The Design and Use of Sensitive Pressure-Jump Sensors to Detect Thunderstorm Gust Fronts. Part I: Pressure-Jump Detector Design

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ABSTRACT

We outline the known properties of atmospheric pressure jumps, including rise-time and pressure-amplitude statistics, and we indicate how these statistics guide the choice of pressure-jump detector components. We review design considerations and test procedures and discuss the practical constraints of inside and outside installations of such detectors. Our tentative conclusion is that a pressure switch with a threshold of 0.5 mb, used with a high-pass filter with about a 3 min time constant, can detect sudden pressure increases reliably. The final choice of components and the evaluation of the sensor for thunderstorm gust-front detection will depend upon the accumulation of operating experience under well-defined meteorological conditions.

1. Introduction

The official U. S. Weather Service definition of a pressure jump is a rise in pressure exceeding 0.005 inch of mercury (0.169 mb) per minute, totaling 0.02 inch of mercury (0.667 mb) or more. Such sudden increases in atmospheric pressure have a variety of meteorological sources including thunderstorm outflows and hydraulic jumps and can provide storm warning information. Tepper (1950) suggested that the detection of the pressure-jump line preceding squall lines can indicate the presence and the motion of a squall line. Subsequent measurements such as those of Williams (1953), Donn *et al.* (1954), Bedard (1966) and Bowman and Bedard (1971) demonstrated that the pressure jump can in fact be used to track the system motion. Bedard and Beran (1977) review the techniques available for detecting thunderstorm gust fronts using surface sensors.

One problem in making pressure-jump studies is that conventional Weather Service barographs do not have sufficient time or amplitude resolution for pressure-jump studies (since they are not designed for this purpose). Hence it is logical to design sensors to respond specifically to the pressure jump, while not responding to the large variety of pressure changes due to other sources, such as local turbulence, low- and high-pressure systems and atmospheric gravity shear waves aloft.

Responding to the analyses of Tepper, the U. S. Weather Bureau developed a pressure-jump detector and operated networks in the Fort Worth, Tex., and Washington, D. C., areas during 1955. Unfortunately, investigators did not publish either the details of the techniques used or the results obtained. Mr. William Hass (private communication) of NOAA's Air Resources Laboratory, who worked with the project, indicates that the detectors operated quite satisfactorily. Using after-the-fact analysis the project scientists tracked pressure-jump lines across the network. (Although the project relied upon local observers to respond to local detector alarms and place phone calls to a central processing location, the designers of this pressure-jump detector network noted the desirability and feasibility of using automatic data transfer and processing.)

The purpose of this paper is to present the design considerations for such sensitive pressure-jump detectors including a description of the calibration techniques applied. These considerations must include a review of the statistics of pressure jumps important to the choice of detector components. Finally, we present an example illustrating the design and operation of this class of sensor.

2. Pressure-jump statistics

Although standard microbarographs are not well suited for such studies, several investigators, either using modified microbarographs or carefully studying standard traces, worked to compile statistics describing the causes and characteristics of atmospheric pressure jumps. The following review of some of these studies emphasizes pressure-amplitude and rise-time statistics. In addition, we consider how pressure amplitude is related to storm motion and intensity. This information is critical in choosing optimum time constants, trigger points and array element spacings. The reference by Bedard and Beran (1977) provides additional background. Unfortunately, the literature contains few references useful in defining the statistics of pressure

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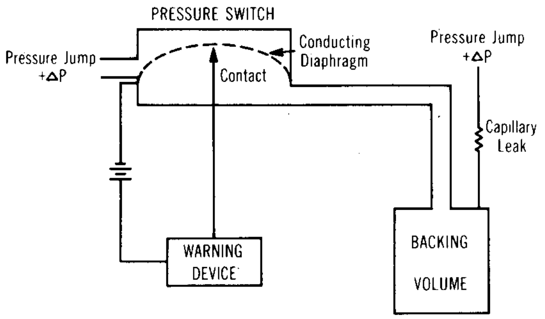

FIG. 1. Schematic view of pressure-jump detector.

jumps related to gust fronts. There is a need for more measurements with quality instruments under well-defined meteorological conditions.

a. Pressure-jump amplitude and rise time

Published case studies showing pressure-jump time series include those of Tepper (1950), Fujita (1959) and Charba (1974). These show positive changes in pressure that occur over a time scale of several minutes with typical amplitudes of several millibars. Bleeker and Andre (1950) summarized pressure-time data from 101 cases, 50 of which occurred in Ohio and 51 in Florida. They found that the most rapid portion of the pressure rise appears over a period of ~10 min. In studies using standard microbarographs the peak pressure is probably underestimated because of the influence of pen-paper friction. The application of a vibrator to the microbarograph reduces the friction considerably. Working with the properties of a squall-line event and averaging data from over 55 stations, Tepper (1950) found that the pressure rises sharply 2.3 mb in 5 min and then falls off gradually.

