rays is their relative constancy, a feature which atones to some extent for the first two by making it possible to extend the experiments in time. Thus, in cosmic ray work one needs detectors of large size that function reliably over long periods of time. It is desirable, therefore, in a counter experiment to measure concurrently all the rates that one needs to know in order to decide whether the data are reliable. Thus the amount of apparatus devoted to monitoring often exceeds in bulk the apparatus needed for measuring the counting rate with which the experiment is concerned. In this pioneering branch of nuclear physics, one is out alone on the frontier; there is little established knowledge to go by, and one must take infinite pains to be sure that an effect one finds is not due to some equipment failure in the middle of the night or to an erratic behavior which might fail to show itself during an occasional test. It is particularly useful in this regard to record all counts on the moving strip of an operation recorder.

Certainly one of the most fruitful recent developments in cosmic ray instrumentation has been the application of electronic techniques to the sorting out of pulses, as regards time of occurrence and amplitude. The physicist now has at his disposal a potent arsenal of basic circuits for this purpose. Many of these circuits were developed before the war, but it took contact with the radar and atomic bomb projects to bring home to American physicists the possibilities of large scale application of electronic circuitry.

Dynamic Accuracy in Temperature Measurement

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The dynamic accuracy of a measuring instrument is concerned with its behavior under changing or dynamic conditions; likewise, its static accuracy is concerned with its performance under static conditions. Since it is relatively easy to define the static test conditions and to reproduce them whenever necessary, the usual accuracy specifications are limited to the static accuracy.

All practical temperature-measuring elements are imperfect dynamically simply because some heat is required to change their temperature and there is only a finite surface area through which the heat can flow. Consider a temperature-measuring element or bulb having a heat capacity of 0.004 Btu per °F and a surface area of 0.024 sq ft. If this element be immersed in a fluid flowing at such a velocity past the surface that the coefficient of heat transfer is 50 Btu/hr/°F/ft^2, the dynamic characteristics may be established. If the temperature is increasing at a rate of 20° F per min, the amount of heat flowing into the element is:

$$q = (20)(60)(0.004) = 4.8 \text{ Btu/hr.}$$

All of this heat must flow through the fluid film surrounding the bulb and, since the rate of heat flow is constant for a given rate of temperature change, the temperature drop over the film may be calculated from the steady state heat transfer equation

$$q = h\ A\ \Delta T$$

$$\Delta T = \frac{q}{hA} = \frac{4.8}{(50)(0.024)} = 4^\circ \text{ F.}$$

Thus, in order to keep the element temperature rising at a rate of 20° F per min, the fluid temperature must remain 4° F higher. In this example, the dynamic error of measurement is 4° F. Similarly, an 8° F drop would be required to cause the element to change twice as fast, or 40° F per min. The dynamic error then varies with the rate of temperature change of the thermal element, so it is generally more convenient to express the dynamic characteristics of a given element in a given medium as the ratio of the dynamic error to the rate of temperature change. This ratio Z has the dimensions of time and is called the "dynamic lag."

$$Z = \frac{\text{(dynamic error)}}{\text{(rate of change)}} = \frac{4}{20} = \frac{8}{40} = 0.2 \text{ min.}$$

When defined in this way the dynamic lag is in fact the time by which the thermometer reading lags the true temperature when both are changing at a constant rate.

Reduction of dynamic error. In terms of the bulb heat capacity, C, its area A, and the heat transfer coefficient h, the dynamic lag is

$$Z = \frac{C}{Ah}.$$

This equation indicates some of the possibilities for reducing the dynamic lag and thus improving the dynamic accuracy. Any increase in the coefficient of heat transfer produces a corresponding decrease in Z. This means that the bulb should be located at a point where the fluid velocity is high, since h increases approximately as the square root of the velocity. By the same token, the coefficient of heat transfer is much greater in agitated liquids than in gases or even vapors at low velocity, so if a choice exists the better medium should surround the bulb.

Another possibility of reducing the lag is to change the thermal element to reduce its heat capacity or increase its area, that is, reduce the value of C/A. The most common method is to reduce the diameter of the element. Occasionally, finned bulbs are used, although the improvement that can be obtained is limited. In general, for bare bulbs or thermocouples, without a protecting well, the internal thermal resistances are negligible compared to the fluid film resistance and the element can be considered as homogeneous and characterized by a single heat capacity and a single thermal resistance as was done in the previous example. Actually, there are small thermal resistances throughout the element which add a fraction of a second to the lag caused by the fluid film, but the latter are much larger, varying from a second or two up to several minutes. This is not the case for thermal elements installed in protective wells, unless exceptionally good thermal contact exists between the sensitive element and the well, since an air space of a few ten-thousandths of an inch between the two can add many seconds to the dynamic lag. In addition, a more complex "two capacity" lag results which will not be considered in this paper.

