A Meteorologically Operated Stack Control System[1,2,3]

GERALD C. GILL AND EUGENE W. BIERLY

The University of Michigan

(Manuscript received 26 November 1962, in revised form 8 March 1963)

ABSTRACT

The standard deviation of wind direction and the mean wind speed have been incorporated into a system for controlling the release of radioactive gaseous wastes from the 200-ft stack of the Enrico Fermi Atomic Power Plant. The meteorological sensor used in the system is a Bendix-Friez Aerovane, located on top of a 100-ft meteorological tower near the stack. Data from the Aerovane are processed by a small analog computer whose outputs are displayed on the control board of the reactor control room and recorded on strip chart recorders. The display enables the reactor operator to know whether the stack is open to the atmosphere or whether the gases are being stored in containment tanks. Averaging times of the meteorological variables may be switched to 3, 6, 12 or 24 minute periods. The paper concludes with a discussion of several representative records from the computer and the Aerovane, pointing out some of the interesting features of this system.

1. Introduction

As an integral part of a study of the natural environment at the site of the Enrico Fermi Atomic Power Plant, Power Reactor Development Company of Detroit, Mich., contracted with the Meteorological Laboratories of The University of Michigan in 1956 to conduct a three year study of the climatology of the plant site area. The Fermi plant is located halfway between Toledo, Ohio, and Detroit, Mich., on the western shore of Lake Erie. Results of this climatological study (Hewson *et al.*)[4] show that there is a very low frequency of calm periods at the plant site, the ventilation rate is high, and although there may be long periods of inversions lasting 60 hr or more, these inversions are confined to the lowest several hundred feet of the atmosphere and to the shoreline area immediately surrounding the lake. A diffusion study was also conducted around the plant site during periods of poor diffusion and low turbulence (Hewson *et al.*).[5] These diffusion experiments were held so that the tower meteorological observations could be correlated with the measured dispersion of zinc-cadmium sulfide particles for off-shore, on-shore, and along-shore wind regimes. The values of Sutton's parameters measured during these experiments have been reported by Hewson *et al.* (1960).[5] The chief result is that diffusion of atmospheric contaminants is generally good.

Power Reactor Development Company further requested the Meteorological Laboratories to design a stack for the release of radioactive wastes to the atmosphere. This stack was designed with the knowledge that there would be sufficient storage capacity for containment of the gaseous waste so that releases need be made only a portion of the time during any one month. The restrictive meteorological conditions tending to increase surface concentrations which were considered in the design of the stack have been discussed by Bierly and Hewson (1962). The result of the stack study was a decision to build a 200-ft stack, 3 ft in diameter with an exit velocity of 60 fps near the reactor on the lake side of the building complex.

The above mentioned studies and calculations in an unpublished report (Bierly[6]) showed that atmospheric dilution of radioactive wastes leaving the stack is adequate for the safety of both on-site and off-site personnel whatever the wind speed. However, to incorporate a safety factor into the minimum dilution values, it was felt that a wind speed exceeding 3 mph was necessary before any radioactive material should be released from the stack. Such a decision would insure that the system

[1] Publication No. 72 of the Meteorological Laboratories, Department of Engineering Mechanics, The Univ. of Michigan.

[2] Contribution No. 25 from the Great Lakes Research Division, Institute of Science and Technology, The Univ. of Michigan.

[3] Research conducted under the sponsorship of the National Science Foundation Grant No. G-11404 and the Power Reactor Development Company, Detroit, Mich.

[4] Hewson, E. W., G. C. Gill and E. W. Bierly, 1961: Meteorological analysis, final report. The Univ. of Mich. Res. Inst., Rpt. 2515-6-F, 48 pp.

[5] Hewson, E. W., G. C. Gill and E. W. Bierly, 1960: Atmospheric diffusion study at the Enrico Fermi nuclear reactor site, a quantitative analysis of diffusion. The Univ. of Mich. Res. Inst. Rpt. 2728-3-T, 19 pp.

[6] Bierly, E. W., 1960: Dilution factors for operational use at the Enrico Fermi Atomic Power Plant. PRDC special report, 27 pp

would still be useable even if the Maximum Permissible Concentrations should ever be lowered.

The calculations referred to are dilution factors for various wind speeds from 1 mph to 25 mph under strong and weak lapse rate, inversion, looping and fumigation conditions. The point of minimum dilution was established for all cases. Computations were made for distances up to 18 mi from the stack. To further insure that there would be adequate dilution, it was concluded that the turbulence level should also be considered, especially when the wind speeds were less than 10 mph. By turbulence level is meant the horizontal spread of the plume and hence the fluctuations in the wind direction.

In an effort to fully automate the Waste Gas Disposal System, Power Reactor Development Company asked the authors to investigate the possibility of incorporating a meteorologically operated control for the stack itself. The outcome of that investigation forms the remainder of this paper. Typical records are included and discussed so the reader will have a knowledge of the capability of this meteorologically operated control system.

It is important to note that this work is truly an application of meteorological variables to a systems engineering problem. Therefore much of the basic reasoning underlying the design is empirical in nature.

