HASL-220
HEALTH AND SAFETY (TID-4500)

INVESTIGATION OF THE RADIOLOGICAL CHARACTERISTICS OF URANIUM MINE ATMOSPHERES

A. J. Breslin
A. C. George
M. S. Weinstein

December 1969

Health and Safety Laboratory
U.S. Atomic Energy Commission
New York, New York

DISCLAIMER

DISCLAIMER

ABSTRACT

Radiological characteristics of the environments of nine representative uranium mines were studied by survey teams equipped to collect and analyze samples underground. Spatial and temporal variations of radon concentration, working level, and radon daughter ratio were investigated for three to four days in each mine by obtaining consecutive measurements at typical locations and operations. Additional measurements included gamma radiation, ore dust concentration, temperature, relative humidity, barometric pressure, and ventilation rate. Data are summarized and discussed in the text, and detailed in three appendices.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLES

FIGURES

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

APPENDICES

I. INTRODUCTION

An investigation of the radiological characteristics of uranium mine atmospheres was conducted in the fall and winter of 1967-68 by the Health and Safety Laboratory (HASL) aided materially by the AEC's Grand Junction Office and U.S. Bureau of Mines' Denver office. Comprehensive measurements of radon and radon daughters were made in nine uranium mines for several days each by teams equipped to collect and analyze air samples underground. Data reduction and a few delayed sample analyses for long-lived radioactivity were performed at HASL. The mines were selected by the U.S. Bureau of Mines to represent a cross section of the industry with respect to size, geology, and geographic location.

The investigation was performed to provide a detailed description of current uranium mine atmospheres. In 1957, the U.S. Public Health Service reported very extensively on mine atmospheres in its well known Handbook #494(1) but important industry-wide changes have occurred since, brought about mainly by markedly increased ventilation for the reduction of radon daughter concentrations and by improved mining technology. The need for current information was highlighted in 1967 by the congressional hearings on the radiation exposure of uranium miners(2) and by Federal Radiation Council Report #8(3) that recommended ".....a more precise definition of the composition of mine atmospheres.....".

This report is primarily descriptive. Virtually all measurements are presented in appendices, but data summaries are given in the body of the report along with appropriate comment. The data include: concentrations of radon gas, radon daughters (working levels), and ore dust; radon daughter ratio; ventilation rate, temperature, humidity, and barometric pressure; estimates of measurement error. It is anticipated that the information presented may be useful for a variety of purposes such as specifying performance for monitoring instrumentation, establishing optimum sampling protocols, and predicting effects of control measures.

II. FIELD INVESTIGATION

A. Scope

A factor stressed repeatedly at the 1967 congressional hearings(2) was the extreme variation of atmospheric characteristics within a mine, and among mines. This investigation could not cover fully the implied spread of conditions, but it was designed to acquire the most useful information within available man-power and instrumentation. Observation of atmospheric variability was an important objective in the adopted scope.

Originally six Colorado mines of varied nature were selected by the U.S. Bureau of Mines, this number being considered the minimum for representativeness. The number was later raised to nine because 1) measurements of radon concentration at the first three mines were found to be invalid and 2) consultants advised that New Mexican mines should be represented because of their growing dominance in total ore production. The three mines selected near Grants, New Mexico are larger and represent newer technology than the first six mines.

Radiological measurements were performed for three to four days at each mine by three, two-man units which sampled and measured independently in different locations within a mine. A unit usually remained in a given location for one or more days. The U.S. Bureau of Mines provided an additional team member to obtain daily measurements of ventilation, temperature, humidity, and barometric pressure in locations occupied by the sampling units. This disposition of the team, yielding very comprehensive data from a few locations, was chosen rather than covering more locations in less detail. The chosen arrangement provided data for making accurate estimates of the means and variances of all radioactive constituents of interest.

Locations selected for measurement were usually in operational areas. The two-man sampling units entered the mine with the day shift miners and proceeded to their respective sampling locations where they performed measurements until the end of the shift. The team members became more adept at setting up equipment and maintaining a sampling rhythm with practice, thus data are more extensive for the mines covered later in the investigation.

B. Uranium Mines

For geographic representation, three mines each were selected in Beaver Mesa, Colorado, in the Uravan Belt, Colorado, and in the Ambrosia Lake district of New Mexico. Average ore assays were fairly uniform, being in the range 0.2 - 0.3% in all mines. The mines were chosen to represent a range of general features as described in Table I. This listing demonstrates the variety of features covered but is not meant to imply that any of the features necessarily influence the characteristics of radioactive air contaminants.

All of the mines were ventilated mechanically with main fans situated at shafts and in most, small booster fans connected to short, flexible ducts were deployed underground to direct air to specific locations*. Drifts constituted the principle conduits for ventilating air.

*The booster fans and ducts were moved as necessary to keep up with excavation and shifting points of operation.

TABLE I

URANIUM MINE FEATURES

Mine	Date of Survey	Location and Geologic Formation	Approx. Depth ft	No. of Miners	Rate of Ore Prod. tons/mo.	Type of Motive Power*	Aver.# Temp. °F	Aver. Rel.# Humidity %	Condition of Surfaces	Ventilation Type	Ventilation Total Rate cfm
A	9/67	Beaver Mesa, Colorado Morrison	160	2	150	pneumatic	51	82	dry, dusty	downcast	5,600
B	"	"	170	20	2500	electric, pneumatic	52	95	dripping, pools of water	downcast-upcast, aux. fans**	50,000
C	"	"	650	11	1600	pneumatic	51	96	scattered pools of water, otherwise dry	upcast	78,000
D	11/67	Uravan Belt, Colorado Morrison	800	12	1100	Diesel	55	73	dry	downcast, aux. fans**	47,000
E	"	"	300 - 600	6	380	electric	49	80	dry	downcast, aux. fans**	36,000
F	"	"	200 - 500	112	5800	electric, electric battery	57	87	wet	downcast, aux. fans**	85,000
G	1/68	Ambrosia Lake, New Mexico, Zuni Uplift	750	30	8000	Diesel	64	83	dry	upcast	100,000
H	"	"	540	27	11,000	electric, Diesel	42	62	dry	downcast, aux. fans**	187,000
I	"	"	550	87	8800	electric, electric battery	59	90	dry	downcast, aux. fans**	103,000

*For slushing and mucking. In all mines, drilling was pneumatic and ore trains were battery-operated.

#During period of survey.
**Booster Fans underground.

Because measurements were obtained in relatively few locations (up to seven) in each mine, regardless of size, it is evident that the larger mines were not covered completely. However, the selected locations were in active areas and typified, as much as possible, different functions and operations (station, drift, stope; drilling, mucking, loading, timbering, track laying).

C. Methods

The basic monitoring unit was a two-man team equipped to collect samples of radon gas concentration, radon daughter concentration and ratio, and ore dust concentration and to measure external gamma radiation. Radon gas and daughter samples were alpha-counted immediately at the sampling location; ore dust samples were analyzed later at HASL. Normally, paired radon gas and paired radon daughter samples were collected simultaneously and alpha-counted.

In each location selected for monitoring, a reference station was established where a pair of radon gas and radon daughter samples was collected at half-hour intervals throughout the day. With each pair of reference samples, a second pair was collected simultaneously either at the reference station or at distances from tens to hundreds of feet away. By this arrangement, variation was examined as a function of time and of distance, while reproducibility was determined from the duplicates. While these measurements were being made, a record was maintained of all mining activities in the area.

Generally, in each monitoring location, a few samples of airborne ore dust were collected over periods of several hours and spot measurements were obtained of external gamma radiation. Temperature, humidity, barometric pressure, and ventilation rate were measured daily.

In most instances, monitoring units remained in the same location for two or more days, repeating the same series of measurements each day.

Radon gas concentration was measured by the "two-filter method"[4]. Air was sampled at 10 l/min for ten minutes through a metal cylinder having a high efficiency filter at each end. At the end of the sampling period, radium-A, decayed from radon in the cylinder and collected on the downstream filter, was immediately measured in an alpha scintillation counter. Radon gas concentration was later calculated by an equation involving sample flow rate and period, cylinder volume, alpha count, and counting time.

Radon daughters were collected on high efficiency glass fiber filters through which air was drawn at 10 l/min for ten minutes. After collection, the filters were alpha counted for 30 minutes in a scintillation detector connected to a strip-chart recorder. From the resultant trace of alpha count rate versus time, the individual concentrations of radium-A, radium-B, and radium-C were calculated by the Tsivoglou method[5] and the working level (WL) was calculated.

Ore dust was collected on a high efficiency glass fiber filter paper for a period of several hours at 20 - 25 l/min. The filters were later analyzed for total alpha activity on scintillation counters at HASL.

Gamma intensities were measured with Geiger-Mueller survey instruments.

III. RESULTS

Detailed results are given in the appendices. Appendix A consists of graphical presentations of radon concentration and WL against time for each sampling location. The graphs contain notations regarding mining activities, ventilation, temperature, humidity, and barometric pressure. Each graph is preceded by a diagram of the location with pertinent information regarding local features. The first four pages of Appendix A explain the symbols that appear on the diagrams and graphs.

Appendix B is a table of daily average radon daughter ratios. The ratios are given relative to radium-A for all locations and also relative to radon for the mines where radon measurements were considered to be valid.

Appendix C is a table of ore dust concentrations.

This section of the text summarizes the results according to magnitudes, measurement errors, variations with time and variations with distance. Section III.A summarizes the magnitude of the radon concentrations, working levels, working level ratios, radon daughter ratios, ore dust concentrations, and gamma radiation levels. Section III.B presents an analysis of the errors associated with the radiologic measurements. Sections III.C through F present information about the degree of variability of radiologic constituents in mine air, principally, temporal and spatial variability.

A. Magnitudes

1. Radon Gas and Radon Daughter Concentrations (WLs)

Individual values of radon gas concentrations were in the range of 4 - 7000 pCi/l.

Following surveys performed in the first three mines, abnormalities were observed in the radon gas data which were eventually traced to operational difficulties with the two-filter method and the data were rejected. These difficulties were remedied prior to subsequent surveys. The radon data in Fig. 1 show the frequency distribution of daily average concentrations for a total of 54 location-days in six mines. The most frequent (33%) concentration interval was 250 - 500 pCi/l. Although not shown in the figure, less than 4% of observed concentrations were in the range of 0 - 100 pCi/l.

Table II lists the daily average radon concentrations by mine and location-day.

Individual values of working level (WL) were in the range from 0.01 - 7.2. Average WL's by mine location and day are given in Table II. These values do not necessarily reflect over-all mine conditions because of the limited number of sampling locations.

The frequency distribution of daily average radon daughter concentrations expressed as WL's is shown in Fig. 2 for 84 location-days in nine uranium mines. The most frequent concentration interval (33%) was 1 - 2 WL. About 20% exceeded 3 WL and somewhat more than 3% exceeded 5 WL.

The distributions of radon gas and radon daughter concentrations are given separately for stopes and drifts in Fig. 3. The distributions of radon daughters in stopes and drifts and of radon gas in drifts are virtually indistinguishable but contrast noticeably with the distribution of radon gas in stopes. A possible explanation for the contrasting distribution relates to working level ratios, the subject covered in the next section.

2. Working Level Ratios

Working level ratio is a convenient if approximate unit expressing the degree of equilibrium between gas and its daughters. It is simply 100 times the WL divided by the radon concentration in pCi/l, i.e., at equilibrium the ratio is unity.

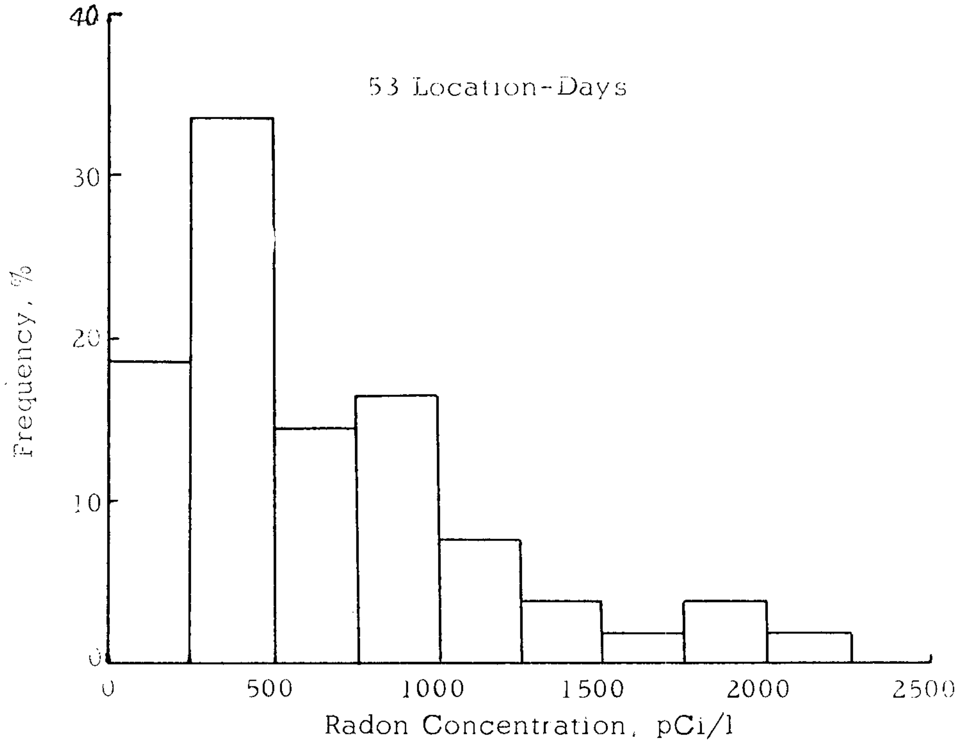


Fig. 1 - Distribution of Daily Average Radon Concentrations

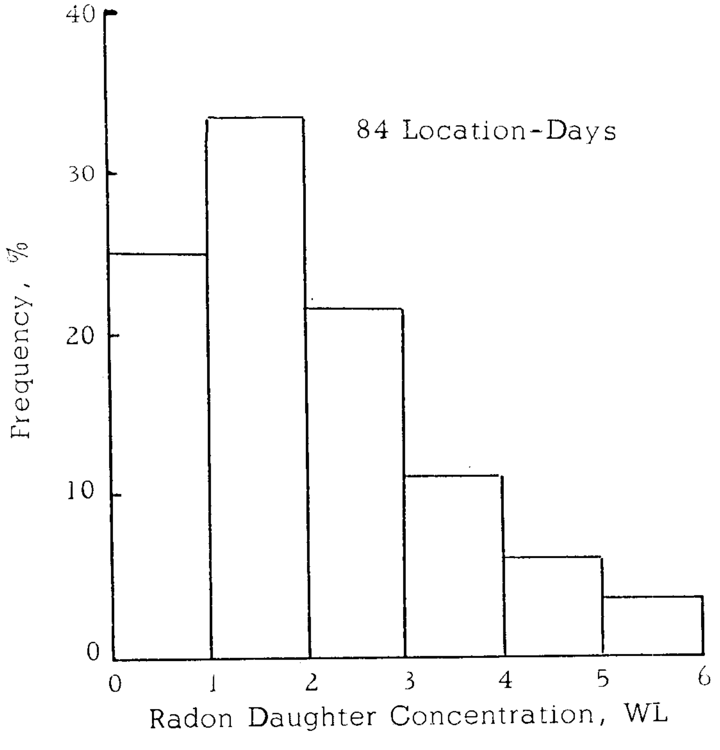


Fig. 2 - Distribution of Daily Average Working Levels.

TABLE II

DAILY AVERAGE RADON CONCENTRATION, RADON DAUGHTER CONCENTRATIONS, AND WORKING LEVEL RATIO

Mine	Location	Rn, pCi/l	Average for each Day Rn Daughters, WL	WL Ratio
A	1 stope fan station		2.8	
			0.94	
			0.67	
	2 stope		4.5	
			2.1	
			1.4	
	3 haulage drift		4.5	
			2.4	
			1.9	
B	1 drift confluence		1.1	
			1.0	
			1.1	
	2 stope		2.1	
			2.4	
			2.1	
	3 stope		2.1	
			2.3	
			2.1	
C	1 stope		5.5	
			5.0	
	2 stope		4.1	
			3.8	
	3 drift confluence		3.8	
			3.8	

TABLE II (cont'd)

Mine	Location	Average for each Day: Rn, pCi/L	Rn Daughters, WL	WL Ratio
D	1 haulage drift	410	0.69	0.17
	2 dead end drift	190	0.66	0.34
		380	1.0	0.27
		330	1.1	0.35
	3 haulage drift		1.1	
			1.0	
	4 stope	420	0.41	0.10
		410	0.78	0.19
		360	0.60	0.17
E	1 dead end drift	650	1.6	0.25
		460	1.3	0.27
		1000	3.1	0.31
	2 haulage drift		1.2	
			1.2	
			2.0	
	3 dead end drift	230	0.36	0.16
		180	0.45	0.25
		270	0.67	0.25
F	1 stope	430	1.4	0.32
			2.1	
	2 stope	490	1.3	0.26
			1.1	
	3 stope	360	2.0	0.56
		360	2.4	0.65
	4 stope	340	1.7	0.52

TABLE II (cont'd)

Mine	Location	Average for each Day: Rn, pCi/l	Rn Daughters, WL	WL Ratio
F	5 drift	87	0.22	0.25
		110	0.27	0.25
	6 stope	220	0.46	0.21
		180	0.42	0.23
	7 drift	540	1.3	0.24
G	1 drift	400	0.82	0.20
		420	1.1	0.26
		380	1.0	0.26
	2 drift, near heading	1300	3.1	0.23
		1800	4.3	0.24
		1600	3.5	0.23
	3 deadend heading	1900	4.0	0.21
		2300	5.1	0.22
	4 heading, off cross-cut	680	1.7	0.25
H	1 cross-cut	330	0.26	0.08
		370	0.43	0.12
	2 cross-cut	830	1.0	0.13
		1000	1.1	0.11
	3 cross-cut	780	1.4	0.19
		820	1.4	0.17
		1100	2.1	0.18
	4 cross-cut	770	1.3	0.17
		920	1.5	0.17
	5 drift	870	2.1	0.25
	6 stope	960	1.4	0.14
		670	1.1	0.16

TABLE II (cont'd)

Mine	Location	Average for each Day: Rn, pCi/l	Rn Daughters, WL	WL Ratio
I	1 drift	84	0.19	0.23
		190	0.23	0.10
	2 drift	160	0.26	0.17
	3 deadend heading	670	2.2	0.33
		640	2.3	0.37
		900	2.7	0.31
	4 cross-cut	1100	3.2	0.28
		1000	3.0	0.29
		1400	3.8	0.26

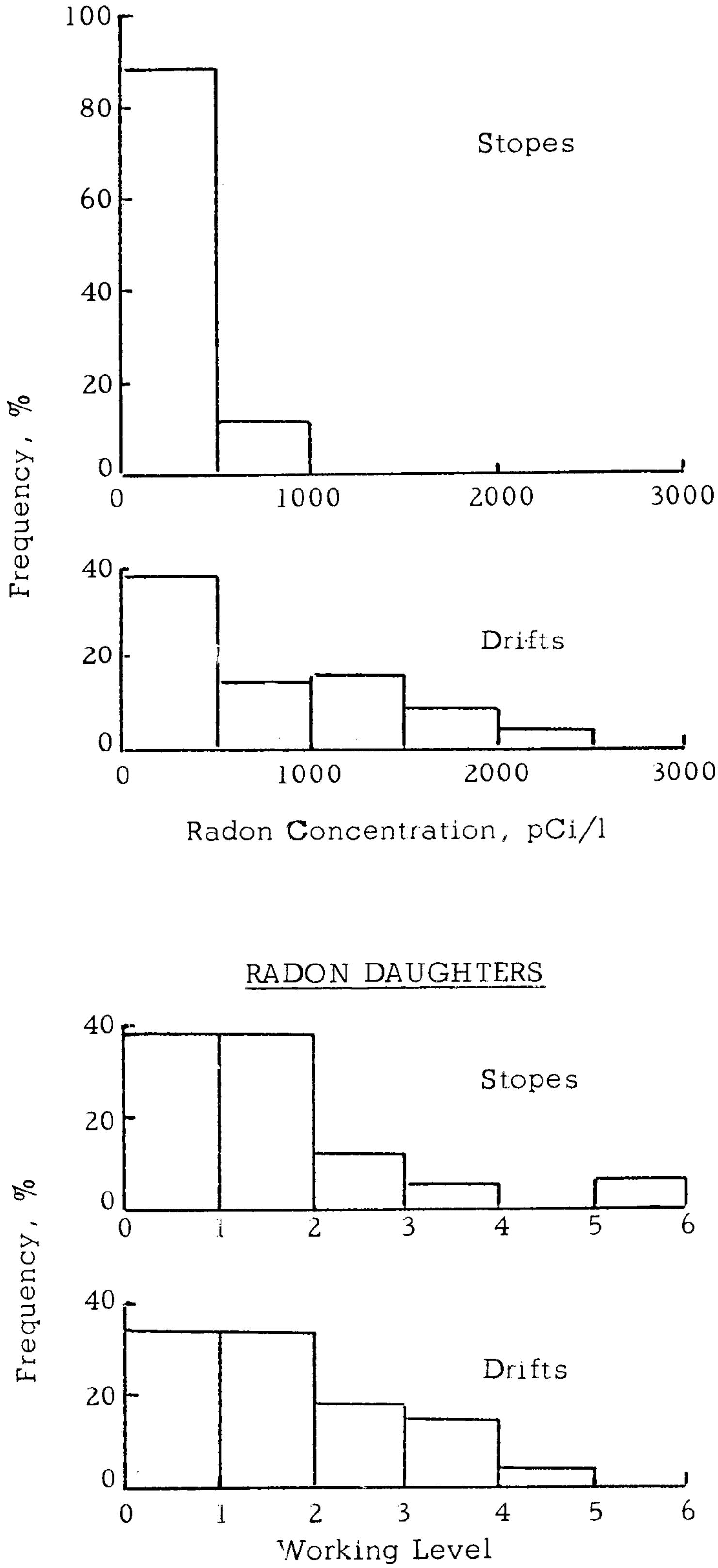


Fig. 3 - Distribution of Daily Average Radon and Radon Daughter Concentrations in Stopes and Drifts.

