United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

EPA-600/2-79-115
June 1979 c. 2

Research and Development

Evaluation of Stationary Source Particulate Measurement Methods

Volume III. Gas Temperature Control During Method 5 Sampling

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EPA-600/2-79-115
June 1979

EVALUATION OF STATIONARY SOURCE PARTICULATE MEASUREMENT METHODS
Volume III. Gas Temperature Control During Method 5 Sampling

by

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Contract No. 68-02-0632

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ABSTRACT

A study was conducted to measure changes in gas temperature along the length of a Method 5 sampling train due to variations in stack gas temperature, sampling rate, filter box temperature and method for controlling the probe heating element. For each run condition, temperatures were measured in the stack, at ambient and at four internal and external positions along the sampling train at one minute intervals. Measurements were continued until the system was observed to reach a state of thermal equilibrium. For several experiments in which typical stationary source conditions were tested, substantial differences between gas temperature and external temperature were observed. Two parameters--the method employed for controlling the probe heater and the gas sampling rate--were also shown to have major influences on gas temperatures and temperature profiles along the sampling train. The results from these experiments, presented herein, demonstrate that gas temperatures cannot be predicted or controlled on the basis of externally measured temperatures. The use of an internal thermocouple, having its reference junction at the back of the probe, to proportionally control the probe heater element is shown to provide a predictable gas temperature and a flat thermal profile along the system. This procedure for controlling gas temperature is recommended as a modification to Method 5.

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ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Kenneth Knapp of the EPA for his encouragement and support of this work and to Philip L. Levins of Arthur D. Little, Inc., who provided a significant contribution in the experiment design and data review and analysis.

I. CONCLUSIONS

Based upon the measurement of gas temperatures within a Method 5 sampling train as influenced by variations in stack gas temperature, sampling rate, filter box temperature and reference point temperature and location for controlling the probe heating element, the following conclusions can be drawn:

- External reference temperatures do not necessarily represent nor permit control of internal gas temperatures. Gradients of up to 100°F can occur under certain conditions.
- Heating and/or cooling of the gases being sampled can occur or can be accomplished over very short distances anywhere along the collection system.
- A gas temperature of 250°F can be maintained at the filter even though the gas is considerably hotter (or colder) at the back of the probe. The thermal gradient across the filter support glass frit is generally less than 10°F.
- Flow-rate variations of 0.5 to 1.2 cfm have only a moderate influence on existing temperature profiles within the system. Higher flow rates tend to smooth out the profile.
- Variations in gas stream moisture content influence the temperature profiles within the train but should not prohibit desired temperatures from being attained.
- The best technique for reliably maintaining desired gas temperatures is by using a proportional controller to regulate probe heating. The reference junction should be mounted internally at the back end of the probe.

II. INTRODUCTION

The Method 5 procedure for measuring particulate emissions from stationary sources, promulgated by the EPA in 1971,(1) involves the isokinetic extraction of a measured volume of particulate-laden gases from the source with a subsequent gravimetric determination of the collected particulate after removal of uncombined water. The sampling apparatus consists of a nozzle, glass-lined probe, high efficiency filter and a series of wet impingers as well as appropriate metering instruments. This apparatus is shown schematically in Figure 1. Method 5 specifies that the probe is "Pyrex glass with a heating system capable of maintaining a minimum gas temperature of 120°C (250°F) at the exit end during sampling to prevent condensation" and that the filter holder is "Pyrex glass with a heating system capable of maintaining a minimum temperature of 110°C (225°F)." These requirements have been amended for fossil-fuel stream generators permitting the probe and filter heating systems to provide a gas temperature between 110°C and 160°C (225°F and 320°F).(2)

Commercially available Method 5 sampling trains utilize manual variac settings to regulate power inputs to the heater elements. The probe temperature is obtained by a reference thermocouple placed on the outside of the glass liner at an arbitrarily selected position near the back of the probe. Temperature control is obtained by manual variac adjustments or by feeding the thermocouple output to a proportional controller. The filter holder is contained within an insulated box resistance heated with a cone or plate element. A small blower is generally added to provide a uniform distribution of heat within the box. Most systems employ thermostatic temperature control.

Such sampling systems presume that temperatures in the gas stream are the same as the externally measured or controlled temperatures. The study reported herein was conducted to test the validity of such an assumption for selected variations in flow rate (0.6 to 1.2 cfm) and stack gas temperature (40°C to 220°C). A principal objective of the study was to determine the best location for placement of a reference thermocouple to assure reliable control of gas temperature within the sampling system.

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(1) Federal Register 36 No. 247, 24875-24895 (December 23, 1971).

(2) Federal Register 39 No. 177, 32852-32874 (September 11, 1974).

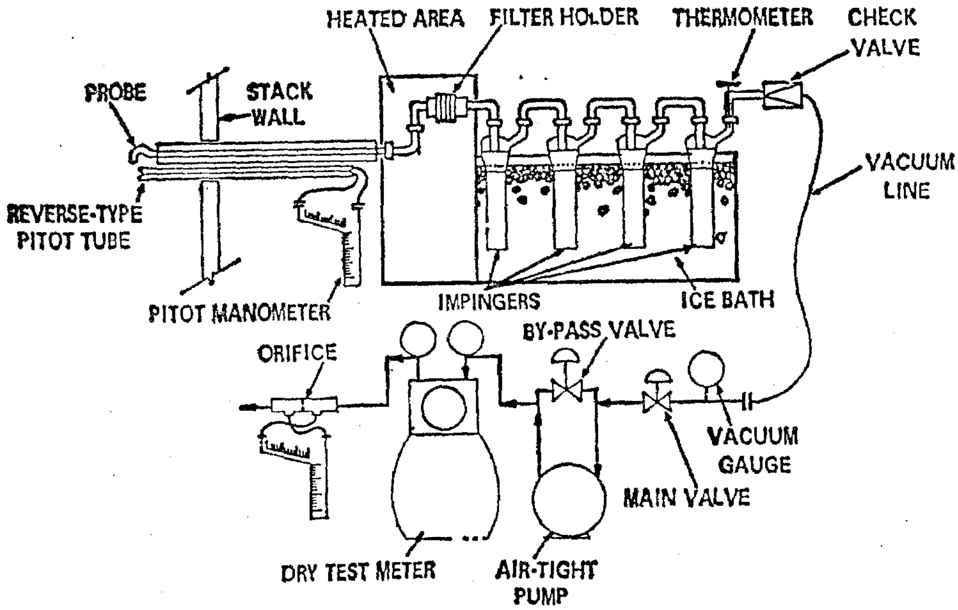

FIGURE 1 Schematic Presentation of a Method 5 Sampling Train

III. EXPERIMENTAL PROCEDURES

All measurements were conducted with a commercial particulate sampling train (Research Appliance Company "Stak-sampler") approved for collecting samples by the Method 5 procedure. Prior to the studies described herein, several small modifications were made to this train to improve its operating reliability for the wide range of conditions encountered in field sampling; modifications having a potential influence on the present study include: (1) covering all external surfaces of the filter box with an additional layer of 1/2" fiberglass and 1/4" transite and (2) wrapping the entire sheathed length of probe liner with nichrome wire, glass tape and asbestos tape to minimize heat loss through system boundaries. Iron-constantan thermocouples were mounted to record temperatures at ten positions, as follows:

No.	Position
1	In stack
2	Ambient
3	Midway along probe liner, external
4	Midway along probe liner, internal
5	Back of probe liner, external
6	Back of probe liner, internal
7	Front of filter, external
8	Front of filter, internal
9	Back of filter, external
10	Back of filter, internal

The externally located thermocouple junctions were placed in direct contact with the glass probe liner or filter holder and were held in place by glass wool tape. The internal thermocouples were introduced through a specially adapted elbow at the back of the probe. This elbow was modified to incorporate a glass tee through which thermocouples (for Positions 4, 6 and 8) were fed and then epoxied in place. The epoxy provided a leak-tight seal. The junctions of the thermocouples were located at the position of interest and were centered in the gas stream by means of standoffs. The gas temperature behind the filter (position 10) was measured by a thermocouple introduced similarly through a glass elbow behind the filter.

The thermocouple leads were attached to a ten-position Acromag temperature indicator having an accuracy of one degree. The probe heating system was controlled by means of a Weathermeasure proportional controller, with the sensing junction located at Position 5, 6 or 10. Filter box heating was carried out with the controls provided on the sampling train.

