The FOF Wind Tunnel

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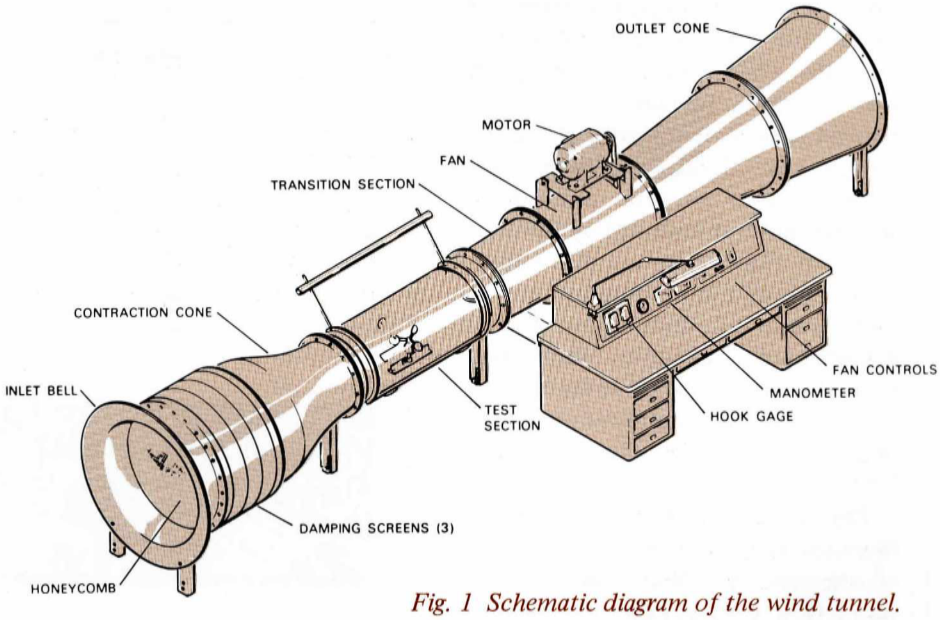

Fig. 1 Schematic diagram of the wind tunnel.

During its early years of making weather observations the FOF frequently accepted the instrument manufacturer's calibration. However, in 1967 the fortuitous detection of a factor-of-two calibration error in one anemometer convinced us that we needed a wind tunnel to perform our own calibration checks. Although wind tunnels are commercially available, researchers commonly design and build their own to provide the features that are most needed for the tasks in mind. Our tunnel was designed to incorporate concepts developed by Julian Pike of the Atmospheric Technology Division's Research Systems Facility (RSF). Perceiving our tasks to be both a large number of calibrations and research into anemometer characteristics, Pike chose to emphasize sophistication and flexibility of the control system.

Figure 1 is a schematic of our tunnel; based on a design by Gerald Gill of the University of Michigan, it was built by the RSF in 1969 and assembled in 1970. The tunnel is 732 cm long with a test section 152 cm long. Its cross section is circular, varying from 218 cm at the inlet to 89 cm in the test section. It is constructed of sheet aluminum and fiber glass with a Plexiglas window over the test section that opens for installation of wind sensors. A nine-blade aluminum fan, driven by a 25 - hp dc motor, pulls air through the length of the tunnel; the air then circulates through the room back to the intake.

The flared inlet bell at the tunnel's front opening contains an aluminum honeycomb and three layers of wire mesh to smooth the flow of entering air. A contraction cone, in which the tunnel narrows to the 89 - cm diameter of the test section, is aerodynamically shaped to prevent turbulence as the airflow accelerates.

Although it was designed to provide speeds from 0 to 26.8 m/sec (60 mi/hr), speeds in fact reach 28.2 m/sec. The primary speed sensor is a Dwyer pitot tube and Hook gage to which all other speed sensors are referenced. At very low speeds, below the threshold of rotating anemometers, a Thermosystems Model 1054 hot-film anemometer is used. Over the balance of the range, speed is conveniently measured by a Gill helicoid propeller anemometer (R. M. Young Co.) that rotates 3.15 revolutions per meter of wind for all wind speeds above 1.2 m/sec. The propeller drives a miniature tachometer generator that provides a speed readout on a digital voltmeter. One of the tunnel's unique features is that the units in which the speed will be displayed (miles per hour, knots, kilometers per hour, meters per second, or feet per second) can be selected by push-button controls.