In a study of several squall-line thunderstorm events, Williams (1948) observed a pressure rise of from 2 to 6 mb sometimes occurring within 5 min. Williams (1953) summarized the pressure-amplitude characteristics for what he called "elevation type waves," which included both squall-line and cold-front related pressure increases as well as those due to "isolated discontinuities" (probably isolated thunderstorms). Goff (1975) found an average peak pressure rise of 2.5 mb for 20 case studies of thunderstorm gust fronts that ranged from 0.8 to 6.6 mb. For some cases he measured shorter rise times (~100 s) than past measurements indicate, which was perhaps due to the better quality instrumentation used.

b. The speed of motion of pressure-jump systems

Williams (1953) also summarized the statistics of propagation speeds for "elevation type waves." These data are pertinent to the choice of detector spacings as well as the estimation of warning lead time offered by a detector located some distance from a point of interest. Most of the disturbances traveled faster than 30 mph (13.4 m s^{-1}).

Tepper (1950), working with a pressure-jump case study, found a propagation speed for the pressure jump of 45.6 mph (20.4 m s^{-1}). Goff (1975) found the average speed of 17 thunderstorm gust fronts was 10 m s^{-1}.

c. Pressure-jump amplitudes and storm system intensity

The work of Bleeker and Andre (1950) indicates a relationship between pressure-jump amplitude and the intensity of the associated weather system. Bleeker and Andre found a linear relationship between amount of rainfall and the maximum pressure amplitude. A relationship of this type is to be expected on theoretical grounds because the pressure measured depends directly upon the height of the column of air cooled by evaporation as well as the magnitude of the density difference induced. These data suggest that statistically a trigger point can be chosen on the basis of some threshold of storm intensity. The higher the pressure level chosen, the fewer the false triggers due to other sources with the larger storms detected preferentially. However, Bleeker and Andre (1950) found no clear relationship between storm intensity and maximum pressure amplitude until they removed from the analysis multicell data and data from thunderstorm cells that did not pass over a significant segment of their array.

3. Design considerations

The original pressure-jump detectors used internal volumes of 55 gal and cost approximately $200 at 1955 prices. They required a thermally stable environment for proper operation. But it is possible to decrease the size and cost while increasing reliability by using techniques developed for the detection of infrasound in the atmosphere. In addition, one can use commercial pressure switches, now available at reasonable cost, for the basic pressure sensor. Pressure switches manufactured in quantity for home appliances (e.g., clothes dryers) use a diaphragm that makes electrical contact when pressures above some desired level occur. These switches make convenient sensors. On the other hand absolute pressure sensors require another level of processing to distinguish pressure jumps from other changes and at this time seem to represent a more expensive and complex alternative.

a. High-pass filter configuration

A pressure switch operated in a high-pass acoustic filter configuration (Fig. 1) responds to sudden changes in pressure while suppressing response to long-period, large-amplitude disturbances. Such filters usually consist of a reference volume to which we connect one side (in our case the negative pressure side) of a differential pressure sensor. A capillary leak from this reference volume to the atmosphere permits long-period pressure changes to leak through so that they appear on both sides of the pressure sensor simultaneously, thus suppressing long-period response. The capillary leak is an acoustic resistor, the value of which can be computed from the Hagen-Poiseuille relation

$$R = \frac{8\mu l}{\pi a^4},$$

where μ is the viscosity of air, l the length of the capillary, a the radius and R the flow resistance.

The reference volume is analogous to an electrical capacitor and, under the assumption that the pressure changes occur isothermally, the capacitor size can be computed from

$$C = \frac{V}{P_0},$$

where V is the internal volume, P_0 the static pressure and C the acoustic capacitance.