All experiments were conducted in a stationary source simulation unit developing 500 cfm of stack gas from an oil-fired burner. The unit is capable of delivering stack gases at a velocity of about 1000 cm/sec and temperatures of 180 to 270°C (290 to 450°F). For each set of runs, the train was assembled and the probe and filter box were preheated to selected temperatures. After the system stabilized, a gas sample was drawn through the system, usually at a flow rate of 0.5 cfm, and temperatures at the ten reference positions were recorded at 1 minute intervals. Sampling was continued until thermal stability was re-established throughout all components. Runs were generally continued at two higher flow rates (0.8 and 1.2 cfm), with all other conditions being held constant. The source simulation unit was located within an enclosed high bay area; therefore, sampling was not influenced by variations in windspeed, rain, cold ambient temperatures and other climatic influences that are typically encountered in the field.

A series of thirteen experiments were planned to evaluate the variations between gas temperature and externally measured temperature, temperature distributions along the sampling train and the influence on temperature from variations in sampling velocity, stack temperature, probe and filter box heater controls and the reference junction position for proportional control of the probe heater. A listing of these experimental conditions and the objective of individual runs is given in Table 1.

TABLE 1

PLAN AND OBJECTIVES OF EXPERIMENTAL RUNS

RUN NO.	CONDITIONS			OBJECTIVE
	Stack Gas	Filter Box Preset Temp.	Probe Heater Control	
1	Hot	300°F	Preset	To observe temperature distribution and gradient for preset heater values.
2	Hot	250°F	Manual adjustment	To measure gradients when gas temperature at back of probe (and in filter box) is maintained at 250°F.
3	Hot	250°F	PC from #5 ~130°F	To see how efficiently the filter can reheat the gas after passage through a fairly cold probe.
4	Hot	225°F	PC from #5 ~140°F	Similar to Run 3, but lower filter box temperature.
5	Hot	225°F	PC from #5 ~200°F	Similar to Run 4, but higher probe temperature set to achieve a gas temperature of 250°F at back of probe.
6	Cold	250°F	PC from #5 ~250°F	To see if probe heating is sufficient to bring a cold stack gas temperature up to 250°F at the exit from the probe and to determine temperature gradients between the gas and external system.
7	Cold	250°F	PC from #5 ~250°F	Similar to Run 6, but including higher sampling rates.
8	Cold	250°F	PC from #5 ~200°F	Similar to Run 6, but with a cold stream saturated with moisture. The proportional control temperature was reduced to 200°F in an attempt to achieve a probe exit gas temperature of 250°F.
9	Cold	250°F	PC from #10 ~250°F	To investigate the ability to control gas temperatures from a reference function located in the gas stream behind the filter.
10	Hot	250°F	PC from #10 ~250°F	Similar to Run 9, but utilizing a hot gas stream.
11	Hot	250°F	PC from #5 ~240°F	To simulate gas temperatures for a coal-fired boiler, with the probe heater reference function external at back of probe.
12	Hot	250°F	PC from #10 ~250°F	Similar to Run 11, but reference point in gas stream behind filter.
13	Hot	250°F	PC from #6 ~250°F	Similar to Run 11, but reference point in gas stream at back of probe.

IV. RESULTS AND DISCUSSION

A summary of experimental results is presented in Table 2. The measured temperatures listed in this table represent the average temperatures recorded at each reference position. As such, they do not reflect temperature cycling, which in some cases can be considerable. Temperatures are given in degrees Fahrenheit to permit a more easily visualized comparison. Selected experimental results are displayed pictorially in a series of figures. In this way, temperature gradients (between the interior and exterior of the system), temperature distributions along the length of the sampling systems and the influence of changes in velocity can be more easily demonstrated.

Figure 2 demonstrates gradients along the probe of 40-50°F. Approximately 10 minutes is required before the desired gas temperature (250°F at back of probe) is achieved and stabilized. If, in fact, the external position at the back of the probe was set to 250°F, the ensuing gradient would result in a gas temperature of 290-300°F. Only a small gradient (about 10°F) is observed for the filter. There is a 10°F swing in temperature over a 5 minute cycle, corresponding to the thermostatic control of the filter box. The gas temperature behind the filter is quite smooth; apparently, the thermal mass of the glass frit is sufficient to damp out the temperature swings. The temperature distribution along the train is shown schematically in Figure 3.

Data from Runs 3, 4 and 5 were used to evaluate the thermal capabilities of the two heating zones, i.e., the probe and the filter box. A proportional controller, with sensor mounted at Position No. 5, was utilized to maintain probe temperature, while the thermostat supplied with the filter box was employed to regulate the external box temperature. The distribution of gas temperature along the train is shown for Runs 3 and 4 in Figure 4. For these runs, the probe heater current was set at a minimal value to evaluate the ability of the filter box to reheat the gas to a desired value (250°F and 225°F for Runs 3 and 4, respectively). Even when gas temperature has dropped to as low as 150°F at the back of the probe, the filter box is able to reheat the gas to a desired temperature. As gas velocity (sampling rate) is increased, the thermal profiles become flatter, as one would anticipate, with gas temperature behind the filter being about 10°F hotter than for the lower sampling rate.

Runs 6 through 9 were conducted with a cold stack gas to see how effectively the system could heat the gas stream to desired temperatures. Thermal gradients at several positions along the train are shown for a typical case (back of probe external controlled at 250°F, filter box at 250°F and 1.25 cfm sampling rate) in Figure 5. Thermal equilibrium is established in just a few minutes with very smooth profiles. A thermal gradient of 45°F is obtained at the back of the probe, resulting in a gas temperature of 285°F. The gas does not cool very much while passing through the filter, exiting at a temperature of 275°F even though the filter box is maintained at 250°F.

TABLE 2

SUMMARY OF RUN CONDITIONS AND AVERAGE TEMPERATURES AFTER SYSTEM EQUILIBRATION

(All temperatures are given in degrees Fahrenheit.)

Run No.	Nominal Sampling Rate (cfm)	Probe Heater Control	Probe Heater Control Point*	Filter Box Temp	Run Time (min)	Measured Average Temperatures at Indicated Positions* (Rounded Off) 1	2	3	4	5	6	7	8	9	10
1	0.5	---	---	300	17	410	105	275	315	235	280	265	275	265	270
2	0.5	---	---	250	20	410	100	255	300	210	245	255	265	260	270
3a	0.5	130	#5	250	18	410	100	155	250	130	140	240	230	250	220
3b	1.25	130	#5	250	16	410	105	215	300	160	195	270	250	275	260
4a	0.5	140	#5	225	10	415	105	175	255	145	160	205	205	210	210
4b	0.8	140	#5	225	12	420	105	195	285	150	175	210	205	215	210
4c	1.25	140	#5	225	18	415	105	220	300	165	200	215	220	220	220
5a	0.5	200	#5	225	8	420	100	240	285	200	235	220	230	225	230
5b	0.8	200	#5	225	6	425	100	255	310	200	240	220	235	220	230
5c	1.25	200	#5	225	8	425	100	260	325	200	245	225	240	220	235
6a	0.5	250	#5	250	23	95	100	300	250	250	320	265	280	275	280
6b	0.8	250	#5	250	25	100	100	280	225	240	310	275	285	285	285
6c	1.25	250	#5	250	20	100	100	275	215	240	305	275	285	285	290
7a	0.5	250	#5	250	16	75	80	295	230	245	310	255	280	---	270
7b	1.25	250	#5	250	19	75	80	270	205	242	285	260	280	---	275
7c	1.6	250	#5	250	25	75	80	260	185	230	270	255	265	---	265
8a	0.5	200	#5	250	18	95	100	355	275	210	325	260	275	260	270
8b	0.8	200	#5	250	8	90	100	340	275	200	315	255	275	255	265
8c	1.25	200	#5	250	15	95	100	315	275	195	305	255	275	255	270
9a	1.25	250	#10	250	29	90	100	235	185	200	250	245	250	265	---
9b	0.8	250	#10	250	18	95	95	210	180	185	230	255	255	275	---
9c	0.5	250	#10	250	35	95	95	195	175	180	215	250	240	265	---
10a	1.25	250	#10	250	40	430	105	250	290	180	230	245	245	260	260
10b	0.8	250	#10	250	33	425	105	230	275	180	225	250	250	265	265
10c	0.5	250	#10	250	26	425	105	200	250	165	195	250	245	265	265
11a	0.5	240	#5	250	17	345	80	320	300	245	330	240	270	---	260
11b	0.8	240	#5	250	17	345	80	320	305	240	330	250	290	---	270
11c	1.25	240	#5	250	17	340	80	325	315	250	340	260	300	---	285
12	0.5	250	#10	250	29	340	85	275	265	205	280	235	255	---	---
13	0.5	250	#6	250	12	340	85	240	240	195	---	235	240	---	240

*A description of the various positions by number is ...

