.8 |
| 270 | 48.0 | -19.2 | 77.0 | -19.4 |
| 280 | 48.0 | -19.2 | 77.5 | -18.9 |

Table 12. Data From the Second Flight Test

| Time (Min) | Original Part | | Modified Part | |
|---------------|-----------------------|--------------------------------|-----------------------|--------------------------------|
| | Current (μ A) | Temperature ($^{\circ}$ C) | Current (μ A) | Temperature ($^{\circ}$ C) |
| 0 | 31.0 | -33.0 | 60.5 | -33.3 |
| 10 | 37.0 | -28.2 | 62.0 | -33.2 |
| 20 | 41.0 | -24.8 | 71.0 | -24.9 |
| 30 | 47.0 | -20.0 | 77.0 | -19.4 |
| 40 | 44.0 | -22.5 | 76.5 | -19.9 |
| 50 | 46.0 | -20.8 | 75.0 | -21.3 |
| 60 | 46.0 | -20.8 | 79.0 | -17.3 |
| 70 | 49.0 | -18.4 | 78.0 | -18.4 |
| 80 | 48.0 | -19.2 | 83.0 | -12.8 |
| 90 | 43.0 | -23.2 | 83.0 | -12.8 |
| 100 | 42.0 | -24.0 | 77.0 | -19.4 |
| 110 | 41.0 | -24.8 | 74.0 | -22.2 |
| 120 | 43.0 | -23.2 | 75.0 | -21.3 |
| 130 | 48.0 | -19.2 | 80.0 | -16.2 |
| 140 | 47.0 | -20.0 | 77.0 | -19.4 |
| 150 | 36.5 | -21.6 | 73.0 | -23.2 |
| 160 | 33.0 | -31.5 | 69.0 | -26.6 |
| 170 | 38.0 | -27.4 | 72.0 | -24.1 |
| 180 | 42.0 | -24.0 | 74.5 | -22.2 |
| 190 | 45.5 | -21.7 | 76.0 | -20.4 |
| 200 | 39.0 | -26.6 | 75.0 | -21.3 |
| 210 | 35.0 | -29.8 | 69.0 | -26.6 |
| 220 | 32.0 | -32.2 | 66.0 | -29.1 |
| 230 | 35.0 | -29.8 | 70.0 | -25.8 |
| 240 | 39.0 | -26.6 | 70.5 | -24.4 |
| 250 | 40.0 | -25.7 | 69.0 | -26.6 |
| 260 | 50.0 | -17.6 | 78.0 | -18.4 |
| 270 | 48.0 | -19.2 | 81.0 | -15.1 |
| 280 | 51.0 | -16.8 | 80.0 | -16.2 |
| 290 | 58.0 | -11.0 | 82.5 | -13.4 |
| 300 | 51.0 | -16.8 | 82.0 | -14.0 |
| 310 | 52.5 | -15.5 | 81.5 | -14.5 |
| 320 | 41.0 | -24.8 | 81.0 | -15.1 |
| 330 | 41.0 | -24.8 | 82.0 | -14.0 |

Table 13. Data From the Third Flight Test

| Time (Min) | Original Part | | Modified Part | |
|---------------|------------------------|--------------------------------|------------------------|--------------------------------|
| | Current (μA) | Temperature ($^{\circ}C$) | Current (μA) | Temperature ($^{\circ}C$) |
| 0 | 22.5 | -40.4 | 50.5 | -40.3 |
| 10 | 23.0 | -40.0 | 52.5 | -39.0 |
| 20 | 26.0 | -37.1 | 56.0 | -36.5 |
| 30 | 26.0 | -37.1 | 58.0 | -35.1 |
| 40 | 26.5 | -36.7 | 58.5 | -34.8 |
| 50 | 25.5 | -37.6 | 53.0 | -38.6 |
| 60 | 26.5 | -36.7 | 54.0 | -39.9 |
| 70 | 28.5 | -35.1 | 58.5 | -34.8 |
| 80 | 28.0 | -35.4 | 56.0 | -36.5 |
| 90 | 25.5 | -37.6 | 56.0 | -36.5 |
| 100 | 24.0 | -39.0 | 52.5 | -39.0 |
| 110 | 22.5 | -40.4 | 52.0 | -39.3 |
| 120 | 27.0 | -36.2 | 58.0 | -35.1 |
| 130 | 25.0 | -38.0 | 53.0 | -38.6 |
| 140 | 27.0 | -36.2 | 56.0 | -36.5 |
| 150 | 24.5 | -38.5 | 54.0 | -37.9 |
| 160 | 24.0 | -39.0 | 53.5 | -38.3 |
| 170 | 28.5 | -35.1 | 58.5 | -34.8 |

A few words are now appropriate about the segment aperture times and the thermistor time constants. The duration of each segment is 37.5 sec. The time constants of the thermistors are 20 sec for the rod and 10 sec for the bead. Current recorded for the 2 segments was read toward the end of the first segment and the beginning of the second segment. This allows about 40 sec separation for the temperatures written as a set. The commutator selects first the original (rod) thermistor and then the bead thermistor. Forty sec is 4 bead thermistor time constants. In 4 time constants, the bead has essentially completed any change which would take place if a new temperature was impressed upon it at the completion of the segment dedicated to the rod thermistor.

