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U.S. DEPARTMENT OF COMMERCE
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Diode and Thermocouple Airborne Temperature Sensors

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BOULDER, COLO.
MARCH 1973

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DIODE AND THERMOCOUPLE AIRBORNE TEMPERATURE SENSORS

G. Conrad[1], L. N. DeVol and J. E. Gunnoe

1. INTRODUCTION

The sensors discussed in this report are, in general, well-known throughout the scientific and engineering communities. However, the described application to the Naval Research Laboratories (NPL) axial-flow vortex probe[2] may be unique. The original AMQ-8 temperature sensor, a special copper-nickel resistance thermometer element, has become difficult to obtain from commercial sources in recent years; therefore, the Research Flight Facility (RFF) has experimented and fabricated prototype assemblies utilizing silicon diodes and copper-constantan thermocouples (TC's), in its search for possible replacements for the original sensor elements (Friedman et al., 1970).

The characteristics in common of diode and thermocouple devices that make them especially suitable for RFF's airborne application are their low cost, commercial availability, and inherent ruggedness, necessary conditions for competitive sensors, mainly because commercially available systems with digital readout capabilities are also relatively inexpensive. More critical requirements for these sensors are accuracy and stability.

This report will discuss RFF's use of both silicon diodes and thermocouple devices as airborne temperature sensors.

2. SILICON DIODES

The well known temperature-sensitive properties of semi-conductors have been exploited for some time. Thermistry has taken its place as a fourth major part of industrial and scientific thermometry. There are other, more specialized uses of semi-conductors for this purpose; one

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[1]Conrad's present affiliation is with the NOAA Albuquerque Seismology Laboratory, Kirtland AFB East, Albuquerque, New Mexico.

[2]Axial-flow vortex probe was originally used with the Bendix AMQ-8 system.

which seems advantageous for temperatures which exist in the environmental range is the p-n junction diode of germanium or silicon (Hinshaw and Fritschen, 1970; also, see Cleary et al.; 1964 for a general discussion of p-type, n-type materials and p-n junction diodes).[3]

This use is based on the fundamental law of current flow in a p-n junction, as given by equation (1):

$$I_F = I_S \exp(qV/KT) - 1 \quad , \qquad (1)$$

which is obeyed to a good approximation over significant ranges of applied voltage and temperature. Here the terms have the following meanings:

I_F = forward current
I_S = reverse or saturation current
q = electron charge (1.6×10^{-19} coulomb)
V = applied bias voltage
K = Boltzmann's constant (1.38×10^{-23} w sec/^oK)
T = absolute temperature (in degrees K)

Deviations from the equation may result from more or less fundamental temperature and voltage dependences of I_S, which, most simply, depend on the junction area and bulk properties of the semiconductor.

If we rewrite equation (1)

$$qV/KT = \ln(I_F/I_S + 1) \quad , \qquad (2)$$

We see that there is a linear relation between V and T for constant values of I_F and I_S. Most devices are more or less linear in the environmental range, with $I_F \cong 1$ mA, $\Delta V/\Delta T \cong 1$ to 2 mV/degree, depending on whether the diode is germanium or silicon and on the junction area itself. This sensitivity is quite high, and although the actual drop across a silicon diode is typically 0.5V, the preferred method of use is simply to pass a constant current through the diode and measure the

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[3]The p-n junction is the junction formed by joining p- and n- type materials into a single crystal structure.

voltage drop. Bridges apparently have not been used, but their use might confer additional sensitivity.

The circuit presently in use by the RFF is shown in figure 1a. The voltage drop across the diode is measured by comparing it with the voltage drop across a fixed resistor. This is accomplished with a high-impedance-input-follower amplifier (see Philbrick, 1966). The resulting difference signal is amplified to ± 5V, corresponding to the temperature range of ± 50C, which facilitates the direct digital readout of the temperature. In addition, this method is suitable for digital recording, although on some of Rff's systems, 0 to 5V is required. The system now in use accomplishes this by biasing the output with 5.000V and dividing with resistors (see fig. 1a).

A critical requirement in the circuitry is the current source for the diode. This must be stable from 0.01 to 0.1 percent, with the latter only useful for "rough" measurements. High grade operational amplifier power supplies may be suitable, but it has been found necessary to add an integrated circuit (IC) regulator to the prototype for service tests. This is not a major problem, since these are small, efficient and inexpensive. Only line regulation and temperature drift specifications are critical in the current source, since the load is virtually constant. In addition, there may be long-term drift in the regulator which may or may not be specified by the manufacturer.

The desirable linear characteristic of the diode permits calibrations to be made at two temperatures. For routine checks, one point may be sufficient.

Just how well the diode will stay within its calibration, or within the variation imposed by other important circuit characteristics, is an interesting question. Almost all semiconductor devices have their electrical behavior influenced from the surfaces of the semiconductor chip in the neighborhood of the p-n junction. These effects can presumably be large enough to cause rejection of the finished device in its intended use, or early catastrophic failure. Considerable advances have been made in cleaning and protecting the critical surfaces, so that long-term drifts, which have little effect on conventional circuit applications,