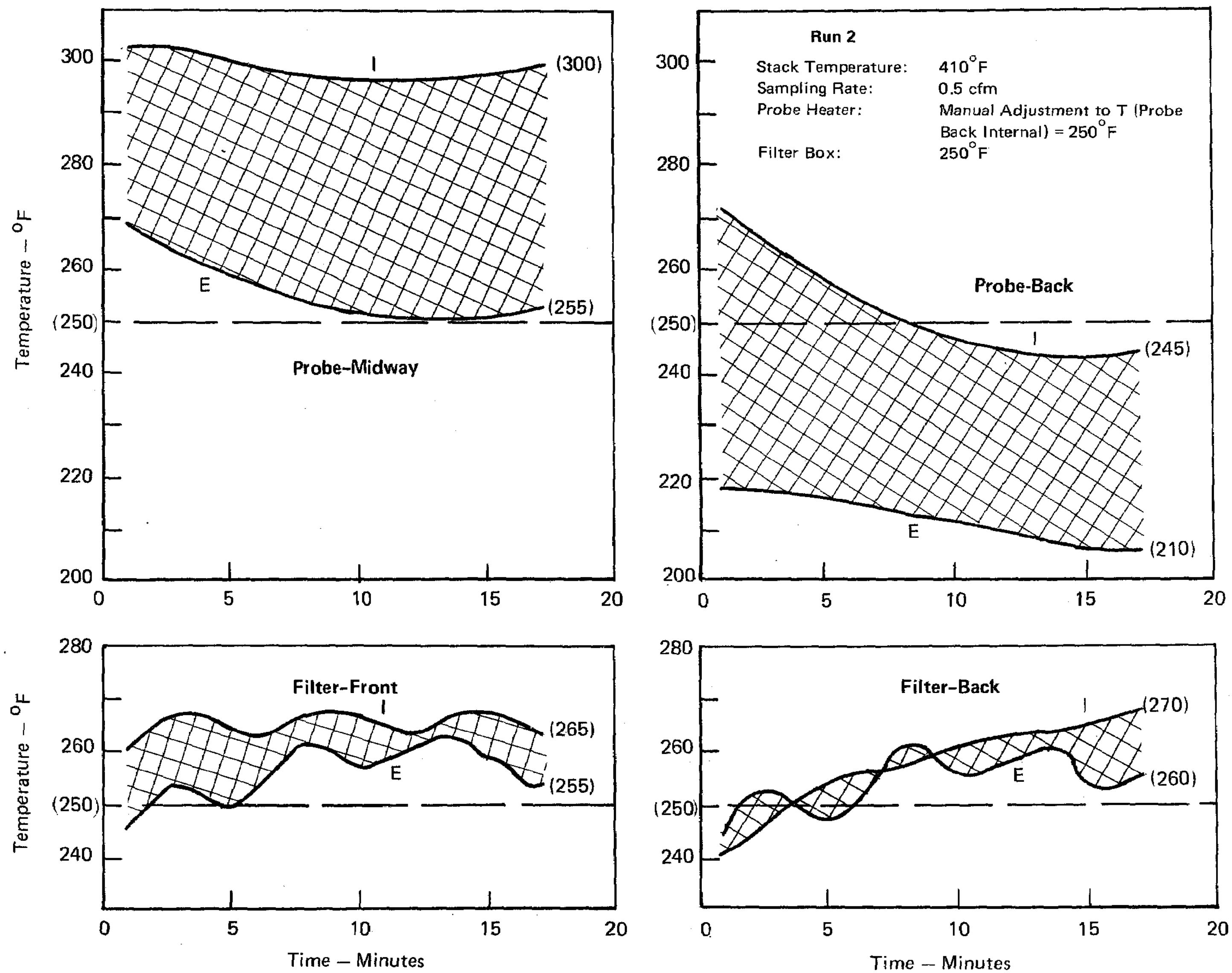

FIGURE 2 Temperature Gradients Across Sampling Train as a Function of Time - Run 2

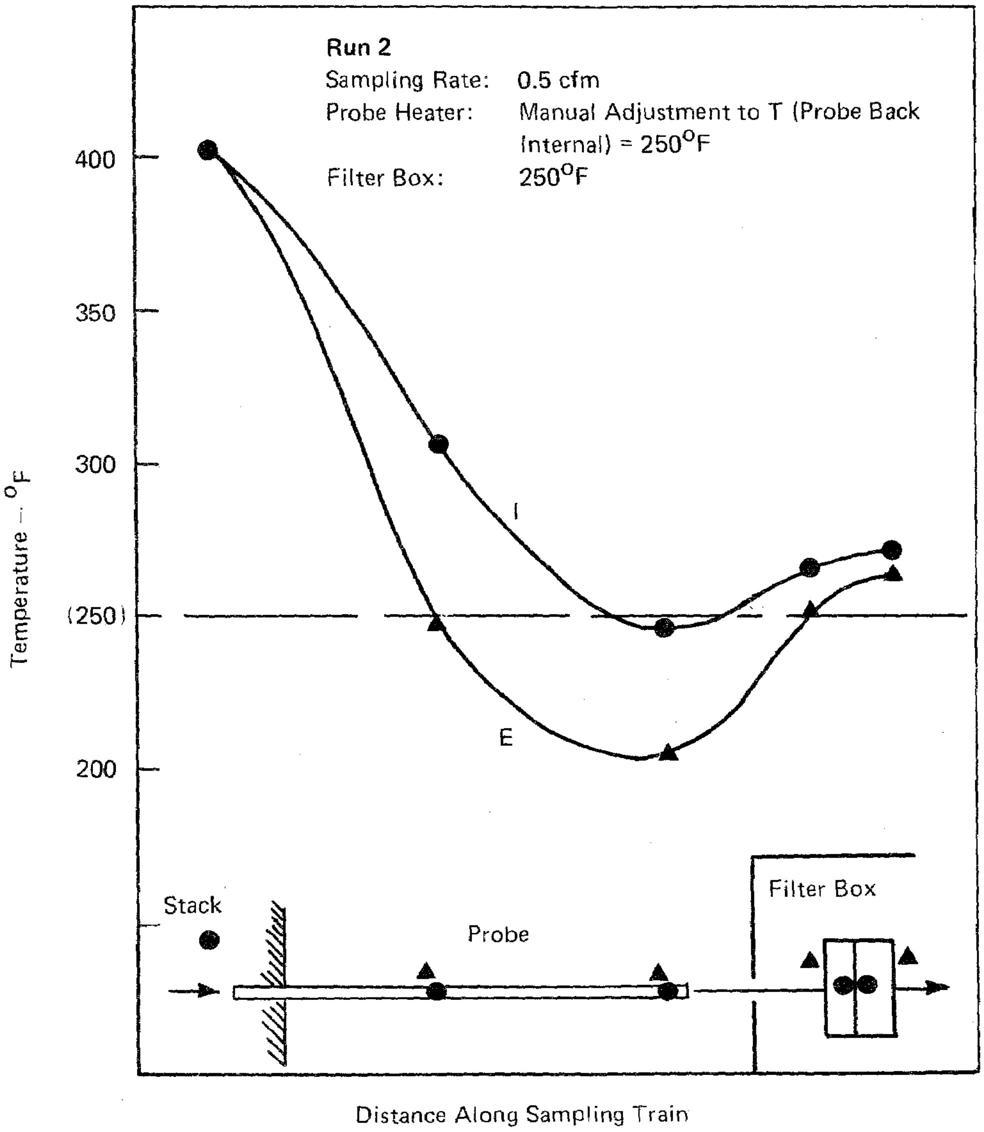

FIGURE 3 Schematic Presentation of Average Gas and External Temperature Distribution Along Sampling Train - Run 2