4. FLIGHT DATA

The data displayed in Table 14 is from 18 flights over a period of 27 months, and all the data is from PR-3 sensors of the original configuration. The letter preceding the flight number identifies the launch location as New Mexico (H), Panama Canal Zone (P), or Alaska (A). Each ambient temperature used as a control was obtained from a radiosonde set manufactured by VIZ Manufacturing Company which was suspended beneath the samplers during the flight. VIZ Model 1091 is designated AN/AMT-12 by the U. S. Army. Specifications published by the manufacturer list the temperature error as "less than 0.45°C average RMS" over the range of +60°C to -90°C. Independent research (Morrissey⁴) cautions that this should be considered nonrigorous in terms of an absolute figure on any data run, but documents the "root mean square deviations in temperature measurements on simultaneously released radiosondes of 0.4°C."

4.1 Data Evaluation

Data from Table 14 will be used to evaluate the second characteristic mentioned in the introduction, that is, the large difference in temperature between similar flights, with flights at the same altitude ± 10 k ft. To accomplish that, the average ambient air temperature on each flight will be a control to which the average inlet air temperature is compared. This relative temperature as defined on Table 14 is plotted versus ambient temperature for each flight in Figure 4. The 3 float altitudes are differentiated by the symbols indicated on the figure.

Table 14. Temperatures Recorded on Recent Flights

| Flight Number | Date | Nominal Altitude (k Ft) | Ambient Temperature (°C) | Inlet Temperature (°C) | Relative* Temperature (°C) |
|---------------|-----------|-------------------------|--------------------------|------------------------|----------------------------|
| H-29 | 22 Aug 73 | 70 | -54.4 | -45.7 | 8.7 |
| H-31 | 28 Aug 73 | 90 | -45.7 | -42.4 | 3.3 |
| H-34 | 6 Nov 73 | 80 | -51.7 | -44.4 | 7.3 |
| P-138 | 12 Mar 74 | 80 | -59.3 | -53.3 | 6.0 |
| P-140 | 14 Mar 74 | 70 | -62.5 | -53.8 | 8.7 |
| H-37 | 12 Apr 74 | 80 | -53.3 | -47.8 | 5.5 |

4. Morrissey, J. F. (1972) Atmospheric Temperature Measurement Using Balloons and Rockets, AFCRL-TR-73-0380 (AD 764185), Copyright 1972 Instrumentation Society of America.

Table 14. Temperatures Recorded on Recent Flights (Cont.)

| Flight Number | Date | Nominal Altitude (k Ft) | Ambient Temperature (°C) | Inlet Temperature (°C) | Relative* Temperature (°C) |
|---------------|-----------|-------------------------|--------------------------|------------------------|----------------------------|
| H-29 | 22 Apr 74 | 70 | -59.5 | -53.3 | 6.2 |
| A-122 | 25 May 74 | 70 | -46.0 | -46.1 | 0.1 |
| A-124 | 27 May 74 | 90 | -41.0 | -40.5 | 0.5 |
| H-46 | 2 Aug 74 | 80 | -50.0 | -44.6 | 5.4 |
| H-49 | 25 Oct 74 | 70 | -61.2 | -49.9 | 11.3 |
| P-141 | 16 Mar 75 | 80 | -54.8 | -42.4 | 12.4 |
| P-143 | 19 Mar 75 | 90 | -49.1 | -39.1 | 10.0 |
| H-58 | 14 Apr 75 | 80 | -56.2 | -42.8 | 13.4 |
| A-127 | 6 May 75 | 80 | -51.5 | -40.8 | 10.7 |
| A-128 | 7 May 75 | 70 | -48.2 | -45.0 | 3.2 |
| A-129 | 8 May 75 | 90 | -49.0 | -35.7 | 13.3 |
| H-71 | 29 Oct 75 | 90 | -50.3 | -39.6 | 10.7 |

Note: * Relative temperature = inlet temperature - ambient temperature.