2. Design of the stack control system

Because the wind speed at the 100-ft level on the meteorological tower at the plant site exceeds 3 mph 96 per cent of the time, on a yearly average (Hewson *et al.*)[4], it was decided that several wind criteria should be the basis of the stack control system. These are:

a) all emissions from the stack should be discontinued whenever the average wind speed is 3 mph or less;
b) resumption of emission should not occur until the average wind speed exceeds 7 mph;
c) the reactor operators should be warned whenever low mean wind speed, i.e., less than 7 mph, and low turbulence, i.e., standard deviation of wind direction less than 5 deg occur together.

Based on these general criteria, the authors prepared the design specifications for the control of the stack in the Waste Gas Disposal System. These specifications are enumerated in Table 1.

The design specifications for the STOP signal were based on the decision that there would be no emission of radioactive gaseous wastes from the stack if the wind speed were below 4 mph. The upper limit was set at 7 mph so that once the stack did close, it would not open again until there was sufficient wind speed to insure adequate dilution of the stack effluent.

The design criteria for the CAUTION signal were not as easily determined. In essence, the CAUTION signal warns the reactor operator that the wind speed and turbulence are both relatively low, but may still provide adequate diffusion potential. The limits set for the OFF and ON conditions of the CAUTION signal were arrived at after careful review of the diffusion experiments (Hewson *et al.*),[5] and the calculations by Bierly.[6]

The limits for both the STOP and the CAUTION signal are not completely fixed and are subject to adjustment if experience shows different limits are desirable.

The term averaging time as used in this paper indicates the period of time over which the meteorological variables are being averaged. The exact details of how such averaging is accomplished have been given by Brock and Provine (1962).

Fig. 1 was prepared to incorporate these same design features into a flow diagram for use in the design of the complete system and in particular the design of the special analog computer needed to give the running mean of the wind speed and the standard deviation of the wind direction.

TABLE 1. Design specifications for the stack control system.

Stack control parameter	Design specifications
CAUTION signal	ON—whenever average wind speed drops below 7 mph and remains below 10 mph and the standard deviation of wind direction drops to 5 deg or less and remains at 8 deg or less.
	OFF—whenever average wind speed exceeds 10 mph and remains above 7 mph, and/or, the standard deviation of wind direction exceeds 8 deg, and remains above 5 deg.
STOP signal	ON—whenever average wind speed drops below 4 mph and remains below 7 mph.
	OFF—whenever average wind speed exceeds 7 mph and remains above 4 mph.
Averaging time	a) to provide separate switches for wind speed and wind direction averaging circuits.
	b) to provide 3, 6, 12 or 24 min averaging times for both wind speed and wind direction circuits.

3. Waste gas stack control computer system

A computer meeting the specifications stated in Table 1 was built by Applied Dynamics Incorporated of Ann Arbor, Mich. The basic computer circuits were designed according to specifications by Brock and Provine (1962).

Fig. 2 is a photograph of the Waste Gas Stack Control Computer installed at the Enrico Fermi Atomic Power Plant.