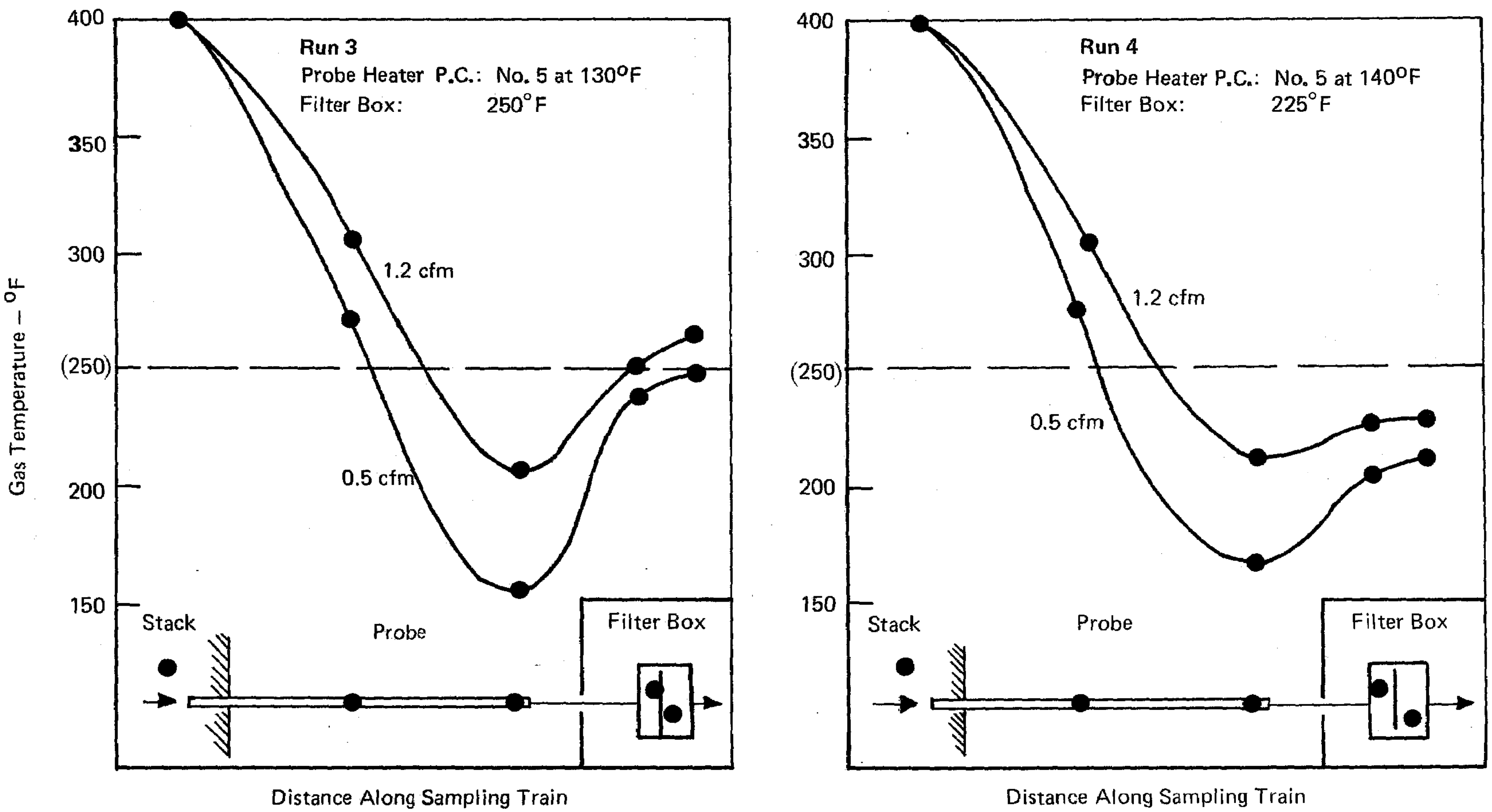

FIGURE 4 Schematic Presentation of Average Gas Temperature Distribution Along Sampling Train as a Function of Sampling Rate - Runs 3 and 4

Figure 6 compares external and internal temperature distributions for Runs 7a and 8a. In the first case, external control at the back of the probe at 250°F (0.5 cfm sampling rate) reveals a 60°F gradient at the back of the probe. The gas temperature is still 270°F upon exiting from the filter. Run 8a was modified to provide external control at 200°F;moreover, the gas stream contained some moisture, having passed through a water bath prior to entering the sampling system. The gradient at the back of the probe for this case was over 100°F. The influence of sampling rate for Runs 7 and 8 is shown in Figure 7. As would be expected, the higher rate results in a flatter profile.

Runs 11, 12 and 13 were conducted to simulate sampling from an ESP-controlled coal fired boiler, evaluating the influence of 250°F probe heater control at Positions 5, 10 and 6, respectively, and a filter box temperature of 250°F. Th experimental data obtained for these evaluations is presented schematically in Figures 8 through 13. When probe temperature is controlled externally at the back of the probe, a very large gradient is observed across the system, with gas temperatures as high as 330°F at the back of the probe and 270°F at the front of the filter as shown in Figure 8. This very large gradient persists at higher sampling velocities, resulting in a gas temperature of 280-300°F at the filter. The distribution of these gradients along the length of the sampling train for two sampling rates is schematically presented in Figure 9. It is interesting to note that the sensible heat of the gas stream is sufficient to raise the external temperature of the filter holder by 10-15°F higher than the filter box temperature.

Figures 10 and 11 present similar data for Run 12. For this case, the probe heater was controlled by a reference thermocouple in the gas stream behind the filter (Position 10). This would be the simplest location for introducing an internal thermocouple into the system in that all particulate has been removed from the gas stream at this point, precluding any sampling train cleanup problems. Examination of Figures 9 and 10, however, indicate that the rather good thermal stability encountered at this reference position results in very large temperature swings in the probe and at the front of the filter. This lack of sensitivity to the gas temperature in other positions of the sampling train makes this reference function position completely unacceptable.

In comparison, the gas temperature at the back of the probe was observed to exhibit the greatest sensitivity to external conditions. Run 13 was performed in which the gas temperature at this point was controlled at 250°F. The results are presented in Figures 12 and 13. These data exhibit a very uniform temperature profile with time, a very small gradient between internal and external positions except at the back of the probe (where the gradient is 50°F), and a very uniform distribution in gas temperature along the length of the system.

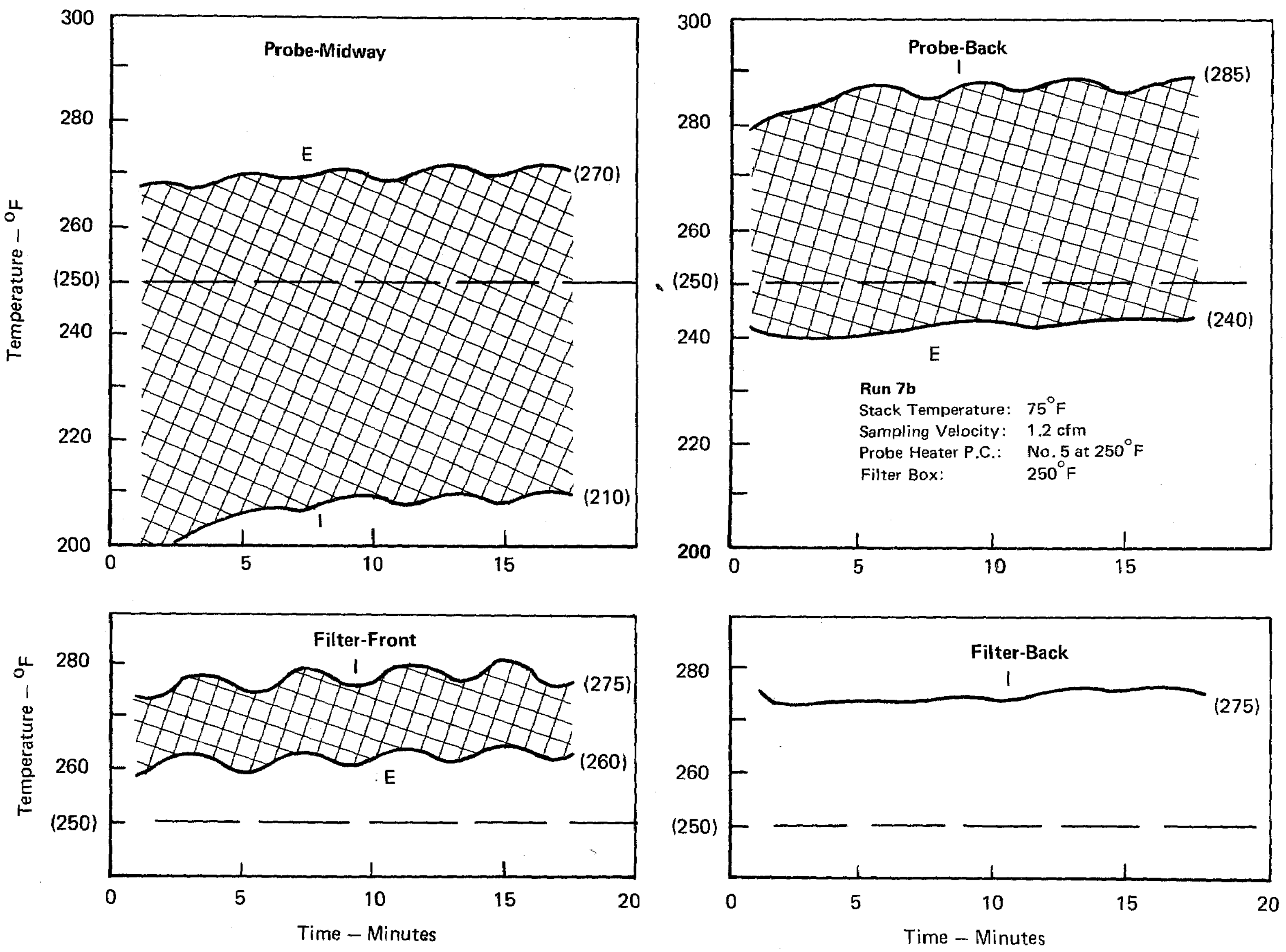

FIGURE 5 Temperature Gradients Across Sampling Train as a Function of Time - Run 7b