The frequency distribution of daily average WLR for 53 location-days is shown in Fig. 4. The rather narrow distribution, with 92% in the interval from 0.1 - 0.4, is an argument for those who prefer to measure radon gas rather than radon daughters for either engineering control or personnel monitoring.

This possibility may be examined more rigorously in statistical terms. The apparent log-normality of the frequency distribution in Fig. 4 is confirmed by the cumulative frequency plot of the same data in Fig. 5. The composite distribution for the six mines has a geometric mean of 0.23 WLR and a geometric standard deviation of 1.6. Thus, if a WLR of 0.23 were adopted to convert radon concentration to WL, 68% of the estimates would fall between 60% and 160% of the value of WL determined by a direct method. However, note that the mean WLR's at individual mines differ from the composite mean and that the individual standard deviations at most of the mines are less than that of the composite distribution. Therefore, improvement in both accuracy and precision might be achieved by setting a value of WLR for each mine based on local measurements.

The distributions of WLR's are shown separately for stopes and drifts in Fig. 6. Although relatively few values of WLR greater than 0.4 were found in this investigation, they all occurred in stopes and accounted for nearly 20% of the values in stopes. This might partially explain the distribution patterns previously shown in Fig. 3. That is, stopes generally have a higher WLR than drifts and, consequently, a higher WL for a given radon concentration. Therefore, the WL distribution in stopes and drifts is comparable despite the lower radon concentration in stopes.

An additional characteristic of WLR's shown in Fig. 7 is the tendency to higher values at higher working levels.

3. Radon Daughter Ratios

The extreme daily average ratios were 0.98 : 0.73 : 0.49 : and 0.27 : 0.09 : 0.04 (RaA/Rn : RaB/Rn : RaC/Rn) for the six uranium mines in which measurements of both radon and radon daughters were obtained. The most frequent ratio in the six mines was 0.53 : 0.27 : 0.16. The distribution of daily average radon daughter ratios is given in Fig. 8. This distribution is plotted for equal intervals of RaB/Rn ratio.

Few of the ratios can be accounted for by simple processes of radon daughter development. To illustrate this point, it is convenient first to note an exception. The highest daily average ratio of 0.98 : 0.73 : 0.49, illustrated

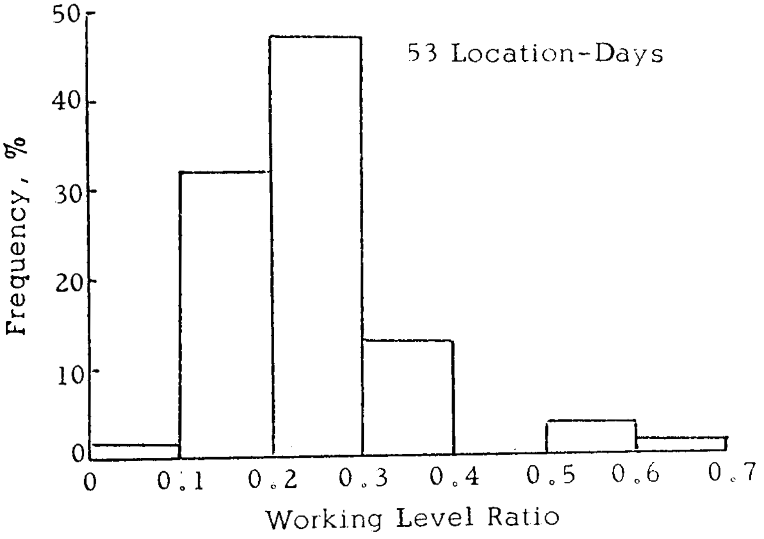


Fig. 4 - Frequency Distribution of Daily Average Working Level Ratios.

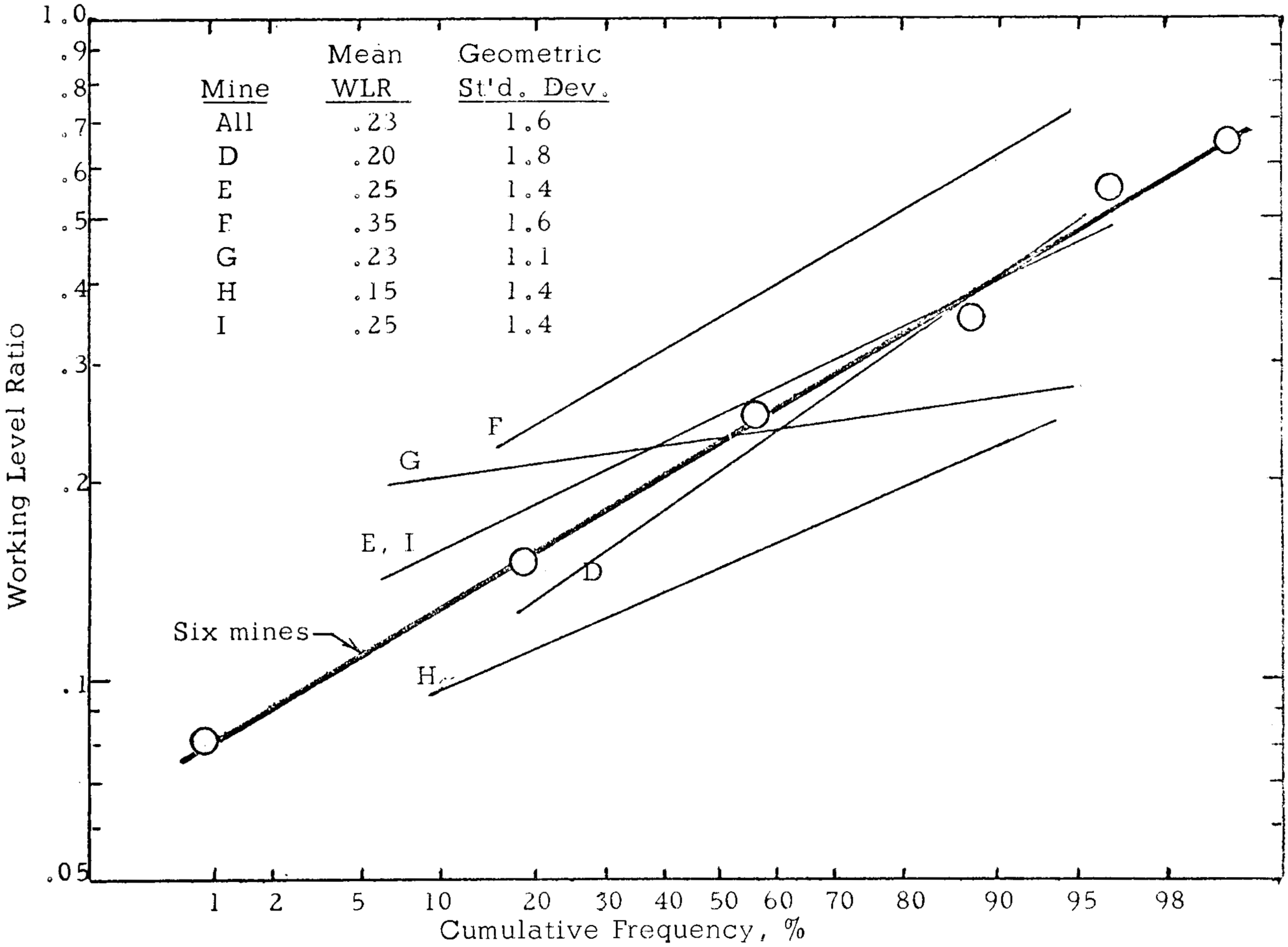


Fig. 5 - Cumulative Frequency Distribution of Working Level Ratios.

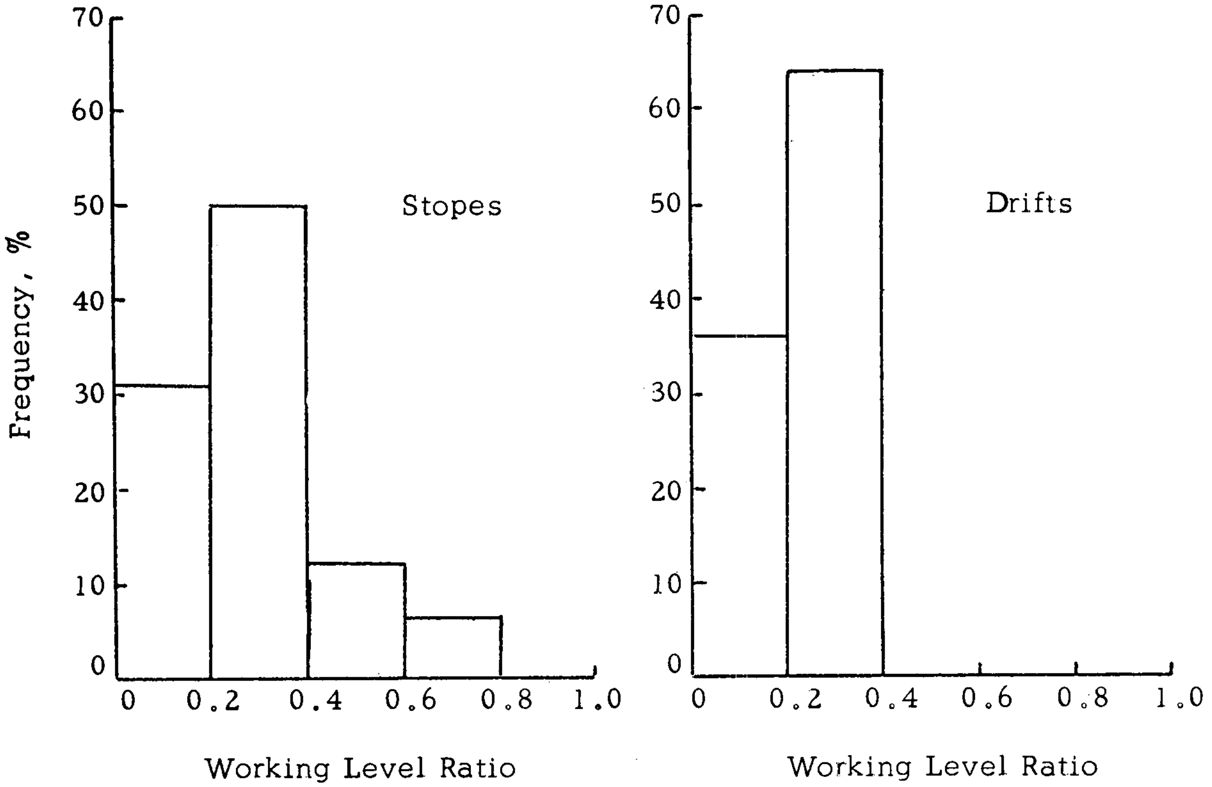


Fig. 6 - Distribution of Working Level Ratios in Stopes and Drifts.

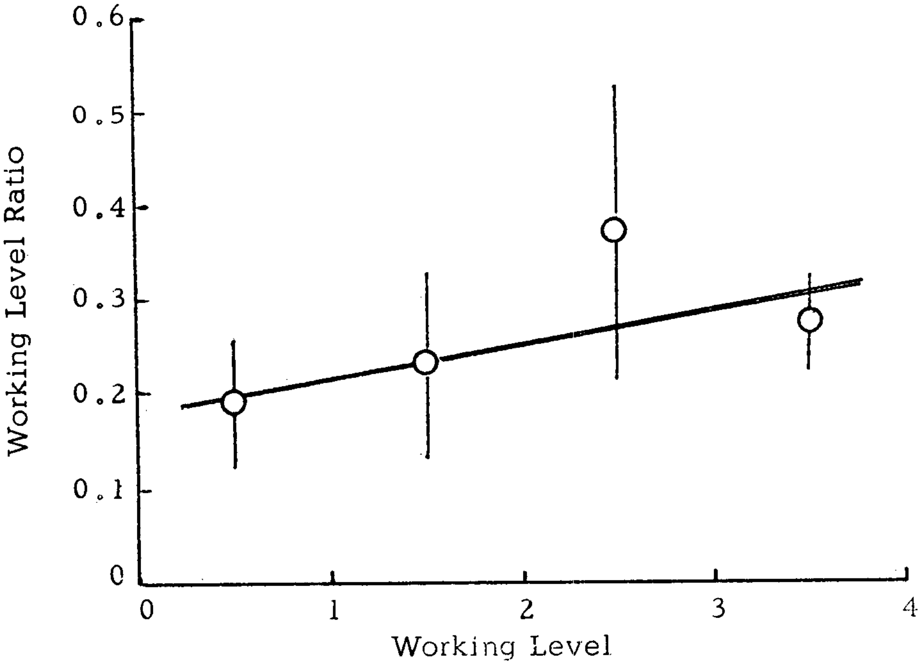
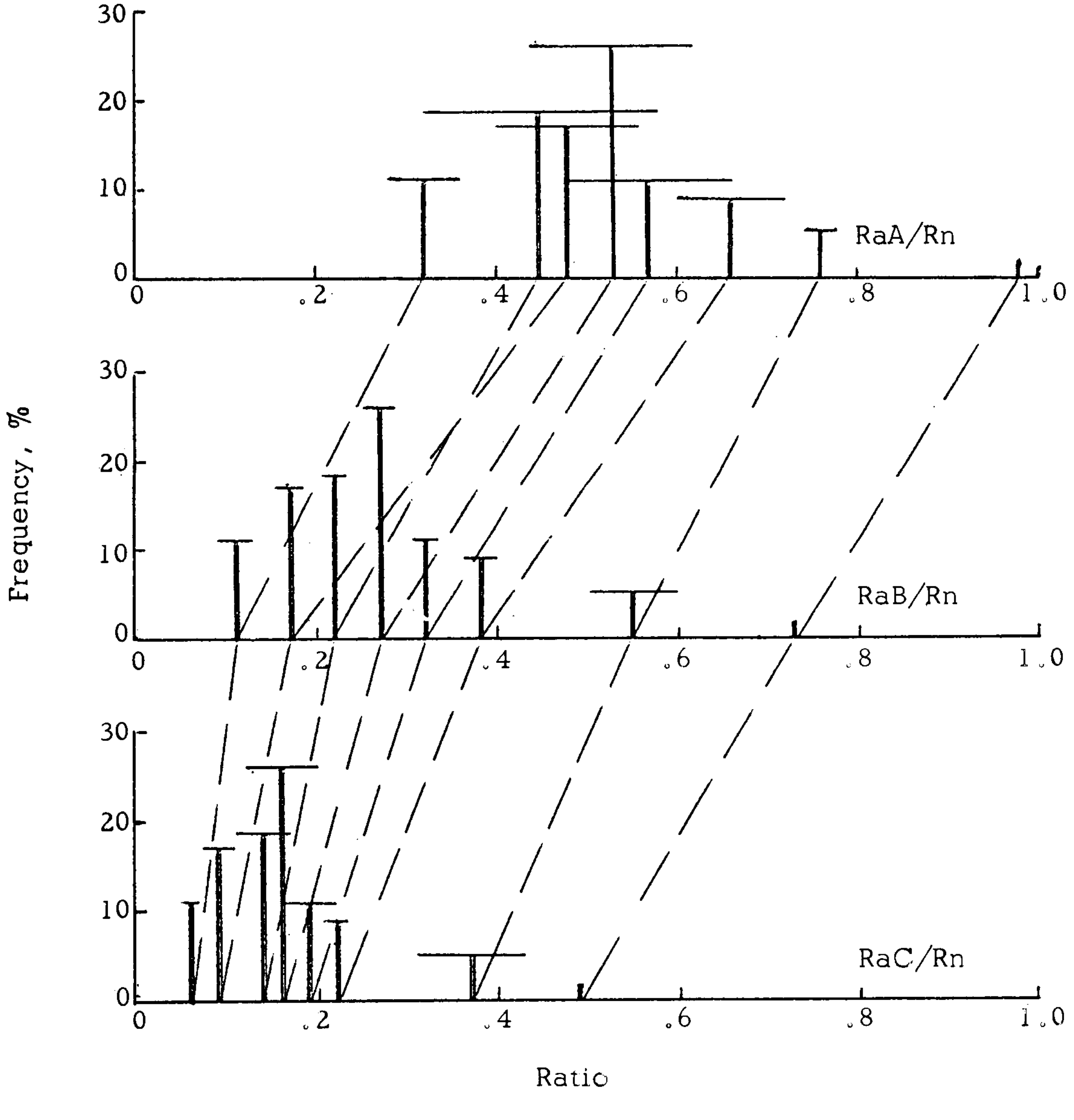


Fig. 7 - Variation of Working Level Ratio with Working Level



Note: Values connected by dashed lined comprise groups of ratios having frequencies indicated by vertical lines; cross bars are standard deviations of the ratios.

Fig. 8 - Frequency Distribution of Daily Average Radon Daughter Ratios for 54 Location-Days.

in Fig. 9 by the right-hand dashed line, approximates that of a parcel of air containing radon that has aged for 60 minutes. This is indicated by line #1 on the figure. In contrast, the most frequent radon daughter ratio, 0.53 : 0.27 : 0.16, depicted by the left-hand dashed line, is incompatible with simple growth processes. Radon with an age of about three minutes would have the appropriate RaA/Rn ratio of 0.5 but the corresponding ratios of RaB/Rn and RaC/Rn would be 0.02 and ~0.001, as indicated by line 2 on Fig. 9. Similarly, for a mine chamber with constant radon emanation into which clean air is being introduced to give one air change every five minutes, the RaA/Rn ratio would be 0.5. But again it may be noted by referring to line 3 that the RaB/Rn and RaC/Rn ratios are much too low. Therefore, it is evident that more complex mechanisms are involved. For example, the ratio in question, 0.53 : 0.27 : 0.16, could be matched by the mixture of two air streams having identical gas concentrations but originating, respectively, from a mine volume ventilated with clean air at 0.02 min^{-1} and one at 0.5 min^{-1}. This ratio is shown by line 4 on Fig. 9. A combination of systematic loss of radon daughters to surfaces by turbulent diffusion and the ventilation effect would also account for a ratio like this. Typically, air in a uranium mine will have a complex contamination history at virtually every location.

A definite inference may be drawn from these ratios concerning the effective age of radon daughters in mine atmospheres. The RaC/Rn value of 0.16 associated with the most frequently observed daughter ratio implies a minimum growth period of 30 minutes since RaC achieves 16% of equilibrium in about 30 minutes. Allowing for the continuous addition of radon that would occur as ventilating air moves through emanating areas, the minimum growth period to achieve a RaC/Rn ratio of 0.16 is about 50 minutes. For the lowest value of RaC/Rn observed with appreciable frequency, ~0.06, the corresponding growth periods are about 15 minutes and 30 minutes. At the other extreme, the minimum growth periods are about 50 minutes and 90 minutes for RaC/Rn values of 0.35 and higher which were observed with a frequency of about 5%.

If losses of radon daughters from the air are hypothesized for the reason mentioned previously, all of these growth periods would be correspondingly longer. In any case, it is evident that some contaminated air remains in the mines for long periods of time before being discharged to the surface. This may occur by way of gradual leakage into main air streams from poorly ventilated areas.

Radon daughter ratios normalized to radium-A were obtained from all nine mines. The frequency distributions of these ratios are shown in Fig. 10 in a manner similar to Fig. 8. The most frequent daily average ratio was 0.64 : 0.42 (RaB/RaA : RaC/RaA). The extreme ratios were 0.96 : 0.84 and 0.25 : 0.11.