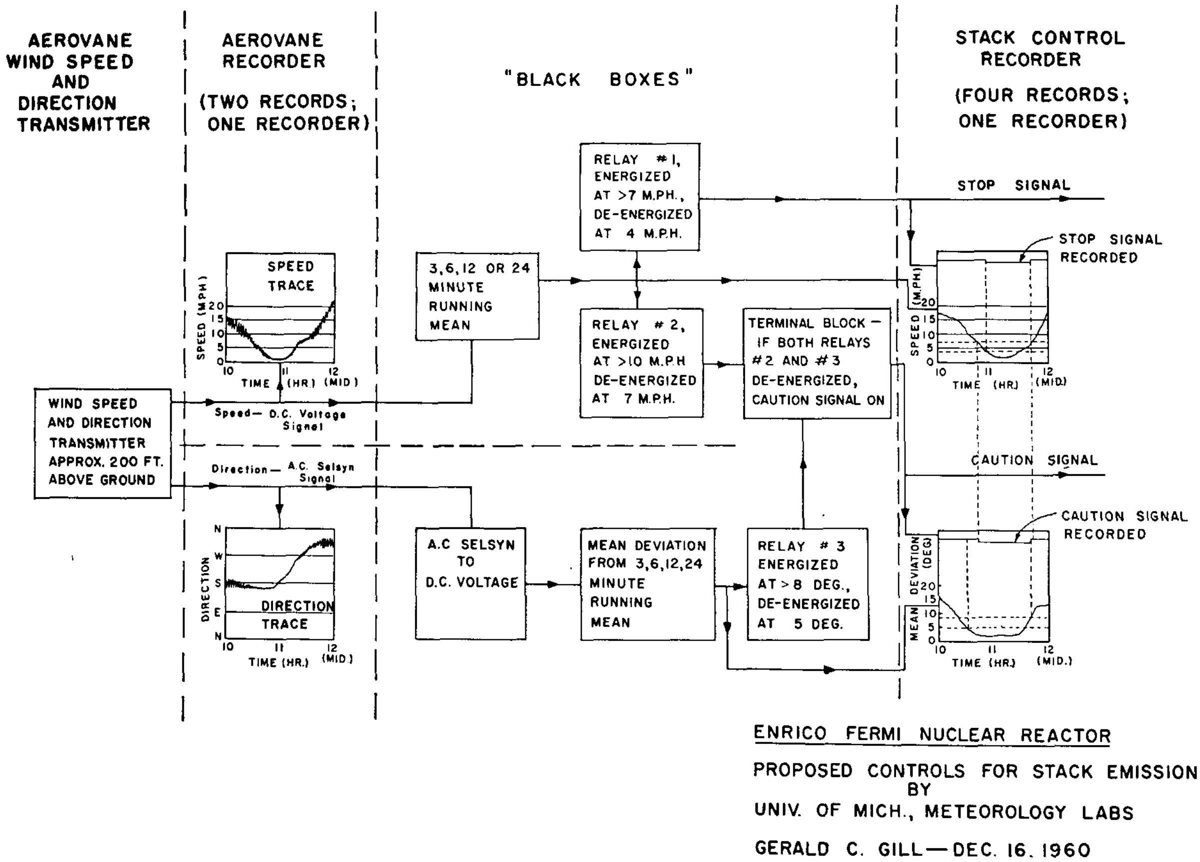

Fig. 1. Block diagram of the proposed meteorologically operated stack control system.

The lower half of Fig. 3 shows a Bendix-Friez Aerovane wind speed and wind direction recorder. The data recorded on the Aerovane recorder serve as input information to the computer. The upper half of Fig. 3 shows the Texas Instrument Company Recti/riter registering the computer output information. These output data being recorded from left to right are the ON and OFF of the CAUTION signal, the standard deviation of wind direction, the running mean of wind speed, and the ON and OFF of the STOP signal.

Fig. 4 shows a portion of the reactor operator control board which is concerned with the emission from the 200-ft stack. Note the signal lights in the lower right corner of the panel. The appropriate lights would be on if the wind speed were so low that the waste gas valve was closed or if the computer output were being bypassed due to some emergency.

The computer utilizes standard components of the manufacturer's line of precision computers. The 16 amplifiers which are used to compute the statistics are standard, interchangeable, stable, high-gain components which utilize precision 0.1 per cent elements in critical areas. Normal daily drift of each amplifier circuit is less than 1 part in 10,000 of full scale recorder deflection. Computer outputs for a given input signal are repeatable to 1 part in 1000 of full scale. To maintain these accuracies, several design features were included for ease in checking and calibration of the circuits.

In the lower right section of the computer, shown in Fig. 2, is the Control Module which contains a multirange voltmeter, a 10-turn precision potentiometer and associated switches and signal lamps.

The 10-turn precision potentiometer is position adjustable and is readable to 1 part in 1000. This Control Module section is used to check operating voltages throughout the computer and to check each amplifier under load conditions. By using the potentiometer and the meter in a null deflection circuit, operating voltages may be measured and adjusted to 1 part in 1000 without putting any additional load on the circuit being monitored.

In the upper central portion of the computer panel, Fig. 2, may be seen the front section of the 16 high-gain DC amplifiers. The four visible components of each amplifier from top to bottom are: a) Amplifier Number, b) Amplifier Output Pushbutton, c) Neon Overload Light, and d) Amplifier Balance Adjust Knob.

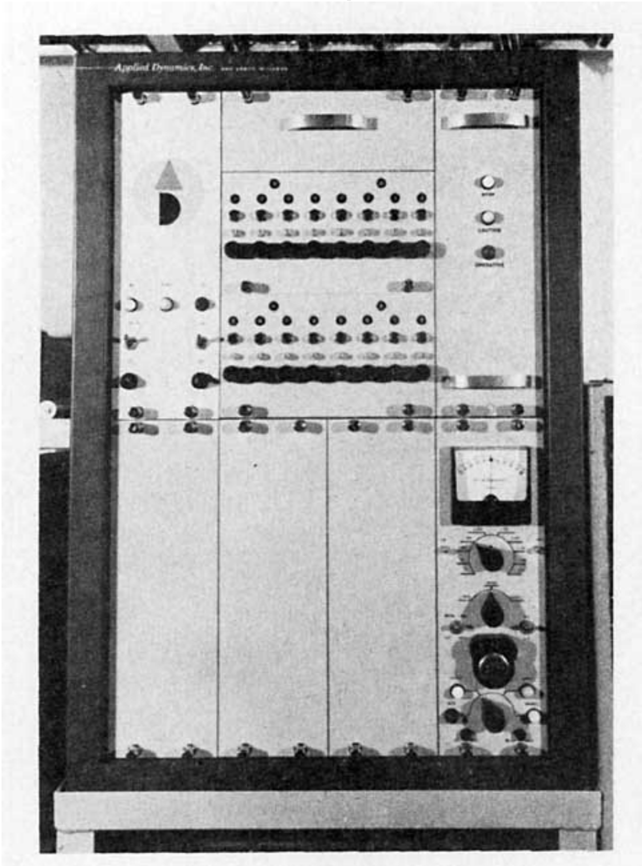

FIG. 2. Stack control computer installed at the Enrico Fermi Atomic Power Plant.