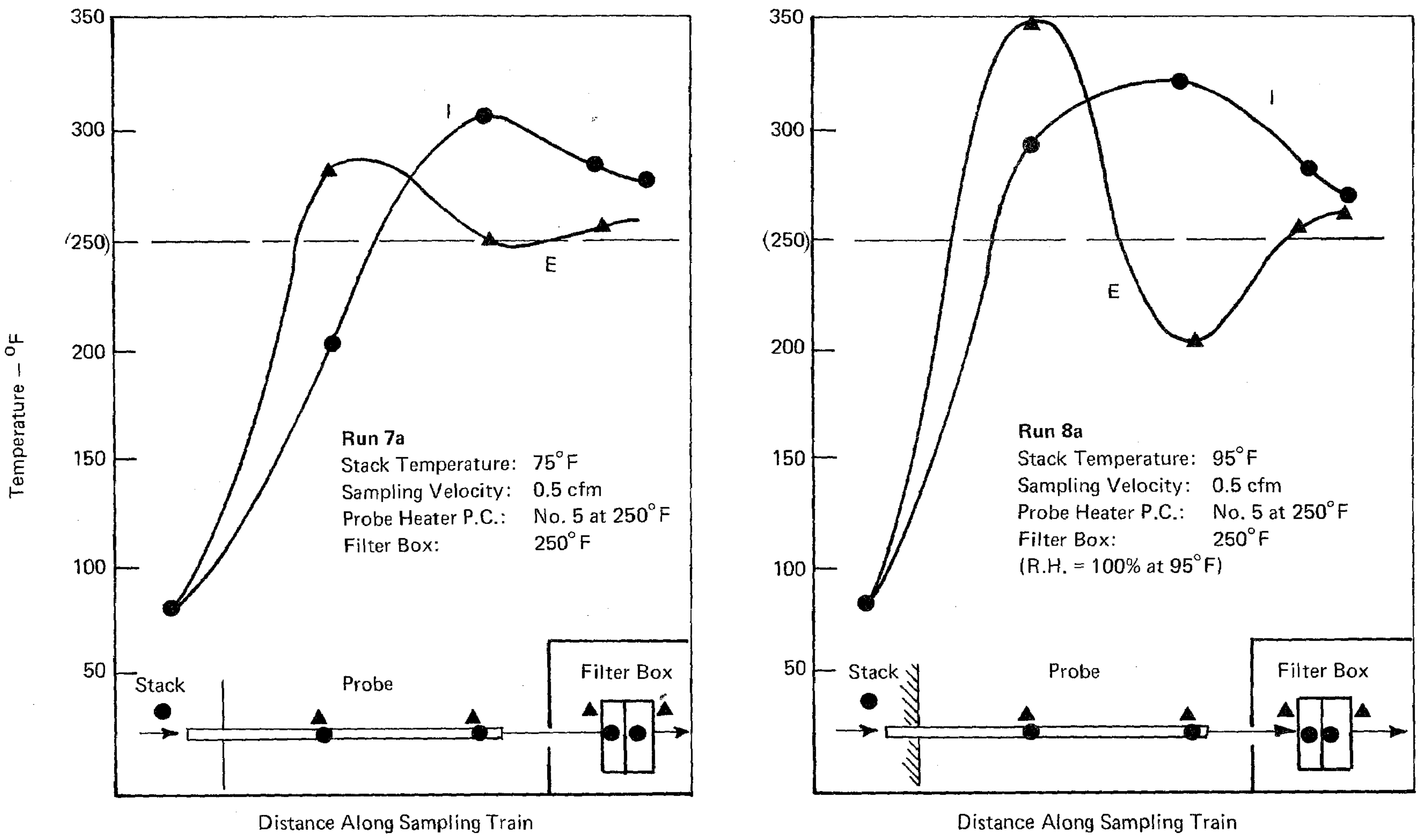

FIGURE 6 Schematic Presentation of Average Gas and External Temperature Distribution Along Sampling Train - Runs 7a and 8a

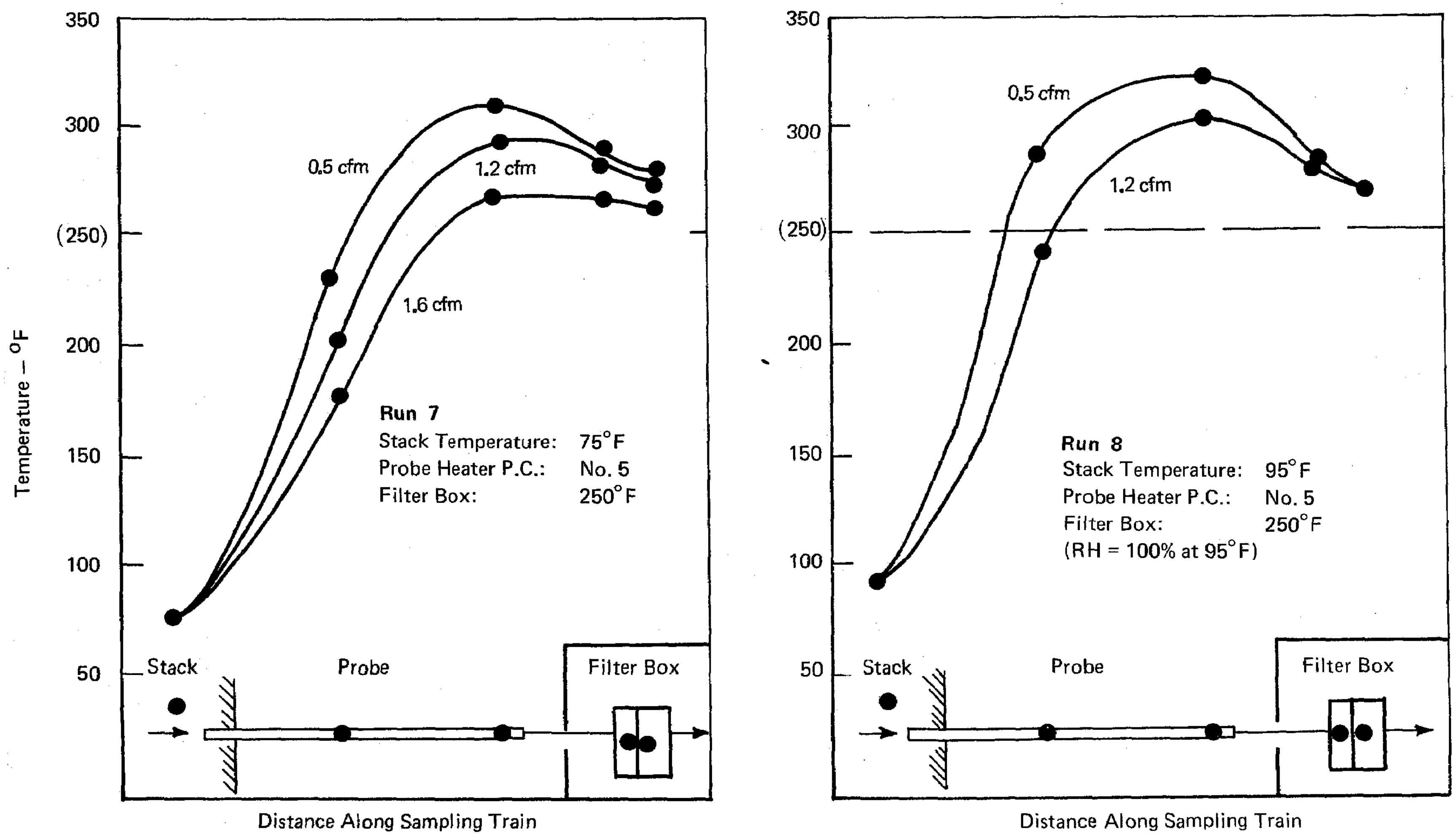

FIGURE 7 Schematic Presentation of Average Gas Temperature Distribution Along Sampling Train as a Function of Sampling Rate - Runs 7 and 8