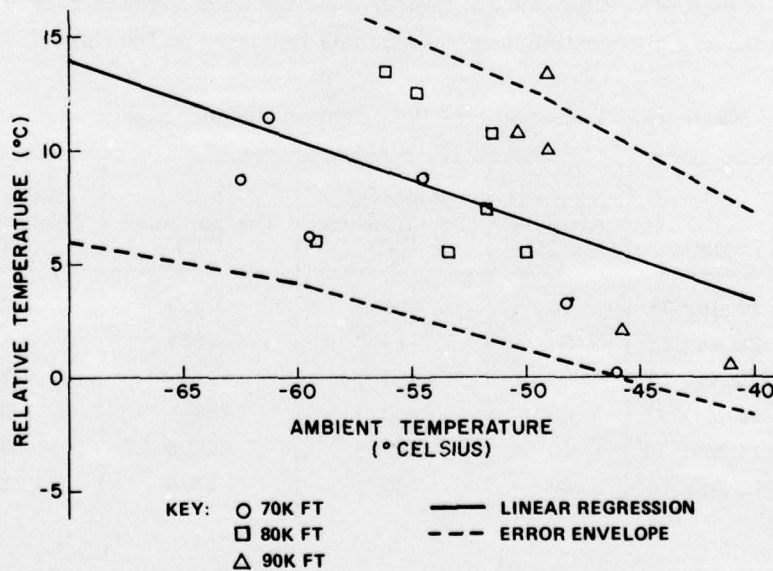


Figure 4. Relative Inlet Temperature Versus Ambient Temperature

The solid line represents a least square linear regression* formulated by:

$$y = 11.09 - 0.36 x \quad (50)$$

where x is the ambient temperature and y is the relative temperature, both in degrees Celsius. Ordinates of 3.3°C and 10.5°C were calculated for abscissas of -40°C and -60°C , respectively, to locate the line. The broken line represents the error envelope listed in Table 3. The empirical data fits the theoretical curves very well.

5. CONCLUSIONS

This analysis began with a description of 2 phenomena which were to be validated or disproved by analyzing the data system. Error envelopes for the circuits involved in the investigation were derived and presented in Tables 3, 7, and 10c. Data were gathered in 2 modes to test the phenomena.

5.1 First Phenomenon

Temperature oscillations during any 1 flight were examined with the dual thermistor flights. In each flight, each thermistor exhibited similar temperature excursions in frequency and magnitude. The resistance of the rod thermistor in the temperature range under discussion ($\sim -30^{\circ}$ Celsius) is approximately 123 k ohms while the bead thermistor is about 11 k ohms. At these resistances, no interference was experienced from radiated radio frequency energy in laboratory tests. Therefore, excursions in the temperature data are most probably indicating actual changes in the sampler inlet air temperature. Should the reader be tempted to compare the data from the two thermistors tabulated in sets, be cautioned to remember that the readings are actually separated by a 37.5 sec commutator segment. Considering the time constants discussed in Section 3.4, it is reasonable to expect temperature differences in the data "sets."

5.2 Second Phenomenon

Large differences in average temperatures among "similar" flights were examined by use of existing flight records. Figure 4 summarizes the data from 18 flights and compares it to the appropriate error envelope. One of the 18 points falls out of the error envelope by about 1°C . Considering the assumptions made about the voltage regulator, ammeter, and radiosonde, this is excellent. It says

* Performed with Hewlett-Packard 9810A calculator with the Statistics Block.

that the differences that were viewed as large were actually within the accuracy of the system. (Also, it should be noted here that some replacement rod thermistors were erroneously purchased at a 10 percent resistance tolerance rather than the 1 percent resistance tolerance on which the calculations are based. Using these 10 percent tolerance thermistors would have spread the data over a larger temperature range.)

5.3 General Comments

As mentioned in the Introduction, the author is not going to pursue the mechanisms which could cause temperature changes, but he will mention several ideas which should be explored. It is the author's opinion that the observed temperature changes are occurring in the air mass surrounding the balloon system and are intimately linked to the heat balance of the entire mass. Energy absorbed by the system through direct sunlight and albedo are significant factors. However, waste energy from the motors and batteries could also be significant, especially if there are eddy currents involving the sampler exhaust. Determining the exact cause of the reported phenomenon is beyond the scope of this report.

As a parenthetical remark, it is worth noting that the temperature of the inlet air is always above the ambient temperature reported by the radiosonde. Linear regressions performed on the data in Figure 4 in sets based on altitude yield a family of curves the slopes of which increase in magnitude as the altitude increases. This hints that a major factor in energy dissipation is convection and that as the air density drops there is less cooling. Presently, not enough data at one altitude and latitude are compiled to pursue this theory and it is beyond the scope of this report.

References

1. PR-3 Flowmeter System Technical Handbook (1969) ASD document No. 3330 by the Applied Science Division of Litton Systems, Inc., for the Dept. of the Air Force under Contract No. F41614-69-R-0442.
2. Stout, M.B. (1950) Electrical Measurements, Prentice Hall, Inc. Pages 405 to 408 have a good discussion on errors in electrical indicating instruments.
3. U. S. Department of Commerce (1967) Handbook of Mathematical Functions, NBS/Applied Mathematics Series No. 55, page 14, for a discussion of error analysis.
4. Morrissey, J. F. (1972) Atmospheric Temperature Measurement Using Balloons and Rockets, AFCRL-TR-73-0380 (AD 764185), Copyright 1972 Instrumentation Society of America.