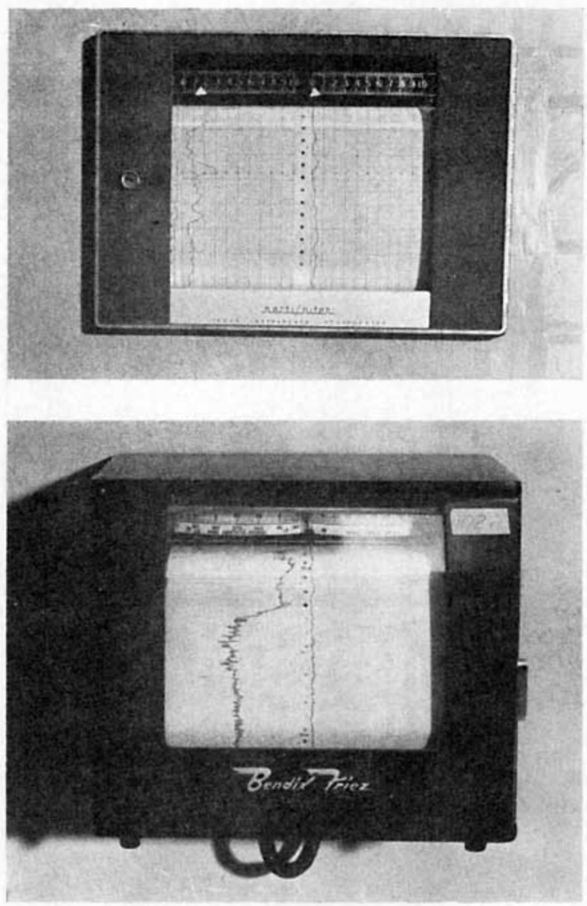

FIG. 3. Bendix-Friez Aerovane recorder in lower section registering wind direction and wind speed. Texas Instruments Recti/riter in upper section registering from left to right, the ON and OFF of the CAUTION signal, the standard deviation of the wind direction, the running mean of the wind speed, and the ON and OFF of the STOP signal (latter scarcely visible).

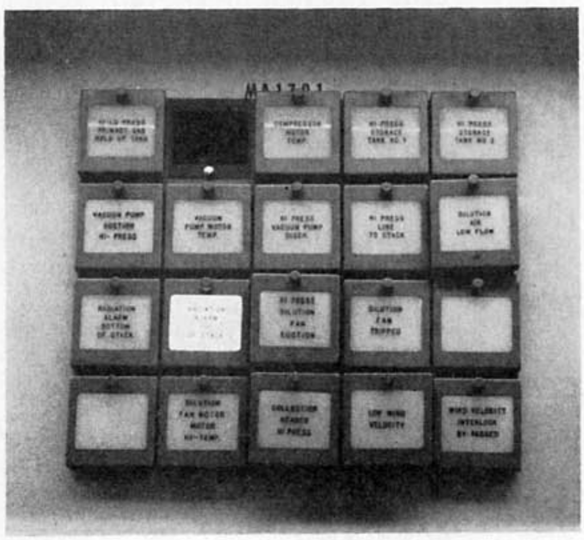

FIG. 4. A portion of the reactor operator control board showing the signal light panel of the Waste Gas Disposal System. Low Wind Velocity signal light is connected directly to the STOP signal of computer.

Whenever a Neon Overload Light is illuminated, it means that the output of that particular amplifier is off by more than ± 1 part in 10,000. To correct this condition, the Control Module is switched to the adjust position. The particular Amplifier Output Pushbutton is depressed and the corresponding Amplifier Balance Adjust Knob is turned slightly until the Neon Overload Light goes out. In continuous routine operation, not more than 2 or 3 amplifiers will need such adjustment each day. At monthly intervals all major circuit voltages should be checked and adjusted where necessary. On the average this monthly check should not require more than one hour of time for a qualified technician.

The averaging circuit to obtain the running mean of the wind speed presented no particular problems electronically; however, obtaining the standard deviation of wind direction did present a major design problem. In normal averaging circuits, an analog voltage is supplied which is linearly proportional to the parameter being sampled. In the case of wind vanes this is done most easily by using a linear single turn potentiometer which supplies a voltage directly proportional to the azimuth angle of the wind. For example, the voltage may read 0 v at 0 deg azimuth and 100 v at 358 deg azimuth. When the vane moves from azimuth 350 deg