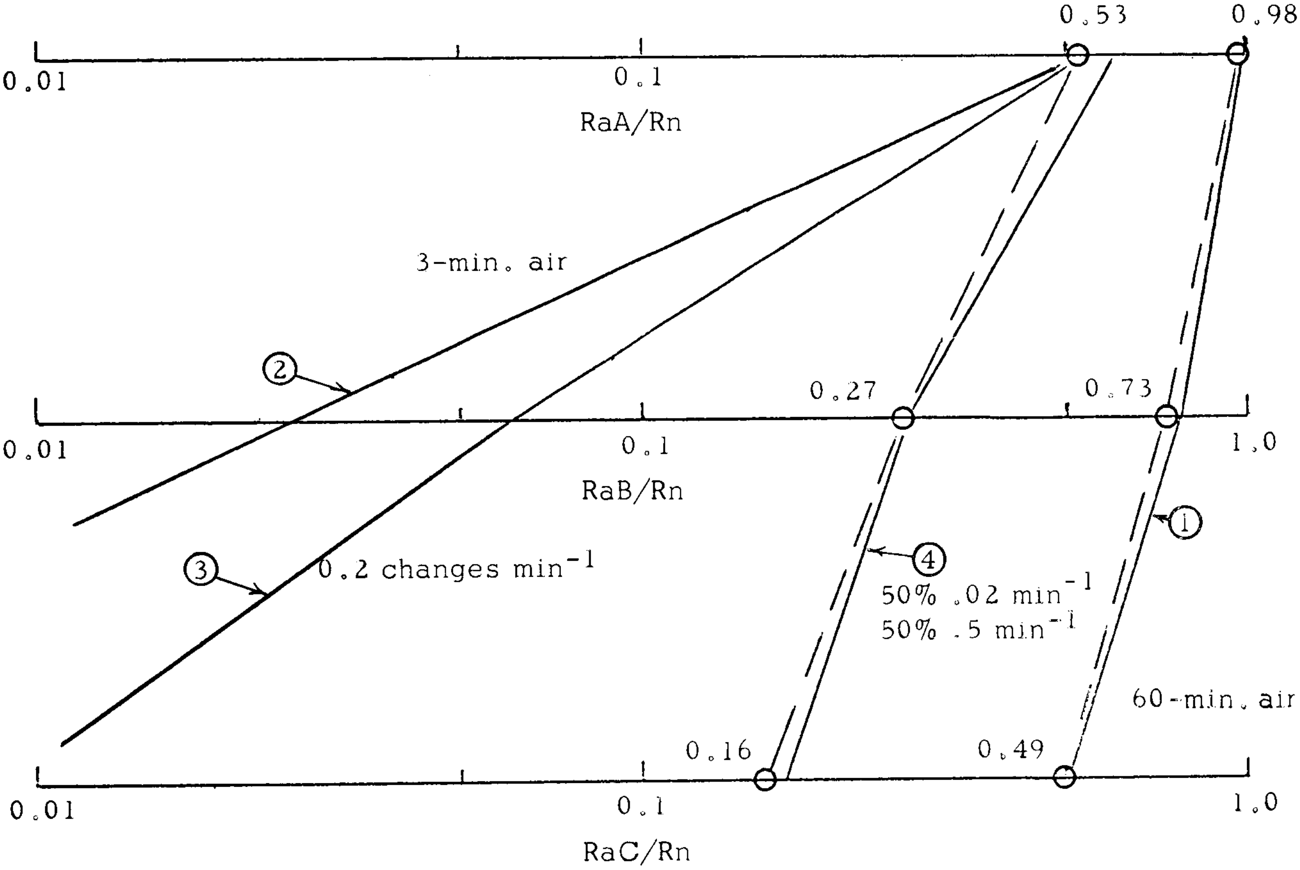


Fig. 9 - Radon Daughter Ratios from Uranium Mines Compared with Ratios Resulting from Growth Models.

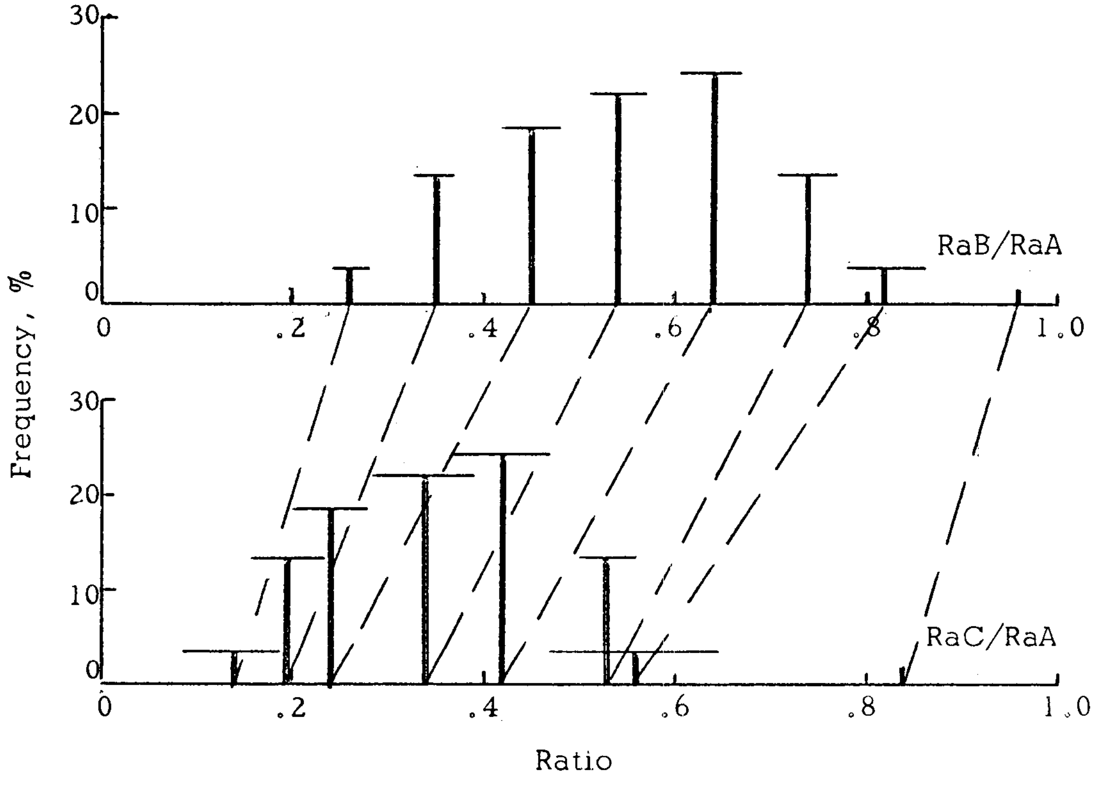


Fig. 10 - Frequency Distribution of Daily Average Radon Daughter Ratios (Normalized to RaA) for 82 Location-Days.

Figure 11 presents the data in another form that facilitates comparison with radon daughter growth models. The average ratios for the several locations in each mine are plotted as RaB/RaA vs RaC/RaA. These values cluster reasonably near to a line representing the ratios expected in a ventilated volume in which radon is emanating at a constant rate. The rate of ventilation, in terms of air changes per hour, is indicated at several points along the line. The compatibility of these ratios with a simple growth model tends to indicate that radon daughter losses explain the behavior of the previously discussed ratios (normalized to radon).

In general, it will be noted that ratios in a given mine vary only over a limited range although this may reflect the arbitrary choice of sampling location in each mine. Interestingly, Mines G, H, and I, all in the Grants area, are represented by generally low ratios. It might also be noted that Mine C had the highest ratios and the highest average WL of all the mines. However, Mine F also had high ratios but had the lowest average WL.

The radon daughter ratios tend to increase at high concentrations of radon daughters just as was the case for WLRs. The data are shown in Fig. 12.

4. Ore Dust Concentrations

From 8 to 19 ore dust (air) samples were collected in each mine by sampling for one to three hours. The resultant concentrations, expressed as total alpha activity, are summarized in Table III. Concentrations were quite variable but not particularly high. One exception was a sample collected in Mine D with a concentration of 1040 dpm/m^3. This value is 14 times greater than the next highest sample in Mine D and nearly 40 times greater than found in any other mine. Although the measurement is considered to be valid, the concentration appears to be atypical.

The variability of ore dust concentration within mines and among mines is not explained by any of the environmental data collected in this study. No correlation could be found between ore dust concentration and ventilation rate, humidity, surface condition, or mining operation. Ore assay was too invariant to account for the observed conditions. It cannot be concluded positively that none of the cited variables have an effect; the absence of correlation may merely reflect inadequate data.

The ore dust concentrations in Table III were calculated from alpha counts delayed for several weeks after the samples were collected to allow for complete decay of short-lived radionuclides. However, about half of the samples also were alpha-counted periodically beginning within a day or

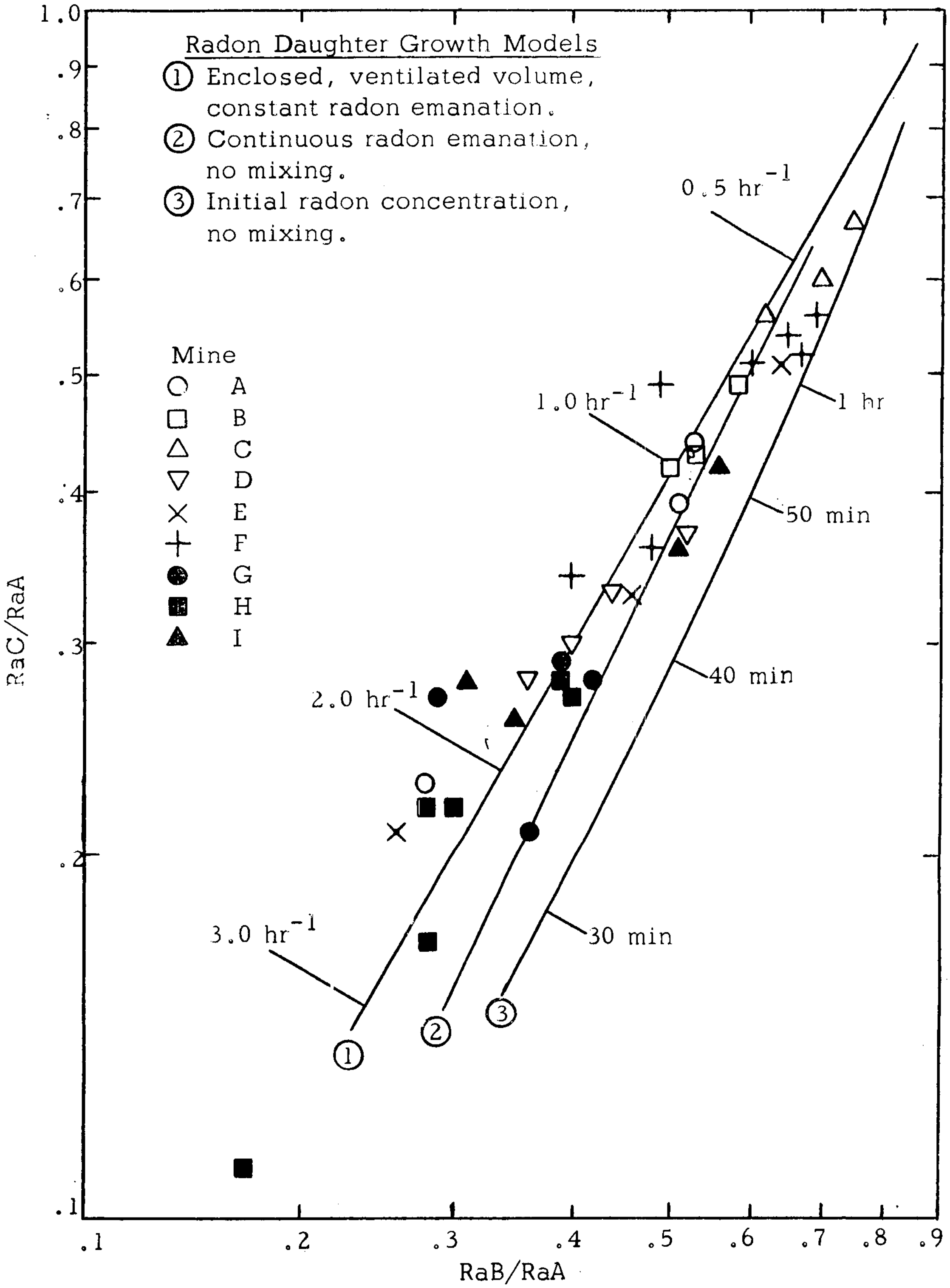


Fig. 11 - Location-Average Radon Daughter Ratios, Normalized to Radium-A, Compared with Radon Daughter Growth Models.

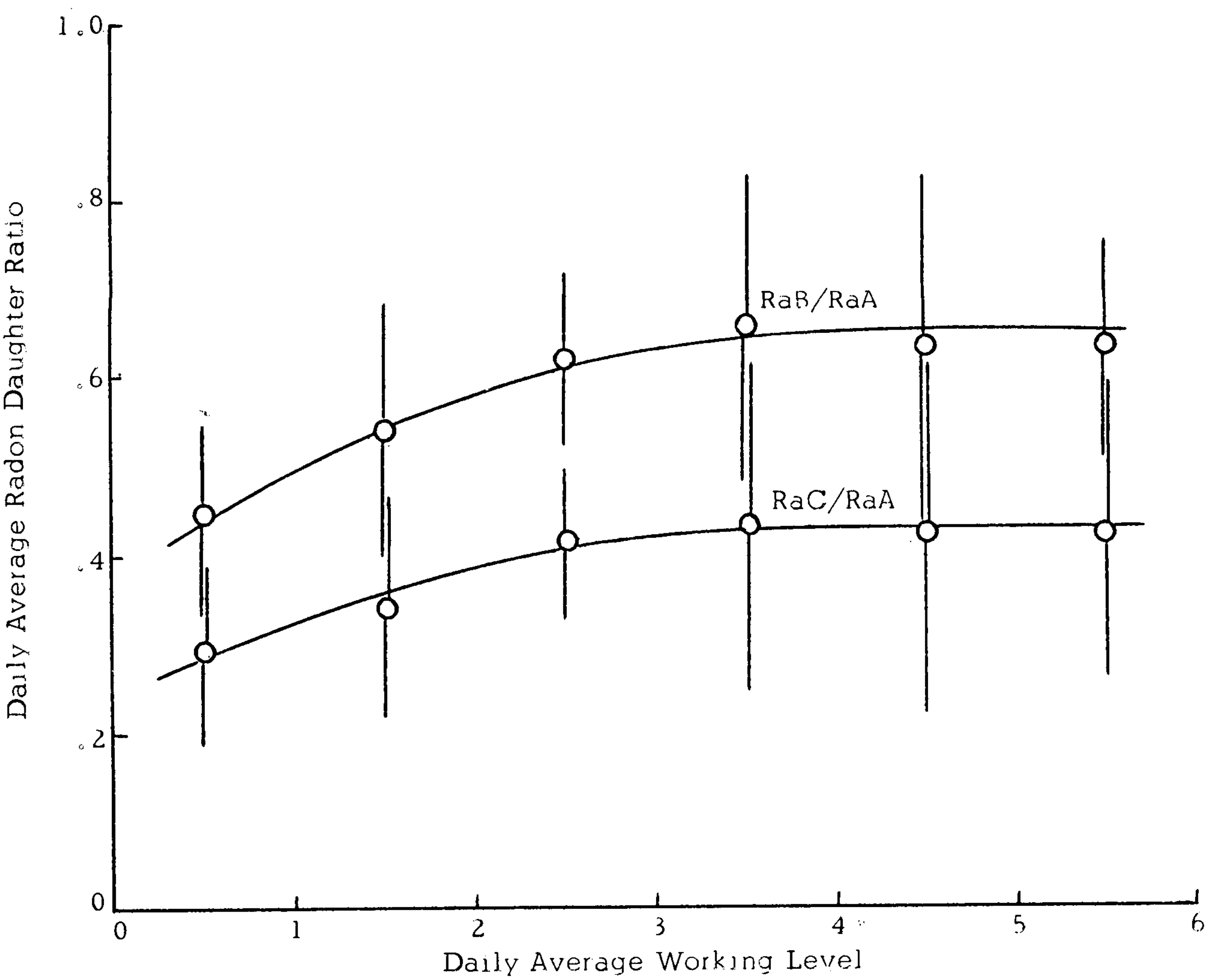


Fig. 12 - Variation of Radon Daughter Ratio with Average Working Level.

TABLE III

SUMMARY OF ORE DUST CONCENTRATIONS

Mine	No. of Samples	Concentration, a dpm/m^3 min.	max.	mean
A	13	0.2	28	12
B	19	0.2	24	4.6
C	12	0.1	6.2	2.2
D	7	8.2	1040 (73*)	170 (26*)
E	8	7.6	26	1.7
F	10	1.6	21	8.1
G	10	1.0	9.6	3.2
H	9	0.7	17	7.7
I	8	0.7	4.8	2.1

*Maximum and mean values with the high sample of 1040 dpm/m^3 omitted.

or two of collection. A component of alpha activity exhibiting a half-life of about ten hours was observed in many of these samples, as shown in Fig. 13. Thorium-B in the thoron-220 decay series has a half-life of 10.6 hours, and the presence of small concentrations of thoron may be inferred from the count data. In no case did the concentration of thoron daughters appear to be more than a small fraction of the radon daughter concentration.

5. Gamma Radiation

Gamma radiation intensities measured with Gieger-Mueller survey meters are summarized in Table IV. Gamma radiation was the most uniform from mine to mine of all the variables measured in this study, a reasonable finding considering the similarity in ore assays. These gamma intensities were low and cause relatively insignificant exposures.

TABLE IV

GAMMA RADIATION

Mine	Gamma Radiation, mr/hr		
	Min.	Max.	Mean
A	< 0.1	0.9	0.33
B	< 0.1	1.1	0.50
C	< 0.1	2.6	0.47
D	< 0.1	2.0	0.33
E	< 0.1	0.8	0.24
F	0.1	0.6	0.24
G	0.2	1.5	0.70
H	0.1	1.1	0.50
I	0.1	1.3	0.20

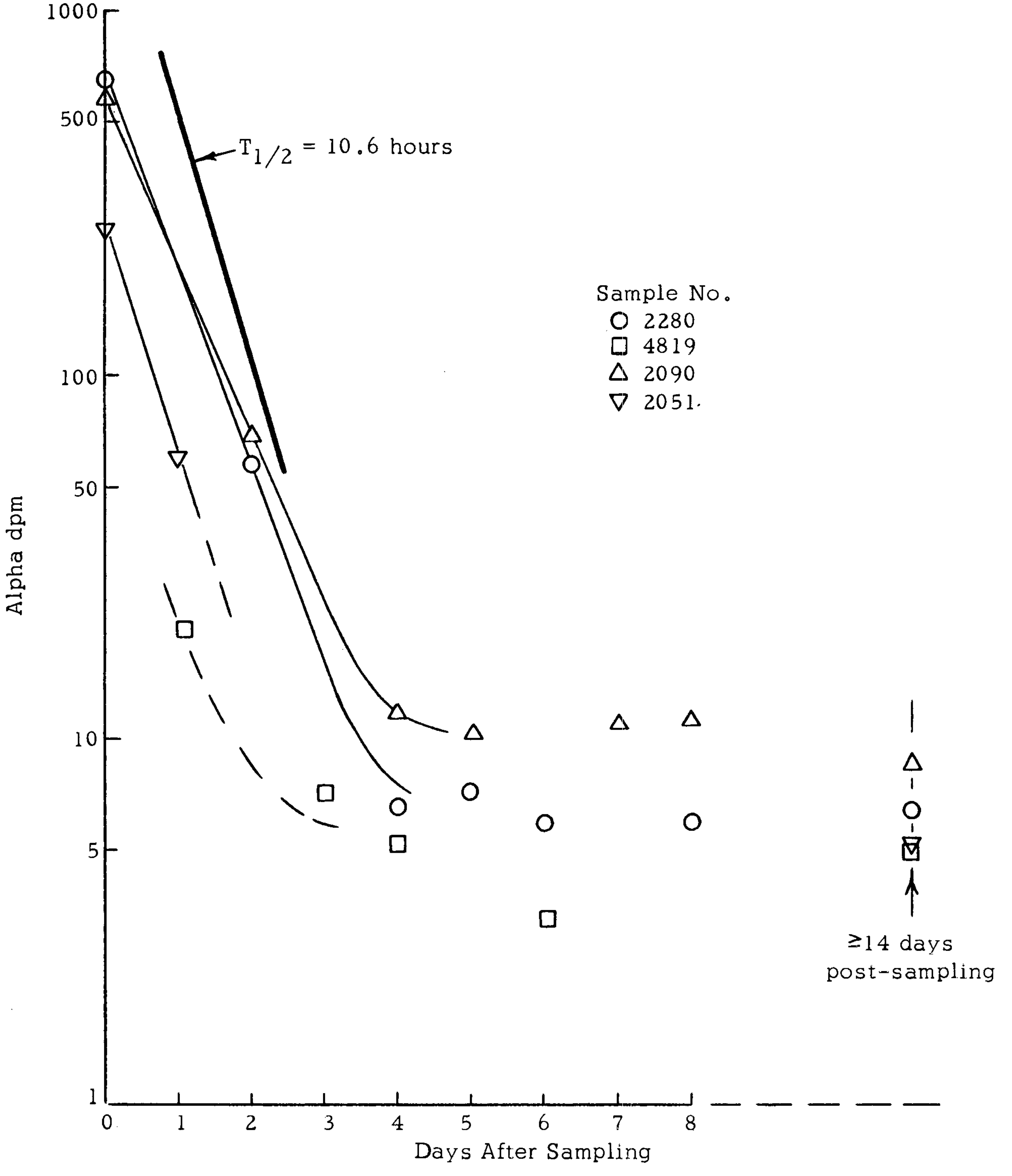


Fig. 13 - Ore Dust Sample Decay.

B. Quality of Measurements

The quality of the measurements performed in this study is presented here because it affects the interpretation of data on variability that is covered in the following section. The information is of additional interest because it indicates the quality of measurements that may be achieved in routine monitoring performed by mine operators and regulatory agencies. The Kusnetz[6] method is the most common method of monitoring in current use and data on the quality of these measurements are presented in Section III.B.3.

Measurements of radon gas concentrations were examined with respect to both accuracy and precision. Measurements of radon daughter concentrations and radon daughter ratios were examined with respect to precision only.