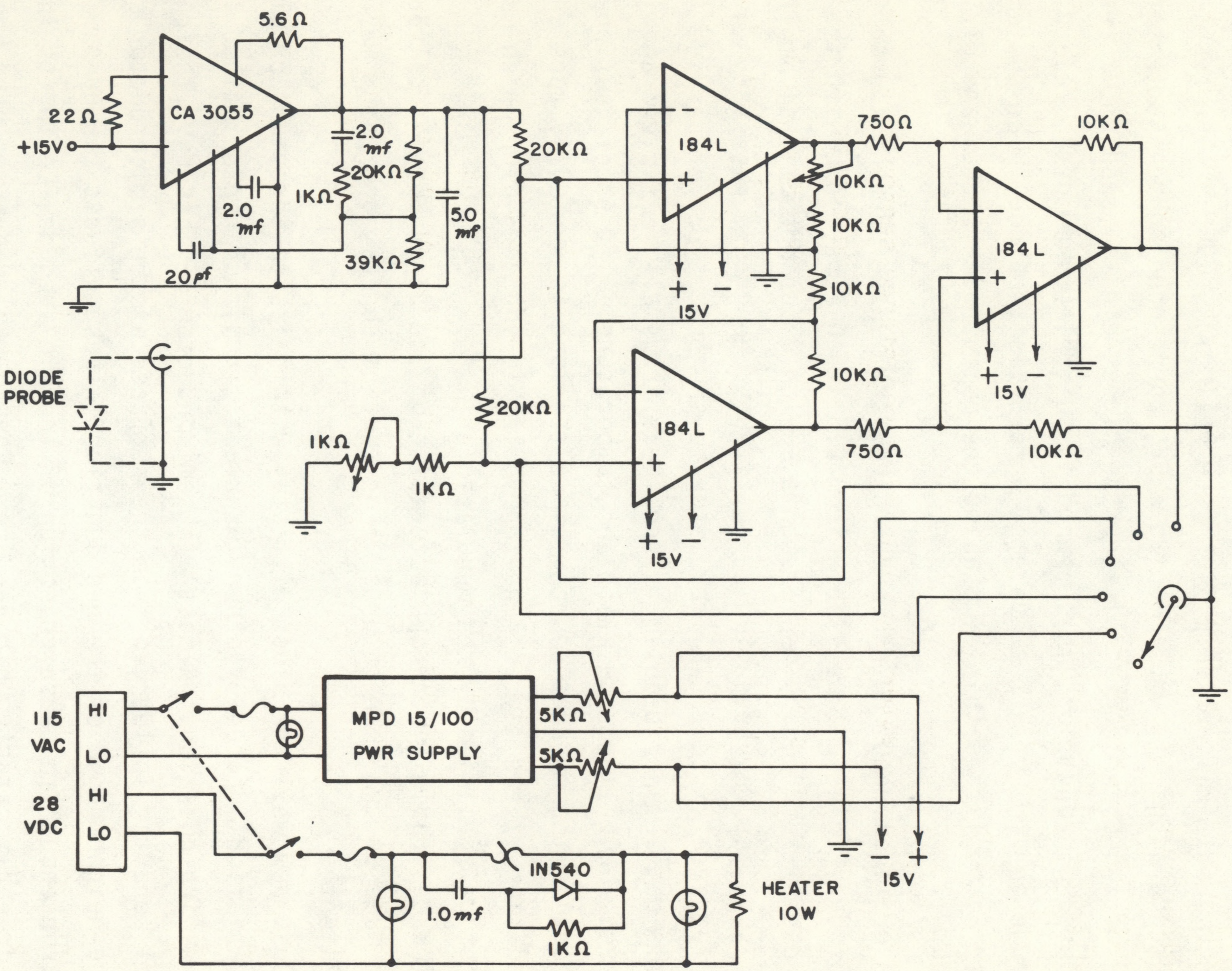

Figure 1a. Diode vortex temperature system.

are the worst type of problem likely to be encountered. In thermometry, any noticable drift is likely to be intolerable, and would render the device non-competitive. RFF's prototype of the diode vortex thermometer uses a glass diode (Unitrode UT 211), which was selected because of its availability, relative low cost, and type of construction. This device is sketched in figure 1b. Silver leads, which are connected to the chip over its whole flat surface, and a lack of any appreciable gas-filled spaces are believed to be desirable from the standpoint of ruggedness (important for airborne use) and speed of response (important for micro- and mesoscale measurements).

RFF's experience to data has shown that the speed of response is comparable to, or better than the AMQ-8 resistance sensor that it replaces. The AMQ-8 is supposed to have a 10-sec time constant (in 10-sec, at normal aircraft speeds, the sensor will have traveled about 1 km). Agreement with other airborne thermometers has been satisfactory for about a year's usage; however, not enough experience has been attained for a definitive critical comparison to be stated.

3. THERMOCOUPLES

One of the most obvious airborne temperature sensors is the thermocouple. Despite its very widespread industrial and scientific application, airborne thermocouple sensors, specifically for ambient temperature measurement, have been rarely used on research aircraft. There are two

1. UNITRODE UT 211 GLASS BODY CA 2mm x 2 mm DIA.
2. SILVER LEAD
3. CERAMIC SLEEVE
4. SENSOR TUBE OF AMQ-8 (6.25 mm DIA.)

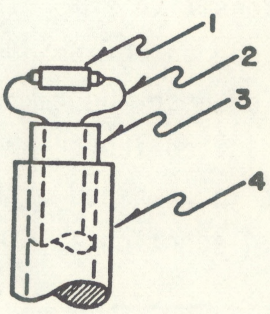

Figure 1b. Diode assembly.

possible reasons for this, namely: the thermocouple's low sensitivity, typically 40 μV/degree, and the requirement of a "cold" or reference junction. A lesser objection is non-linearity, especially in the environmental, or low temperature range. If accurate and direct readout of the sensor is required, non-linearity can pose a serious problem. It is felt that these disadvantages can be overcome, making the advantages of thermocouples, such as their low cost, ruggedness, and speed, attractive for airborne application.