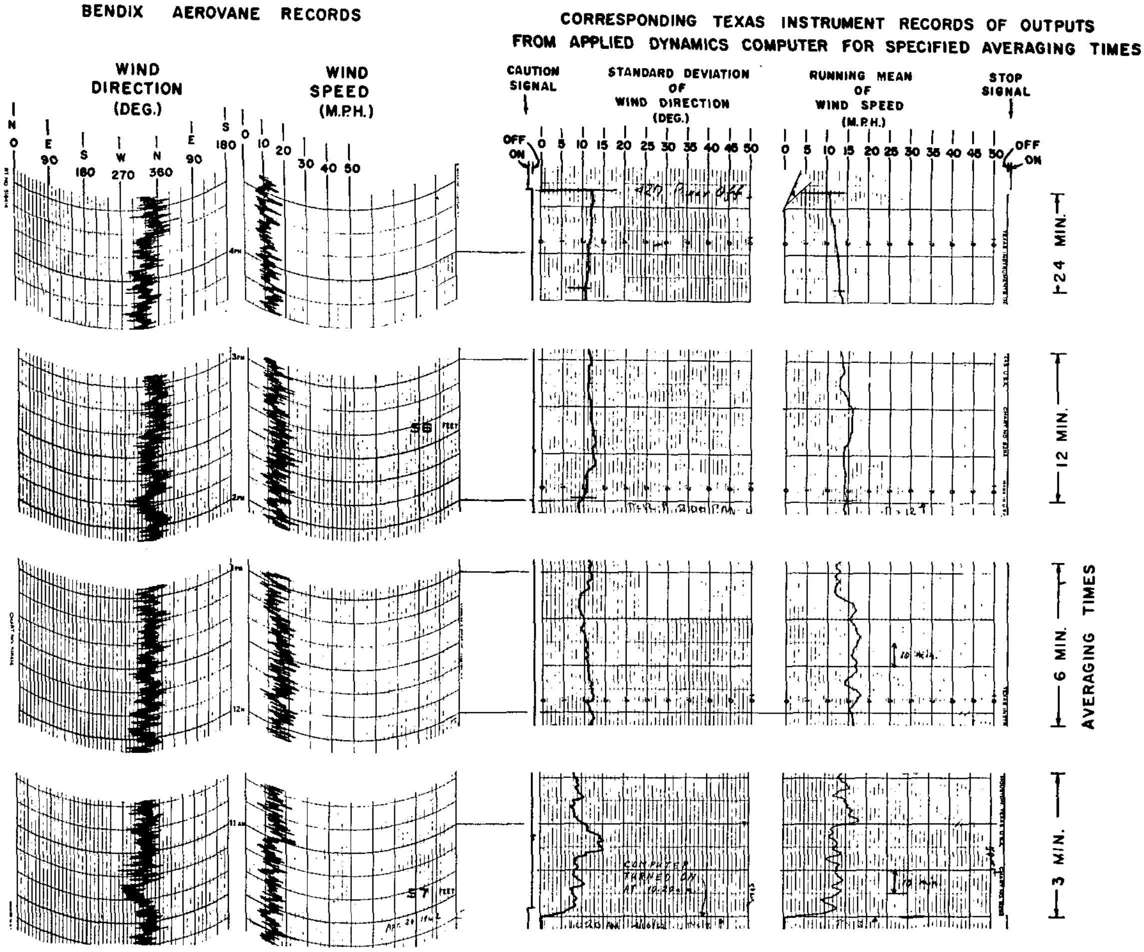

Fig. 5. Typical records from the Bendix-Friez Aerovane recorder and the Texas Instruments recorder showing the effect of different averaging times on the output traces.

through 358 deg to 0 deg, the analog voltage suddenly drops from 100 v to zero. If the vane should swing back and forth through the North or 0 deg position, the voltage transmitted would vary between 100 v and 0 v rather quickly. Such sudden voltage changes would result in large values of the standard deviation of the direction if these changes were passed on to the measuring circuit.

This problem was solved by employing two single-turn potentiometers, 180 deg out of phase with each other, in conjunction with a hysteresis loop and biasing network to accomplish a smooth voltage transition to the standard deviation circuit. There is no evidence from the records of the standard deviation of the wind direction to indicate when such switchings occur, thus showing that the system works as designed. See the upper portion of Fig. 7.

The voltage settings needed to energize or de-energize the three relays which operate from the running mean of the wind speed and the standard deviation of the wind direction are all adjustable. This permits different limits from those given in Fig. 1 for the ON and OFF values of both the CAUTION and the STOP signals. For instance, the STOP signal might be initiated when the mean speed dropped to 6 mph and continue until the speed increased to 10 mph instead of the 4–7 mph values indicated in Fig. 1.

The computer is designed on a Fail Safe basis. This means that as long as the computer is functioning normally, an operative signal is given. However, should the computer not be operating correctly for any reason, such as a power failure or absence of input signals to the computer, then the operative signal is removed and the STOP and CAUTION signals are placed in the ON position.

4. Typical records from the system

Fig. 5 is shown to illustrate the effect of different averaging time on the output trace when the input variable remains relatively steady. A day was selected when relatively steady NW winds were expected to