1. Radon Gas Concentration

The accuracy of radon gas measurements by the two-filter method was determined by comparison with flask samples collected simultaneously in the mines and analyzed in a pulse-type ionization chamber at HASL.[7] Twenty-two comparative measurements made at six uranium mines are shown in Fig. 14. The linear correlation is good, the coefficient of correlation being 0.94. The least-squares line, $Y = 1.16X$, indicates a slight bias with the two-filter data tending to be higher than the flask data. Either contamination of filters used in the two-filter method or leakage from flasks in transit to HASL could account for this tendency. Regardless of its source, the bias is not great enough to compromise the validity of the field measurements.

The precision of the two-filter measurements was tested by comparing duplicate measurements. Duplicates were obtained several times a day by each two-man survey unit. The precision, expressed as the coefficient of variation* is given in Table V for six mines (radon gas measurements for mines A, B, and C are considered invalid).

*Coefficient of variation, $V = \frac{s}{\bar{x}}$

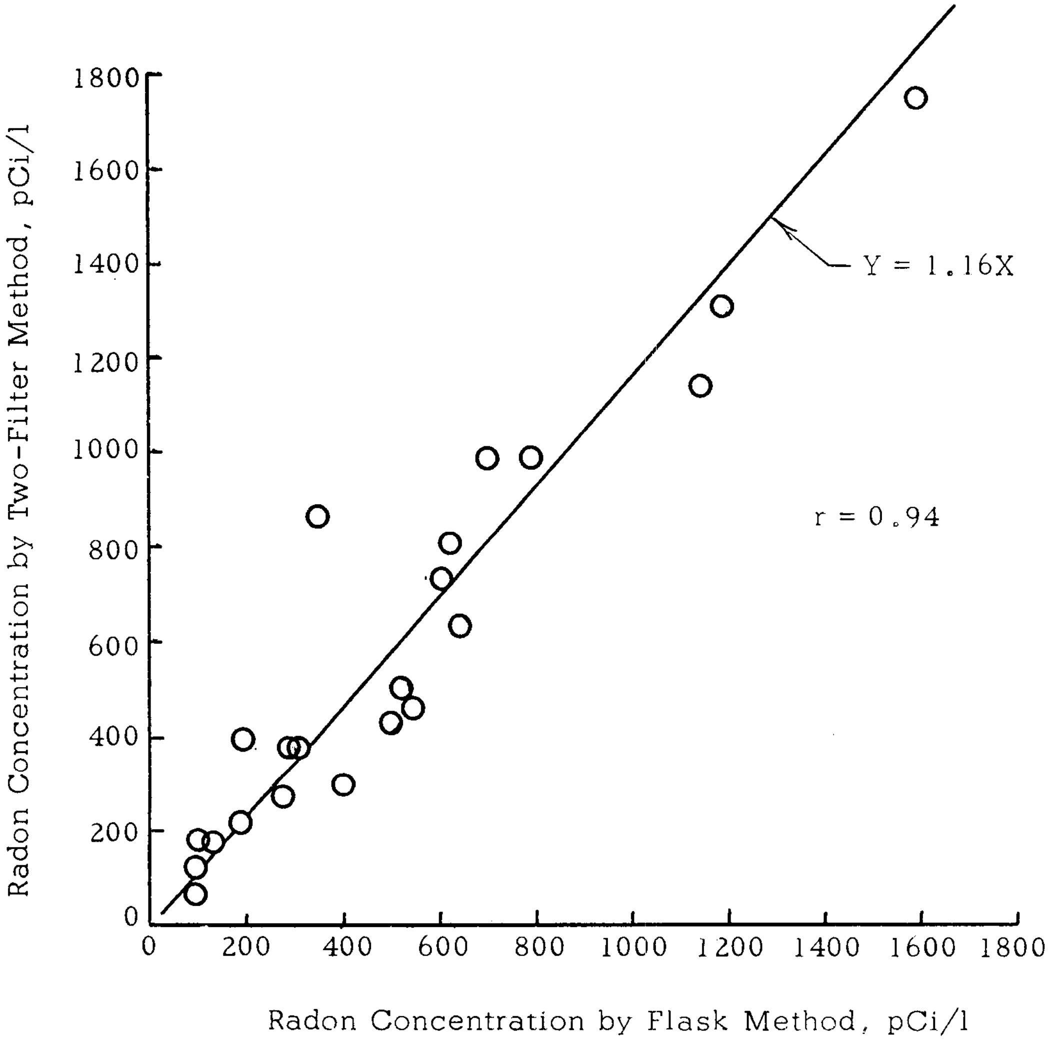


Fig. 14 - Comparison of Field Measurements by the Two-Filter Method and the Flask Method for Radon Determination.

TABLE V

PRECISION OF RADON GAS MEASUREMENTS

Mines	Survey Unit	No. of Duplicates	V, %	95% Confidence Limits, %
D, E, F	1	29	19	± 6
	2	15	14	± 5
	3	33	23	± 8
G, H, I	1	29	16	± 4
	2	29	11	± 5
	3	30	17	± 6

The precision was independent of radon concentration in all of the measurement series. The general improvement in precision at Mines G, H, and I relative to Mines D, E, and F may reflect improved technique attained by practice and experience.

2. Working Level Measured by the Tsivoglou Method

There is no independent method for measuring radon daughter concentration. Accuracy, therefore, can only be inferred from the procedures employed in the measurements. As a matter of policy in this study, special care was applied to all aspects of the measurements.

The efficiencies of alpha scintillation counters used for filter samples were checked daily with plutonium alpha standards and counter backgrounds were checked periodically every day underground. Self-absorption factors were measured by a standard technique[8] and applied in calculating disintegrations per minute from counts per minute.

Sample air flows were measured with rotameters calibrated for mine air density and for pressure drop across the sample filters. Actual static pressures at the flowmeter inlets were measured during sampling runs with pressure gauges mounted on the sampling instruments and applied in calculations of sample volumes. Filter holders and connections between filter holders and flowmeters were tested for leakage in the laboratory prior to field use.

In summary, good practice was adhered to conscientiously in all of the measurements. The resultant accuracy was comparable to that attained with good practice but cannot be estimated quantitatively.

The precision of radon daughter measurements was checked by comparing duplicates. Duplicates were collected several times each day by each two-man survey unit. The precision of WL measurements, expressed in terms of the coefficient of variation (V) is given in Table VI.

TABLE VI

PRECISION OF WORKING LEVEL MEASUREMENTS

Mines	Survey Unit	No. of Duplicates	V, %	95% Confidence Limits, %
A, B, C	1	15	8.7*	± 5.5
	2	31	7.8	± 2.2
	3	12	12	± 5.5
D, E, F	1	32	4.4	± 1.4
	2	27	4.8*	± 4.4
	3	38	18	± 2.5
G, H, I	1	31	4.7*	± 1.6
	2	33	12	± 8.7
	3	30	12	± 3.2

*Concentration Dependent

The confidence limits in Table VI indicate the highly approximate nature of the individual values. The overall average of 9% is probably a reliable estimate of general performance and seems reasonably good for a field method. It is notably better than the precision of the radon gas measurements.

The precision was independent of concentration except for three cases indicated by asterisks in Table VI. The coefficients of variation listed for the three excepted cases are actually median values for the range of WLs encountered by the respective survey teams. Fig. 15 shows the coefficient of variation as a function of WL at Mines A, B, and C. The coefficient of variation increases sharply at WLs much below 1 but relatively few of the measurements at these mines were in that low range.

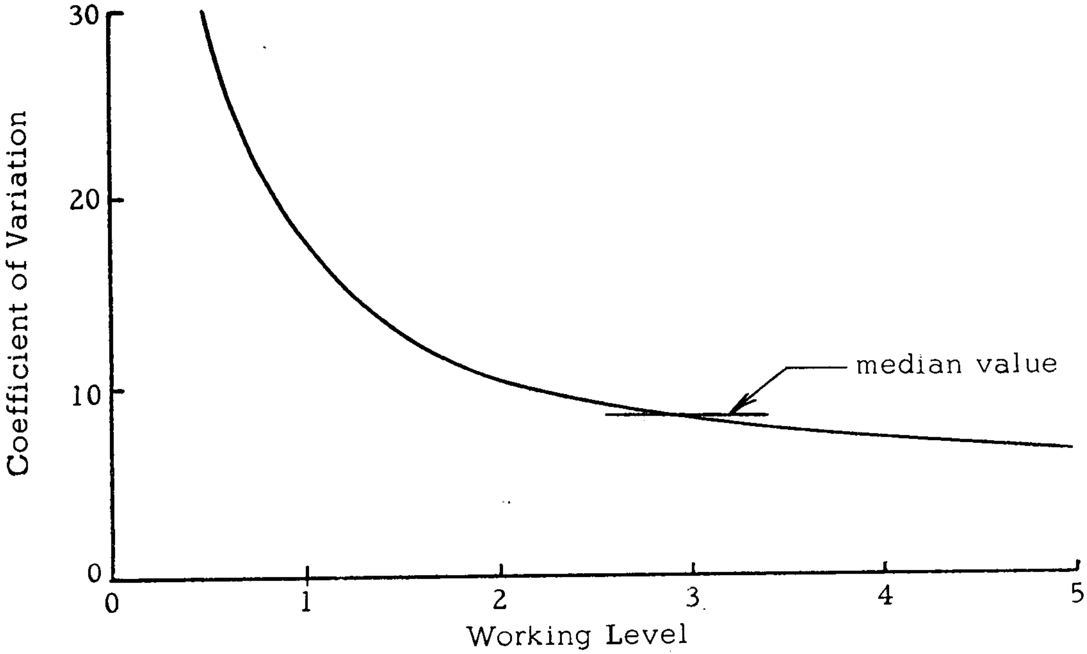


Fig. 15 - Precision for Measurements of Working Level by Tsivoglou Method: One Survey Team at Mines A, B and C.

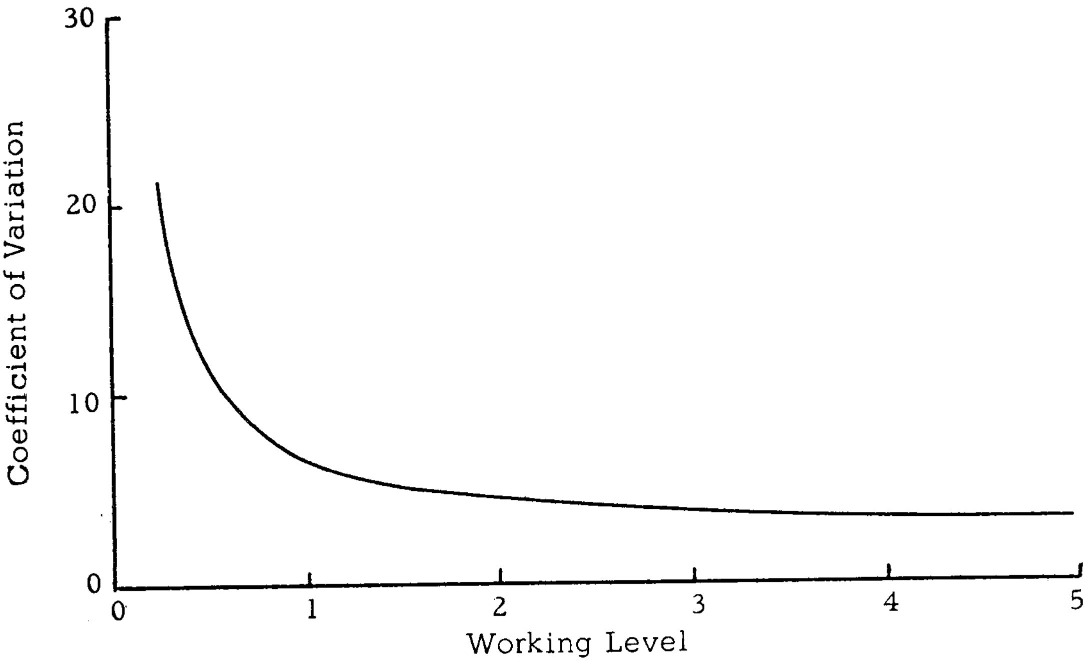


Fig. 16 - Precision for Measurements of Working Level by Kusnetz Method: All Survey Teams, Mines D, E and F.

3. Working Level Measured by the Kusnetz Method

During surveys at Mines D through I, most of the duplicate samples that were used to determine the coefficient of variation for WL measured by the Tsivoglou method were also used to determine the coefficient of variation for the field method devised by Kusnetz[6] which is now virtually standard for measuring WL in uranium mines. This was done solely to test the reliability of the method; the derived WL data were not used in this report for any other purpose.

Duplicate filter samples, after being counted for 30 minutes in scintillation detectors to obtain data for Tsivoglou calculations, were removed and placed on a flat, clean surface and measured with an Eberline PAC-1SA alpha survey meter. The alpha count rate at 40 minutes post-sample-collection was used in a calculation of WL in accordance with the Kusnetz method described in his paper and in U.S. Public Health Service Handbook 494. The coefficients of variation (V) determined for these paired measurements are given in Table VII.

TABLE VII

PRECISION OF WORKING LEVEL MEASUREMENTS BY THE KUSNETZ METHOD

Mines	Survey Unit	No. of Duplicates	V, %
D, E, F	1	18	4.6*
	2	26	4.5
	3	28	5.0*
G, H, I	1	28	2.7*
	2	31	6.2
	3	29	11*

*Concentration dependent

These precision levels are remarkably good, with one exception, and in general are better than the corresponding precision levels in Table VI for the Tsivoglou method. Finding better precision for the Kusnetz method than for the more rigorous Tsivoglou method seems quite reasonable in view of their inherent sources of error. The Kusnetz method requires but one measurement of collected radioactivity from which WL is calculated by simple extrapolation in accordance with an assumed alpha decay curve. For the Tsivoglou method, on the other hand, there are three separate measurements of collected radioactivity, each having an inherent error, from which the WL is calculated by simultaneous equations. In this process, small measurement errors are propagated to yield a larger error in the calculated WL. Consequently, the precision of the Tsivoglou method is poorer than for the Kusnetz method but conversely it should be more accurate because it takes account of radon daughter ratio at the time of sampling whereas the Kusnetz method does not.

Most of the coefficients of variation were concentration dependent as indicated by the asterisks in Table VII. Thus, the listed coefficients are median values for the ranges of WL encountered. The coefficients of variation for measurements at Mines D, E, and F are shown graphically in Fig. 16 (page 30) as a function of WL. Although the precision tends to be poorer at values of WL less than 1, it may be noted that it is still reasonable at values as low as 0.3 WL. Better precision, if required, undoubtedly could be obtained by sampling larger volumes of air.

The previous point concerning the relative accuracy of the Tsivoglou and Kusnetz methods is more theoretical than actual. The WLs calculated by the two methods from appropriate alpha measurements on the same filter papers were in good agreement. Fig. 17 shows a logarithmic plot of data obtained by the two methods applied to 178 samples. An idealized $X = Y$ line is drawn on the figure rather than the linear least-squares line, $X = 0.04 + 1.03Y$.

Although a few values are widely dispersed from the line, the scatter over the two-decade spread of WLs is moderate and the standard deviation of differences between paired values is 15%. The linear correlation coefficient of 0.94 and the slope of 1.03 for the line of best fit are further evidence of good agreement. Actually, according to calculations by Kusnetz, the error in estimating WL should be no more than a few percent at the daughter ratios that predominated in this study (see Section III.A.4). Most of the scatter in Fig. 17 is probably caused by counting errors inherent in the measurements of alpha activity.

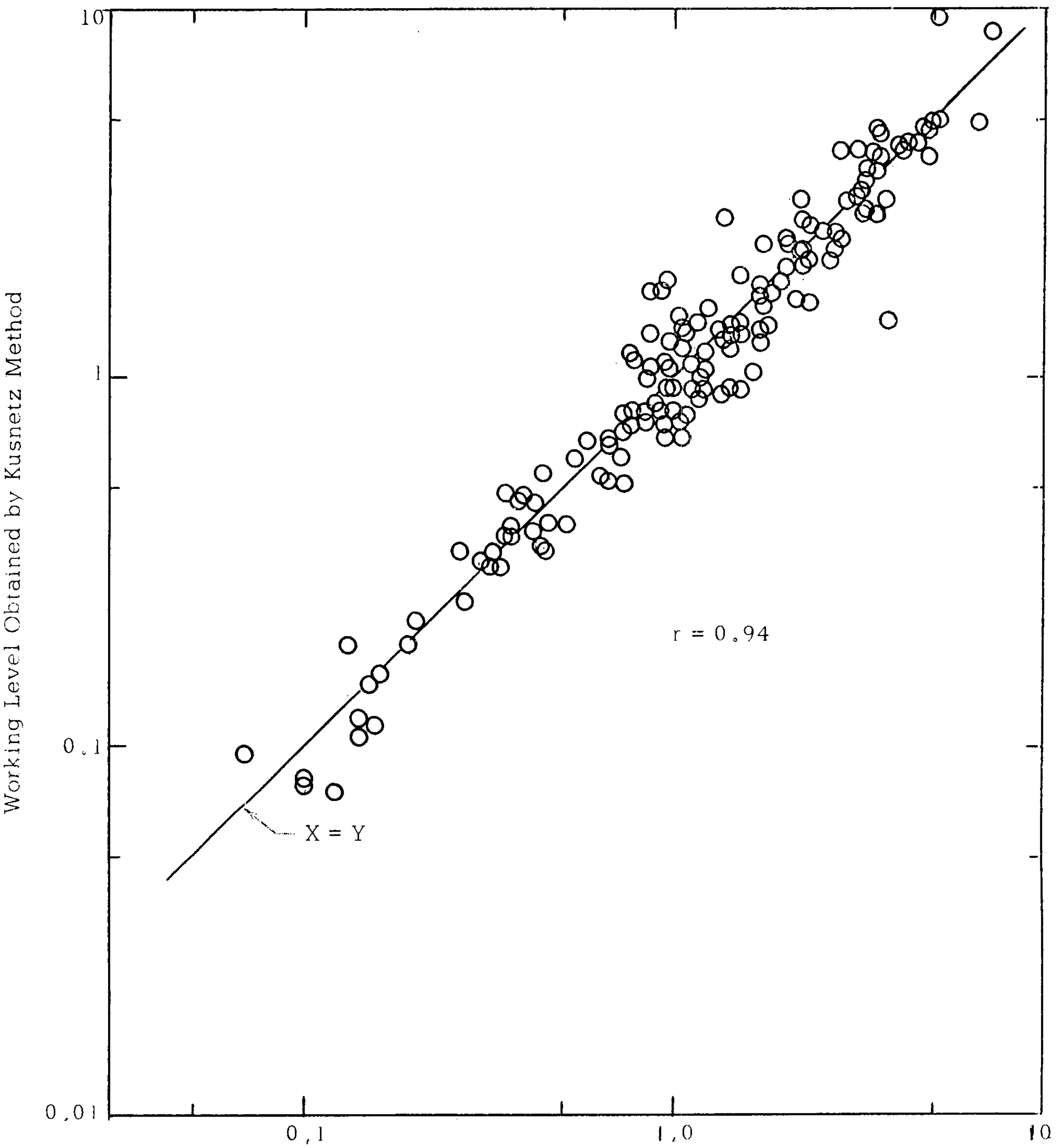


Fig. 17 - Comparison of Working Levels Obtained by the Kusnetz and Tsivoglou Methods.

4. Radon Daughter Ratios

The reproducibility of radon daughter ratios was checked by duplicate measurements. Results expressed in terms of coefficient of variation (V) are given in Table VIII for ratios of RaB and RaC to RaA from all mines and for ratios of RaA, RaB and RaC to radon for the mines from which radon concentration data are available. For the most part, these errors are too large for much confidence to be placed in single measurements of radon daughter ratio but the daily mean ratio at a fixed sampling location should be adequate for hazard evaluation. Taking the largest error, 38%, as an example, the standard error for a mean based on ten measurements would be only 12%.

TABLE VIII

PRECISION FOR MEASUREMENTS OF RADON DAUGHTER RATIOS
(Coefficient of Variation, V, %)

Mines	Survey Unit	RaB/RaA	RaC/RaA	RaA/Rn	RaB/Rn	RaC/Rn
A, B, C	1	13	26			
	2	14	24			
	3	21	32			
D, E, F	1	24	38	29	23	22
	2	16	27	20	16	27
	3	19	32	37	30	25
G, H, I	1	9.6	28	23	29	30
	2	23	29	27	21	28
	3	19	34	23	25	20

5. Summary

Aside from interpreting atmospheric data presented in this report, the most significant finding in regard to measurement quality is the excellent reliability of the Kusnetz method for measuring WL. Its reproducibility is quite good (~± 5%) over a wide range of WLs and even though it is poorer at very low concentrations, it is still satisfactory (± 15%) at a concentration of 0.3 WL. The method is not strictly accurate because of inherent approximations, but Kusnetz[6] calculates that errors from this source do not exceed

10 to 12%. In the current field tests, good agreement was found with measurements by the theoretically rigorous Tsivoglou method.

The precision found in this study reflects the techniques and capabilities of the HASL survey personnel and would not necessarily hold for measurements by other groups. As a matter of fact, Table VII indicates variations even among sampling teams using identical methods and instrumentation. Typically, sample volumes now collected in routine monitoring by mine operators are 10 to 50 liters compared to the 100 liters used in this study, so somewhat poorer precision might be expected. Nevertheless, the Kusnetz method is entirely satisfactory as a routine field method and gives reliable data when applied with adequate attention to standards of good practice.

The errors associated with measurements of radon gas concentration by the two-filter method and radon daughter concentration (WL) by the Tsivoglou method are reasonable for field monitoring but cannot be ignored in a study of variations in the mine atmospheres. Consequently, in some of the data presented in the following section, corrections have been made for errors of sampling and measurement.

The variability of radon daughter ratios measured by the Tsivoglou method is too large for any confidence to be placed in individual measurements. Thus only daily average ratios are presented in this report (Results section and Appendix B).

C. Variations with Time

1. Variation of radon gas concentration and Working Level

The degree of fluctuation of radon and WL with time varied greatly among locations even within a given mine. Fig. 18 shows two disparate conditions, one of the more widely fluctuating and one of the more stable atmospheres found in this investigation. Both locations happen to be in the same mine.

It may be noted that the greater fluctuations are at relatively low concentrations. There is, in fact, a correlation between fluctuation and concentration that will be mentioned below.

As is the case at locations 1 and 4 in Mine I, there was a tendency for the general degree of fluctuation to persist from day to day in a given location. This is apparent in the graphical presentation of concentration measurements on a time basis for all locations given in Appendix A.

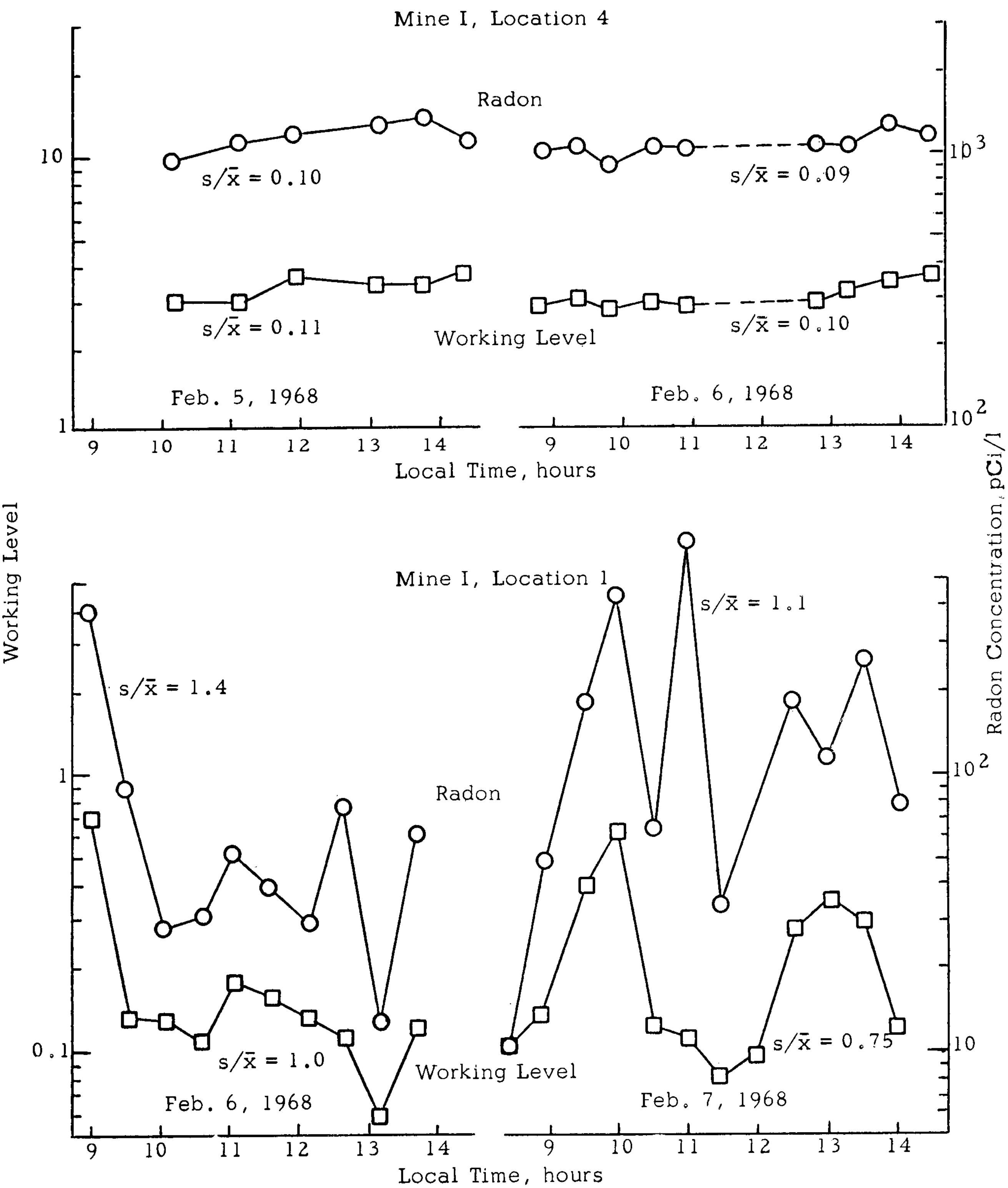


Fig. 18 - Variation of Radon Concentration and Working Level with Time at Fixed Sampling Locations.

The more stable atmospheres tended to prevail. Most fluctuations, expressed as coefficients of variation of half-hourly concentrations grouped by day and location, were from 0 - 0.3. Whether these values are regarded as high or low necessarily reflects one's point of view but they are quite low in comparison to fluctuations of air contaminants in other situations such as typical industrial facilities.

The frequency distributions of coefficients of variation of radon gas and WL are shown in Fig. 19. As indicated in the previous section, sampling and measurement errors were large enough to magnify concentration variances, especially in the more stable atmospheres. Consequently, coefficients of variation are presented in two forms, gross values calculated directly from the concentration measurements and net values that were corrected for the coefficients of variation for duplicates. (The net coefficients are the square roots of the differences in the squares of gross coefficient of variation and the coefficient of variation for duplicate samples.) These values represent true atmospheric fluctuations more correctly. About 85% were $\leq$ 0.3 for radon gas and about 80% were $\leq$ 0.3 for WL.

Regarding the relatively few WL coefficients of variation that exceeded 0.5, all were in drifts, all but one were at average WL's less than 1, and all but two were at average WL's less than 0.5. Moreover, there is a general tendency for both radon and WL to fluctuate less in stopes than in drifts. Fig. 20 illustrates this point with the frequency distribution of net coefficients of variation shown separately for stope and drift concentration measurements. More than half of the net coefficients of variation in stopes were $\leq$0.1 compared to much lower fractions in drifts. Conversely, drift measurements accounted for all of the values exceeding 0.5.

The distributions in Fig. 19 suggest that radon gas levels are somewhat more stable than WL's. This tendency is confirmed in Fig. 21 which shows the cumulative frequency distribution of the respective coefficients of variation for the locations where both kinds of measurements were obtained. The finding of greater stability for radon seems reasonable in view of radon's larger diffusion coefficient and its insensitivity to some of the factors that effect radon daughter concentration such as rapid radiologic growth and decay, and loss by deposition.

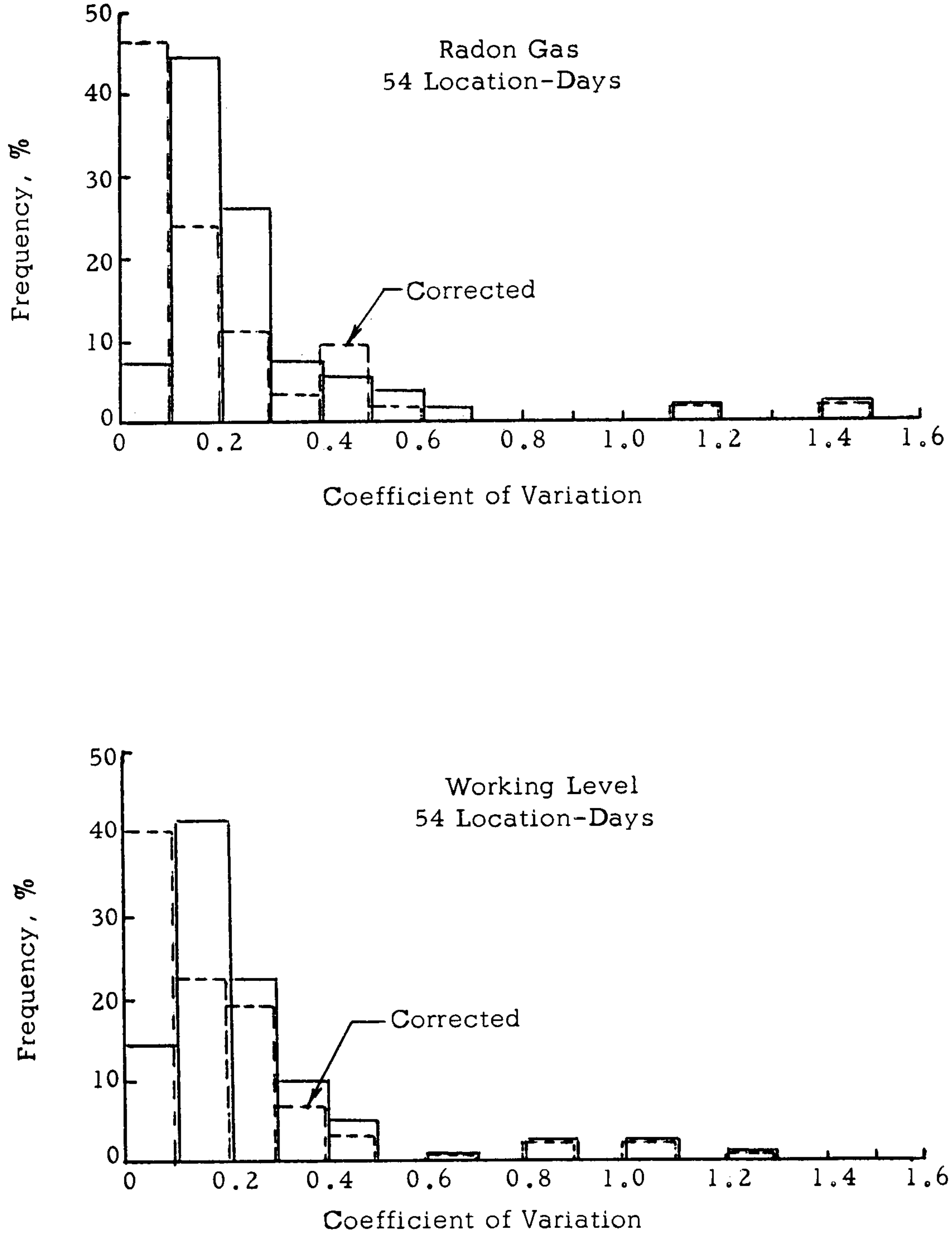


Fig. 19 - Frequency Distribution of Coefficients of Half-Hourly Variation of Radon Concentration and Working Level for All Daily Groups of Measurements at Fixed Locations.

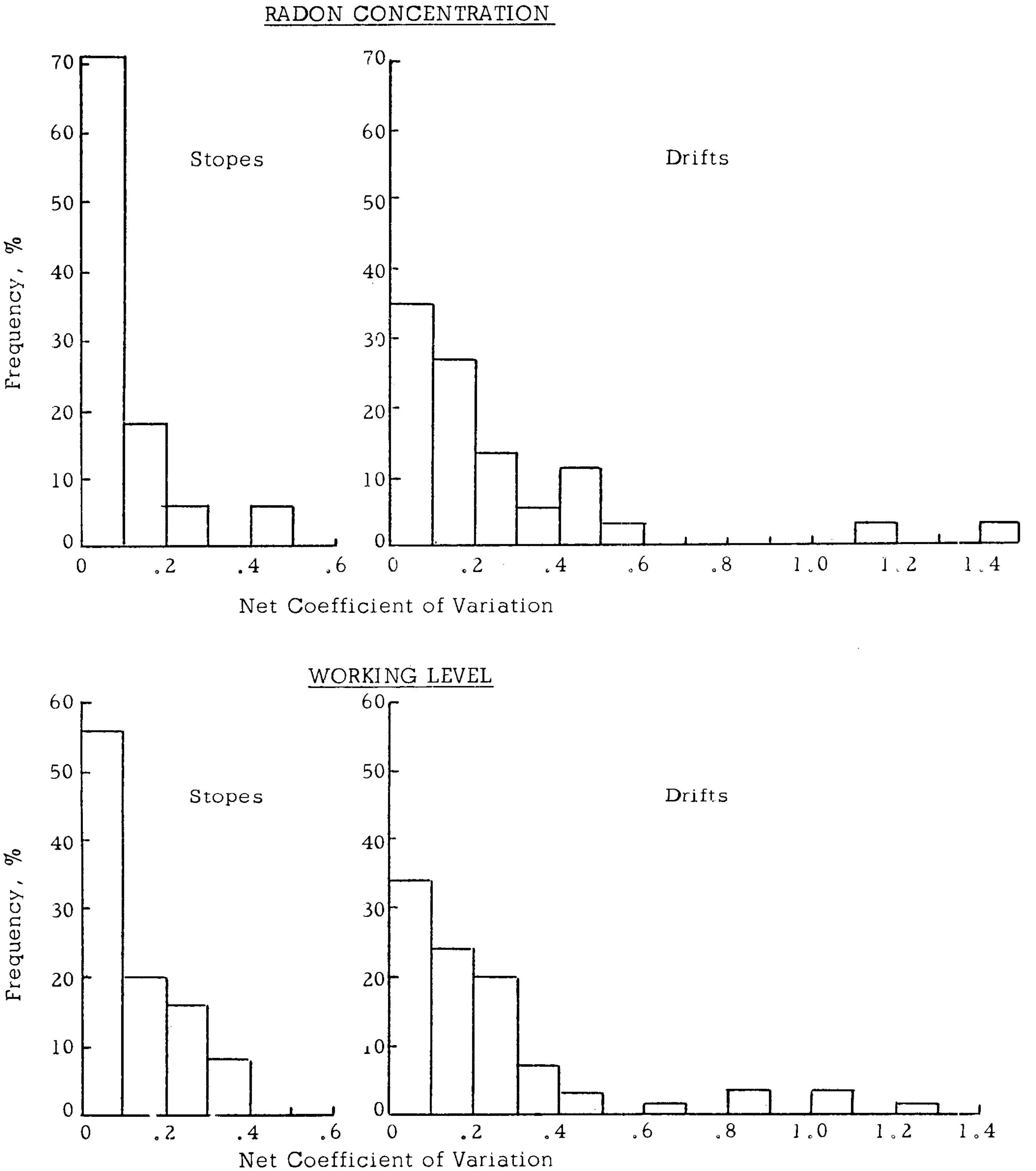


Fig. 20 -Frequency Distributions of Net Coefficients of Half-Hourly Variation of Radon Concentration and Working Level in Stopes and Drifts: All Daily Groups of Measurements at Fixed Locations.

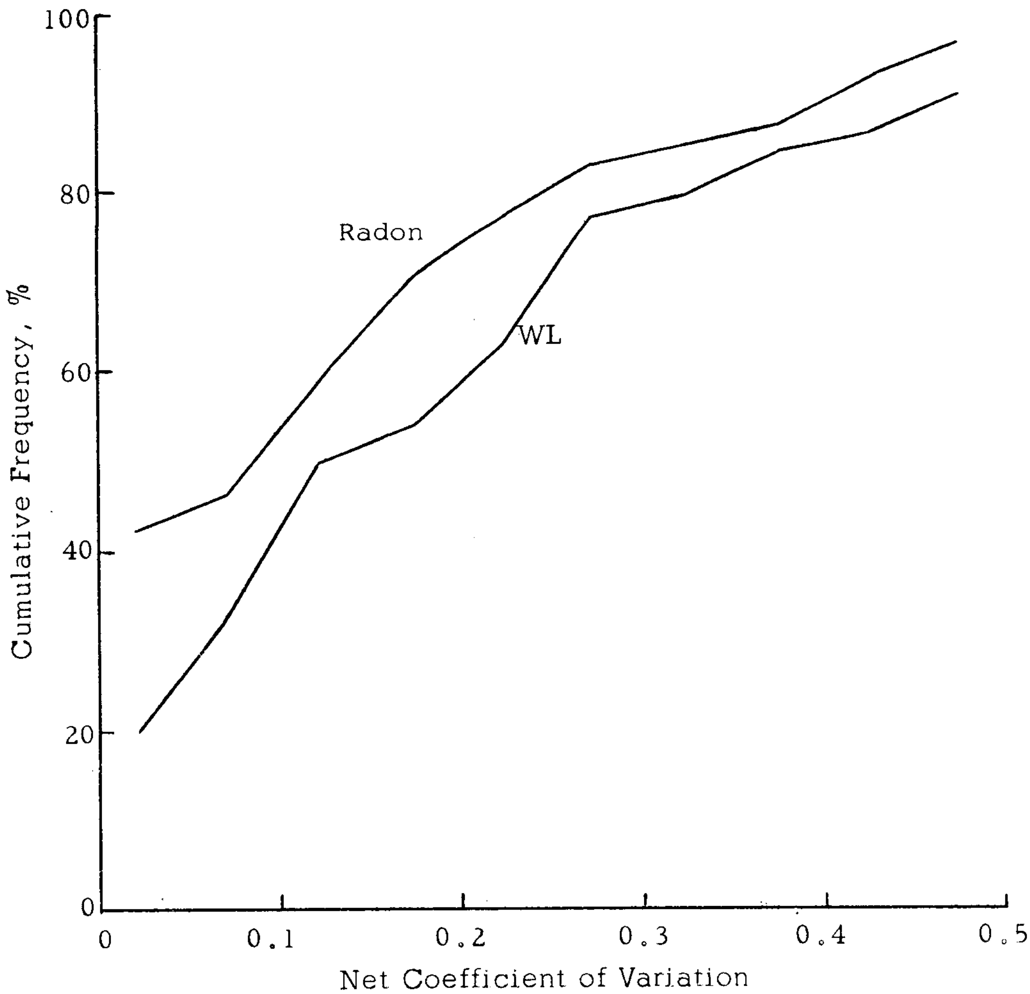


Fig. 21 - Cumulative Frequency Distributions for Net Coefficients of Half-Hourly Variation of Radon Concentration and Working Level for All Daily Groups of Measurement at Fixed Locations.

All daily groups of consecutive concentration measurements met Kolmogorov-Smirnov test criteria for both normal and log-normal frequency distributions. Since a distribution that is definitely of one kind cannot be the other as well, this probably indicates that the sample groups were too small for an unambiguous characterization of the distribution functions. Nonetheless, since the distributions meet criteria for normality, this justifies applying the normal law of error in calculations of sampling frequency. An example of this is given in the Discussion. Another useful finding was that most of the variations in samples collected during a day at fixed locations were randomly distributed with time. On the other hand, this was not true in all cases as shown by sequential sampling data in the appendix.

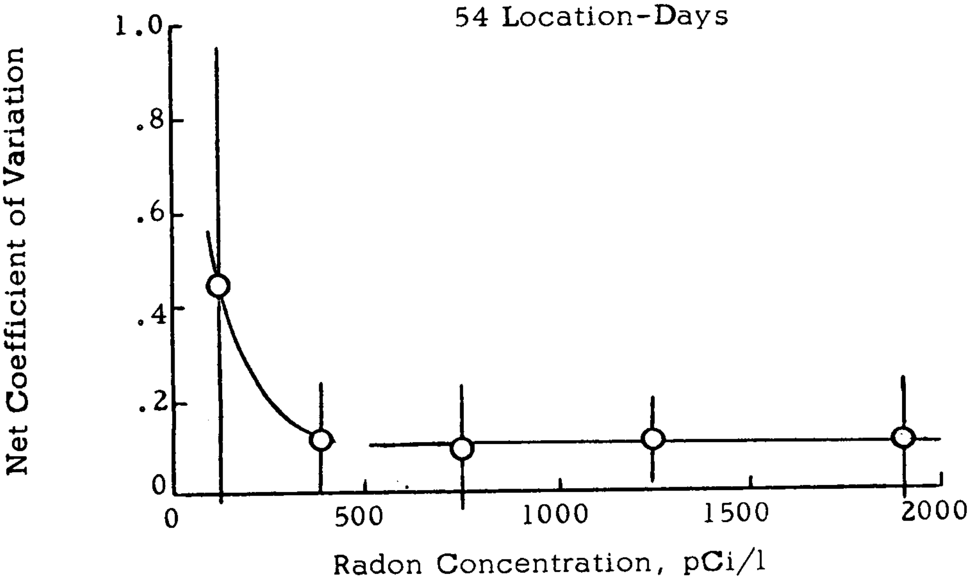
Variation of both radon gas concentration and WL correlated with concentration is indicated in Fig. 22. This correlation is far more pronounced when measurements at a few individual mines are examined separately. It is particularly evident in Mines E and I in which the sampling stations were in a line along main air courses. The data are shown in Fig. 23.

No particular pattern can be distinguished in fluctuations of daily average concentrations. In Table II, the daily average WL's differed remarkably in the three locations examined in Mine A whereas the daily averages were nearly invariant in Mine B. Mine A was probably atypical in that the ventilation system was undergoing basic changes during the three days of observation and concentrations were altered substantially in this small mine. In other mines, daily variations were both large and small, most exhibiting stability in some areas and fluctuations in others.

In statistical terms, the degree of fluctuation in daily average concentrations were reasonably similar to the half-hourly fluctuations. The frequency distributions of the coefficients of variation of daily average radon concentrations and WLs are shown in Fig. 24. For the most part, variations were moderate. As was noted for half-hourly fluctuations, the daily variation of radon gas appears somewhat less than that of WL. This is confirmed by the cumulative frequency distributions in Fig. 25 for locations from which both kinds of measurements were obtained. Some correlation was found between daily average variations and concentrations as was the case for half-hourly variations. The relationships are shown for radon and WL in Fig. 26.

Considering data from all mines as a group, there was virtually no correlation between half-hourly variation and daily variation.

Variation of Net Coefficient of Half-Hourly Variation with Radon Concentration



Variation of Net Coefficient of Half-Hourly Variation with Working Level

Figure 22

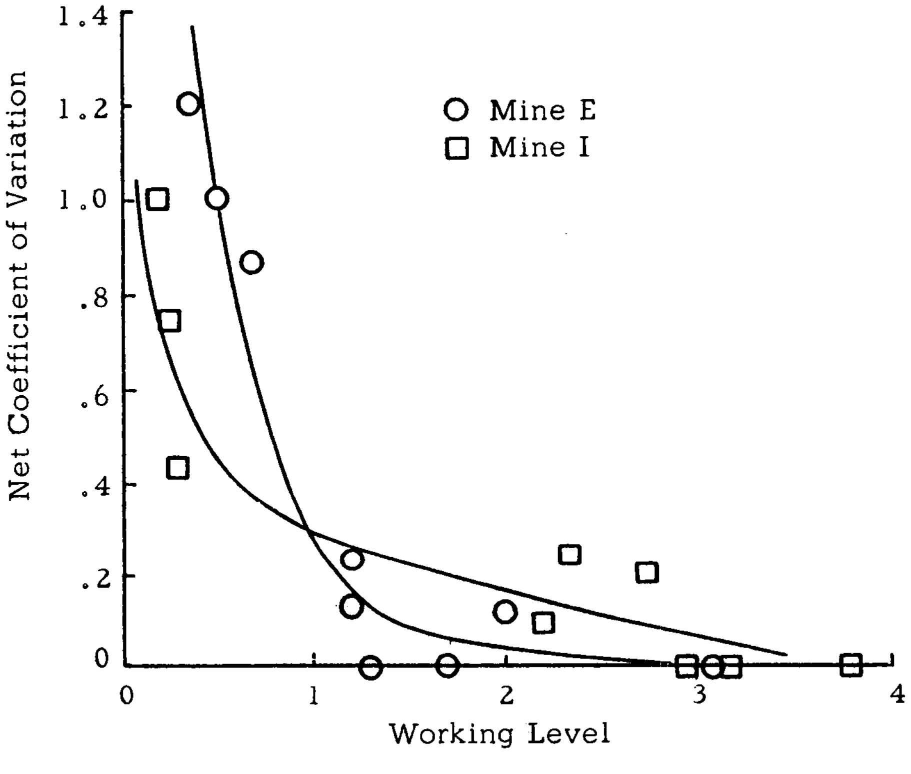
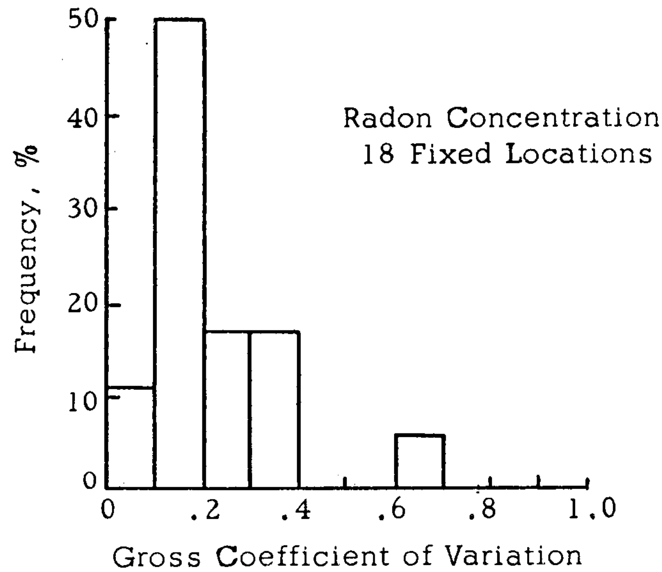


Fig. 23 - Variation of Net Coefficient of Half-Hourly Variation with Working Level at Fixed Locations in Mines E and I.



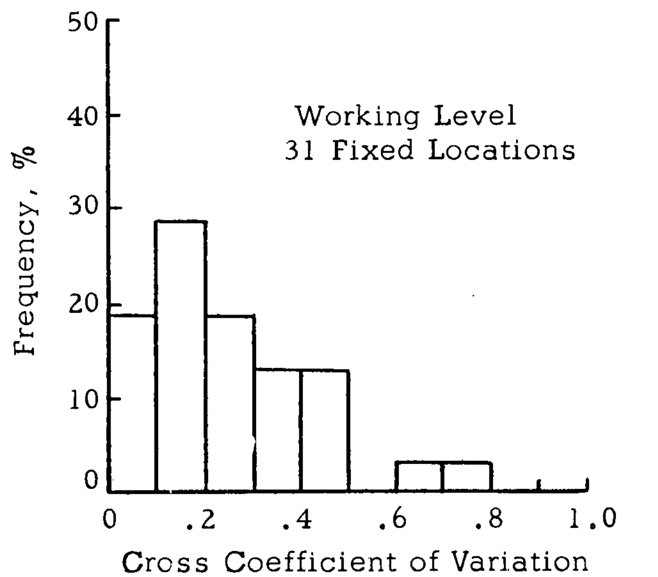


Fig. 24 - Frequency Distributions of Gross Coefficients of Variation of Daily Average Radon Concentration and of Working Level.

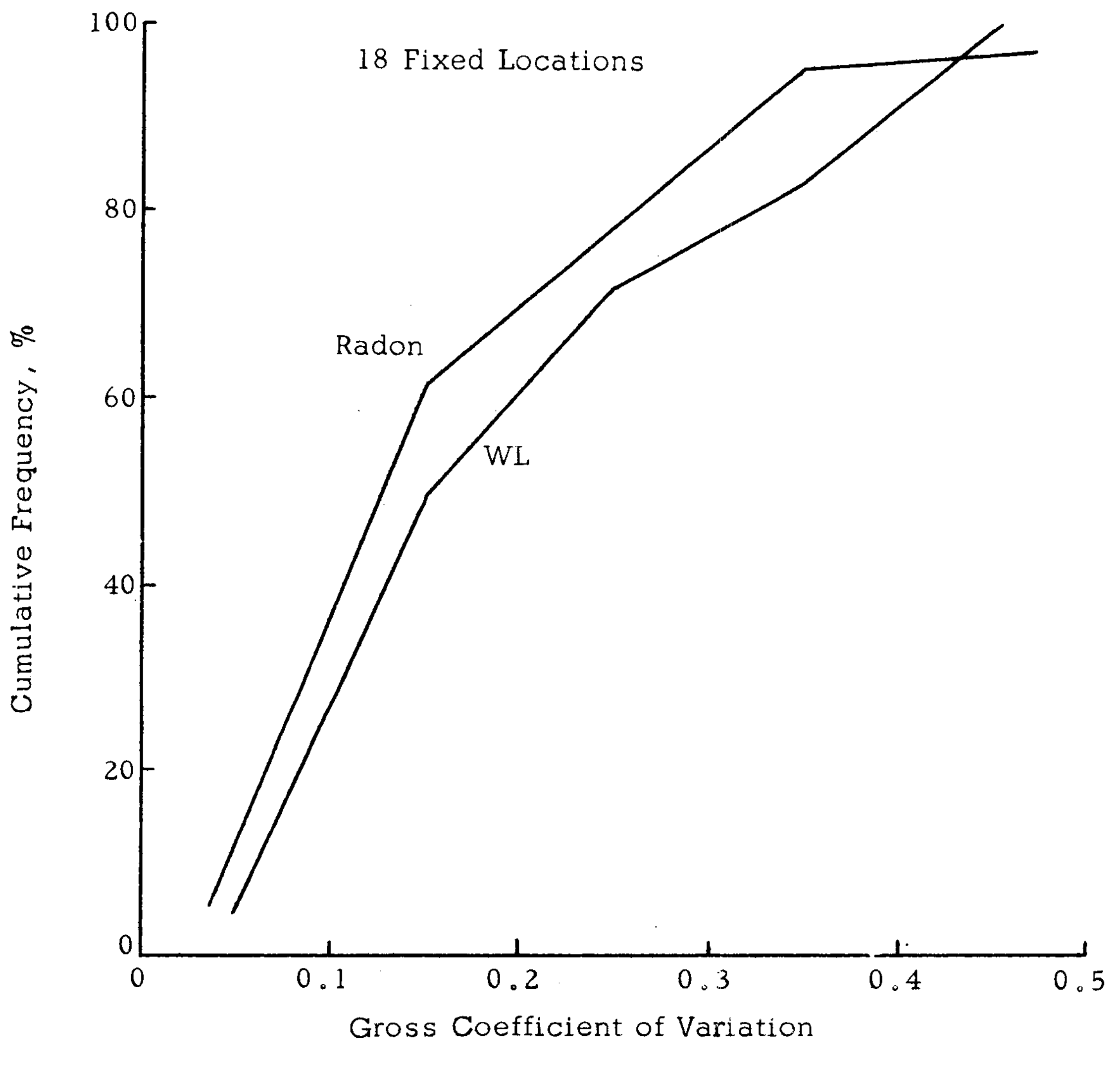


Fig. 25 - Cumulative Frequency Distribution for Gross Coefficients of Variation of Daily Average Radon Concentration and Working Level.

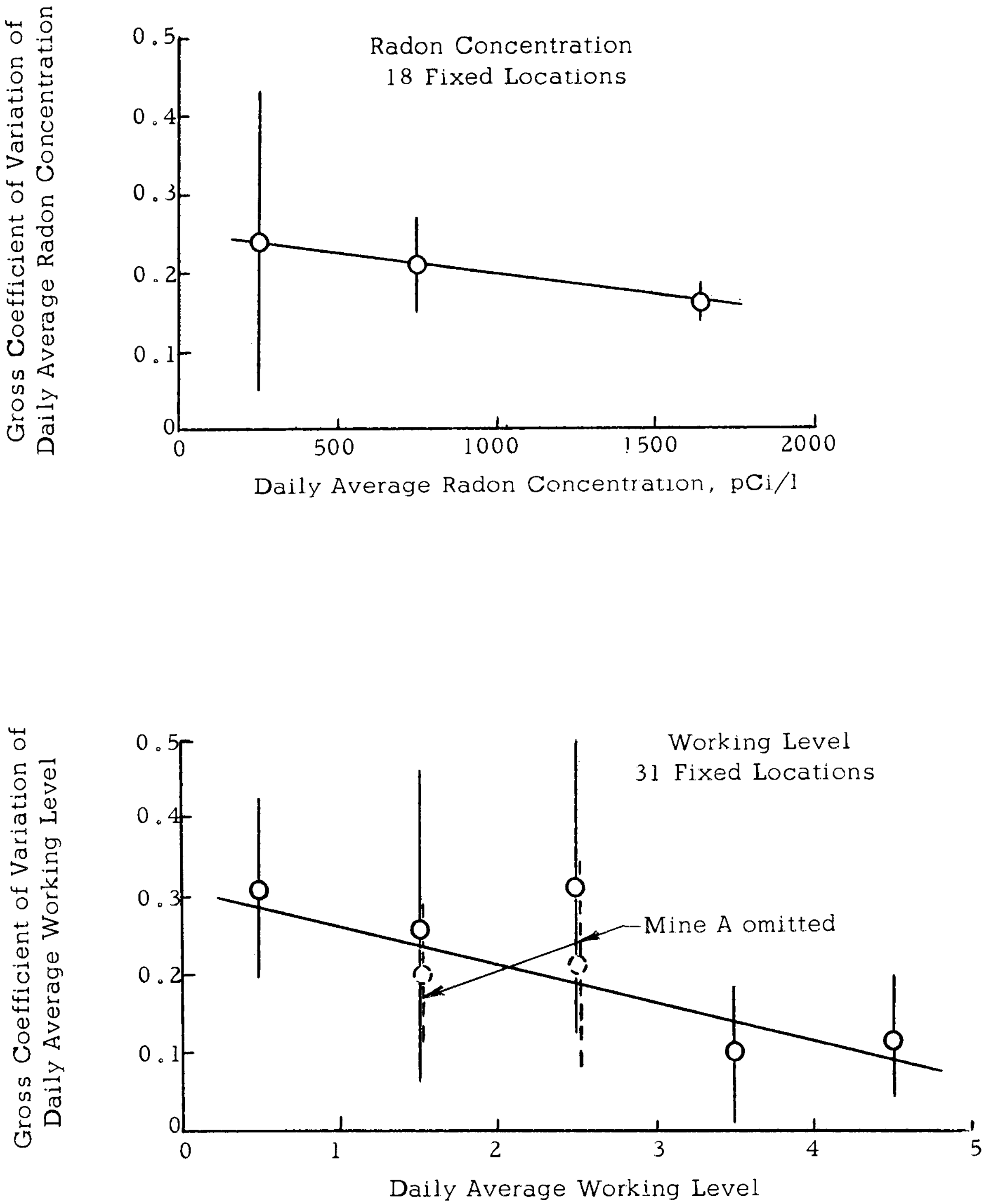


Fig. 26 - Gross Coefficient of Variation versus Daily Average Concentration for Radon Concentration and Working Level.

2. Variation of Working Level Ratios (WLR)

Because of rather poor precision in the measurement of WLR's (15 - 30%), examination of individual consecutive values of WLR cannot be fruitful. However, in well over half of the sampling locations, the coefficients of variation for daily groups of consecutive measurements, were no greater than the coefficients of variation for duplicate samples. Thus, a high degree of stability in half-hourly values of WLR may be inferred for those cases. About 75% of the gross coefficients of variation were less than 0.3 and the highest value was 0.64.

This relative stability tends to be carried over into the day to day values of WLR. At the locations where measurements were continued for two or more days, 39% of the coefficients of variation for daily average WLR were less than 0.1 and 78% were less than 0.3.

3. Variation of Radon Daughter Ratios

As in the case of WLRs, individual measurements of radon daughter ratios were too imprecise to have much validity. But again, as in the case of WLR, it may be inferred with reasonable confidence that in fixed locations, variations during a day were trivial for the most part because the coefficients of variation for duplicate samples substantially accounted for half-hourly variations in more than half of the daily groups of consecutve samples. Moreover, the net coefficients of variation exceeded 0.25 in only about 10% of the groups.

In still another parallel with WLRs, a large majority of the gross coefficients of variation of daily average radon daughter ratios were less than 0.2.

D. Variations with Distance

1. Variation of Radon Concentration

At distances from tens to hundreds of feet between points of simultaneous measurements, radon concentrations may agree exactly or differ by more than an order of magnitude. Expectedly, differences in concentrations tend to be greater at longer distances of separation but even at a few hundred feet, concentrations are just as likely to be identical as to differ by a factor of two or three. Concentration differences, expressed as the sample pair difference divided by the pair mean, are plotted against distance of separation in Fig. 27 for all mine areas.

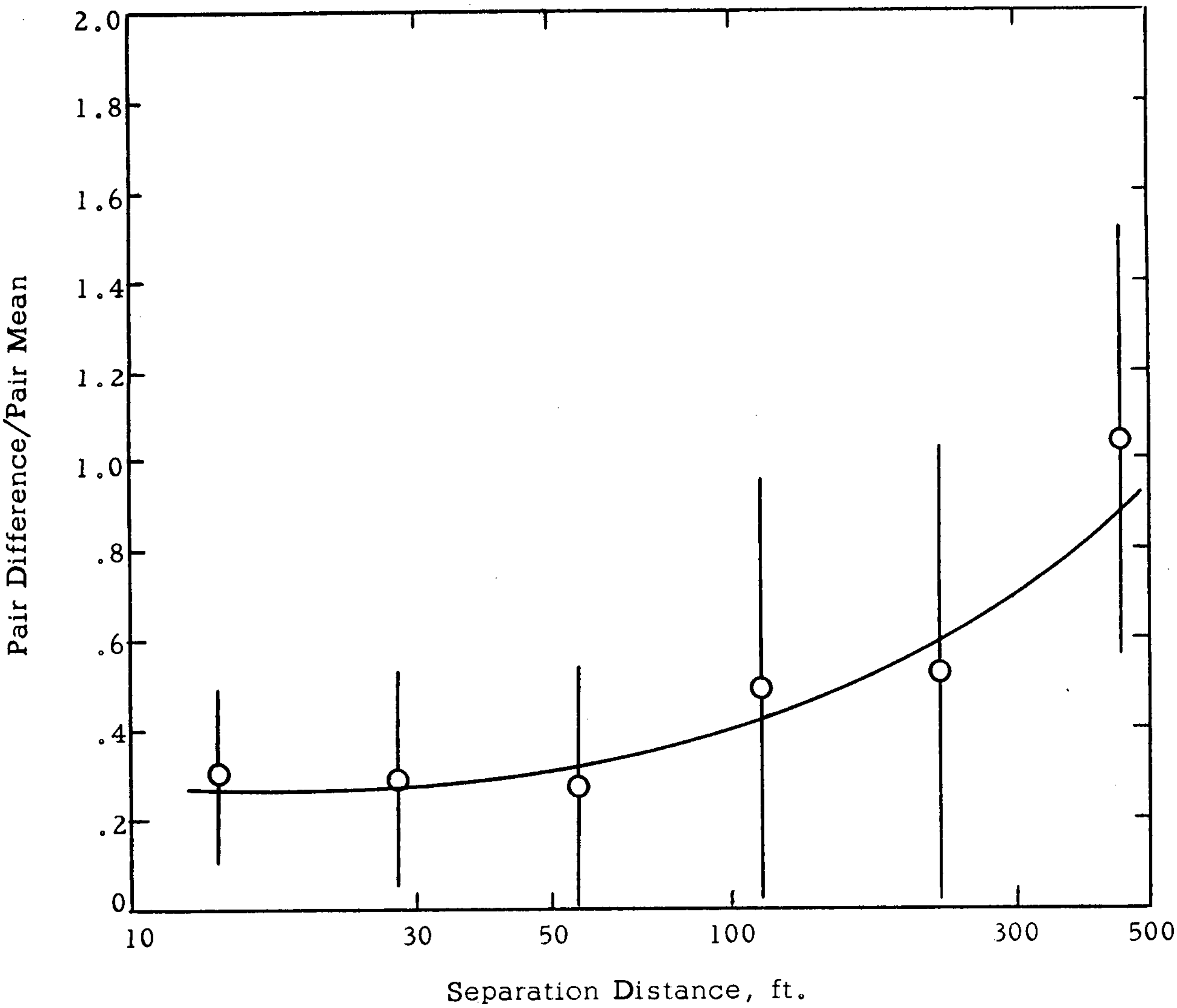


Fig. 27 - Variation of Radon Concentration with Distance - All Locations.

Radon concentrations tend to be more uniform in stopes than in drifts as indicated in Fig. 28 in which data from the two types of mine area are plotted separately. Within stopes, concentration differences appear to be independent of distance and are uniformly low. The concentration differences in drifts are greater and exhibit a correlation with distance although the correlation is manifest only at distances greater than those covered in stope measurements.

2. Variation of Working Level

The patterns of WL differences at various distances are generally similar to radon. Fig. 29 shows the relationship of WL differences with distance of separation for all mine areas. Data are plotted separately for mean concentrations greater than and less than 1.5 WL, indicating slightly more uniformity at the higher concentrations. (This concentration effect was not evident in the radon data.)

Data from drifts and stopes are shown separately in Fig. 30, indicating, as in the case of radon, smaller concentration differences in stopes. However, in contrast to the radon data, the WL differences in stopes increase at greater distances of separation. Although this divergence in behavior of radon and radon daughters may be real, it is also possible that it is due either to the relative paucity of stope data or the considerably greater error in radon measurements, or a combination of both. As a matter of fact, the exact shapes of all curves in Figs. 27 - 30 are somewhat speculative because of the wide standard deviations of the data.

On the other hand, the general trends indicated in the figures are probably valid. For example, the tendency to greater spatial uniformity of WL at higher concentration (Fig. 29), is very likely another manifestation of the tendency to greater temporal stability of WL at higher concentrations previously noted in Fig. 26. Of course, if this parallel exists for radon daughters, it would be expected for radon as well but the greater temporal stability of radon at higher concentrations shown in Fig. 26 is not reflected in the separated-pair data. Possibly there are too few of the latter for this effect to be detected.

The greater uniformity of both radon and radon daughters in stopes compared to drifts (Figs. 28 and 30) parallels the previous data on greater temporal stability in stopes compared to drifts shown in Fig. 20 and seems reasonable if stope atmospheres are visualized as confined, more or less well-mixed, parcels of air in contrast to moving drift air as the air stream

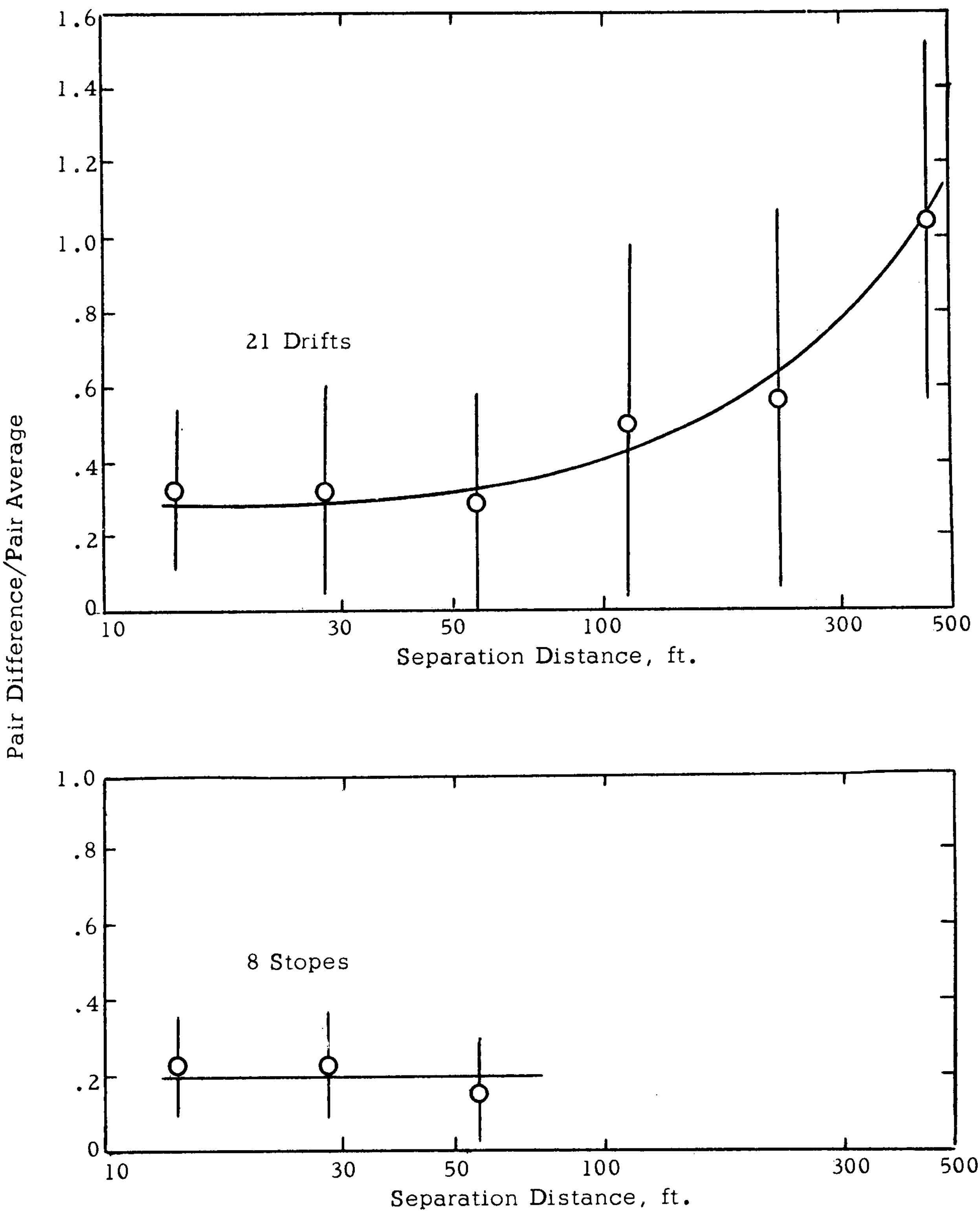


Fig. 28 - Variation of Radon Concentration with Distance in Stopes and Drifts.

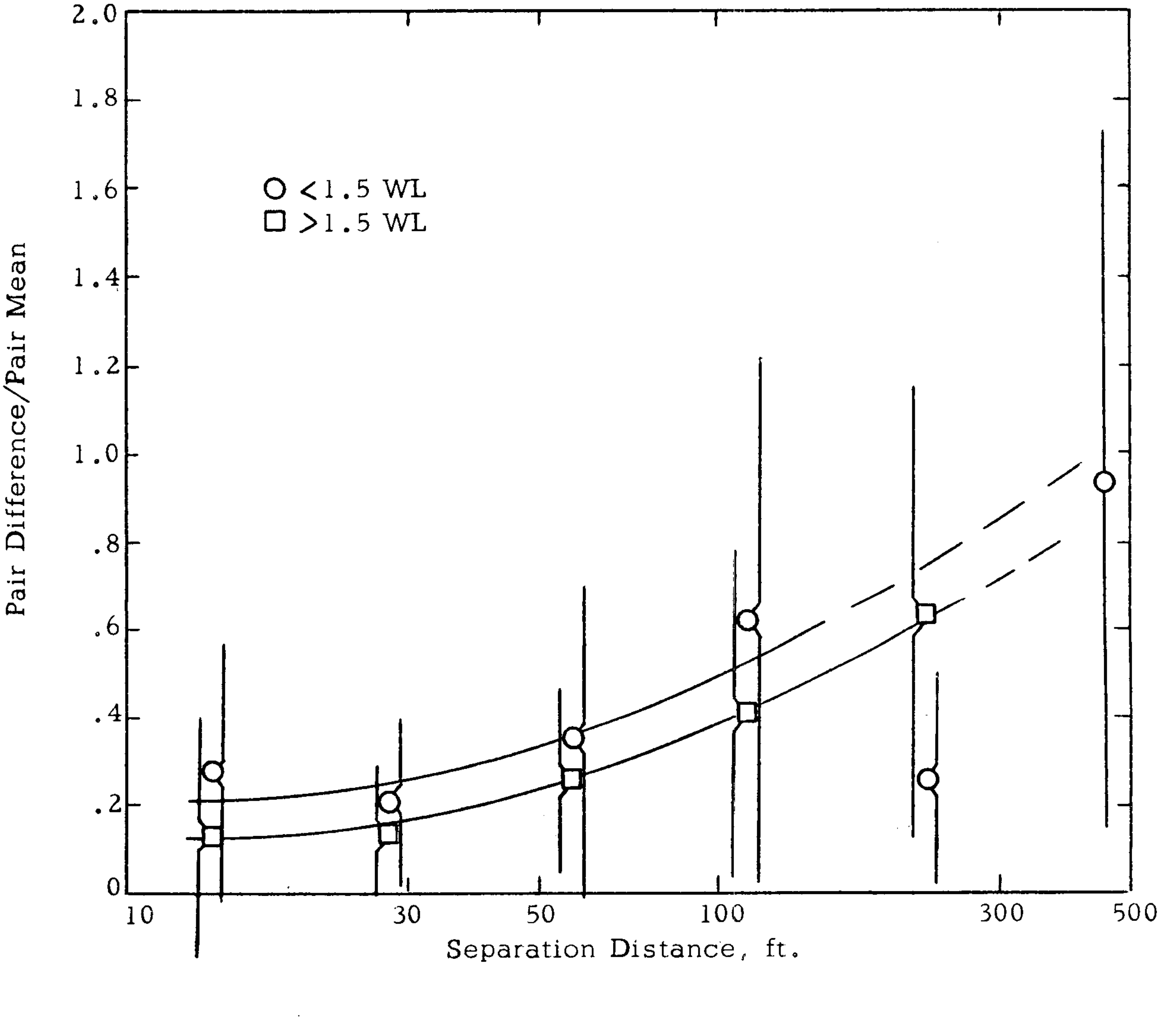


Fig. 29 - Variation of Working Level with Distance - All Locations.

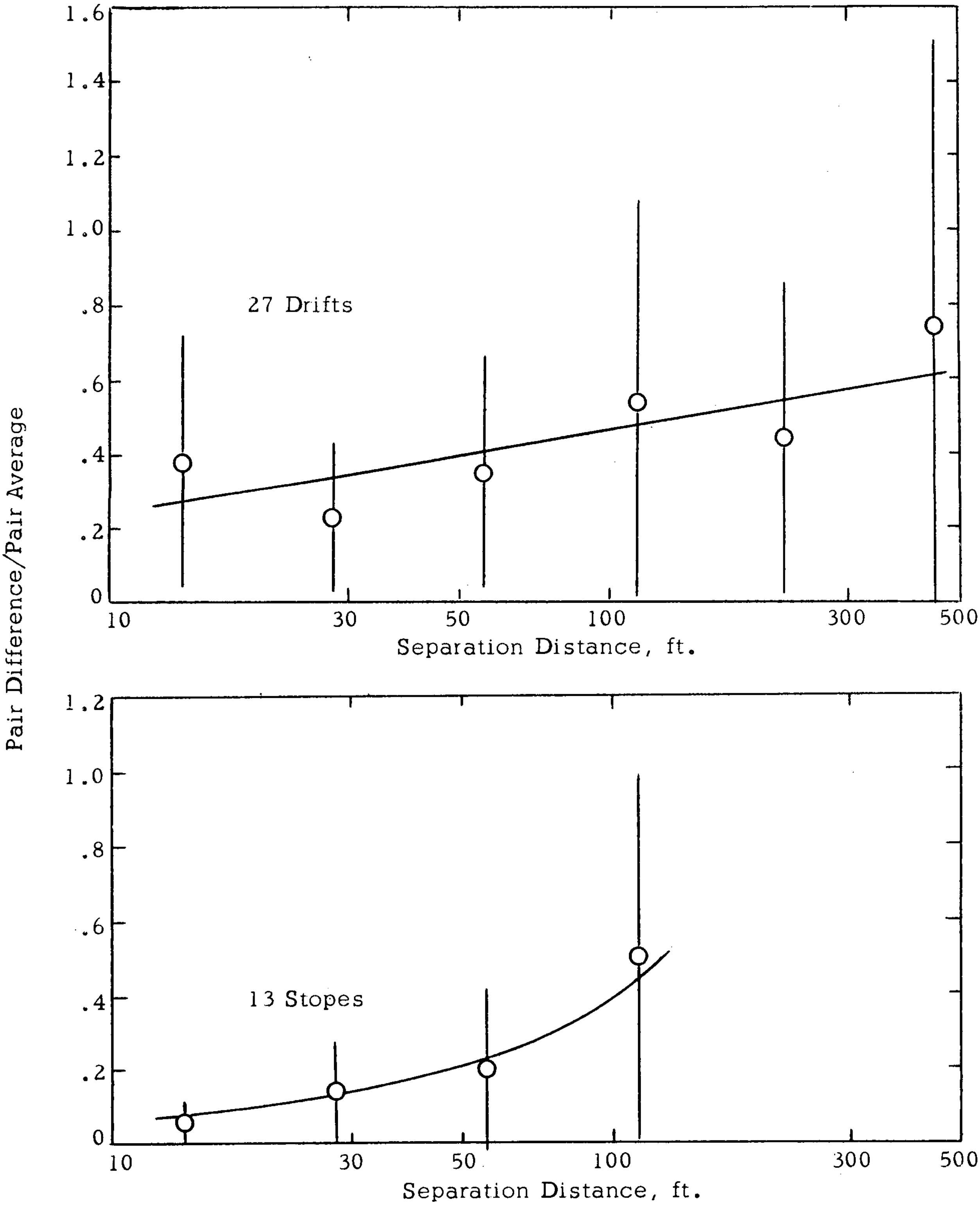


Fig. 30 - Variation of Working Level with Distance in Stopes and Drifts.

collects radon emanating from surfaces and merges with other contaminated air streams. That this distinction is not sharp is made quite evident by the widespread, overlapping difference ratios in the two figures.

In a few instances, simultaneous measurements of WL were made at separated locations in sections of drifts devoid of any sources of contamination other than radon emanation from the drift surfaces. Presumably the differences in WL are attributable to the combination of the accrual of emanating radon, growth of radon daughters in the air stream, and losses of radon daughters from the air stream to surfaces. Working level differences would be expected to be positive in direction of air flow. Increase in WL per lineal foot of drift varied from 0 - 3.4%; the mean was 1% $\pm$ 1%. The values may not be typical since the number of observations was quite small.

E. Variation in Working Level with Operations

Insofar as could be deduced from the data, routine mining operations had no effect on WL. However, no measurements were obtained directly after blasting, said to be the cause of temporary elevations in radon and radon daughters.

The WL measurements were reviewed, location by location, and on days when there were periods both of inactivity and of one or more operations performed at the reference sampling station, the average WLs during the active and inactive periods were compared. The results are given in Fig. 31 as percentage changes in WL, either positive or negative, during active periods with respect to inactive periods. The changes appear random. Actually, there is a greater number of diminished concentrations but the cumulative percent increase almost exactly balances the cumulative percent decrease. No consistent changes in either direction appear to be associated with specific types of operation.

F. Variation in Working Level with Humidity

In general, a single measurement of relative humidity was obtained daily in each sampling location, the time of measurement being more or less random. There was a correlation coefficient of 0.46, significant at the 0.001 level, between these measurements of humidity and daily average WLs for data pooled from all mines. The relationship is shown in Fig. 32.

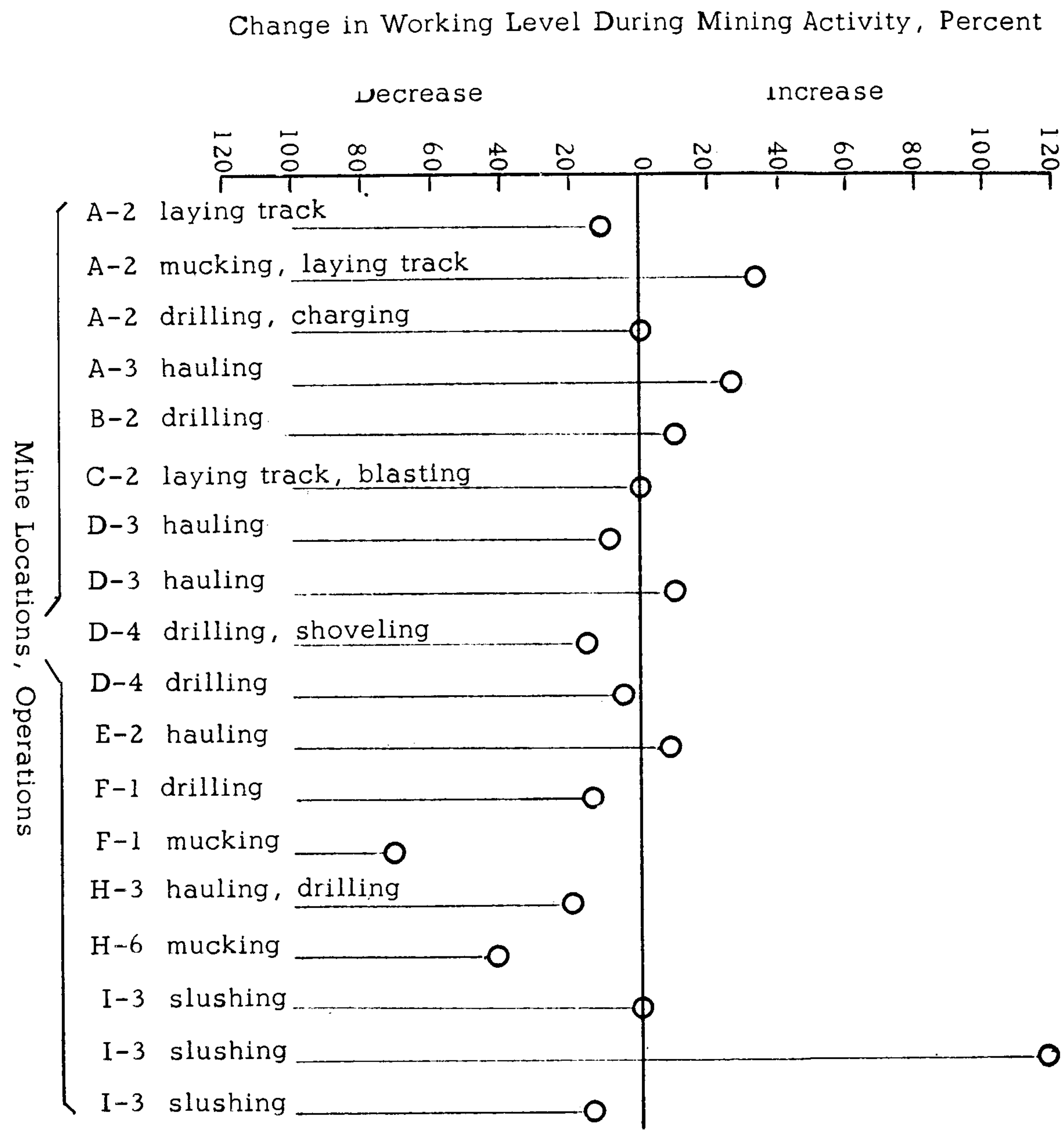


Fig. 31 - Effect of Mining Operations on Working Level.

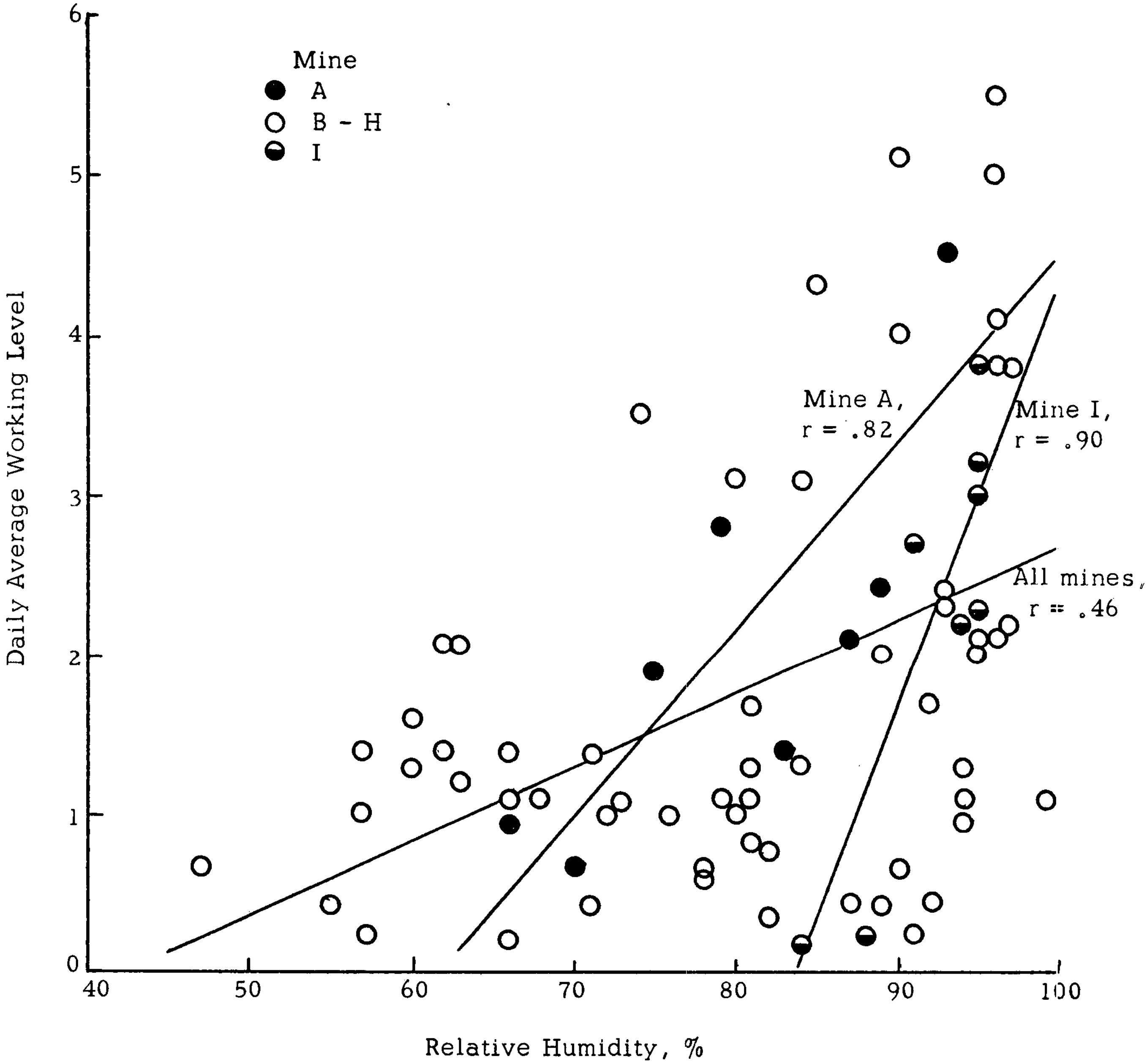


Fig. 32 - Average Working Level versus Relative Humidity.

A tentative explanation for this association is that ventilating air picks up both moisture and radon daughter contamination as it courses through the mines.

In data taken from individual mines, a significant correlation was found only for Mines A and I but the correlation coefficients were quite high, 0.82 and 0.90, respectively, and the least-square-lines of best fit of both were steep compared to the line for all mines.

IV. DISCUSSION

The nine uranium mines covered in this investigation represent a range of radiologic characteristics as well as a variety of physical features. Because engineering observations and measurements were only incidental to the main objective of describing radiologic characteristics, the degree to which the radiologic environment is related to physical conditions could not be examined except for the association of WL and humidity, described in Section III.F.

The range in average WL among mines was fourfold, 4.3 WL in Mine C contrasted with 1.2 WL in Mine F. (Again the reader is cautioned that these figures should not be construed as overall mine averages - each is an average of the several locations chosen for sampling.) Referring to Table I, it is interesting that ventilation at the four largest mines, including Mine F, was quite similar in terms of volume rate per ton of ore mined per month $\left(12 - 17 \frac{\text{cfm}}{\text{ton/mo.}}\right)$ and considerably lower than in any of the other mines. The ventilation rate at Mine C was second highest at $52 \frac{\text{cfm}}{\text{ton/mo.}}$. As a matter of fact, there is an approximately inverse relationship between total ventilation rate and ore production, probably reflecting more efficient use of air at the newer and larger mines.

Average ore dust concentrations extended from 1.7 to 26 a dpm/m^3. The ore dust concentration at Mine C, where the highest average WL was found, was among the lowest of the mines whereas at Mine F, the ore dust was third from the highest.