Thus, the combination of a pressure switch and a high-pass filter offers a simple solution to this detection problem. The particular time constant chosen must be short enough to suppress long-period pressure changes but long enough to insure reliable detection of the pressure jumps of interest.

In practice, complex equivalent circuits can occur, especially if the equivalent capacitance of the sensor is significant with respect to the reference volume C or if we cannot ignore the resistance of the tubing connecting the system together. For the simplest case considered here, the time constant τ of the system high-pass filter is the product RC. The acoustic resistor can take the form of a standard hypodermic needle and the capacitor constructed from any convenient volume that is structurally rigid and thermally insulated.

b. Structural rigidity

The requirement for structural rigidity becomes clear if we consider that a volume change of 0.01% in a closed volume will produce a pressure change of about 0.1 mb at standard conditions. If a volume of 250 cm^3 is used this corresponds to a 0.025 cm^3 volume change.

c. Temperature response

Another consideration is thermal response. If the temperature changes by 1°C in a closed volume of air the pressure will change more than 3 mb at standard conditions. Such thermally induced pressure changes appear superimposed on variations due to atmospheric pressure changes and, unless reduced, will dominate them.

One method of obtaining thermal stability is to bury the sensor while routing the sampling port to the surface. Geiger (1973) reviews data showing the diurnal variation of temperature as a function of depth. In sandy soil the daily temperature fluctuations at a depth of $\sim$40 cm are smaller by about one order of magnitude relative to those at the surface. Thus even relatively shallow burial can suppress the influences of local temperature changes.

Two techniques help greatly in reducing thermal effects. Using layered insulation for both an outer enclosure and around the backing volume itself increases the thermal time constants. Packing the volume with steel wool suppresses convection pressure noise and helps suppress short-period, thermally induced pressure changes because of the increased heat capacity.

We have built a low-cost pressure-jump detector following these design principles. It consists of a 250 cm^3 volume, filled with stainless steel wool, with a standard hypodermic needle used as the flow resistor. These components are placed within foam insulation in a fiberglass box suitable for wall mounting. Use of reasonably priced commercial pressure switches keeps the cost of the assembly below $50 including lightning protectors, batteries and an electronic oscillator for sending data over phone lines.

d. Building installations

We have installed this type of pressure-jump detector inside buildings which has required attention to the building-atmosphere time constant and internal sources of pressure noise as well as the influence of the building on the streamlines of the flow and hence on the local pressure field.

One must insure that the building time constant is short enough that atmospheric pressure changes couple into the structure. Even a small leak is sufficient to insure this for most structures. For a tube 10 cm in length and 1 cm in radius the flow resistance is about 0.05 Ω. If a leak of such a size exists in a structure 10 m×10 m×3 m, the structure acts as a low-pass filter with a time constant of 15 s. Because of existing heating and ventilating ducts, most structures will have time constants much shorter than this estimate and thus permit accurate recording of atmospheric pressure jumps.

A further consideration applying to installation of such sensors in buildings is that modern air conditioners can develop significant pressure differences between the building and the outside atmosphere. Opening or closing of doors and windows of airconditioned buildings can introduce step functions of pressure in excess of 1 mb superimposed on the atmospheric pressure field. Venting the pressure sensor input directly to the atmosphere through a short tube is a simple solution to this problem.

Local turbulent flow fields can produce pressures that

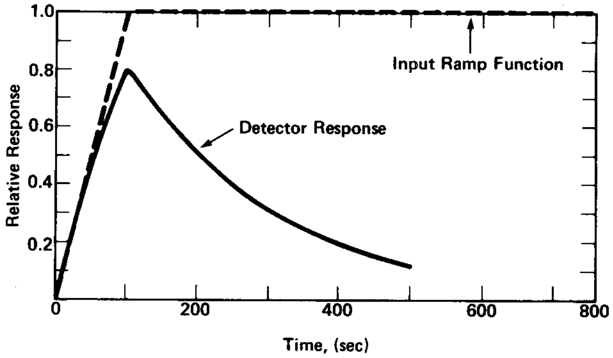

FIG. 2. Response of detector to ramp function with 100 s rise time.

are not representative of the atmospheric pressure field over some larger area. Small openings distributed over the surface of a building can provide some spatial integration of the pressure and give a more representative measurement. Underground burial also tends to help in this regard by placing the sensor below the atmospheric boundary layer, thus reducing wind-induced noise. In some extreme cases, a local-pressure-noise-reducing device, similar to that described by Daniels (1959) and Bedard (1977), could provide spatial averaging and added noise reduction.

e. Exposed installations

In practice, above-ground outdoor mounting of sensors might be desirable as in a low-lying area subject to flooding. Or mounting sensors on existing telephone poles could be expedient in rural areas with few buildings. In such cases a detector incorporating an increased thermal time constant is required.