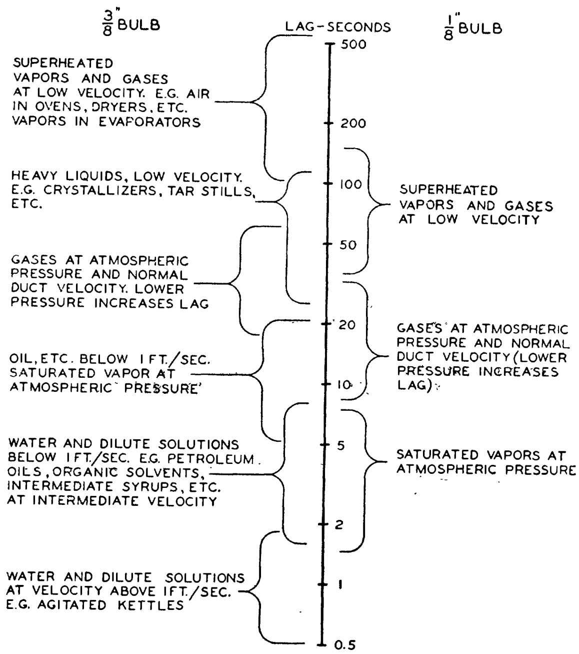

FIG. 1. Normal thermal lags.

Even with good installation practice and the use of bulbs with low C/A values, the lag is often larger than can be tolerated and measurement of transient changes cannot be made with any accuracy or control results are miserable. In Fig. 1, approximate values of normal bulb lags are given for a variety of conditions for bulbs $\frac{3}{8}$ in. and $\frac{1}{8}$ in. in diam. These values are not limited to liquid- and gas-filled thermal systems; they apply equally well to a bare thermocouple $\frac{1}{8}$ in. in diameter or to a thermocouple welded into a $\frac{3}{8}$-in. tube, since the C/A values will be essentially the same.

This table shows that bulb lags are often quite large. One should also remember that the possibility of using small-diameter bulbs is generally limited to noncorrosive and nonerosive gases and vapors; furthermore, a $\frac{1}{8}$-in.-diam bulb is often too frail to stand the mechanical forces encountered in flowing streams of viscous liquids.

Derivative conpensation for dynamic lag. In view of the rather obvious requirements for faster speed of response, it seems desirable to point out another way of improving the dynamic accuracy of thermal systems.

As in most compensation problems, the method is quite simple. A quantity proportional to the error is measured and the appropriate correction is applied to the instrument reading. In this case, the error is the temperature difference between the sensitive element and the temperature of the medium:

$$\Delta T = \left(\frac{dT}{dt}\right)\frac{C}{Ah} = Z\left(\frac{dT}{dt}\right).$$

Since the error is proportional to the rate of change of bulb temperature, dT/dt, one merely needs to measure this rate of change, multiply by the appropriate bulb lag and add this correction to the bulb temperature to obtain the corrected or true temperature.

The pneumatic temperature transmitter offers an easy solution to this problem. Consider the simplified circuit of a force-balance pneumatic transmitter as shown in Fig. 2. A gas-filled thermal system has its bulb immersed in the process medium and the force resulting from the gas pressure on the diaphragm is balanced by the biasing spring and the force from the balancing bellows. An increase in bulb temperature, for example, will move the baffle away from the nozzle, decreasing the nozzle back pressure and increasing the relay valve output pressure (P_0). This increase in output pressure results in a flow

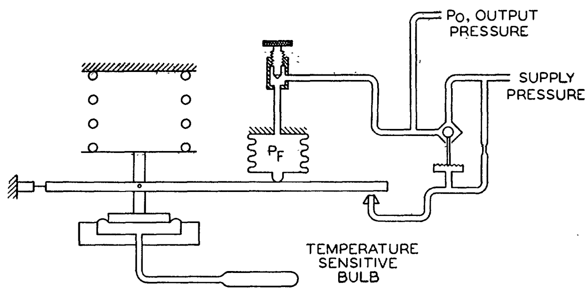

FIG. 2. A simplified schematic of a Transaire force-balance temperature transmitter.

into the balancing bellows through the open-needle valve and applies an opposing force to the diaphragm of sufficient magnitude to substantially prevent movement of the diaphragm and baffle. The change in balancing bellows pressure P_F (and the output pressure P_0) is then directly proportional to the change in bulb pressure, which is in turn proportional to its temperature.

By suitable calibration, a balancing bellows pressure change of, say, 3 to 15 psi can be made to correspond to the desired temperature span of the transmitter. The output pressure is then transmitted to a pressure receiver also having a span of 3 to 15 psi. Ambient temperature and barometric pressure compensation would, of course, be required in any complete instrument, although they are not shown.

Returning to the derivative or "dynamic compensation" for thermal lag, we note that the rate of pressure rise in the balancing bellows is directly proportional to the rate of temperature rise of the gas-filled bulb. Increasing pressure in the balancing bellows will require the flow of air into the bellows. In fact, the rate of flow is directly proportional to the rate of pressure rise in it. Introducing a capillary or needle valve restriction in the line to the balancing bellows will result in a pressure drop which is proportional to the rate of temperature rise of the bulb.

The output pressure of the relay valve will then be equal to the balancing bellows pressure plus this pressure drop. Suitable adjustment of the restriction allows selection of the appropriate lag correction factor to neutralize the dynamic error. The adjustment dial on the restriction can, in fact, be calibrated directly in terms of the time lead (or dynamic compensation factor) introduced by it.

Adjustment of the dynamic compensation factor can be made in a number of ways. Generally, the lag of the thermal element can be estimated from tables with sufficient accuracy and the dynamic compensation factor is set equal to this lag.

It is believed that the use of a derivative transmitter to achieve dynamic compensation for the inevitable lag of thermal elements offers a valuable and unique tool in the field of temperature measurement and control which makes possible a degree of speed and accuracy not previously obtained.

Velocity and Flow Measurements with an Improved Thermal Instrument

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Precise measurement of the velocity of free air currents moving at rates as low as 5 ft/min has always been a difficult problem. It is one, however, that is constantly present in a wide variety of applications such as meteorology and microclimatology research, air conditioning, heating and ventilating work, measurement of rate of flow in gas or air systems, hay and tobacco drying processes, and general process control.

A new type of electrical anemometer that has recently been developed for applications such as these allows velocities as low as 5 ft/min to be determined with accuracies previously limited to high velocity measurements. The new instrument, which is known as an Air Meter, operates by placing a heated precious-metal thermopile in the airstream. The flow of air past the thermopile tends to bring the thermopile wire, consisting of a succession of thermojunctions, to the same temperature throughout. The thermal differences between these junctions induce a thermal direct voltage proportional to the temperature differences. Thus, flow of air past the thermopile tends to reduce this temperature difference and, therefore, to reduce the direct voltage generated by the thermopile.

The thermopile, or sensitive element of the anemometer, is made up of alternate sections of thermocouple materials butt-welded to obtain a continuous wire. This wire is then heated by passing an alternating current through it. Cold junctions of the thermopile are obtained by attaching alternate junctions to copper mounting studs, thereby supplying sufficient heat conductivity away from the junctions to keep them at ambient temperature. The other junctions, not in contact with the copper studs, are heated by the alternating current. Alternate junctions therefore become the hot and cold junctions of the thermopile.

Normally, maximum voltage is obtained with zero air velocity, and zero output represents a large cooling effect by a high air velocity. However, when high accuracy is desired over a wide range of velocities, a second series of thermocouples can be arranged with opposite polarity and shielded from any air currents. With these couples arranged to buck the voltage from the velocity pickup thermopile, zero voltage output is obtained for zero air velocity and full-scale indication of the indicating or recording instrument is obtained for the particular air velocity desired. Sensitive instruments of this type are well suited to process control, the rapid response of the electric signal operating controls and giving warning of deviations.

The principle of placing a heated thermopile in an airstream for determining air velocities has many advantages over older types of anemometers. Thermal anemometers have no moving parts to introduce frictional errors, which are very important in low velocity measurement. Also, they are not affected by icing. This thermopile type anemometer has additional advantages over the usual hot-wire types in that the indicating or recording instrument consists of a measurement of direct current voltage instead of a small change in resistance. The errors introduced by lead resistance are thus much less. Errors introduced due to change in air temperature are compensated for, since both cold and hot junctions are equally affected by any change in ambient temperature. The instrument measures the temperature difference between these junctions, all of which are exposed to the airstream. Likewise, radiation effects tend to cancel.

A two-thermocouple arrangement which lends itself to an inexpensive type of construction has been incorporated into a standard low-cost model which has proven very versatile and reliable in laboratory and field use. The indicating meter is small and can easily be held in the palm of the hand while taking readings. The thermopile element is a separate probe which may be plugged directly into the indicating meter, or which may be used at the end of graduated extension wands or cables. For applications requiring extreme sensitivity and accuracy for very exacting research measurements, a larger instrument has also been developed.

Experience has proved this type of thermal anemometer to be exceptionally stable. One instrument has operated continuously for a year in the laboratory and a second instrument, designed for indication of nondirectional air flow, has operated for the same period on top of a building and has consistently indicated wind velocity without failure or zero shifts.

The Air Meter is well adapted to remote recording on standard strip-chart potentiometers or other standard types of indicating or recording instruments which operate from direct voltage. The ability of anemometers of this type to measure extremely low velocities, combined with their inherent stability, ease of operation, low power requirements, and adaptability to remote indication or recording, suggests many applications of a widely varying nature.