Speed Controls

The choice of units is only one of the features of the control system. Basically, speed control is provided by silicon controlled rectifier (SCR) control of the 25 - hp dc motor. The SCR controller in turn is manipulated by varying a 0- to 5 - mA dc control current in one of four modes.

Continuous Mode. By means of two rheostats (for coarse and fine control) the current is manually varied from 0 to 5 mA, thus varying tunnel speed from zero to top speed. Speed, as detected by the Gill helicoid propeller anemometer, is displayed on the digital meter in the units of choice.

Discrete Mode. The control current is selected in uniform steps between 0 and 5 mA so that speed varies stepwise from zero to top speed, and any given speed may be attained at the push of a button; this type of tunnel manipulation is achieved by feedback control. (For a more complete discussion of feedback control, see "The FOF Computer-Controlled Environmental Chamber," in this issue.) The Gill helicoid propeller anemometer with its tachometer generator provides a feedback voltage proportional to speed. As indicated earlier, the primary speed sensor is the pitot tube and Hook gage. An important feature of this control mode is the ability to fine-tune the system so that the speeds realized from pushing buttons correspond closely to selected values. But in any case, during fine tuning, the correspondence between push-button and true speed as measured by the pitot tube and Hook gage was determined. Table 1 displays this correspondence for each system of speed units. During discrete mode operation the digital meter also displays speed in the selected units, although the displayed speeds are less accurate than those given in Table 1.

The discrete mode of tunnel operation is preferred for routine calibrations of anemometers. While the speed is varied from 0 to 28 m/sec and back to zero in uniform steps, a segment of chart on the anemometer's recorder is produced through its own translator. The recorder dead band is immediately evident and verification that the wind system correctly registers steady speed at several values is provided. Although this latter concern may sound trivial, in fact, in calibrating wind systems for the International Field Year of the Great Lakes, eight of the 11 tested were found to register wildly fluctuating speeds at certain speed settings. The defective translators were subsequently modified by the manufacturer.

Recently two additional control modes, proposed and designed by Fred Brock,[1] have been added.

Ramp Mode. This control mode, more accurately called the "ramp up/down mode," allows continuous variation of tunnel speed between zero and a selected top speed, then a return to zero. Three controls permit selection of the period (i.e., time between zeros), the proportioning of time between the up and down ramps, and the top speed. Normally 50% of the period is assigned to each ramp. Figure 2(a) illustrates the wave shape of the control current under ramp control and the resulting wave of wind speed, indicating that the fan stops shortly before the current drops to zero.

The ramp mode is used to determine the threshold response of an anemometer and to compare different kinds of anemometers. Figure 3 is a plot of wind speed as sensed by the Thermosystems hot-film anemometer and the Gill helicoid propeller anemometer under ramp control. The data were recorded on magnetic tape and processed by computer to yield the curves in Fig. 3. It is evident from the record of the hot-film anemometer that wind speed had already increased to 0.5 m/sec when the propeller anemometer began to turn. Similarly it can be seen that the wind speed was still 0.1 m/sec when the propeller anemometer stopped; hence its starting and stopping speeds were 0.5 and 0.1 m/sec.

The same comparison, using the Gill

TABLE 1
Tunnel Speeds Corresponding to Push-Button Number for Each of Five Wind-Speed Units

	TRUE SPEEDS				
Button	m/sec	mi/hr	kt	km/hr	ft/sec
1	2.0	5.0	5.1	10.0	10.1
2	4.0	10.1	10.1	20.1	20.1
3	6.0	15.0	15.0	30.1	30.1
4	8.0	20.1	20.0	40.1	40.0
5	10.0	25.1	25.0	50.1	50.1
6	12.0	30.0	30.0	60.0	60.0
7	14.0	35.0	35.0	69.8	69.8
8	16.0	39.9	39.9	79.6	79.5
9	18.0	44.9	44.7	89.3	89.1
10	20.0	49.7	49.7	99.0	92.4
11	21.9	54.5	54.3	101.5	
12	23.8	59.4	54.6		
13	25.7	62.7			
14	27.6				
15	28.2				