Whereas the detector described above for use in thermally stable environments has a thermal time constant of about 45 min, a detector incorporating a larger (1000 cm^3) stainless steel thermos bottle and thicker insulation provides a thermal time constant of about 3 h. This model detector is mounted in a ventilated, white outside case to provide protection for the sensor from direct solar radiation.

f. Slowly varying pressure fields

An additional consideration is the influence of longer term pressure changes on detector response. For example a pressure rise or fall of 1 mb h^{-1} occurring for a time period of more than about 10 min will result in a limiting offset in the detector threshold of 0.042 mb for the choices of component values indicated later. By limiting offset is meant the maximum, constant pressure difference appearing across a differential pressure sensor equipped with a high-pass filter, resulting from the application of a constant rate of change of pressure. The offset will not exceed this limiting value though the change continues at a constant rate for many hours (as is typical with atmospheric low or high pressure systems). As a result of such a pressure rise (fall) the threshold is decreased (increased) for a pressure jump of 1 mb by about 4%. Also, such changes, though they do cause variations of the threshold of array detectors, influence all of the array elements proportionally since the scale of low and high pressure areas is usually measured in hundreds of kilometers, whereas the array dimensions for pressure jump detectors now in use are less than 20 km in their longest dimension. Thus, the effect is small and will result in increases or decreases in the detection time for all the sensors of such arrays. The detection of events or velocity computations should not be changed except for pressure jumps just at the threshold of detection.

4. Pressure-jump detector component values

A goal is the choice of the shortest possible high-pass filter time constant that permits reliable detection of pressure jumps. This is because short time constants for a high-pass filter reduce response to unwanted long-period pressure fluctuations. Since typical atmospheric pressure jumps are more like ramp functions than step functions, one method of evaluating detector components is to numerically pass ramp functions with various rise times through a high-pass filter and evaluate the resultant response. The sequence of Figs. 2–4 illustrates the response of a high-pass filter with an RC of approximately 180 s to rise times of 100, 300 and 600 s. These figures show the relative response of both input wave forms and the filter output, normalized to the input peak value, plotted as a function of time. Note that for a rise time of 600 s (10 min) the pressure across the detector reduces to about one-third of the peak input value. The way to use these curves is to pick the minimum absolute peak pressure-jump detection threshold and the longest rise time of interest and determine if the detector would trigger. For example a threshold pressure of 2 mb with a rise time of 600 s would cause about 600 μb peak pressure across a sensor. If the sensor trigger point were set to 500 μb, the sensor would remain above the trigger level for over 300 s.

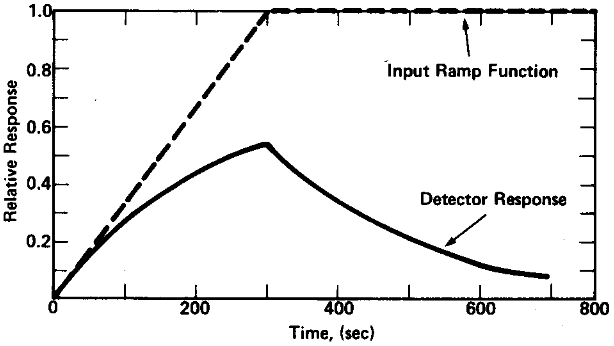

FIG. 3. As in Fig. 2 except for 300 s rise time.

Because of the variability in rise time that actually occurs with atmospheric pressure jumps, the trigger point occurs at different times for different rise times. This means that the time constants for arrays of these detectors must be matched. This disadvantage is balanced by the advantages of simple processing and low cost offered by such a detector. On the basis of past pressure-jump statistics the choice of an RC of 180 s and a trigger point of 0.5 mb seems reasonable. However, both the RC and the trigger point settings are adjustable and the optimum settings could be different for different weather systems or different regions.

Fig. 5 shows a plot of the maximum fractional pressure appearing across the detector switch as a function of the rise time of the pressure jump. It also shows the ranges of settings for the trigger level and the limits of the RC time constants for an initial manufacturing run. For the distribution of flow resistances used the time constant is between 165 and 196 s. (Note that one can tighten the tolerances considerably.) A chief problem associated with the mismatch of detectors occurs when the sensor is exposed to only a marginal amount of pressure to trigger. In such instances, whether or not a detector triggers at all is a function of the particular RC and trigger level. Another problem is that marginally triggered sensors may show variations in the initial trigger times. This results in errors in azimuth and velocity determinations that use the sequence of arrival information for an array of sensors. However, an event with a pressure amplitude of 1 mb and a rise time of 5 min will produce negligible azimuth and velocity errors for most applications, assuming an array spacing of about 1 km. We minimize error by matching sensor characteristics where close array spacings require the determination of arrival times to within 10 s. At a typical gust-front travel speed of 10 m s^{-1}, the transit time across a 1 km array is 100 s.

5. Calibration techniques

We apply several techniques to the task of evaluating and calibrating sensitive pressure switches and measuring the time constants of assembled pressure-jump detectors. Any method of calibration consists in a method of generation as well as a means of specification. To calibrate the trigger point of sensitive pressure switches, a water manometer primary standard can be used that measures pressure differences <0.001 inch of water; however, we also need to maintain and control very small pressures. To do this we match thermal time constants on both sides of the manometer and provide sufficient heat capacity and insulation to insure that changes occur slowly.

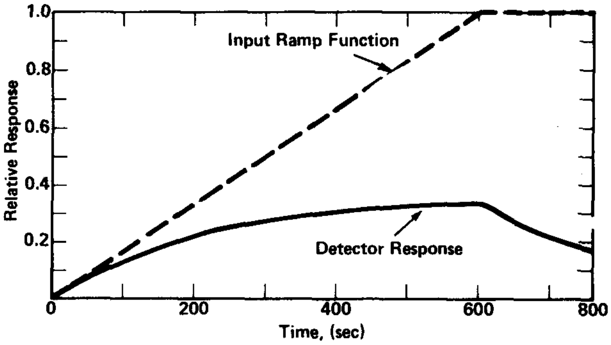

FIG. 4. As in Fig. 2 except for 600 s rise time.

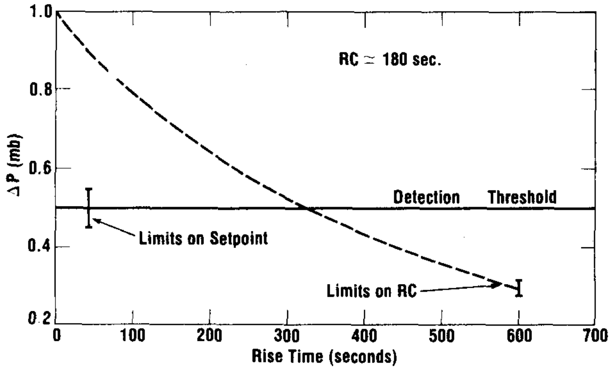

FIG. 5. Maximum pressure appearing across sensor for a 1 mb ramp function as a function of rise time.

Matched lengths of tubing and insulated buffer volumes provide the matched time constants and stability. A variable volume element with a fine adjust capability permits us to adjust the differential pressure across the switch. When the calibration involves extremely small pressure changes (in the range of 0.1 to 25 μb), we use an alternate system, similar to that described by Bedard (1973).

We must also measure and check the calibration and time constants of the computed detectors. One means of doing this is to apply a known step function of pressure to the detector and measure the detector trigger time. Ideally, the output of a pressure-jump generator will not be influenced by the presence of the instrument being calibrated. A small fan with a variable rotation rate used in conjunction with a sensitive gage generates and specifies the desired pressures; simple switching arrangements permit the application of step functions. Note that the diaphragms of some types of pressure switches change their rest position (and hence calibration) significantly with different orientations relative to the gravitational force. Hence it is important to make calibrations for the orientation that will exist in actual use or insure that orientation effects are negligible.

6. Design details

Fig. 1 shows a schematic view of a pressure jump detector and Figs. 6 and 7 show details of our designs. We have used two types of pressure switches, one manufactured by Micro Pneumatic Logic and the other

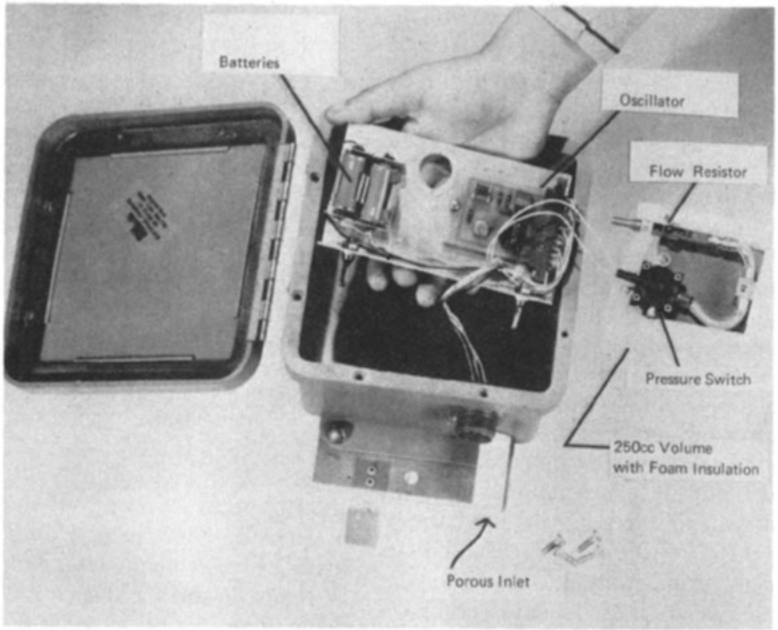

FIG. 6. Pressure-jump detector design for use in thermally stable environments.

by Fairchild Industrial Products. These or equivalent pressure switches will provide an electrical contact closure when the differential pressure across the switch exceeds some pre-set value. The 250 cm^3 volume is made from standard PVC tubing and filled with medium-grade stainless steel wool. For a flow resistor we use a 2 inch long, 28 gauge hypodermic needle mounted in a length of rigid tubing for mechanical protection. The computed flow resistance is 725 000 Ω, which provides a time constant of 180 s at standard conditions.

Flow resistors built by manufacturers of fluidic components will work in this application. We have used flow resistors manufactured by Corning Fluidic Products. Using these or equivalent commercial products can simplify production greatly.

Fig. 8 shows the results of applying pressure step functions to the detector. The observed trigger duration agreed closely with that predicted from system component values. In practice we provide a battery across the switch contacts. Closure, resulting from a pressure jump, causes the battery voltage to appear across an

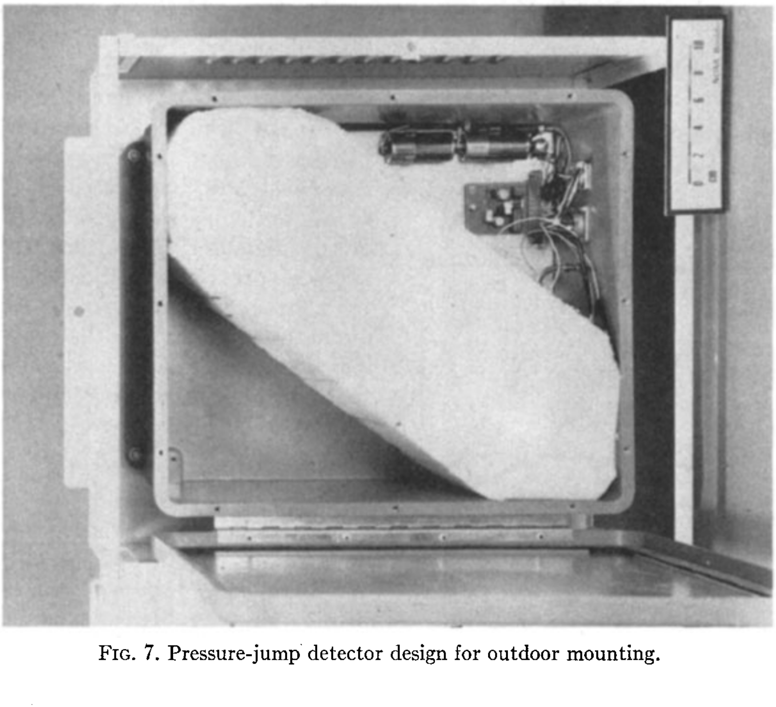

FIG. 7. Pressure-jump detector design for outdoor mounting.