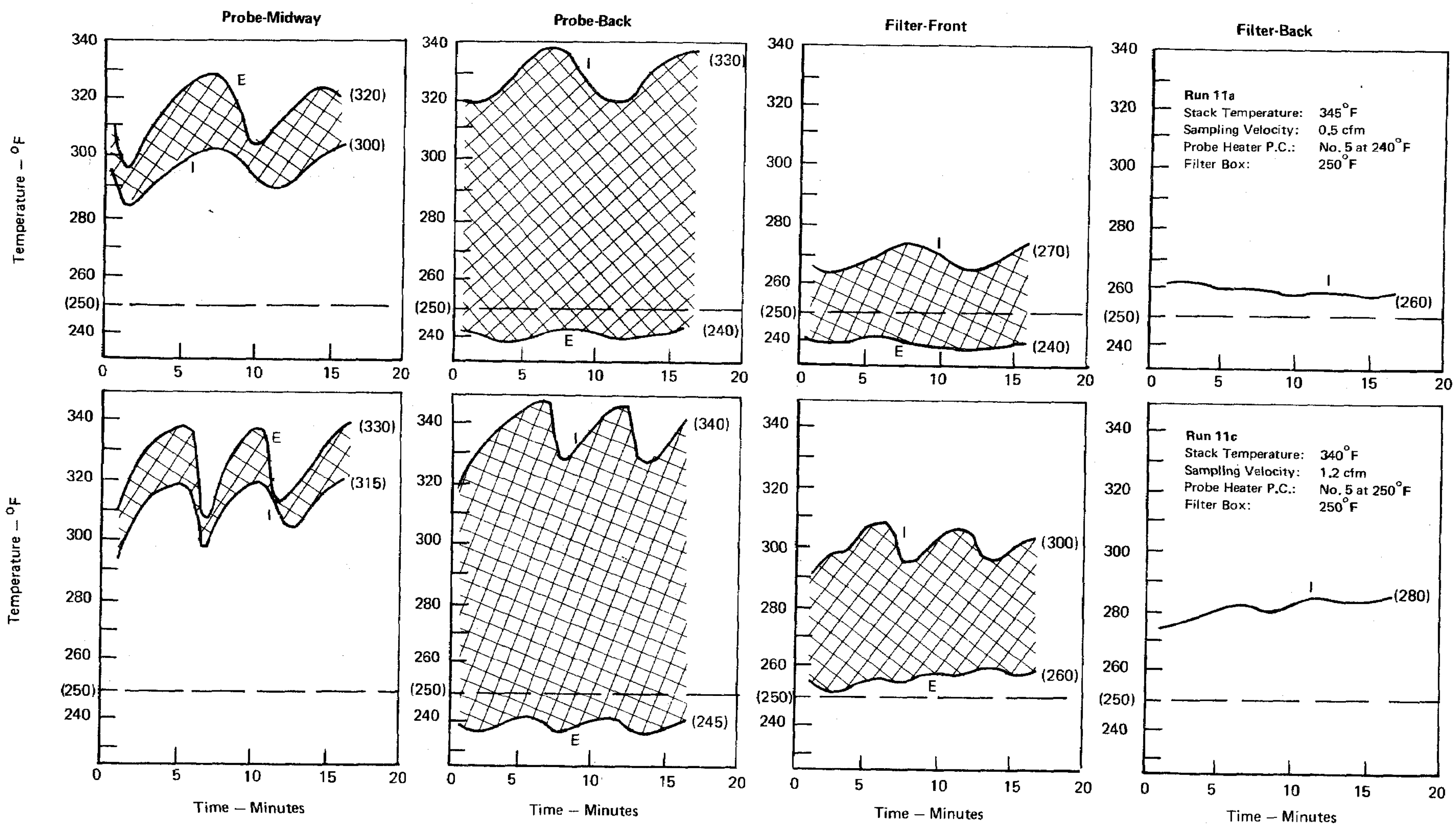

FIGURE 8 Temperature Gradients Across Sampling Train as a Function of Time - Runs 11a and 11c

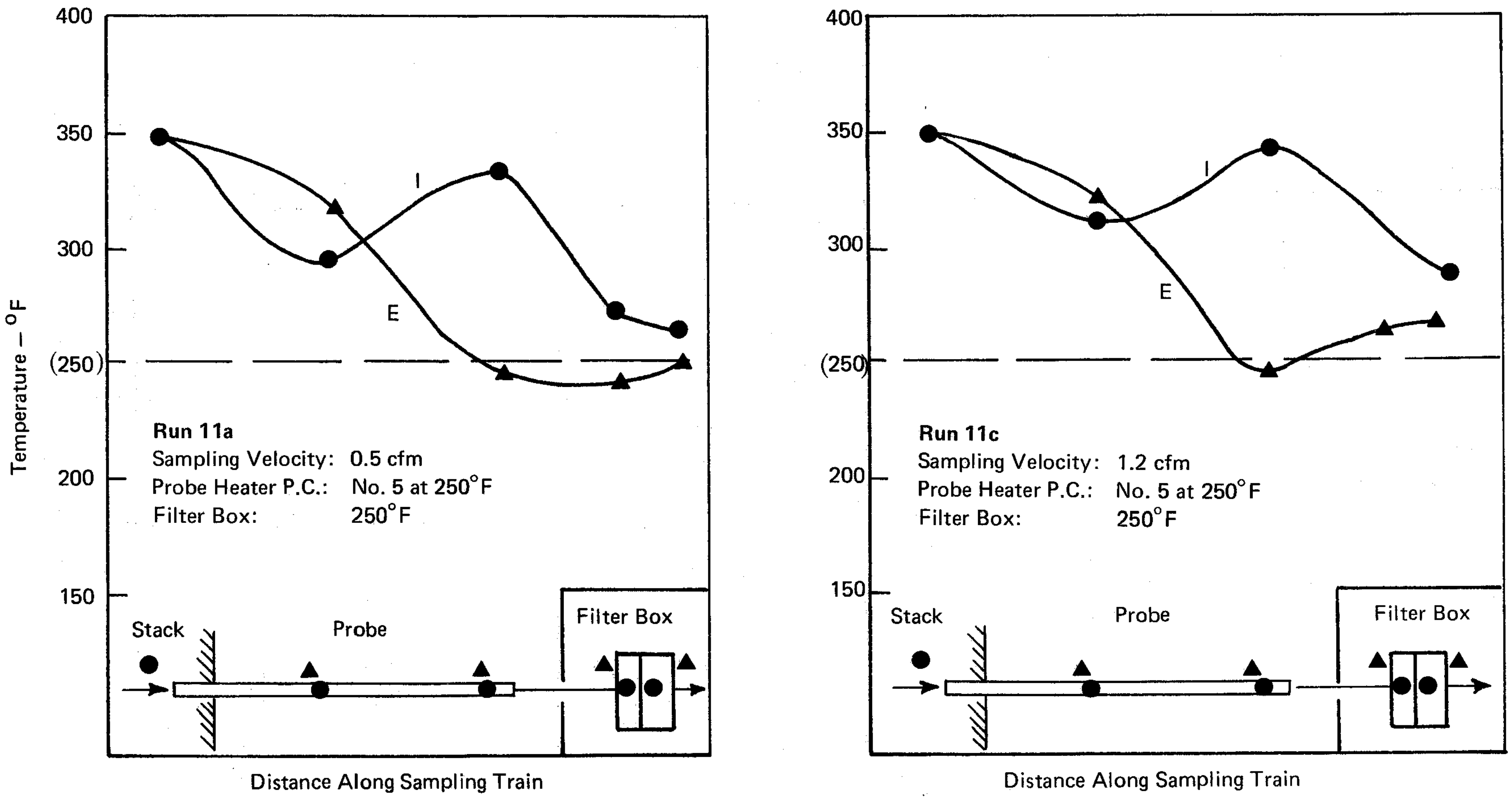

FIGURE 9 Schematic Presentation of Average Gas and External Temperature Distribution Along Sampling Train - Runs 11a and 11c