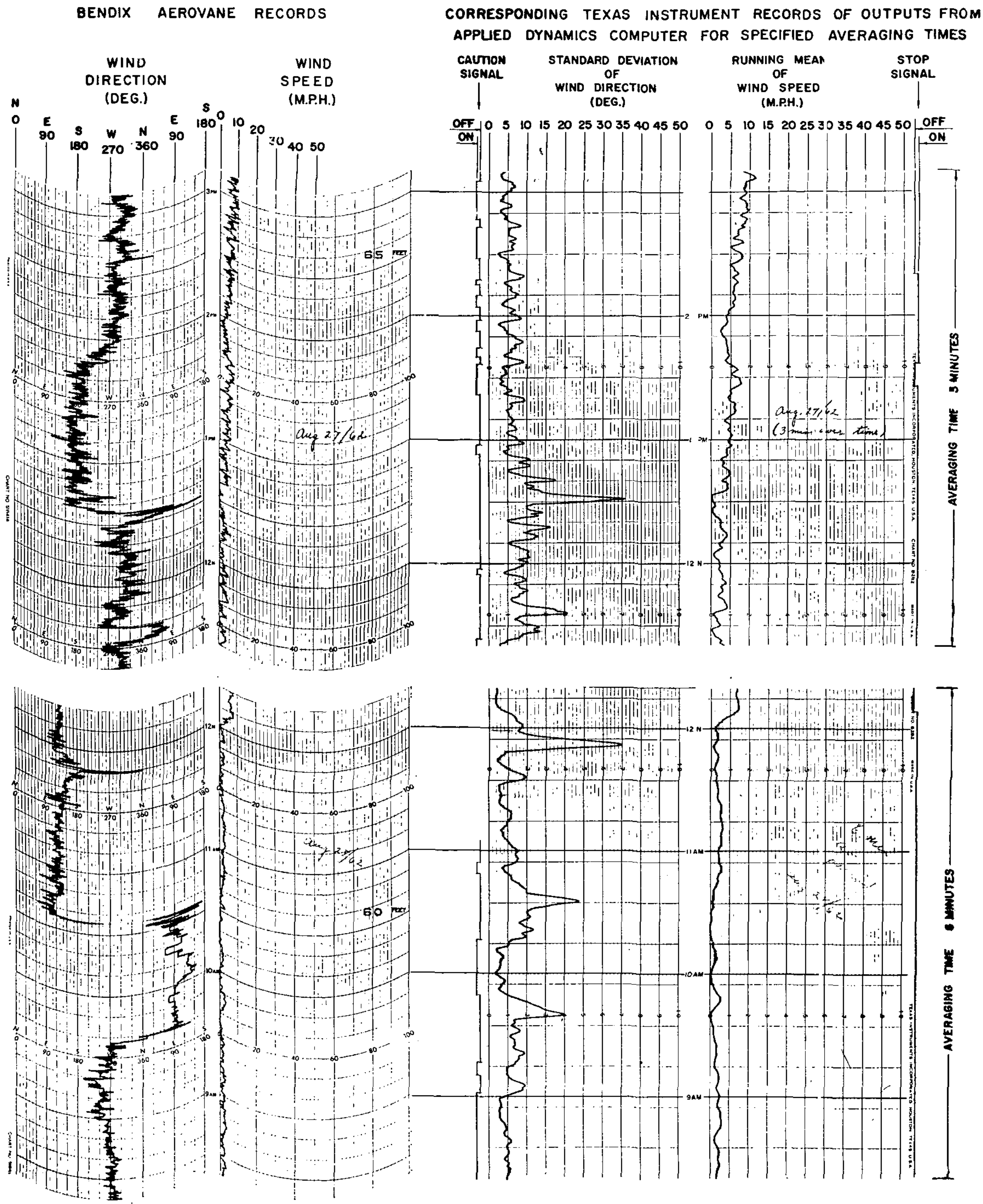

FIG. 6. A typical set of records from the stack control system using 3 min averaging times in the upper section and 6 min averaging times in the lower section.

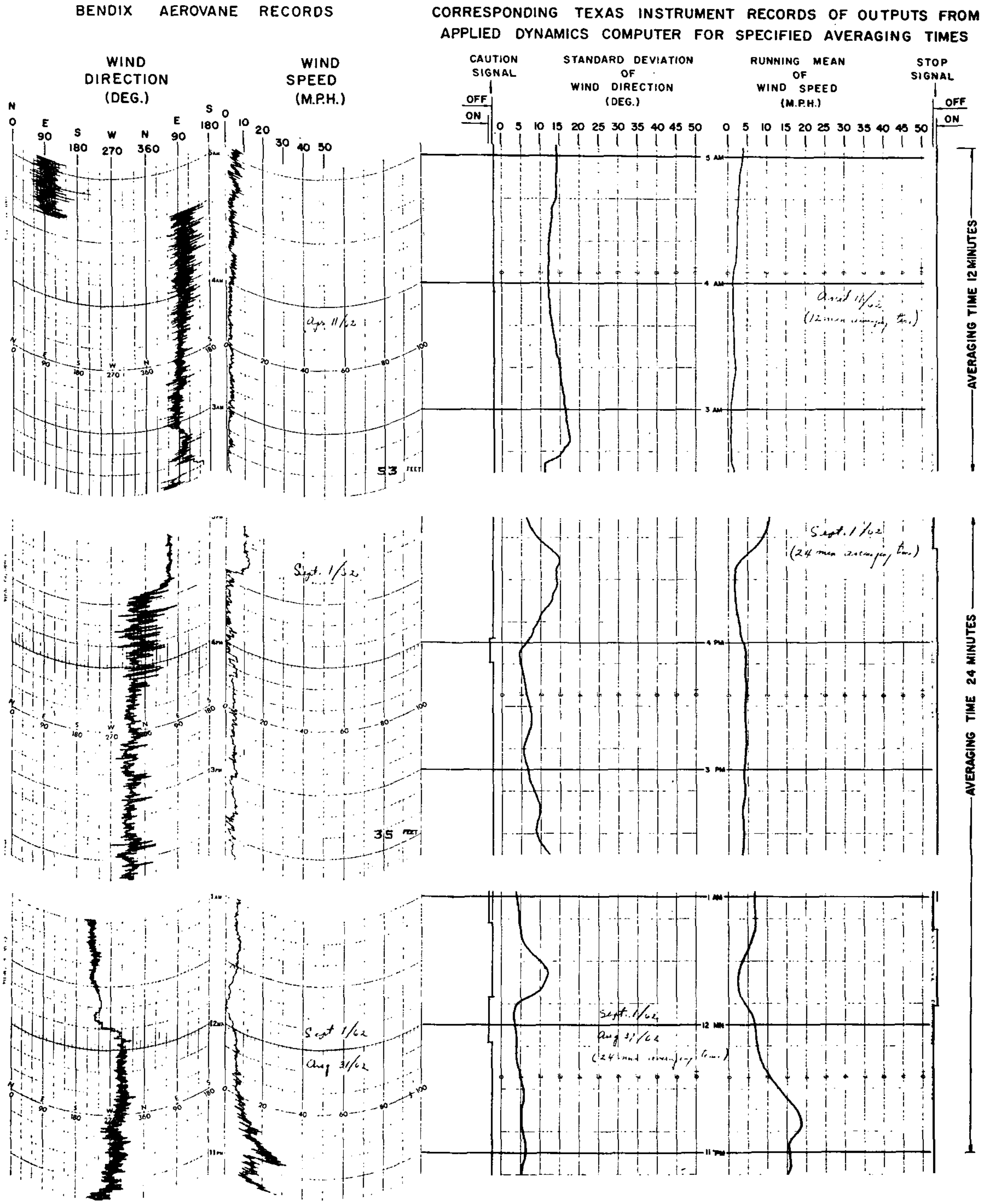

FIG. 7. A typical set of records from the stack control system using 12 min averaging times in the upper section and 24 min averaging times in the middle and lower sections.

continue for several hours. The computer was switched to an averaging time of 3 min and then turned on at 1020 EST. This averaging time was continued for approximately $1\frac{1}{2}$ hr, then the computer was switched to an averaging time of 6 min for a similar period. Throughout the day, successive switchings were made to the 12 and 24 min averaging times. Fig. 5 shows one hour samples from each of these four different averaging times. As can be seen from the Aerovane traces, the wind speed and wind direction remained at relatively constant values throughout the period.

Attention is drawn to the following points in Fig. 5.

a) Within about 1 min after the computer was switched on, the running mean of the wind speed exceeded 7 mph and the STOP signal switched from ON to OFF.
b) The STOP signal remained OFF throughout the day because the running mean of the wind speed remained greater than 4 mph until a power failure occurred at 1627 EST, thus testing the Fail Safe feature of the computer.
c) Within about 2 min after the computer was switched on, the running mean of the wind speed exceeded 10 mph and the CAUTION signal went from ON to OFF.
d) About 3 min after the computer was turned on, the standard deviation of the wind direction reached 8 deg. This would have activated the CAUTION signal from ON to OFF if the running mean of the wind speed had not reached 10 mph a minute earlier.
e) Inspection of the running mean of the wind speed trace for the different averaging time shows that wind speed fluctuations of periods shorter than the averaging time are largely damped out.
f) The successive degrees of smoothing of both the standard deviation of wind direction and the running mean of the wind speed records for the four different averaging times are quite noticeable as one would expect.

From tests such as the one portrayed in Fig. 5, it was decided that averaging times of 12 or 24 min would probably be the most suitable for controlling stack emissions since such averaging times would avoid short periods of OFF and ON of both the CAUTION and the STOP signals, yet provide adequate protection for plant operations.

Fig. 6 and Fig. 7 show typical records from the plant for 3, 6, 12 and 24 min averaging times. These figures contain the simultaneous records from the Aerovane recorder and the computer output recorder. Notice the following points in these records:

a) The upper set of traces of Fig. 6 with a 3 min averaging time and the middle set of traces of Fig. 7 with a 24 min averaging time show that the average wind speeds were comparable and generally below 7 mph in both cases. Therefore, with respect to the wind speed, the CAUTION signal would be on most of the time. The wind direction traces were comparable, with respect to general turbulence, but even so, the CAUTION signal was frequently switching from ON to OFF and vice versa in the 3 min averaging time record of Fig. 6. In fact, there were seven complete OFF-ON cycles in a 2-hr period. In the case of the 24 min averaging time the large number of OFF-ON cycles was eliminated, there being only one complete cycle in a two hour period. Since it would be undesirable to have short periods of OFF and ON of the CAUTION signal for the operational release of waste gases, the superiority of the longer averaging time is apparent.

b) Notice the middle traces of Fig. 7 between 1630 and 1640 EST when the wind direction changed about 80 deg. With the 24 min averaging time, the standard deviation reached a peak of 15 deg at the end of the slow swing, but by this time, the small angular wind vane movements had decreased markedly so that the standard deviation dropped to about 5 deg.

c) The lower set of traces of Fig. 7 from 2300 EST to 0100 EST show that during the period from 2300 to midnight there was an almost continual small angular fluctuation in the wind direction giving a standard deviation of about 5 deg. From 0005 to 0020 EST the small angular fluctuations were markedly reduced in amplitude, but there was a slow 70 deg change in the wind direction. This relatively large change in wind direction caused the standard deviation of the wind direction to rise from 4 to 12 deg. Such a sequence of events has an interesting implication on the diffusion of an effluent from a stack. During the period 2300 EST to midnight, the effluent would probably have been dispersed within a solid angle of 15–20 deg; however, during the period from 0005 to 0020 EST, the effluent would probably have been in a relatively narrow cone while making a wide arc with the stack as the point of origin.

d) Referring to the middle section of the lower set of traces in Fig. 6, it can be seen that the Aerovane recorder switched from one south position to the other south position. A careful analysis shows that between 0935 and 0940 EST, the wind direction fluctuated through an angle of 230 deg with an average shift of 180 deg. This caused a peak standard deviation in the wind direction of 20 deg. Between 1030 and 1036 EST, there were three or four pen excursions of 60 deg or more followed by the 360 deg shift of the recording pen.The rise of the standard deviation of the wind direction to almost 24 deg was caused by the 60 deg fluctuations prior to the switching of the recorder pen. The large rise in the standard deviation between 1147 and 1153 EST was caused by a fluctuation of 180 deg and return which gave a significantly higher value of the standard deviation than the one at 1036 EST when the switching by the aerovane recorder occurred.

e) The upper set of traces of Fig. 7 shows that there is no serious error in recording the standard deviation of the wind direction when the computer switches from one potentiometer to the other potentiometer. From 0420 to 0450 EST the standard deviation of the wind direction increased from 13 to 14 deg. Potentiometer switching took place at 0438 EST when the Aerovane recorder jumped 360 deg, but there was no significant increase in the value of the standard deviation of the wind direction as shown on the Texas Instruments recorder. The small increase in the standard deviation was due to the large fluctuations in wind direction prior to the 360 deg switch. This can be compared to the slow movement of the wind vane between 0230 and 0250 EST when the fluctuations of the vane ranged between an azimuth angle of 040 deg and 160 deg. This movement caused the standard deviation of the wind direction to increase 6 deg, from 11 deg to 17 deg.

5. Conclusions

To assist in the safe operation of an atomic power plant, a meteorologically operated stack control system has been developed, tested and installed. This system uses an Aerovane as the meteorological sensor. The wind speed and wind direction signals from the Aerovane are recorded and simultaneously sent to a small analog computer for processing. The running mean of the wind speed and the standard deviation of the wind direction for selected averaging times are obtained from the computer as well as CAUTION and STOP signals based on certain preset limits of these parameters. The valve leading to the stack is physically opened or closed depending upon the computer output. Provisions are made to contain the radioactive waste gases should the stack be closed. The stack control may also be bypassed should an emergency situation dictate such action.

The computer is quite versatile, permitting the selection of averaging times of 3, 6, 12 and 24 min on both the wind speed and wind direction circuits. Internal adjustment is also possible of the ON and OFF limits of both CAUTION and the STOP signals. For the Enrico Fermi Atomic Power Plant's operations, averaging times of 12 or 24 min appear better than the shorter averaging times with some preferences for the 24 min period. The longer averaging times keep the stack either open or shut for relatively long periods which is desirable for the release of waste gases. The present settings for the CAUTION and STOP signals relays as shown in Fig. 1 appear to be excellent in the light of the tests run on the system.

It is too early to report on the maintenance requirements of the entire system. However, the component parts of the system, Aerovane recorder, Texas Instruments recorder and the analog computer itself have low maintenance as individual units. Thus there is no reason to suspect that when put together these components should cause any particular maintenance problems.

A system such as the one described above would seem to have application in other areas where waste gases are released to the atmosphere on a routine basis. Although storage tanks are an integral part of the system described, other means of gas utilization could be employed when the stack valve is closed.

In addition to the complete system, the computer which obtains the running mean of the wind speed and the standard deviation of the wind direction does have application wherever average values of these meteorological variables are needed.

Acknowledgments. The authors wish to express their gratitude to all the persons associated with this project, principally to Mr. Fred V. Brock of the University of Michigan, Meteorological Laboratories, Mr. Charles Kleecamp and Dr. Edward Gilbert of Applied Dynamics Inc., and Mr. John G. Feldes, Power Reactor Development Company who have been very instrumental in transforming an idea into a reality.

REFERENCES

Bierly, E. W., and E. W. Hewson, 1962: Some restrictive meteorological conditions to be considered in the design of stacks. *J. appl. Meteor.*, **1**, 383–390.

Brock, F. V., and D. J. Provine, 1962: A standard deviation computer. *J. appl. Meteor.*, **1**, 81–90.