The small signals generated by thermocouple devices are at present easily amplified by small efficient and relatively inexpensive operational amplifiers. The reference junction problem may be solved by any of a number of commercially available devices which operate on the principle of supplying a small voltage in series with the thermocouple tabulated voltage at the temperature of the thermocouple-to-copper circuit connections, and varies with this temperature. Another class of devices may also be employed. These include: thermostats, ovens or authomatic ice-water baths, all of which can probably be made more reliable but are larger, heavier, and more costly — the first two may be difficult to justify for light aircraft use but do not generally present insurmountable problems with the heavier research aircraft now in service with the RFF. Moreover, these devices may be desirable or even required for the most accurate measurements.

RFF is presently using the variable voltage supply type of device (Consolidated Ohmic Devices, type EZT213 compensators).[4] These devices are actually Wheatstone bridges, powered by a mercury cell, with a temperature-sensitive arm. The thermocouple is connected to the copper circuit diode on the bridge module so that the temperature-sensitive arm is at or near the temperature of this "cold" junction.

As indicated above, the resulting temperature-dependent output of the bridge is combined with the thermocouple signal to simulate a system with a cold junction at OC or some other suitable fixed temperature.

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[4] Consolidated Ohmic Devices, 115 Old Country Road, Carle Place, New York 11514.

Although this type of device is small, inexpensive, and has given satisfactory service over a number of years, it may be the most questionable part of the sensor system, although the stated accuracy and stability is ± 0.2 degrees.

The third problem area, the non-linearity in the thermocouple voltage-temperature function, has been overcome in a variety of ways. The method that will be described here is somewhat specialized and has its advantages. For most purposes, the non-linearity of some common thermocouples can be described by a square term in the temperature (in the environmental range), similar to

$$E = at + bt^2 \quad , \tag{3}$$

where:

E = output
t = temperature (^{o}C)
a and b are both constants

The method is to generate the square term by using a Wheatstone bridge with a linearly temperature-sensitive arm, such as a metallic resistor (Conrad, 1968). The bridge power supply is a thermocouple which is also linearly temperature-sensitive; for this purpose, the thermocouple is sufficiently linear. By coincidence, the output of common thermocouples (40 μV/degree) and the temperature coefficient of resistivity of the common metals (0.003 to 0.004/degree) will supply the correct range of outputs from an equal-arm bridge to a high impedance load. Thus the bridge output, E_B is given by

$$E_B \cong K\,(t - T)^2 \quad , \tag{4}$$

where T is the temperature at which the bridge is balanced. Then if E_B is series-connected with the thermocouple to increase the signal (absolute value) at temperatures below zero,

$$E = E_t - E_B = at + bt^2 - Kt^2 + 2KTt - KT^2 \quad . \tag{5}$$

If K ≅ b, a linear relation appears, with a change in slope and displacement of the origin. For copper-constantan, b ≅ 0.04 μV/degree) the ± 50C range; $K \cong (0.004)(40)/4$ for an equal-arm bridge, using a metal such as copper (or many others). The 0.004 value is the temperature coefficient; 40 (=μV/degree) is the thermoelectric power of the copper-constantan thermocouple supplying the bridge voltage. Then, $2KT \cong 4$ μV/degree, $KT^2 \cong 100$ μV. These effects on the characteristics are observed, and satisfactory performance of a bench prototype is reported in Conrad, 1968. A sketch of the basic circuit is shown in figure 2a.

Construction of an airborne prototype has confirmed the utility of this method. This has required some changes from earlier work (Conrad, 1968), as shown in figure 2b. The ice-water-bath-battery-potentiometer combination has been replaced by a reference junction compensator which simulates a 50^0 reference. The amplifier output bias and attenuator (Conrad, 1968) were eliminated, since these functions were within range of the gain and offset controls of the AD232 operational amplifier.

The resistance of the 50^0 compensator and its thermocouple, greater than 100 ohms, caused a significant loss in bridge output, which was corrected by the addition of a second temperature-sensitive bridge-arm, thereby, doubling the bridge output.

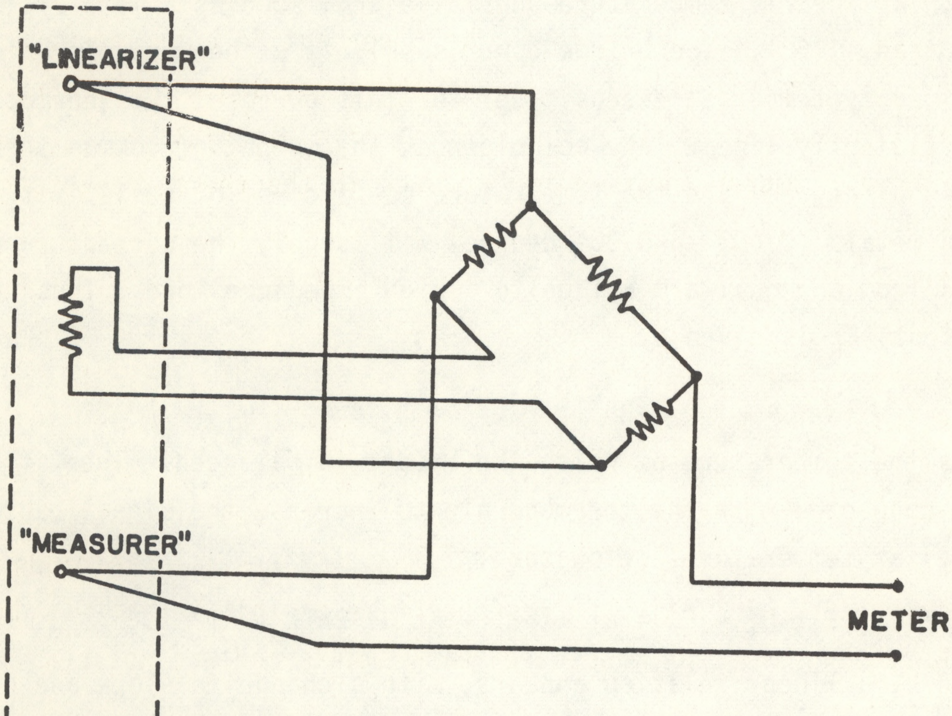

Figure 2a. Principle of TC linearization.

The relatively small-valued input resistor was used because it was part of a precision network, which included the feed-back resistor in common encapsulation. This network, which had the correct gain, was fortuitously available. The low input resistor loaded the signal source about three percent, which was easily trimmed up.

The main themes of the entire effort, simplicity and economy, were somewhat obscured during construction of a sensor head for the airborne prototype. This sensor requires two thermocouple junctions and two temperature-sensitive resistors. these require compact assembly, and exposure to, but protection from, the environment in the AMQ-8 vortex probe.

An additional requirement was imposed, namely, that the sensor head be extensible at the ends of its eight leads from the probe. This permits sensor calibration, in a temperature bath, while the remainder of the system is still installed and undisturbed on the aircraft. Detail is shown in figure 3. A desirable alternative assembly might use an O-ring seal in place of the plastic sleeving shown.

Temperature-sensitive bridge resistors were constructed of 25 μm diameter, 40 cm lengths of 70 percent Ni, 30 percent Fe enameled wire[5], which had a room temperature resistance of 150 ohms, and a temperature coefficient of 0.004 per degree. The winding core material was a 5 mm length of 250 μm diameter constantan wire used in the thermocouple construction. Before winding, which was completely manual, a droplet of freshly mixed liquid epoxy adhesive was applied to the core which had 50 μm of teflon insulation. The epoxy was necessary because the enamel insulation gave evidence of unreliability on the fine Ni - Fe wire. The two Ni - Fe coils and thermocouples were epoxied into a 20 mm length of 3 mm brass tubing. The thermocouples, covered with a thin coat of epoxy, were allowed to protrude approximately 1 mm from the sensor assembly. This attempt to increase the durability of the unit resulted in producing a slower sensor. In fact, the response time of this sensor was just fast enough to be useful for mesoscale measurements and was noticeably

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[5]Obtained from Consolidated Reactive Metals, Mamaroneck, New York.

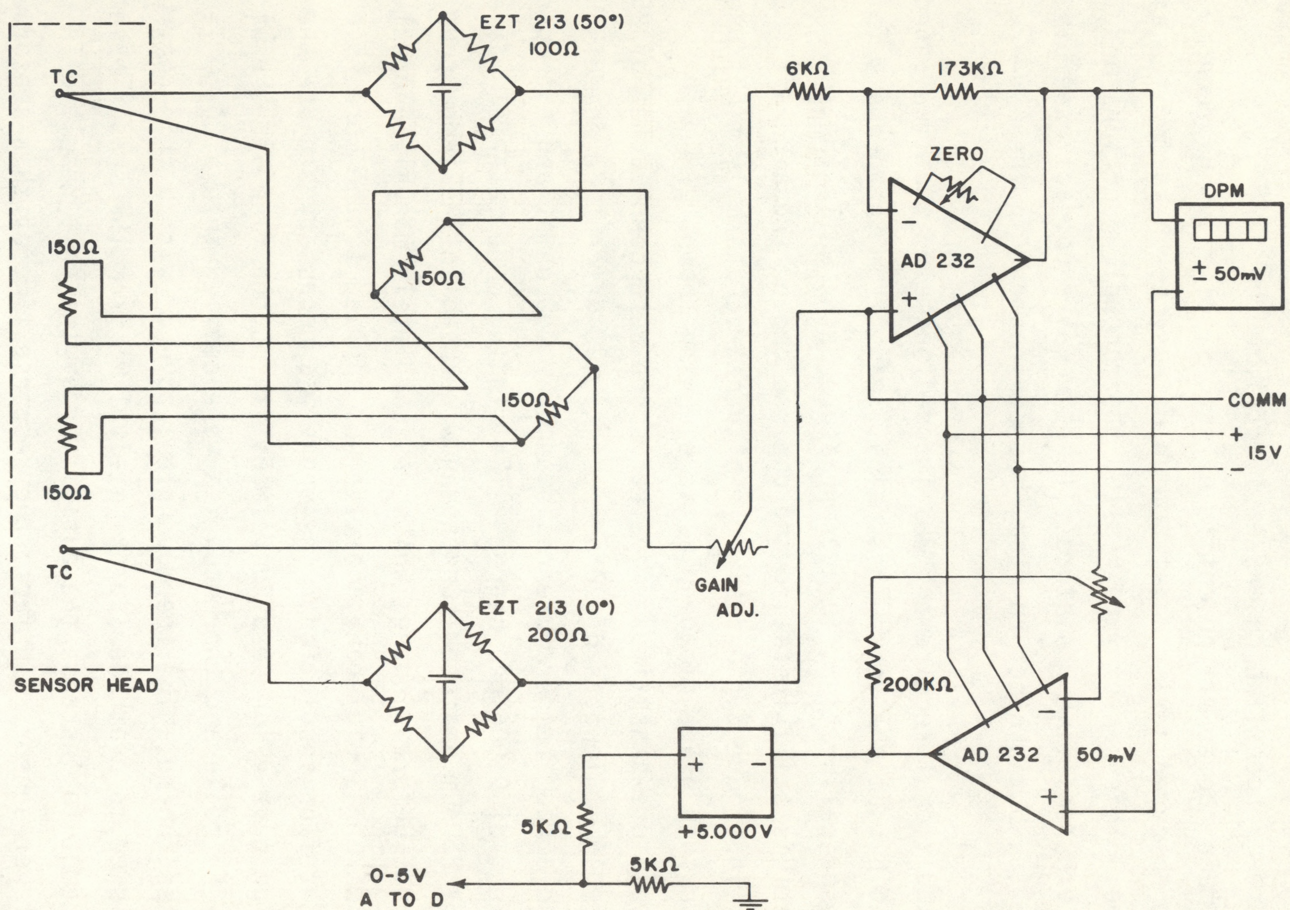
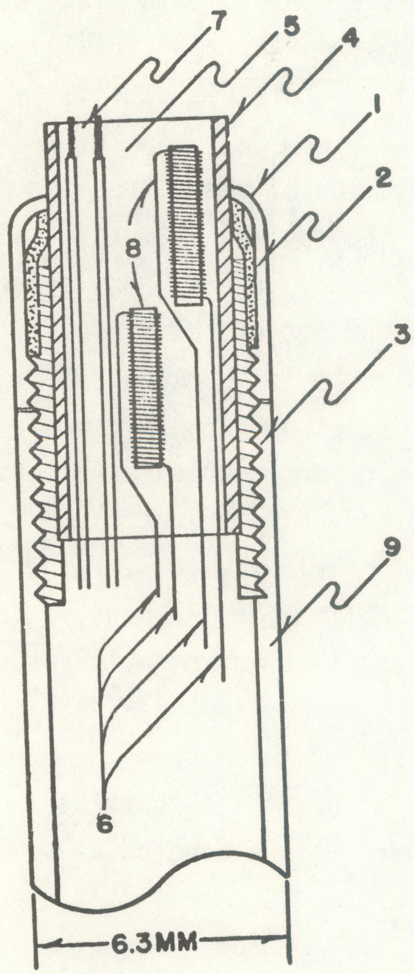


Figure 2b. Airborne prototype TC circuit.

slower than the Rosemount total temperature sensor (102CS2CA), also installed on the RFF aircraft. A few additional millimeters exposure of the thermocouple junctions might be sufficient to give a very large increase in speed. A time constant of 1 sec or less can be expected (this would correspond to a sampling distance of about 0.1 km at normal aircraft speeds).

Bench tests were made on the assembled sensor, before final electrical and mechanical assembly. The linearized thermocouple output was compared with the temperature measured directly by one of the thermocouples in the sensor assembly. Good linearity was obtained. On one run, a slope (thermoelectric power) of 41.9 μV/degree was obtained with a



1. CAP, COOPER TUBING
2. SEAL, PLASTIC SLEEVING
3. SCREW, 10-32 SS, DRILLED OUT, END TURNED DOWN
4. BALL-POINT PEN TUBING, CA. 3mm x 15mm
5. EPOXY-FILLED
6. INTERMEDIATE LEADS FROM TEMPERATURE SENSING RESISTORS (8): 150 μm MAGNET WIRE
7. TWO COPPER-CONSTANTAN T.C.s 250 μm WIRE, 50 μm TEFLON INSULATED
8. TEMPERATURE SENSING RESISTORS: 40cm of 70 Ni-30Fe WIRE (25 μm DIA.; WOUND ON 5mm LENGTH OF CONSTANTAN T.C. WIRE AS IN (7)
9. 6.25mm ALUMINUM TUBING EPOXIED AT LOWER END (NOT SHOWN) INTO SPINNER VANE OF VORTEX HEAD

Figure 3. Schematic - pictorial of TC sensor head.

correlation coefficient, r, equal to 0.9999776, and a standard deviation, $S_{y/x}$, of voltage on temperature of ± 6.5 μV, for a 12-point run over the range +36C to -47C. On another day, the results appeared to be more typical, a slope of 42.2 μV/degree and $S_{y/x}$ = ± 32.4 μV. Measurements were made over the range of + 50C to - 65C, beyond which deviations of more than 1 degree appeared.

Final assembly of the head was completed after all eight wires had been passed through the AMQ-8 probe body. The final calibration was accomplished with the probe installed on the aircraft skin, and the sensor extended abcut 30 cm from the probe but connected to its circuits in the interior of the aircraft. It should be mentioned that this capability appears to be non-existent among commercially available airborne snesors. Obviously, there is no special reason that this capability should be limited to thermocouples; we believe that this capability is very desirable.

The problems encountered in the construction of the airborne prototype, led to a search for simplification. The obvious target for simplification was the second temperature-sensitive bridge-arm. One direct method to compensate for the loss of bridge output signal caused by resistance in the linearizing thermocouple circuit is to raise the bridge resistance. Since increases of up to two orders of magnitude would be required, cascaded through the final output, along with a corresponding increase in the Ni - Fe coil size, this method was discarded.

An alternative approach is to amplify the bridge signal, either at the input or output. At present, the availability of inexpensive (about $4) operational amplifiers TO-5, DIP, suggest this as an obvious route to follow. Some attractive features of this method include: the sharing of a power supply with the main amplifier; release from the requirement $\Delta R/R \ll 1$, whre R is the bridge-arm resistance; note that the linearity of the bridge unbalance with temperature changes depends on this criterion (Conrad, 1968).

We should also note an even more attractive method; one which "halves" the system used in the airborne prototype. This is accomplished by using the summing property of an operational amplifier (Philbrick et al., 1966).

The amplifier can add input signals at each of its two input terminals, the signal being gain-weighted inversely as input resistors connecting them to the terminal, and polarized in accordance with the input termianls that they happen to be tied to. The only condition imposed is that the sums of the weights, for gains (which is actually the ratio of the feedback resistance to the input resistance), at the two inputs be equal, but this is relatively simple to arrange.

The signal sources can be independent except for a common reference point, or they can arise at various points of the same network, as is the case in this application. Bench type prototypes are discussed below.

Figure 4 represents the simplest application of this kind for direct readout of temperature. The preamplifier was used to avoid having to work with low-level signals during early stages of the development program. A built-in zero degree compensator was an added inducement. Since the overall gain required for temperature digits was 250 for the initial set-up, a single stage of amplification would have been sufficient. The battery between stages is used to bias the bridge, simulating the 50^{o} balance temperature, (analogous to Conrad, 1968).

The bridge (and temperature-sensitive arm) was raised to 400 ohms, arbitrarily, to minimize signal loss, although the amplifier flexibility permits considerable independence.

The bridge output signal was amplified twice (compared to the main thermocouple signal). This was done for the reasons discussed at some length above, i.e., the signal loss caused by high source impedance. However, the preamplifier transforms the impedance level of the thermocouple circuit so that theoretically only about 10 percent more gain was required, instead of 100 percent.

The 52 mV bridge bias will, of course, bias the LM 201 output. This is useful for certain applications, in table 1, but not in the present case. It was found that the LM 201 was capable of offsetting this bias by means of the asymmetrical compensating network (see fig. 5). These network values were found by a trial and error approach. A sample of the resulting data is shown in table 1.

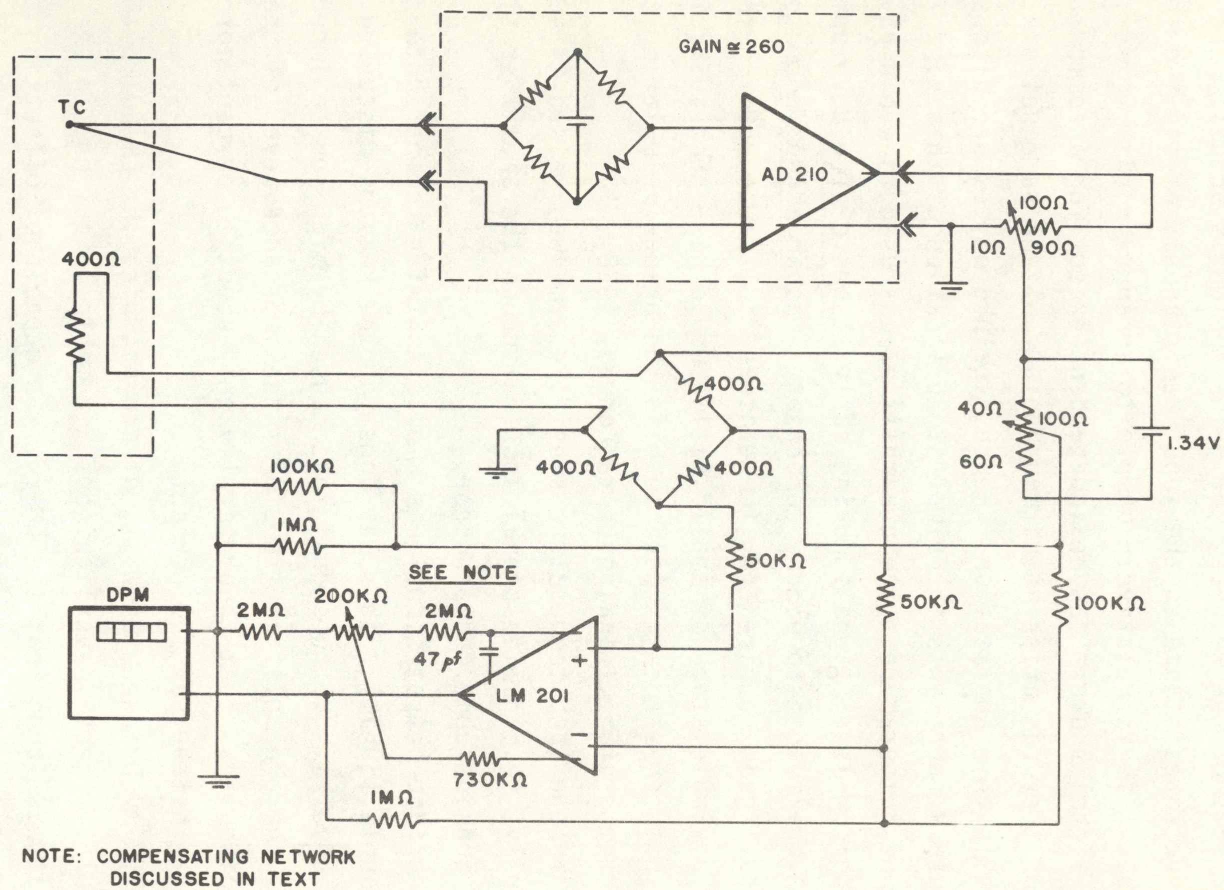


Figure 4. First prototype of summing amplifier TC linearizer.

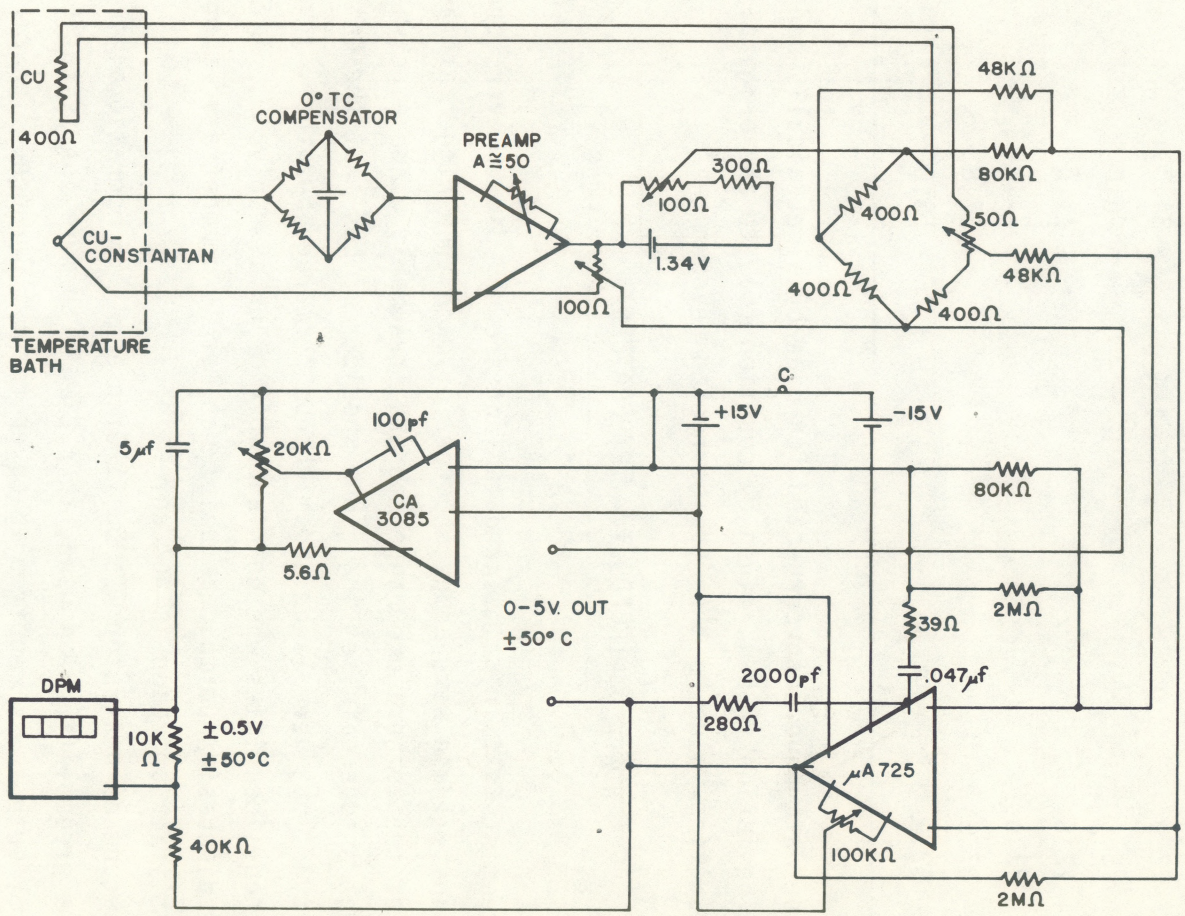


Figure 5. Summing amplifier.

Table 1. Sample Data

READOUT (CORRECTED)	TEMPERATURE
47.4 C	46.2 C
45.4	44.0
22.9	24.3
5.6	6.0
- 12.5	- 11.5
- 23.6	- 23.5
- 37.3	- 37.8
- 52.4	- 53.0

These data have been corrected for bias by algebraically adding the average deviation (A.D.), given by equation (6), to the original readout (the resulting value is then the corrected readout).

$$A.D. = \frac{\sum_{1}^{8} (\text{READOUT} - \text{TEMPERATURE})}{8} = -0.6C \qquad (6)$$

The agreement is fair; similar data (not shown), did however, show larger deviations. These were about an order of magnitude higher at the extreme limits of the temperature range and are presumably associated with the incorrect bridge gain setting. One should remember that the entire non-linearity is not very large and might be perturbed by other, irrelevant system non-linearities whether favorably or unfavorably.

The discussion up to this point has merely demonstrated that the summing amplifier approach is not unfeasible.

A second demonstrator was built with a μA 725 operational amplifier. The same preamplifier was used, this time with more justification, since a 0 to 5V output was required to cover the ± 50C range. The circuit used is shown in figure 5. The distribution of gain between stages was partly determined by the availability of high-grade resistors for the μA 725 operational amplifier and the desire to keep the signal source at low impedance. The same bridge was used as with the LM 201. The CA 3085 regulator was connected only after basic operation of the 0 to 5V circuit had been satisfactorily established. Here again, the initial design overlooked the preamplifier. It was soon found that the output at -50C was too high. The error was equivalent to 3C or 4C at -50C. Too much bridge gain was the most probable cause for this error. Trial and error procedures soon led to the 48 kilohm bridge input resistors shown. These represent a ratio of 1.67 greater than the main signal gain. Using the known resistance in the biasing and preamplifier circuit, approximately 1.13 is required; however, there may be other factors involved. Note that the 100 mV bridge bias also appears in the μA 725 output so that the range is 0 to 5V for ± 50C output.

Figure 6 shows a plot of some typical (sample) data. The correlation coefficient was computed to be 0.99982 over the temperature range of + 50C to - 65C; the standard deviation of voltage on temperature in this case is equivalent to ± 0.6C for the 36 best data points. Temperatures were obtained utilizing an independent thermocouple and compensator.

To obtain a direct temperature readout, a bias of 2.500 V is subtracted from the amplifier output, and 1/5 the difference displayed as temperature in digital form on a digital-panel-meter (DPM) as shown. The bias is obtained from the CA 3085 regulator.

Despite considerable effort, really close argument between DPM readings and the independent thermocouple (e.g., within ± 0.2C) over the + 50C temperature range could not be obtained. At best, the agreement corresponded to that indicated by the 0 to 5V readout (see fig. 5) or a little better.

4. CONCLUSION

The development described here represents rather obvious applications of inexpensive temperature sensors. As such, they have to compete, especially in the aerospace environment, with a considerable variety of similar devices, both new and established. At present, the durability and economy of thermocouples are available in a number of commercial instruments, some of which may have the requisite accuracy. While the bridge linearizer

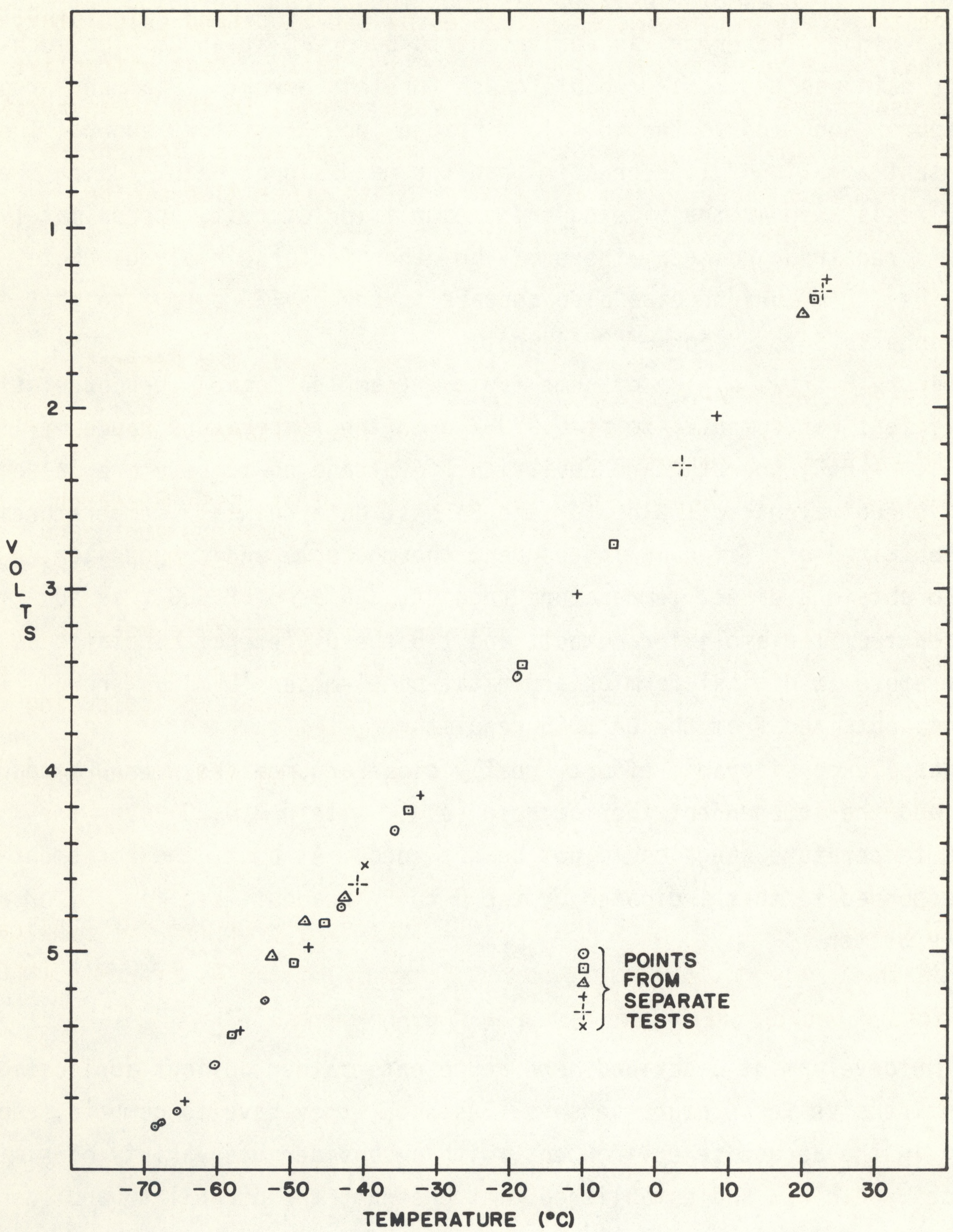


Figure 6. TC summing amplifier test.

described here is potentially minimal in cost, this may be a secondary factor in research and development. There are obvious alternatives.

It should be possible to generate the square term digitally using components widely available, as evidenced by the $100-hand calculator; digitization is becoming rapidly cheaper (Zis, 1972). Most attractive is the use of analog multipliers as squarers, these, in the cheap versions are not noted for their accuracy, but as indicated above, the entire square term is a perturbation and errors in its generation can be tolerated as higher order perturbations.

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