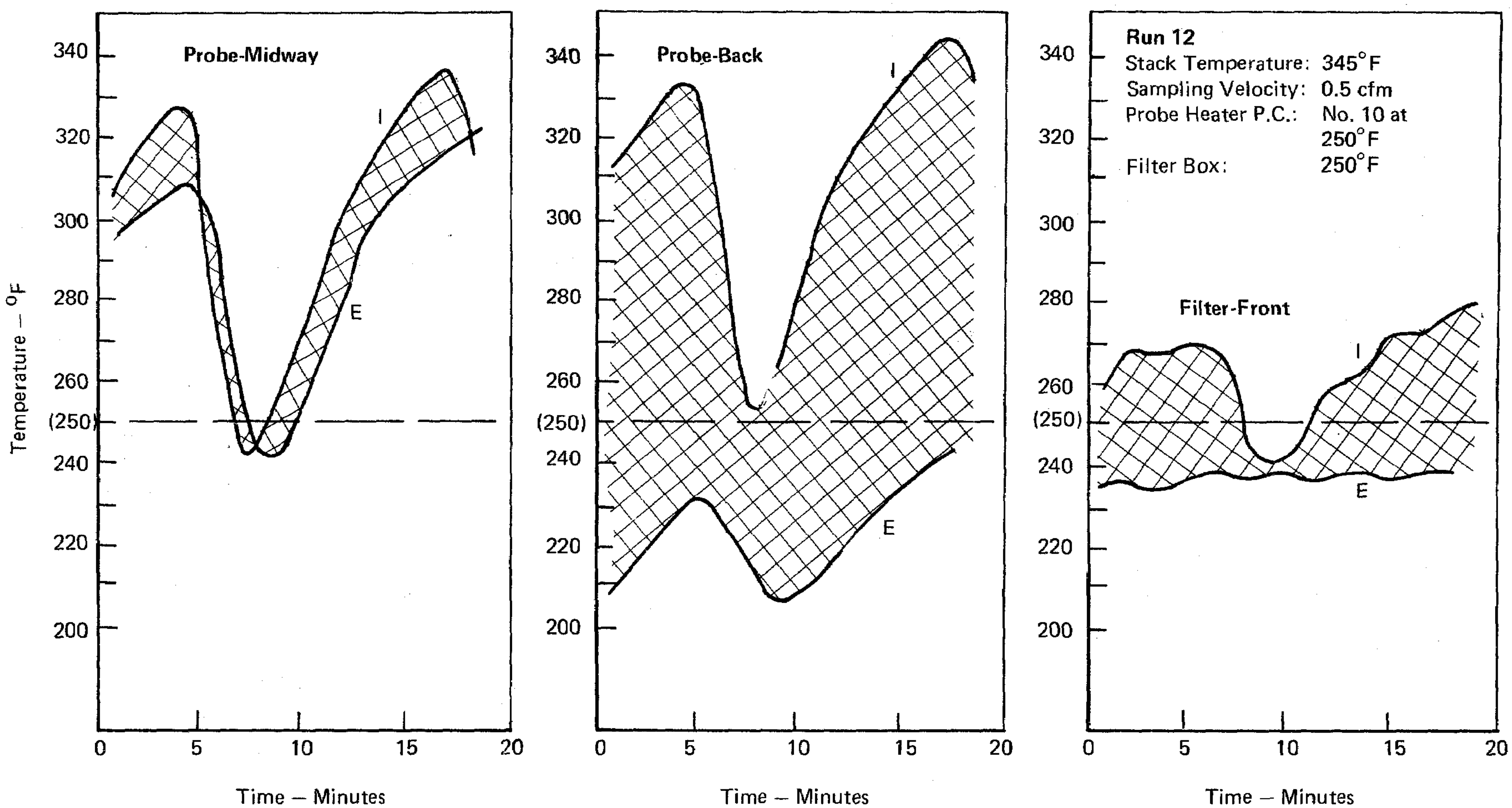

FIGURE 10 Temperature Gradients Across Sampling Train as a Function of Time - Run 12

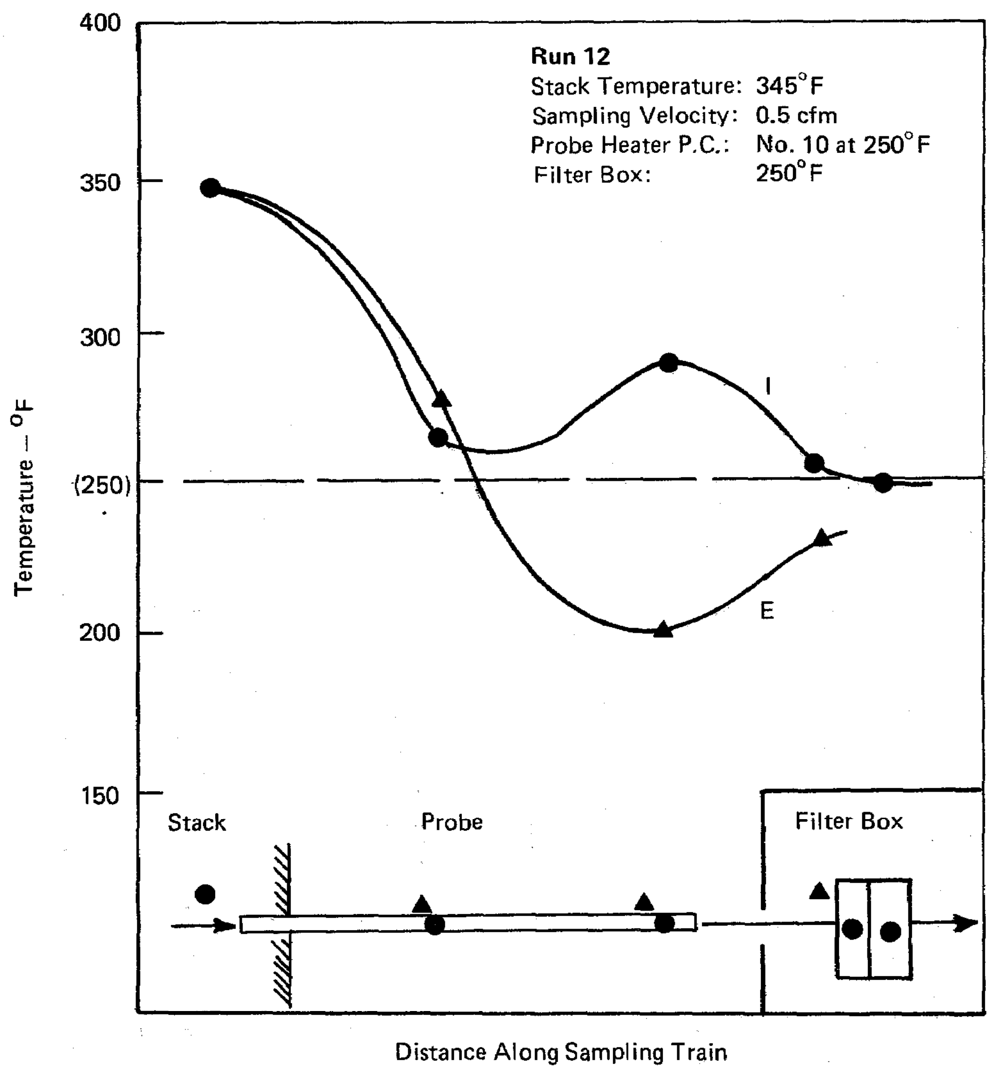

FIGURE 11 Schematic Presentation of Average Gas and External Temperature Distribution Along Sampling Train - Run 12