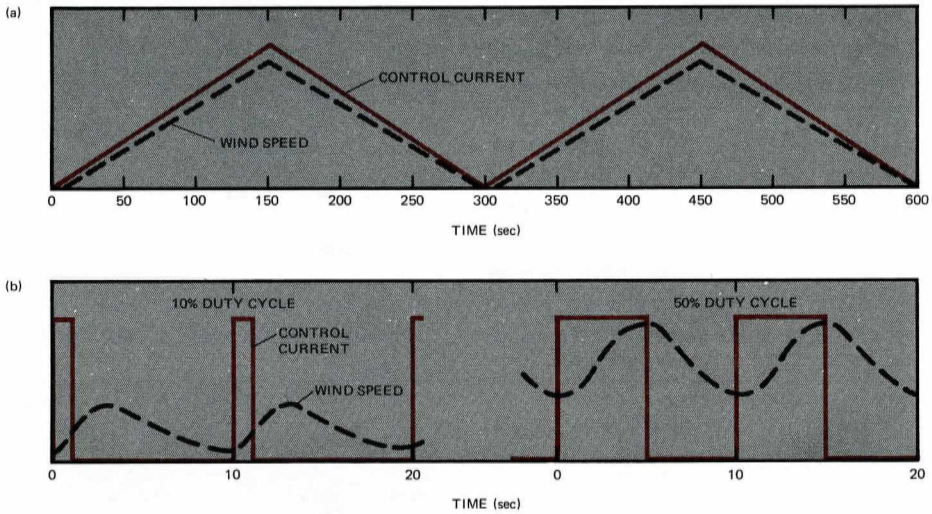

Fig. 2 Shape of wind speed wave in the tunnel resulting from control currents of (a) triangular and (b) rectangular shapes. Specific values of current and speed would be measured along the vertical axes.

[1] Brock is with the RSF and serves as project engineer for the Portable Automated Mesonet, now under development.

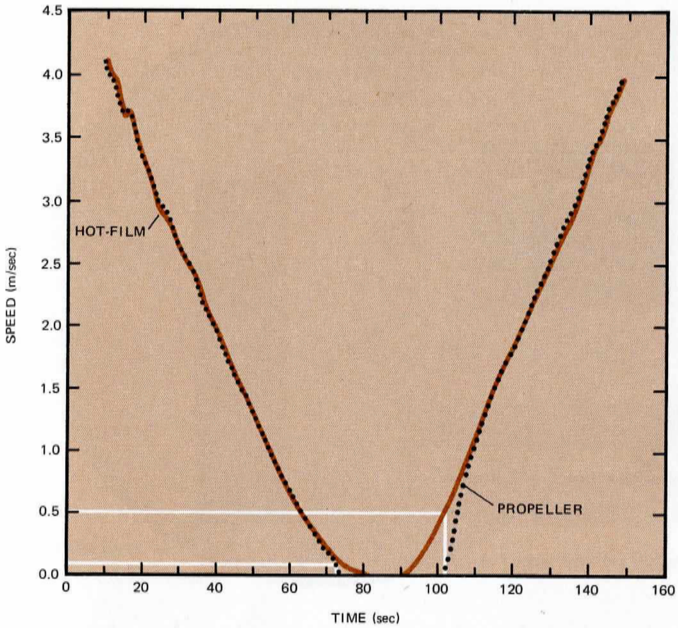

Fig. 3 Records of wind speed from Thermosystems hot-film anemometer (solid line) and Gill propeller anemometer (dotted line) during ramp down *and* ramp up *control.*

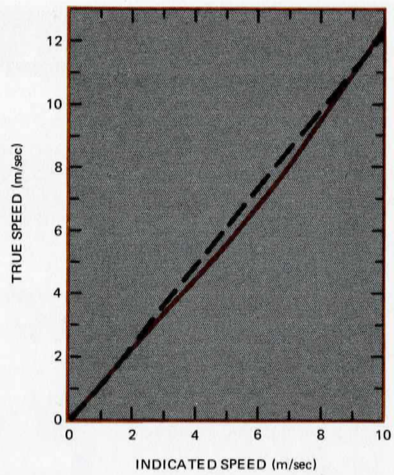

Fig. 4 Calibration curve of Thermosystems hot-film anemometer (solid line) determined using Gill propeller anemometer as a secondary standard. Dotted line portrays the linear calibration appropriate for the mean pressure of 830 mb at the tunnel.

propeller anemometer as a secondary standard, yielded the calibration curve of the hot-film anemometer shown in Fig. 4. The calibration assumed a linear response of the Gill propeller anemometer at speeds above 1.2 m/sec and 3.15 revolutions per meter of wind.

On/Off Mode. The on/off mode is used to produce a periodic variation of tunnel speed. Wave forms like those shown in Fig. 2(b) describe the variation of control current. Three controls set the amplitude of the current, its duty cycle, and the total period. The figure illustrates schematically the resulting wave forms of tunnel wind speed for 10% and 50% duty cycles and a 10 - sec period. It should be noted that, even for a 50% duty cycle, the wave form is not sinusoidal.

The on/off mode is used to test the response of mechanical anemometers. Figure 5 is a plot of wind speed as sensed by the Thermosystems hot-film anemometer and the Gill propeller anemometer under on/off mode control. The data were processed by computer to yield the curves in Fig. 5; the hot-film anemometer may be taken to be in phase with the tunnel speed. In this example the period is 10 sec and the mean speed is 7 m/sec, giving a gust wavelength of 70 m. The propeller anemometer is in exceptionally good agreement with the hot-film system, in accord with theory (Gill, 1967), which shows that it should register better than 99% of the amplitude of sinusoidal fluctuations whose wavelength exceeds 30 m. Even so the propeller exhibits detectable phase lag, underestimation of the maximum, somewhat greater overestimation of the minimum, and consequent overestimation of the mean in a varying wind speed.

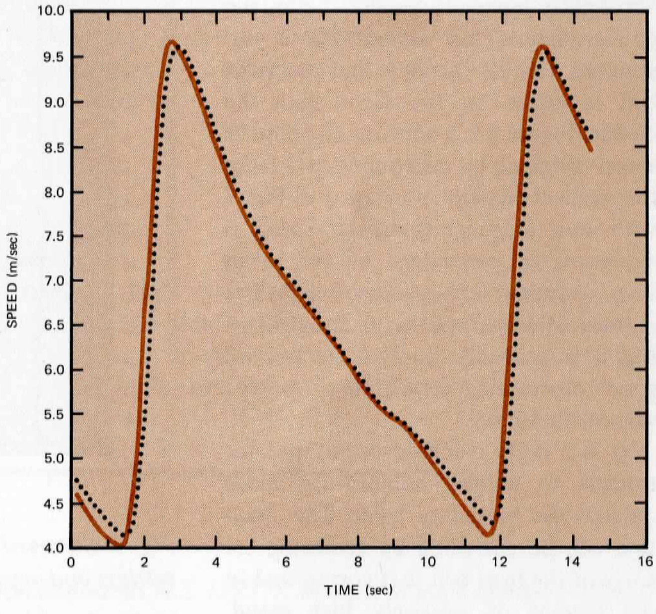

Fig. 5 Records of wind speed from Thermosystems hot-film anemometer (solid line) and Gill propeller anemometer (dotted line) during on/off control.

Figure 6 is a photograph of the entire control panel. As a safety feature an ignition key is required to operate the tunnel. At the top are a digital clock (left) and a meter showing total accumulated running time of the tunnel (right). Directly below the clock is the digital readout of wind speed from the propeller. The two rheostats for *continuous* mode control appear at the bottom right corner. The push buttons for *discrete* mode control and unit selection are at the bottom left. The controls for *ramp* and *on/off* modes are in the center black panel. Circuit drawings are available on request for the original modes and the recently added *ramp* and *on/off* modes.

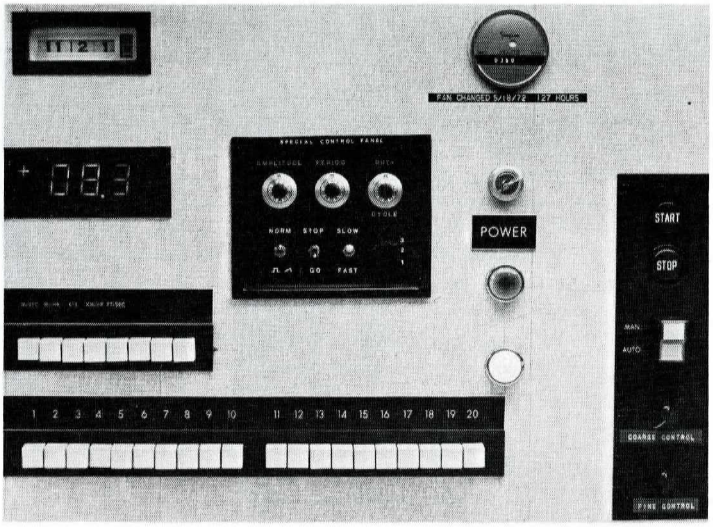

Fig. 6 The control panel of the wind tunnel.

Cross-Tunnel Profiles

Figure 7 shows the profiles observed from bottom to top of the tunnel for each of four speeds and the mean expressed in percentage of the mean flow outside the boundary layer. The hot-film system was used to measure the speeds. The boundary layer is 2.5 cm thick. A minimum along or slightly below the center line is a consistent feature at all speeds. Moreover, speeds are slightly higher above than below the center line. This asymmetry is accounted for by the fact that the inlet bell is closer to the floor than the ceiling. Figure 8 is a contour mapping of speed obtained by combining data from the vertical transect portrayed in Fig. 7 with two diagonal transects. Speed is expressed in percentage of the mean flow outside the boundary layer. The pattern of lesser speeds to the right of Fig. 8 is probably due to the control panel obstructing return flow on that side of the tunnel.

It is a fairly common occurrence for tunnels to exhibit nonuniform speed outside the boundary layer. The situation can be corrected by screening the parts of the inlet bell that correspond to the regions of relatively high speed. Because it is a tedious, trial-and-error procedure, there are no immediate plans to do so with the FOF tunnel.

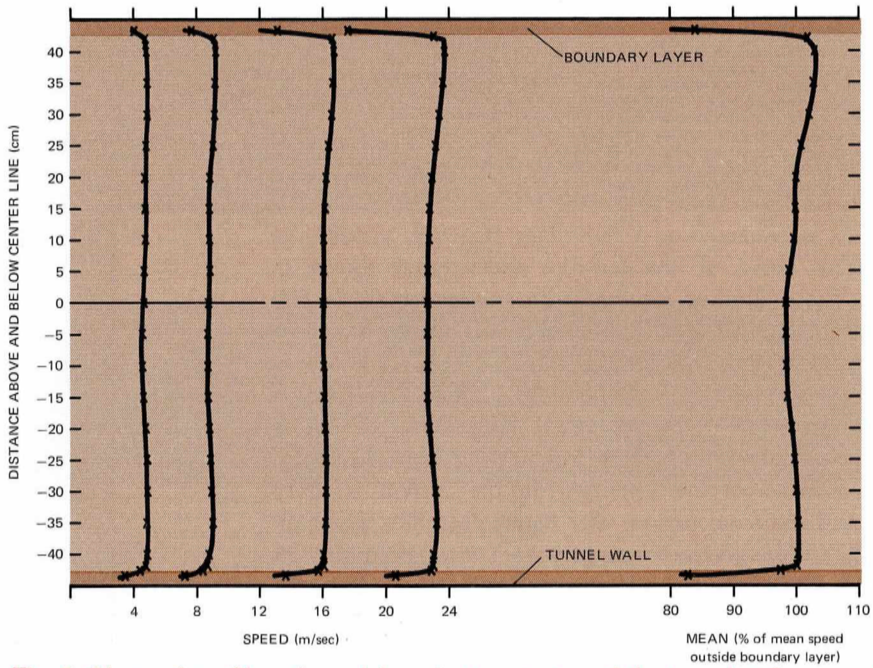

Fig. 7 Observed profiles of speed from bottom to top of the tunnel at four speed settings and average profile for the four runs.

Turbulence Spectra in the Tunnel

The hot-film anemometer was used to investigate the spectrum of turbulence along the axis of the tunnel. Speed was recorded at intervals of 0.1 sec, permitting analysis of spectra up to a frequency of 5 Hz. A spectrum analysis performed on the output of the hot-film anemometer at zero speed established the noise level of the system. Tests run at speeds ranging from 2.3 to 12 m/sec showed no turbulence at the high-frequency (short-wavelength) end of the spectrum. The spectra begin to rise above the noise level at low frequencies equivalent to a wavelength of 3 or 4 m and the spectra resemble that of red noise.

Figure 9 shows a 20 - sec segment of speed fluctuations observed in the tunnel at a mean speed of about 12 m/sec. The most evident fluctuations are those occurring at intervals of about 1.25 sec. This corresponds to a wavelength of 15 m, which is somewhat greater than the length of the room.

In summary, the tunnel flow is evidently laminar and subject to some relatively long-wave fluctuations that may be related to the return flow in a furnished room or other causes.

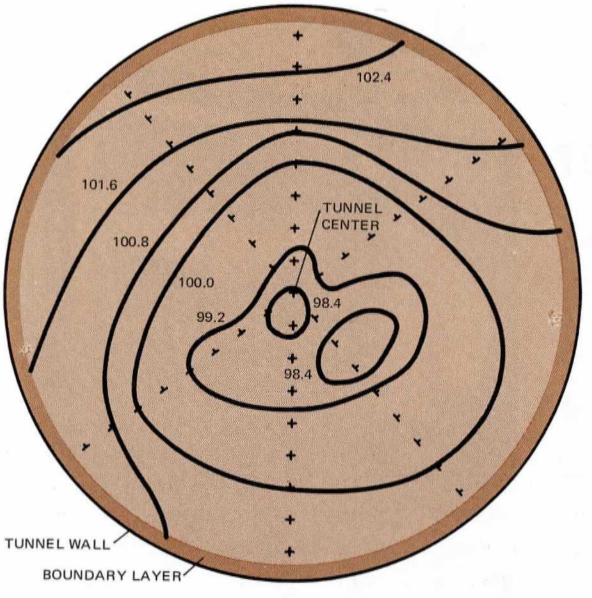

Fig. 8 Isopleths of speed in the tunnel are expressed in percentage of mean speed outside the boundary layer (flow is into page).

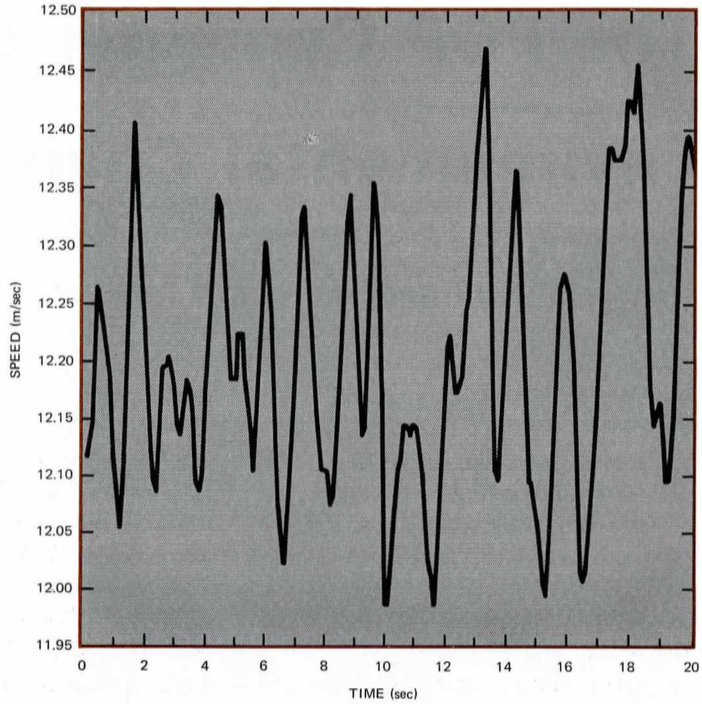

Fig. 9 Hot-film anemometer record of tunnel wind speed during steady flow from observations at 0.1 - sec intervals. The record shows a range, during 20 sec, of ±2% about the mean.

Acknowledgments

This narrative describes the original work of Julian Pike and Fred Brock in designing and developing a wind tunnel with unique features. Both have been patient and generous with their time in explaining operation of the tunnel controls and reviewing drafts. Brock also conducted the comparison test of the hot-film anemometer and the propeller anemometer and the determination of turbulence spectra. Barry Weiss gathered the data along tunnel transects that were used to describe profiles and flow contours.

Reference

Gill, G. C., 1967: On the dynamic response of meteorological sensors and recorders. *Proceedings of the First Canadian Conference on Micrometeorology*, Part I, Meteorological Service of Canada, Toronto, 1 - 27. •

Harold W. Baynton earned his M.S. (1957), an M.A. in mathematics (1959), and Ph.D. (1963) from the University of Michigan. He has worked as a weather forecaster and research meteorologist with the Meteorological Service of Canada (1942-1955), as a research meteorologist with the Systems Division of the Bendix Aviation Corporation (1958-1963), and as a climatologist with the Martin Company (1963-1964). He came to NCAR as a meteorologist in 1965. During his term with NCAR he has also served as an affiliate professor at Virginia Polytechnic Institute (1967-1970). Baynton is a Fellow of the Royal Meteorological Society and a member of the American Meteorological Society and the Air Pollution Control Association. His primary work is in the field of instrumentation with emphasis on the selection and use of instruments in field programs.