oscillator, which sends a tone over a data line. This is only one of a number of possible methods of transferring data back from a remote location. A number of detectors with different tone frequencies can be multiplexed on a single dedicated data line. We are evaluating the potential of large arrays of these detectors for storm warning, particularly for gust-front systems and their associated wind shears which are hazardous to aircraft. Fig. 9 shows an example of a recording of a pressure jump (center trace) and three triggers from pressure-jump detectors located in a triangular array about 0.6 km on a side. The center trace of the curvilinear chart record is from a microbarograph used with an electronic high-pass filter (RC = 2200 s) to reduce very long-period pressure changes. The upper three traces are event markers corresponding to pressure jump detectors, with the lowest trace from a detector colocated with the microbarograph. The reference microbarograph used (Ball Engineering model EX 350b) or an equivalent sensor permits evaluation of the pressure-jump detector response to known atmospheric pressure changes.

7. Concluding remarks

We have described two alternate pressure-jump detector designs for use either within buildings or exposed locations. Comparisons between numerical results from pressure-jump simulations and laboratory calibrations indicate that the sensors operate as expected. A review of pressure-jump statistics and preliminary results from field tests also helped to guide our choice of detector components. Our tentative conclusion is that a pressure switch with a high-pass filter with about a 3 min time constant can reliably detect sudden pressure increases. The final choice of components and the evaluation of the sensor for thunderstorm gust-front detection will depend upon the accumulation of operating experience under well-defined meteorological conditions.

Concepts change from impractical to practical as a supporting technology progresses. We suggest that arrays of pressure-jump detectors may now be a practical tool for the meteorologist. Current field tests at Chicago's O'Hare Airport, at Dulles Airport, and in conjunction with National Severe Storms Laboratory experiments in Oklahoma are evaluating their usefulness for the detection of thunderstorm gust fronts.

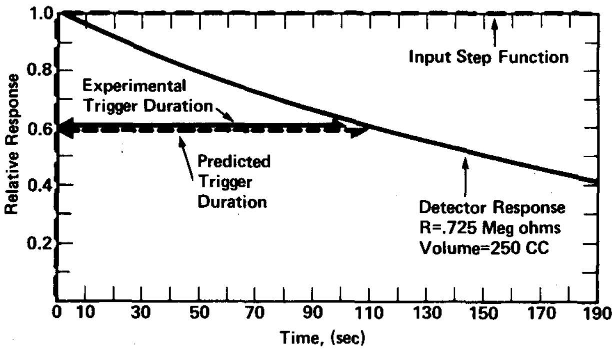

FIG. 8. Experimental and predicted response of pressure-jump detector to applied stepfunction.

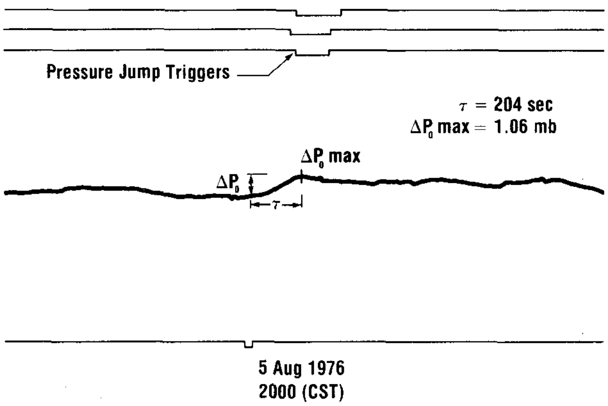

FIG. 9. Example of a pressure jump and associated pressure-jump detector responses recorded by an array operated during a National Severe Storms Laboratory gust front experiment.

Acknowledgments. We thank Mr. William Hass of NOAA's Air Resources Laboratory who provided us with information concerning unpublished, past Weather Service work with pressure-jump detectors. Support from the Federal Aviation Administration's Systems Research and Development Service enabled us to improve and test new pressure-jump detector designs.

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