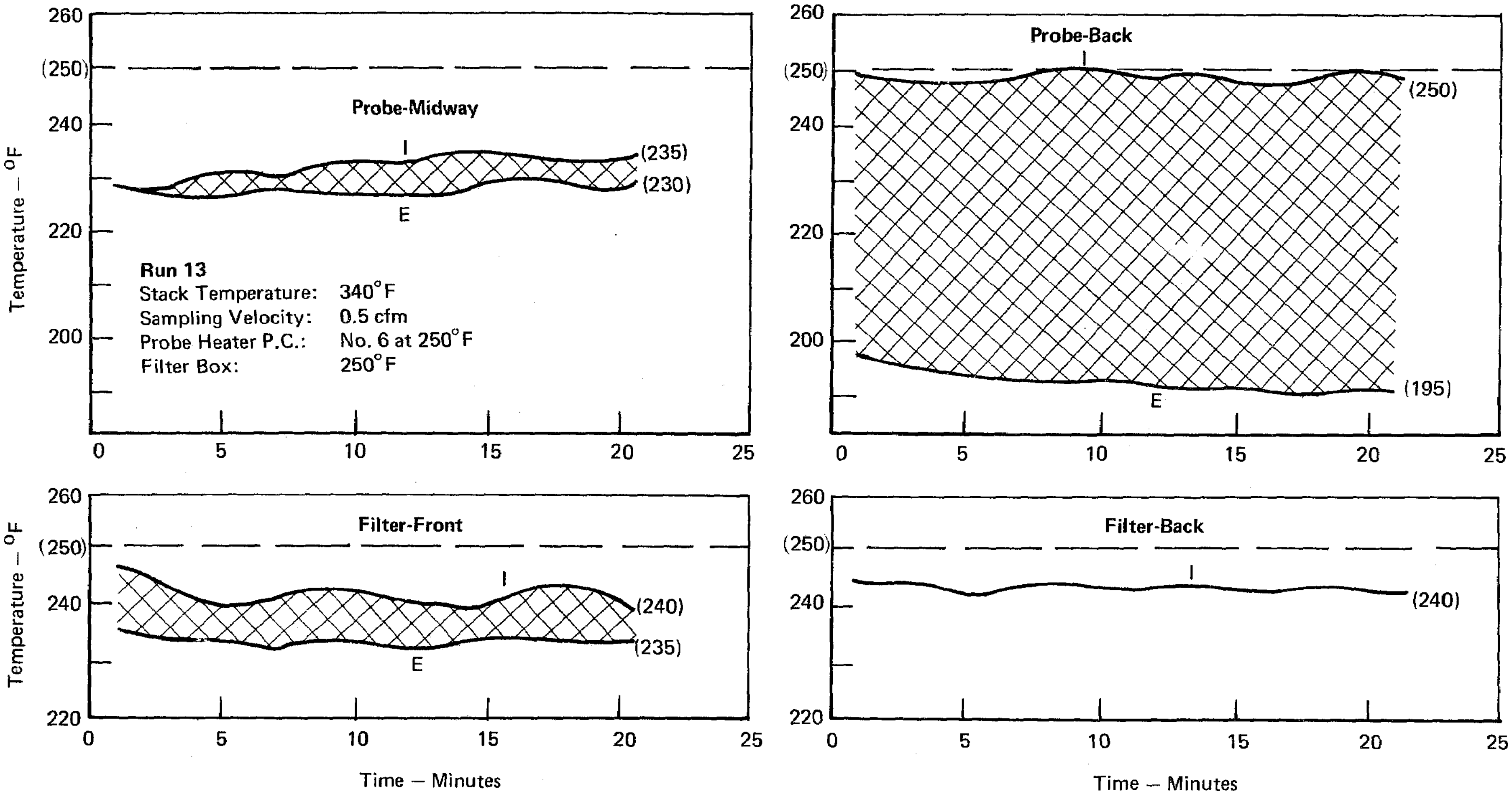

FIGURE 12 Temperature Gradients Across Sampling Train as a Function of Time - Run 13

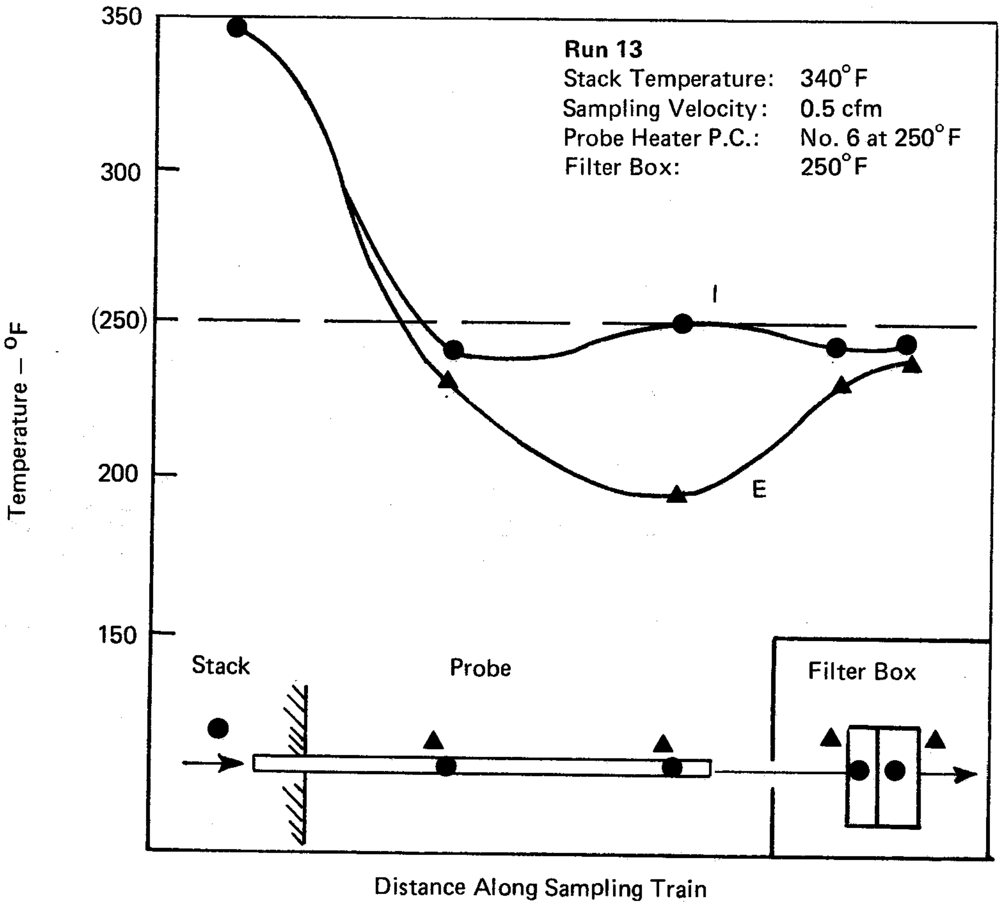

FIGURE 13 Schematic Presentation of Average Gas and External Temperature Distribution Along Sampling Train - Run 13

For the range of experimental conditions considered in the set of runs summarized in Table 2, including variations in stack temperature, sampling rate and reference position for controlling the probe heater, it is evident that large thermal gradients, appreciable temperature swings with time and unpredictable gas temperature distributions along the train are encountered in all cases where the probe heater is controlled on the basis of an external reference temperature or gas temperature behind the filter. However, it has been demonstrated that very good control of gas temperature can be achieved by proportional control of the probe heater element from an internal reference point at the back of the probe. To minimize loss of particulate by collection on the internal thermocouple and incomplete recovery during the train cleanup, it is recommended that the reference thermocouple be enclosed in a 1/16 inch stainless steel sheath that is epoxied in place at the point of entry into the sampling system. Only a slight modification to the glass elbow joining the probe to the filter holder is required. In this way, a gas temperature of 250°F at the exit of the probe as called for by Method 5 can be maintained accurately and reliably.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-79-115	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE EVALUATION OF STATIONARY SOURCE PARTICULATE MEASUREMENT METHODS Volume III. Gas Temperature Control During Method 5 Sampling		5. REPORT DATE June 1979
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Edward T. Peters and Jeffrey W. Adams		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arthur D. Little, Inc. Acorn Park Cambridge, Massachusetts 02140		10. PROGRAM ELEMENT NO. 1AD712 BA-18 (FY-76)
		11. CONTRACT/GRANT NO. 68-02-0632
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, N.C. 27711		13. TYPE OF REPORT AND PERIOD COVERED Interim 10/73 - 2/77
		14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES
Volume I was issued as EPA 650/2-75-051a, June 1975.
Volume II was issued as EPA 600/2-77-026, February 1977

16. ABSTRACT

A study was conducted to measure changes in gas temperature along the length of a Method 5 sampling train due to variations in stack gas temperature, sampling rate, filter box temperature, and method for controlling the probe heating element. For each run condition, temperatures were measured in the stack, at ambient and at four internal and external positions along the sampling train at one minute intervals. Measurements were continued until the system was observed to reach a state of thermal equilibrium. For several experiments in which typical stationary source conditions were tested, substantial differences between gas temperature and external temperature were observed. The method employed for controlling the probe heater and the gas sampling rate were shown to have major influences on gas temperatures and temperature profiles along the sampling train. The results from these experiments demonstrate that gas temperatures cannot be predicted or controlled on the basis of externally measured temperatures. The use of an internal thermocouple, having its reference junction at the back of the probe, to proportionally control the probe heater element is shown to provide a predictable gas temperature and a flat thermal profile along the sampling train. This procedure for controlling gas temperature is recommended as a modification to Method 5.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Air pollution * Particles * Flue gases Collecting methods Evaluation * Temperature control Revisions		13B 21B 14B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 31
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE