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A PROPOSED IMPROVED METHOD OF RADIOSONDE HUMIDITY SENSING

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"This technical report has been reviewed and is approved for publication"

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The carbon humidity element has been used in most U.S. radiosonde flights for the past twenty-five to thirty years. Although it is arguably the best radiosonde humidity sensor in use, the carbon element has physical characteristics that result in significant measurement errors as employed in today's synoptic radiosonde flights. The principal characteristics causing errors are its requirement to be in temperature equilibrium, its poor time response at low temperatures, and its poor sensitivity at low relative humidities. In this report it is proposed to employ the carbon element in a servo loop designed to control the temperature of the element in such a way as to maintain the measured relative humidity at 33 percent. The temperature of the element will then be used to determine either dew point or the partial pressure due to water vapor. This method will eliminate or significantly reduce the errors arising from the main error sources and from some others as well.

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1. INTRODUCTION

The carbon humidity element used in the U.S. radiosondes for the past twenty-five to thirty years was developed in the 1950s. Since that time, its manufacturing process has not been tightly controlled because it has usually been procured by a performance specification. Indeed the element in use today exhibits much less hysteresis and is made with a different type of carbon due to environmental considerations. Nevertheless, the general principal of operation is the same. A description of the element and how it responds to humidity is given by Marchgraber.[1]

> The carbon type humidity element consists of a humidity-sensitive film which is deposited by a spraying or dipping process on a base plate. The electrical resistivity of the film varies with the humidity of the sensed environment, thus providing an electrical transducer for the measurement of water vapor in the atmosphere.

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1 Marchgraber, R.M. (1959) *Carbon-Type Humidity Element, Resistance ML-476( )/AMT*, USASRDL Technical Report 2052.

> The electrical resistivity is determined by the distribution of the carbon particles which are in suspension within the humidity-sensitive film. The film, because of its composition, expands with the absorption of water, thus separating the suspended carbon particles and raising the electrical resistivity. Conversely, the carbon particles are brought closer together by the desorption of water vapor and, consequently, the electrical resistivity decreases . . .

Also from Marchgraber,[1] comes a note concerning the complex nature of physical processes involved in the response of the device to the atmosphere and the degree to which this response is understood.

> The approach toward solving the different problems connected with the carbon-type humidity element was largely empirical because of the lack of knowledge about the complex mechanism of water vapor absorption and desorption, the electrical conduction within the film, and the boundary effects between film and plastic base and between film and electrodes.

In this quote, Marchgraber is only referring to the problems in understanding the steady state characteristics of the element in the laboratory. In a later paper Grote and Marchgraber[2] discuss simulating the dynamic behavior of the element. It was found necessary to use a third order response function to adequately define the element's response to a step function of humidity as measured in the laboratory. This was not unexpected and a similar higher order response was noted by Kobayashi,[3] where the response of the "outer surface" and "inside" of the film are discussed.

In radiosonde applications, the carbon element is located in a duct that serves the dual purpose of shielding the element from rain and insolation (Figure 1). Since the carbon element responds to relative humidity, knowledge of the air temperature is necessary to compute any of the absolute measures of humidity . . . that is dew point or absolute humidity. In radiosonde applications the air temperature is measured using the thermistor (Figure 1). The current shape of the duct was the result of a redesign in the early 70's due to the work of Morrissey and Brousaides,[4] quantifying the magnitude of the temperature-induced errors using the earlier duct. The principal differences between the old and new ducts are an extended curved exit, blackening of the inside walls and a secondary air path beneath the duct. While the redesigned duct reduced the errors due to insolation, it did not eliminate them and didn't

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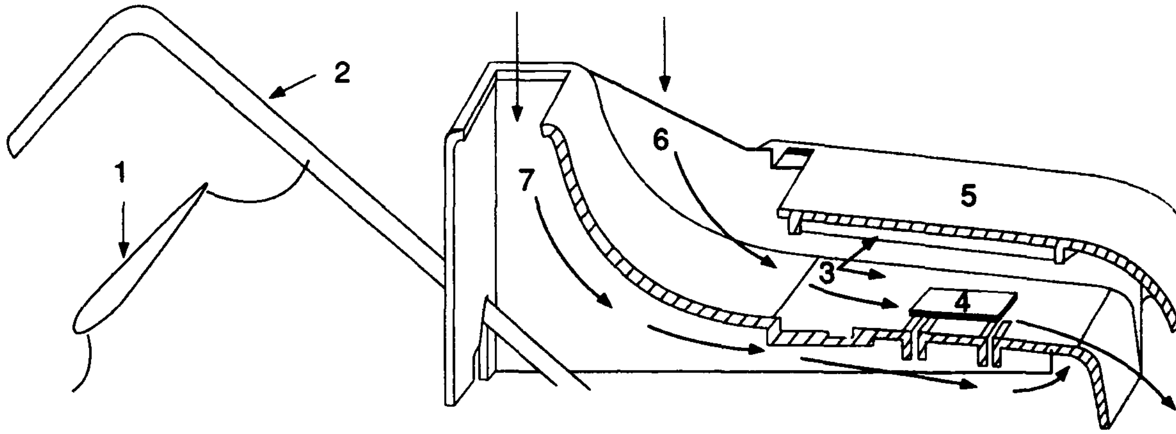
2 Grote, H.H. and Marchgraber, R.M. (1963) *The Dynamic Behavior of the Carbon Humidity Element ML-476*, USAELRDL Technical Report 2379.

3 Kobayashi, J. (1960) Investigations on hygrometry, *Papers in Meteorology and Geophysic*, **XI**:Nos. 2-4.

4 Morrissey, J.F. and Brousaides, F.J. (1970) Temperature-induced errors in the ML-476 humidity data, *Journal of Applied Meteorology*, **9**:No. 5.

treat other temperature effects such as lag. Brousaides and Morrissey,[5] studying the redesigned duct, found the measurements to be in error by about 10 percent of the measured value due to insolation effects above 500 mb. A similar temperature-induced error above 500 mb of about 8 percent of the measured value is due to the thermal lag of the element, Brousaides and Morrissey,[5] and has the same sense as the insolation error.



1. THERMISTOR
2. THERMISTOR SUPPORTS
3. LOW REFLECTANCE BLACK POLYSTYRENE PLATES
4. HUMIDITY ELEMENT
5. WHITE REFLECTIVE TOP SURFACE
6. PRIMARY AIR FLOW
7. SECONDARY AIR FLOW

Figure 1. Cross Section of the Radiosonde Humidity Duct.

Besides the temperature effects, there are two other characteristics that result in significant errors: 1) the element has poor sensitivity at low relative humidities (RH < 25 percent) and 2) its response time characteristics degrade markedly at low temperatures. Because of the low sensitivity at low RH, it is standard practice not to report humidities below 20 percent RH on synoptic radiosondes. Because of the response time degradation, the depiction of humidity features with vertical scales of less than 400 m will be very limited at temperatures of –20°C or

[5] Brousaides, F.J. and Morrissey, J.F. (1974) *Residual Temperature-Induced Humidity Errors in the National Weather Service Radiosonde*, Final Report, AFCRL-TR-74-0111, Instrumentation Papers, No. 215. AD780643.

lower. All three of these error producing characteristics can severely affect the measurement accuracy at any altitude, but their combined influence is most often felt at higher altitudes (>4 km).

In recent years there has been an increasing requirement for more accurate humidity measurements. These requirements come from satellite applications that require improved humidity data both to calibrate and to validate their systems performance, from new atmospheric models that are sensitive to middle and upper troposphere moisture, and from military applications with the increased emphasis on electro-optical systems. Not only is there an increased need for accuracy in general, but many of new requirements are for increased accuracy at the higher altitudes where the current measurements are most deficient.

2. ERROR SOURCES

As mentioned earlier, since the carbon element responds to relative humidity, it is necessary to know the air temperature to determine any absolute measure of humidity. More specifically, the surface temperature of the film itself is the defining temperature since heat transfer considerations dictate this to be the same as the air immediately in contact with the surface. There are really three temperatures important to this measurement: 1) the free air temperature, 2) the surface temperature of the film, and 3) the air temperature as measured by the thermistor. Any differences between these temperatures introduce error into the humidity measurement. The magnitude of error from temperature differences between the carbon element and the air is given in Table 1 taken from Brousaides and Morrissey,[5] where it is broken into components, insolation effect and thermal lag effect.

Table 1. Residual Temperature Induced Errors in Daytime Humidity Measurements

Layer (mbar)	Insolation Error (Percent of Measured Value)	Thermal Lag Error (Percent of Measured Value)
1013-701	3	3
700-501	6	4
500-351	9	6
350-250	14	9

The magnitude of error caused by temperature differences between the thermistor and the air is less than the insolation and lag effects and, during the day, of the opposite sense. For example, at 5 km the temperature of the thermistor would be about 0.3 C above the air temperature, resulting in about a 2 percent error in any absolute humidity calculation.

As pointed out in Grote and Marchgraber,[2] and in Kobyashi,[3] the time response of the carbon element is not a simple first order function. Indeed Grote and Marchgraber,[2] found they required a third order response. It should also be pointed out they found the response different for positive and negative humidity changes. Indeed the previously referenced quote from Marchgraber,[1] about the need to use empirical means is even more apropos when considering the element's dynamic behavior. Figure 2 is a composite of three separate figures in Grote and Marchgraber,[2] demonstrating the effect of temperature on the time response characteristics.

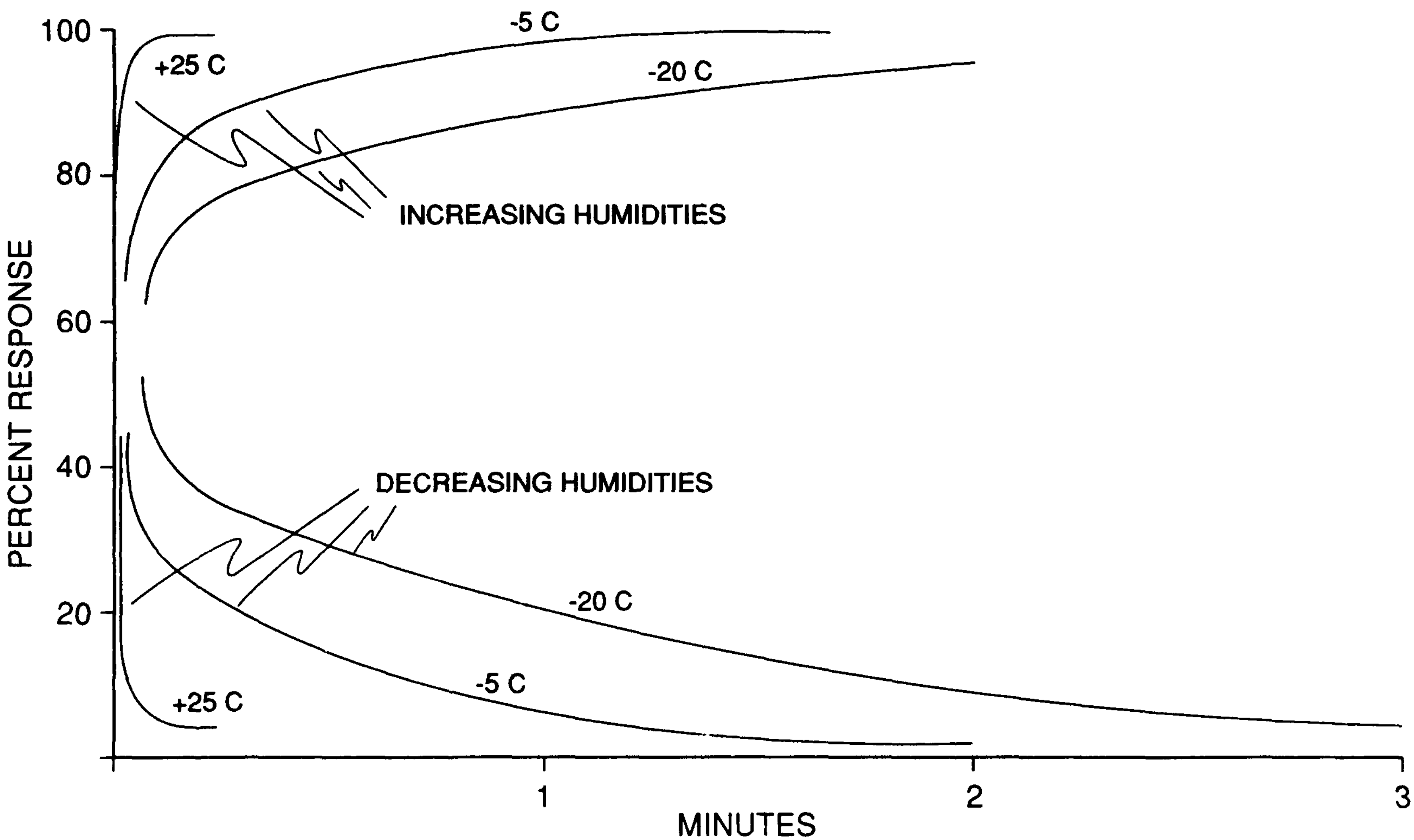


Figure 2. Time Response of Carbon Element.

The problem associated with the measurement at low humidities is far from clear. The low sensitivity at low humidity resulted in the data being coded as having a dew point depression of -30 C whenever the element indicated less than 20 percent RH instead of the measured value. The shape of the calibration curve for low RH cases is not altogether clear. Brousaides,[6] found differences in the data reduction used in the military and weather bureau evaluators, while Wade and Wolfe,[7] show four distinctly different tracking curves for carbon elements. There has been renewed interest in the low RH performance of late, for example, Melfi, Whiteman, and Ferrare,[8] and Wade and Wolfe.[7]

There are other areas of concern expressed and investigated over the years that deserve passing comment. When the element passes through very high humidity or becomes wetted from liquid water the calibration curve is altered. This has not been documented to my knowledge except under very severe wetting. Another area is hysteresis, Marchgraber[1] documented the calibration under both increasing and decreasing humidity values showing very pronounced hysteresis effects. However, more recent elements exhibit less pronounced hysteresis effects. Figure 3 shows a calibration curve for a recently manufactured batch of elements.

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6 Brousaides, F.J. (1975) The radiosonde hygrometer and low relative humidity measurements, *Bulletin of the American Meteorological Society*, **56**:No. 2.

7 Wade, C.G and Wolfe, D.E. (1989) Performance of the viz carbon hygristor in a dry environment. *Proceedings of 12th Conference Forecasting and Analysis.*

8 Melfi, S.H., Whiteman D., and Ferrare, R. (1989) Observation of atmospheric fronts using Raman lidar moisture measurements. *Journal of Applied Meteorology*, **28**:No. 9.

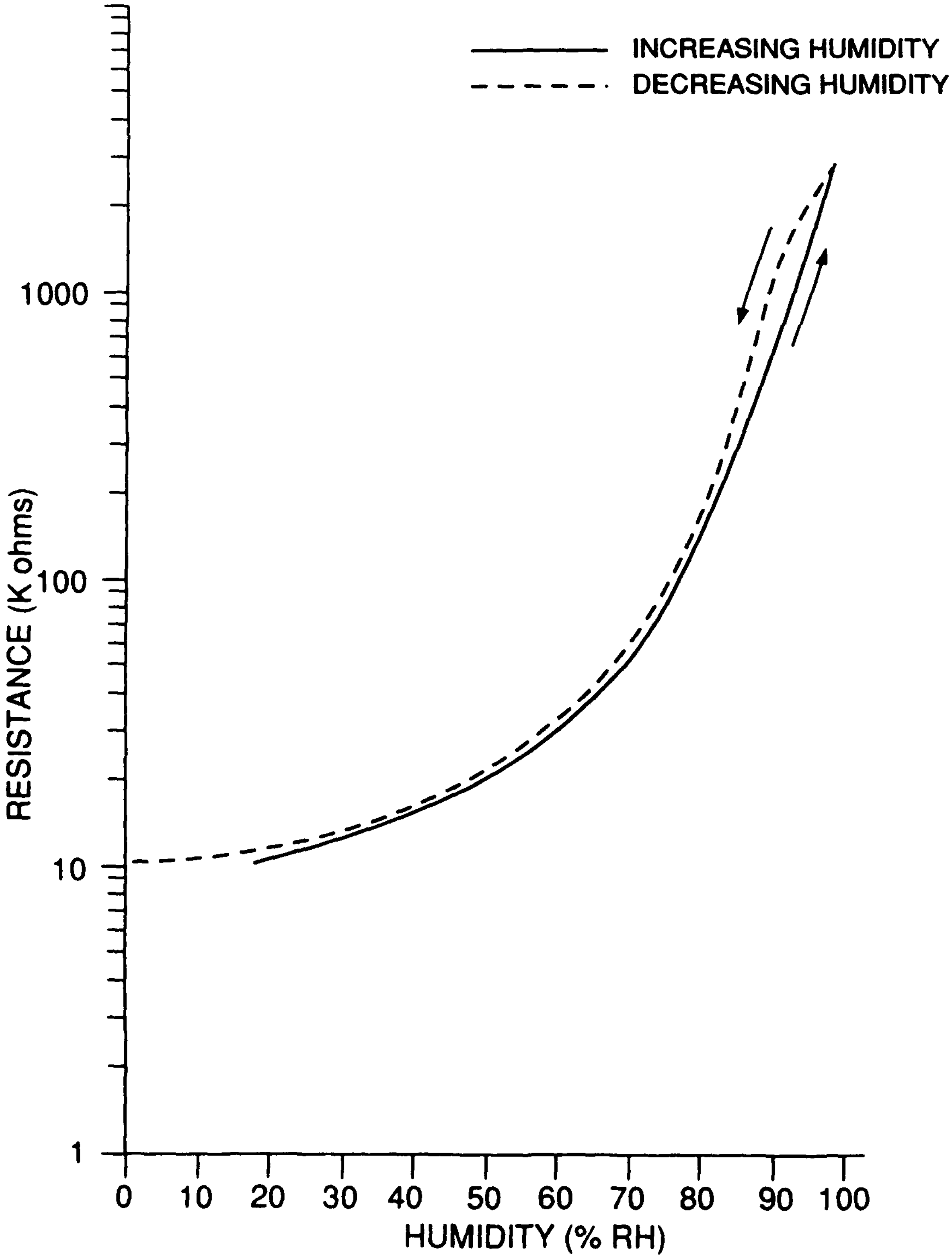


Figure 3. Carbon Element Calibration Curve.

3. PROPOSED SENSOR

The proposed sensor is not a new element but a new technique for using the currently available carbon element. It is proposed that the resistance of the carbon element be used as the control element of a servo loop designed to maintain the element at a constant humidity by changing the temperature of the element. This is analogous to the way a dew point hygrometer operates; the dewpointer adjusts its surface temperature to maintain 100 percent RH. With the carbon element it would be possible to select any RH value but there are excellent reasons to select 33 percent RH. The carbon element has a unique point at 33 percent RH where its resistance has almost no temperature dependency as shown in Figure 4. This allows the servo loop to be designed to maintain the resistance of the element constant rather than humidity. Another reason for selecting this point is it is above the area where the element exhibits a diminished sensitivity. A third reason for the selection is that it would require significantly less heating/cooling power than higher humidities. For example, if it were maintained at 100 percent RH like the dew pointer, it would require a 46 C depression at 20 C to measure a 3 percent RH, while selecting 33 percent RH allows us to measure 3 percent RH with a 32 C depression. As can be seen from the calibration curve (Figure 3) the element shows practically no hysteresis at 33 percent RH.

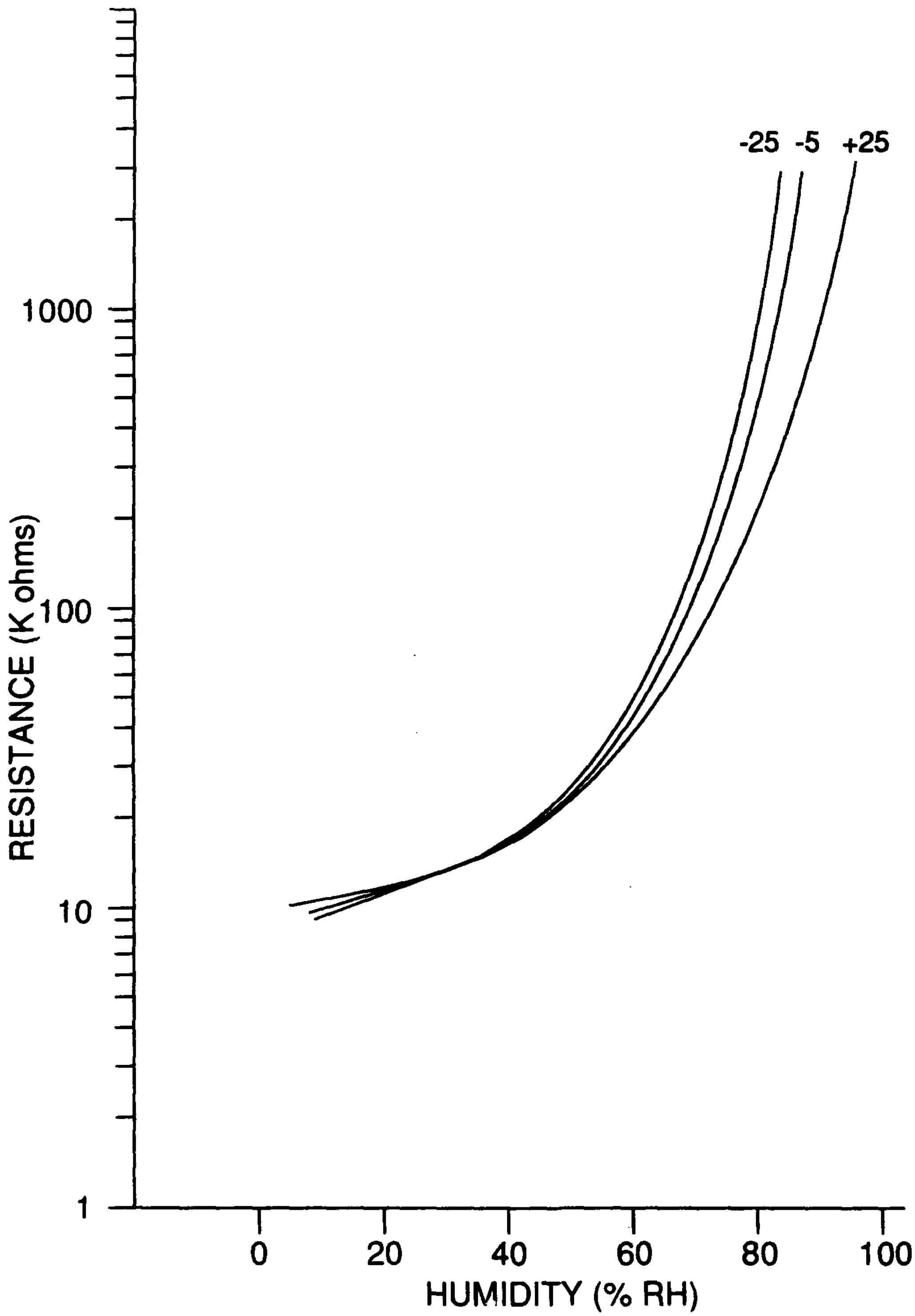
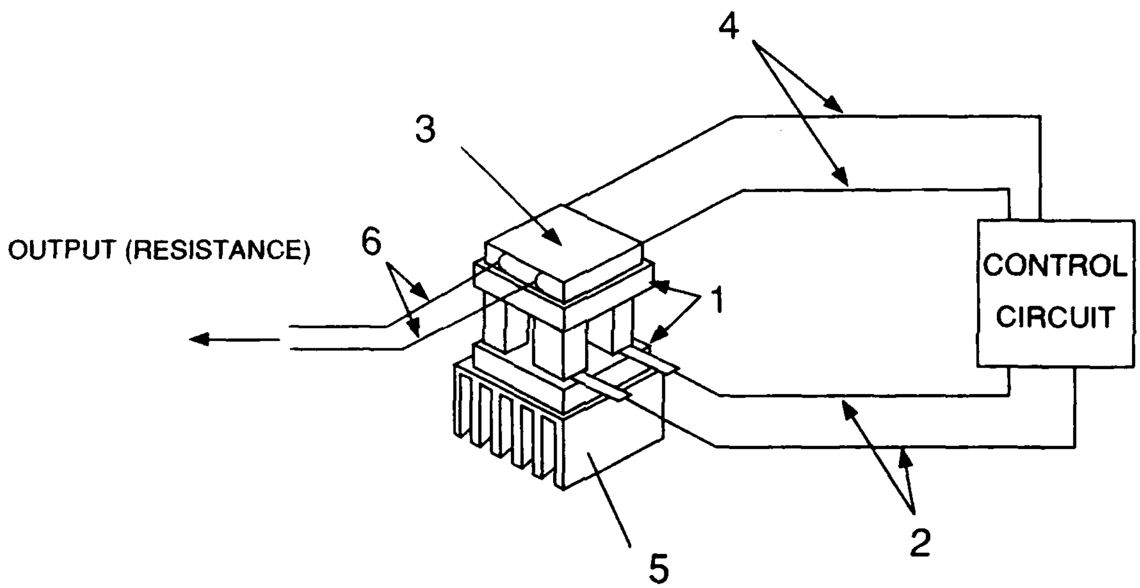


Figure 4. Variation of Carbon Element Calibration with Temperature.

Figure 5 shows a block diagram of the proposed system. The resistance of the carbon element will be used to control a Peltier cooler that will be used to heat/cool the carbon element to maintain its resistance constant at its 33 percent RH value. A thermistor will be mounted on the Peltier surface beside the carbon element or may be embedded in or deposited on the substrate. The resistance of this thermistor is then telemetered to the ground instead of the resistance of the carbon element since this is the temperature for 33 percent RH. Initial thermal loading calculations indicate that a simple single-stage Peltier cooler will be sufficient to allow measurement to 3 percent RH and could be powered by the same size battery currently used in the radiosonde. To accomplish this the carbon element would have to be reduced in size to a square 1.5 cm on a side.



1. PELTIER COOLER PLATES
2. PELTIER COOLER LEADS
3. CARBON ELEMENT WITH THERMISTOR EMBEDDED
4. CARBON ELEMENT LEADS
5. HEAT SINK
6. THERMISTOR LEADS

Figure 5. Block Diagram of Proposed Sensor.

The cost of the sensor should not be more than about $40.00 in experimental quantities exclusive of development costs and should be about $20.00 or less in quantities of 500 or more. The Peltier cooler can be procured for $12.00 in tens of units and $8.00 in 100 or more, a suitable thermistor can be obtained for $5.00, and the electronics, mainly an op amp, will cost no more than $5.00. The cost of the carbon element is difficult to estimate at this time but should not be an increase of more than $5.00 over the carbon element it is replacing and if ever produced in equivalent numbers should not cost any more. Indeed eventually it might require much less calibration testing since only the value at 33 percent RH would be needed, the other cost would be an additional battery at $5.00. This might not be necessary if the humidity circuit were cut off at some altitude or the current battery were beefed up to provide additional capacity.

4. EFFECT ON ERROR SOURCES

As pointed out above, the three characteristics of the carbon element that cause most of its sensing problems are: 1) its being an RH instrument requiring knowledge of its surface temperature, 2) its low sensitivity at low RH, and 3) its increasingly long response times at lower temperatures. The proposed sensing technique should significantly reduce the errors caused by all of these.

The first of these is overcome by the measurement of the surface temperature of the element. This result could have been achieved by implanting a thermistor in an element that was not thermally controlled, but then both the thermistor resistance and the carbon element resistance would need to be telemetered and the low RH problem and time response problem would still be there.

The low sensitivity at low RH problem will be totally eliminated because the element will never experience low RH values but will be maintained at 33 percent RH at all times. In fact low RH values should be one of the most sensitive areas. If the element can be maintained within 1 percent RH of 33 percent RH, then if the real RH is 5 percent the error in measuring this should be less than 0.5 percent RH. It should be noted that the same effect that causes the high sensitivity at low RH will cause a loss of sensitivity at high RH. If, as above, the element can be kept within 1 percent RH at 33 percent RH, this would result in a 3 percent RH uncertainty for an ambient of 100 percent RH.

The problem of increasingly long response times at low temperatures should also be eliminated for the most part. First, the fact that it will be part of an active servo loop will allow designing a faster response. In addition, there are physical properties of the sensor that will collaborate with the servo loop to improve the response. A system designed around 33 percent RH only has to maintain a constant carbon element resistance. The fact that the resistance remains constant at all temperatures indicates that the amount of water is invariant with temperature at 33 percent RH. This indicates that even though the RH of the free air changes there is no net mass transfer to the sensor when it goes from one equilibrium state to another. This will allow the servo loop to react to the surface effects mentioned by Kobyashi,[3] and return the sensor to equilibrium before any significant volume effects occur. Data in Grote and Marchgraber[2] indicate that even at -20 C more than 20 percent of the response to a step function change occurs in less than 1 second.

5. DISCUSSION

The proposed sensing technique appears to have many benefits. It promises to remove or reduce the impact of all of the sources of error that currently beset the radiosonde humidity measurement taken with the carbon element. The statement referenced earlier, Marchgraber,[1] stating the need to use an empirical approach to solving problems is still true for development of this technique because we cannot provide an analytical model of the physical transfer processes involved. This is not a severe restriction because there is a great deal of laboratory and flight data on which any empirical approach can depend.

Because of the large body of data on the element it is not necessary to perform extensive laboratory development work. It is suggested the development could undergo both laboratory and flight testing in parallel. The laboratory testing should be designed to optimize the response time of the system and to calibrate the instrument. Getting flight data on the ability of the sensor to respond to low humidities, the amount of battery capacity actually required, and its response to known meteorological conditions, such as thin cirrus decks, warrants initiation of flight testing before all laboratory performance data is complete.

As mentioned previously it is anticipated that this instrument would represent an increase in cost of less than $20.00 per instrument in reasonable quantity. For this reason it should be a candidate for use in any of the mesoscale studies using a dense radiosonde network where improved measurements are needed. It should also be used in any other test programs requiring better humidity measurements such as satellite calibrations, intercomparisons with lidar humidity measurements, and radiosonde intercomparisons in general. Indeed if the cost could be brought a little lower it would be a candidate for synoptic soundings.

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