Mean gamma radiation by mine was more uniform, varying from 0.2 - 0.7 mr/hr.

The foregoing gross radiologic characteristics confirm that the mines represent a range of conditions and probably comprise a typical cross section of the industry.

Interpretation of the results given in this report necessarily depends on one's interests and responsibilities. The authors are not competent to discuss all of the possible applications but have noted a few aspects that may be of general interest.

The great variability of radiologic conditions claimed by several witnesses at the 1967 Congressional Hearings is confirmed by the measurements performed in this investigation. Nevertheless, variations over the time spans covered in this study are within reasonable limits and some general patterns can be observed. The greater variability of WL at lower concentrations, clearly portrayed for specific locations by the comparative graphs in Fig. 18 and confirmed as a general tendency by Fig. 22, is compatible with the following, rather simple conception of the process by which ventilating air becomes contaminated.

Radon emanation and ventilation rate at any location in a mine are variable. This variability will appear to be quite marked as the virtually clean, background air enters the mine and makes its first contact with emanating radon. But as the air progresses through the mine, increasing its content of radon and radon daughters, the variation in emanation rate is superimposed on an ever greater "background" and is relatively diminished. A hyperbolic function, much as Fig. 22 suggests, would be expected in this case.

In this simple model, the WL ratio also would increase as ventilating air courses through the mine. This tendency appears in Fig. 7 showing an increase of WLR as a function of WL. Similarly, radon daughter ratios would be expected to increase with WL, a tendency that may be seen in Fig. 12.

It may be noted that the cited figures have very broad standard deviations of mean data points. At least one reason for this is that these figures are based on data pooled from all of the mines, necessitated by the relatively few points of observation in each mine. This undoubtedly blurs the kinds of effect under discussion. It's speculative whether these tendencies would be stronger in extensive observation from a single mine.

In summary then, ventilating air near the mine inlet is characterized by low but highly variable concentrations of radon and radon daughters and low WL ratios and radon daughter ratios. As the air moves through the mine, concentrations increase, becoming relatively more stable, with increasing ratios. The majority of both WLR and radon daughter ratios indicate that ventilating air effectively remains in mines for fairly long periods of time. This is seen directly in Fig. 11 where radon daughter ratios are associated either with growth periods on the order of 30 minutes to more than an hour or with very low ventilation rates. As has been shown by Evans[9], the inevitable growth of radon daughters with time is a compelling reason to expedite the removal of ventilating air after it becomes contaminated. This point is illustrated by Fig. 33 in which WL and WLR are plotted against time for the case of continuous, uniform emission of radon into a volume of air, an idealized description of ventilating air moving through a drift. The most frequent WLR found in this investigation, ~0.25, is equivalent to a growth period of 30 minutes according to Fig. 33. The highest WLR's would be equivalent to ages of well over an hour. The benefit to be gained by more expeditious removal of the air is shown by the WL curve: reduction in growth period from 30 to 20 minutes causes a two-fold reduction in WL. While it is true that simple models may not accurately characterize mine atmospheres, as was seen in Section III.A.3, the basic principle illustrated by Fig. 33 is valid.

Probably more of the total residence time of ventilating air is spent in stopes and other large, open areas than in drifts where air velocities are on the order of several hundred feet per minute. Sealing off areas that are no longer in use is a well-established principle in the industry but was not applied as rigorously as possible in several of the mines covered in this study.

Many of the results have pertinence to atmospheric monitoring. One important finding is the good precision in the Kusnetz method of measuring WL. This identifies atmospheric fluctuations as the main source of error in estimates of average concentration. However, there is adequate information on atmospheric fluctuations to make some judgements on the confidence that can be placed in a single measurement in given circumstances or, conversely, the number of measurements needed to obtain some standard of precision in an estimate of average concentration.

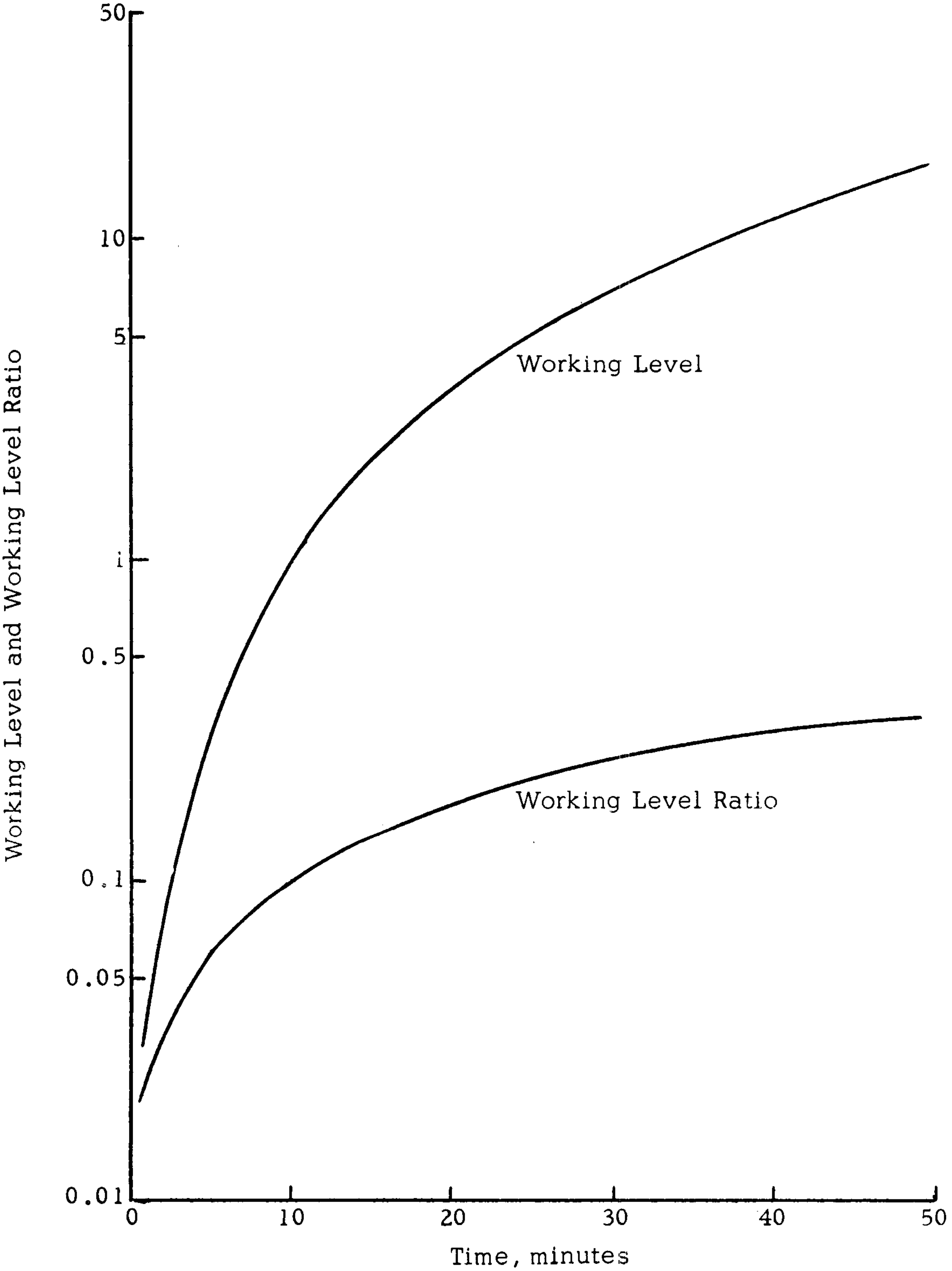


Fig. 33 - Growth of Working Level and Working Level Ratio with Continuous Emission of Radon at 100 pCi/min.

For example, according to Fig. 19, about 80% of the gross coefficients of variation* are ≤ 0.3. Therefore, a single sample will give an estimate of the mean concentration on the day of collection to within $\pm$ 30% in the majority of cases. But the estimate can be improved by collecting additional samples. The standard error of the mean concentration based on three measurements would be reduced to $\leq$17%. This calculation is predicated on normal distribution of concentration values, shown to hold for samples collected in this investigation.

Since not all of the concentration fluctuations are random with time, sampling, whether singly or in replicate, should be at random times to avoid bias in the estimate of mean concentration. This is made more feasible by the finding that concentrations are independent of mining operations. Hence, sampling need not and, in fact, should not be timed to coincide with any particular schedule.

Atmospheric fluctuations tend to be greater at lower concentrations as shown in Fig. 22. Generally, then, more samples are needed at 0.5 WL, say, than at 2 WL to achieve a comparable error in estimating the mean concentration. It might be inferred that an increase in sampling frequency may be necessary as radon daughter concentrations are reduced by improvements in control, but less precision is required in the evaluation of lower levels of exposure.

Within stopes, the exact location of a sample is not critical. According to Fig. 30, a sample is closely representative of concentrations within a radius of 10 to 20 feet. Consequently, the "breathing zone" sample which is so important in monitoring exposures in the dusty trades above ground is not a requirement in stopes. But in drifts, concentration differences may be quite large at short distances. Another characteristic in drifts is a gradual increase in concentration in the direction of air flow except at points of marked change such as the confluence of two air streams.

---

*Gross rather than net coefficients of variation are used here because they include the sampling measurement errors which would be components of any measurements. However, note that the sampling and measurement errors will differ among practitioners.

It should be remembered that the foregoing remarks pertaining to monitoring and atmospheric fluctuations are generalities. Deviations will occur in specific instances. This is manifest in the broad standard deviations common to most of the graphs. Moreover, these statistical patterns are based on observations of several days in each mine. In particular, the coefficients of variation for atmospheric fluctuations should not be used to estimate behavior over longer time periods.

V. SUMMARY

Comprehensive measurements were performed for three to four days in each of nine uranium mines to provide a detailed description of the radiologic environment. Basic measurements consisted of radon, working level, radon daughter ratio, ore dust concentration, and gamma radiation. These were supplemented by measurements of temperature, humidity, barometric pressure, and ventilation.

Measurement techniques were generally satisfactory although better precision in some would have been desirable. In particular, the Kusnetz method of measuring WL was quite reliable over a wide range of concentrations.

Nearly all of the measurements are presented in the appendices either in graphical or tabular form. Diagrams of sampling locations are also given. Summaries of various aspects of the data are given in the body of the report.

Individual values of radon concentration were in the range from 4 to 7000 pCi/l; the range of WLs was 0.01 to 7.2. Averaged by mine, the range of WLs was 1.2 to 4.3.

Overall frequency distributions of radon concentration, WL, WLR, and radon daughter ratios are given and to the extent practicable, general characteristics of concentrations and their variations are identified. Temporal variations of concentrations were moderate for the most part, greater stability being observed in stopes than in drifts and at higher than at lower concentrations. Spatial variation was less in stopes than in drifts. Radon exhibited slightly greater stability than radon daughters (WLs) both in half-hourly and in daily concentrations.

Certain aspects of the data are compatible with a simple concept of the progress of air contamination. The data also are useful in establishing sampling procedure and frequency.

REFERENCES

1. Holaday, D. A., et al.
   Control of Radon and Daughters in Uranium Mines and Calculations on Biologic Effects
   U.S. Dept. Health, Education and Welfare, PHS Publ. #494 (1957)

2. Radiation Exposure of Uranium Miners
   Hearing before the Subcommittee on Research, Development, and Radiation of the Joint Committee on Atomic Energy
   Congress of the U.S., U.S. Govt. Printing Office, Wash., D.C. (1967)

3. Guidance for the Control of Radiation Hazards in Uranium Mining
   Staff Report of the Federal Radiation Council, Report #8 Revised, Sept. (1967)

4. Thomas, J. W. and LeClare, P. C.
   A Study of the Two-Filter Method for Radon-222
   Health Physics, 18, (to be published Feb. 1970)

5. Tsivoglou, E. C., Ayer, H. E. and Holaday, D. A.
   Occurrence of Nonequilibrium Atmospheric Mixtures of Radon and its Daughters
   Nucleonics, 11, 40-45 (1953)

6. Kusnetz, H. L.
   Radon Daughters in Mine Atmospheres - A Field Method for Determining Concentrations
   Amer. Ind. Hyg. Assoc. Quarterly, 17, 85-88 (1956)

7. Harley, J. H. (Editor)
   Manual of Standard Procedures
   USAEC Report NYO-4700 (Second Issuance) (1967)

8. Shapiro, Jacob
   An Evaluation of the Pulmonary Radiation Dosage from Radon and its Daughter Products
   Univ. of Rochester Atomic Energy Project Report UR-298 (1954)

9. Evans, Robley D. and Kolenkow, Robert J.
   Radium and Mesothorium Poisoning and Dosimetry and Instrumentation Techniques in Applied Radioactivity
   Annual Progress Report, MIT-952-5, May (1968)

Acknowledgment

The execution of this investigation depended on the efforts of many people, notably, Health and Safety Laboratory personnel who worked long hours under arduous field condtions. We were also fortunate in having the cooperation of the U.S. Bureau of Mines and the AEC Grand Junction Office.

The late Mr. E. W. Felegy of the Bureau of Mines office at Denver selected mines for study and arranged for access to the mines by HASL survey teams. In addition, the following Bureau of Mines engineers worked directly on the surveys, escorting HASL personnel in the mines and obtaining ventilation measurements: Robert L. Rock, Donald K. Walker, Paul P. Schapiro, and Raymond C. Derzay.

Messrs. Don R. Hill and Ellsworth F. Stein of the Grand Junction Office arranged for vehicles and personal safety equipment and assisted in the shipment and storage of instrumentation.

The actual hard work of collecting and analyzing air samples in the mines was done by Robert Epps, Henry Franklin, Ronald Fedore, Andreas George, Lawrence Hinchliffe, Ronald Knuth, Peter Loysen, David Rimberg, and Evan Wasserman of the Health Protection Engineering Division, Martin Weinstein of the Radiation Physics Division, and Robert W. Doherty of the Radiochemistry Division.

Duncan Holaday reviewed the work at several stages and offered helpful comments and suggestions and Dr. Bernard S. Pasternack of New York University provided consultation in the statistical treatment of the data.

Miss Mildred Sidorsky typed and assembled the report virtually unaided, offered many useful comments and suggestions on format, and displayed an abiding equanimity throughout numerous revisions.

APPENDIX A

GRAPHS OF RADON CONCENTRATION AND WORKING LEVEL

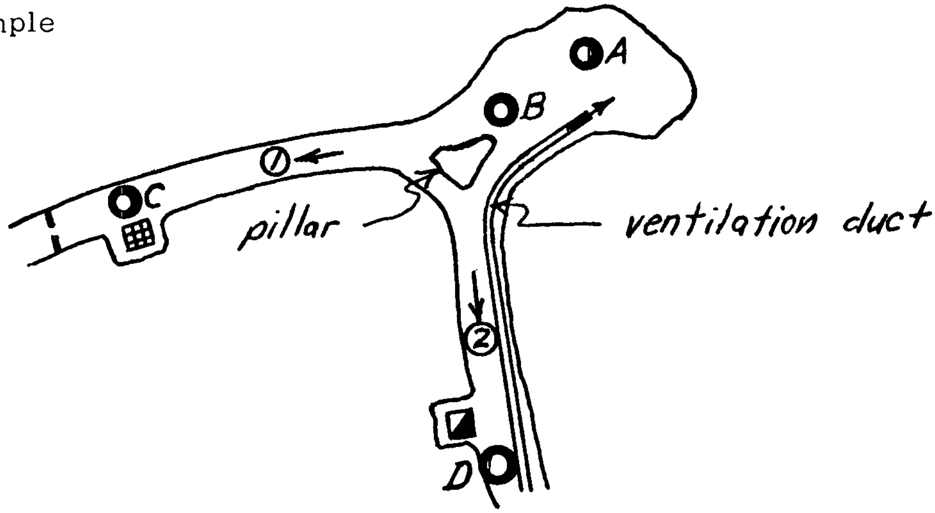
All measurements of radon concentration and working level are presented in the following graphs. There is a diagram of local features and sampling locations and a graph of concentrations plotted against time for each area that was studied. In a few cases, one diagram pertains to two or more graphs.

All ventilation, temperature, humidity and pressure data are given as well as notations of operations that occurred during sampling periods. The completeness of ventilation data varies considerably among locations.

The conventions shown on the next three pages are used in the diagrams and graphs.

<u>DIAGRAMS OF SAMPLING AREAS</u>

Example



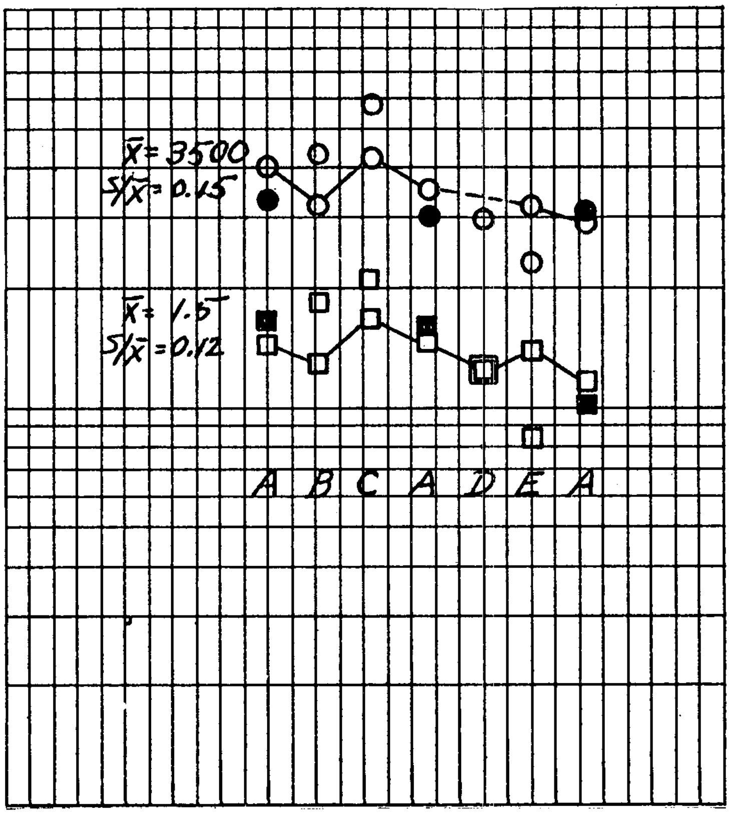
<u>SYMBOLS</u>

○ A, ○ B, ... - sampling locations; A designates reference (fixed) location; B, C, ... designate remote (variable) locations.

①, ②, ... - points at which ventilation data (given in tables beneath diagrams) apply.

→	direction of air flow		winze
8	fan	[S]	slusher
	air door		grizzly
	air seal	⊠	ore pass
	raise	>>>	incline

GRAPHS OF CONCENTRATION DATA



SYMBOLS

○ ●	radon concentration
□ ■	working level
—○— —□— }	concentration at reference (fixed) location
– – –	missing measurement
○ □	concentration at remote (variable) location
● ■	duplicate measurement at reference location
◎ ▣	identical concentrations
A, B, C, . . .	location of remote measurement shown on mine diagram; A indicates location coincident with reference sample, i.e. duplicate measurement.
$\bar{x}$	mean concentration
$s/\bar{x}$	coefficient of variation

OPERATIONAL AND ENVIRONMENTAL DATA
(presented below each graph)

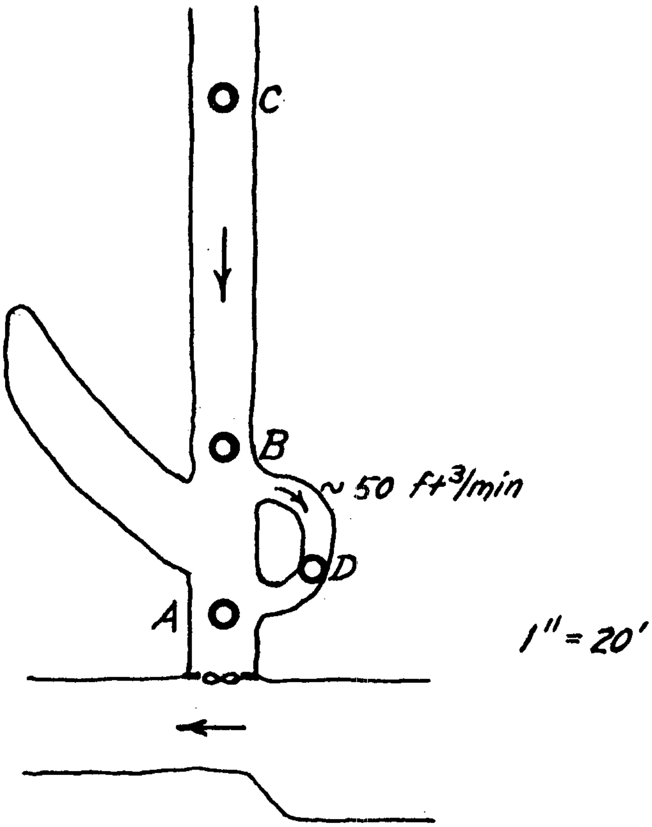
Ventilation - numerals refer to "ventilation notes" under mine diagram.

Operation - letters designate types of operation according to the following code:

B	blasting	L	loading round
C	charging	M	mucking
D	drilling	N	none
DP	dumping	S	slushing
H	hauling	SH	shoveling
W	wetting down	T	laying tracks
———>	continuing operation	TB	timbering

Location Code - letters refer to sampling locations on mine diagram indicating vicinity of operation.

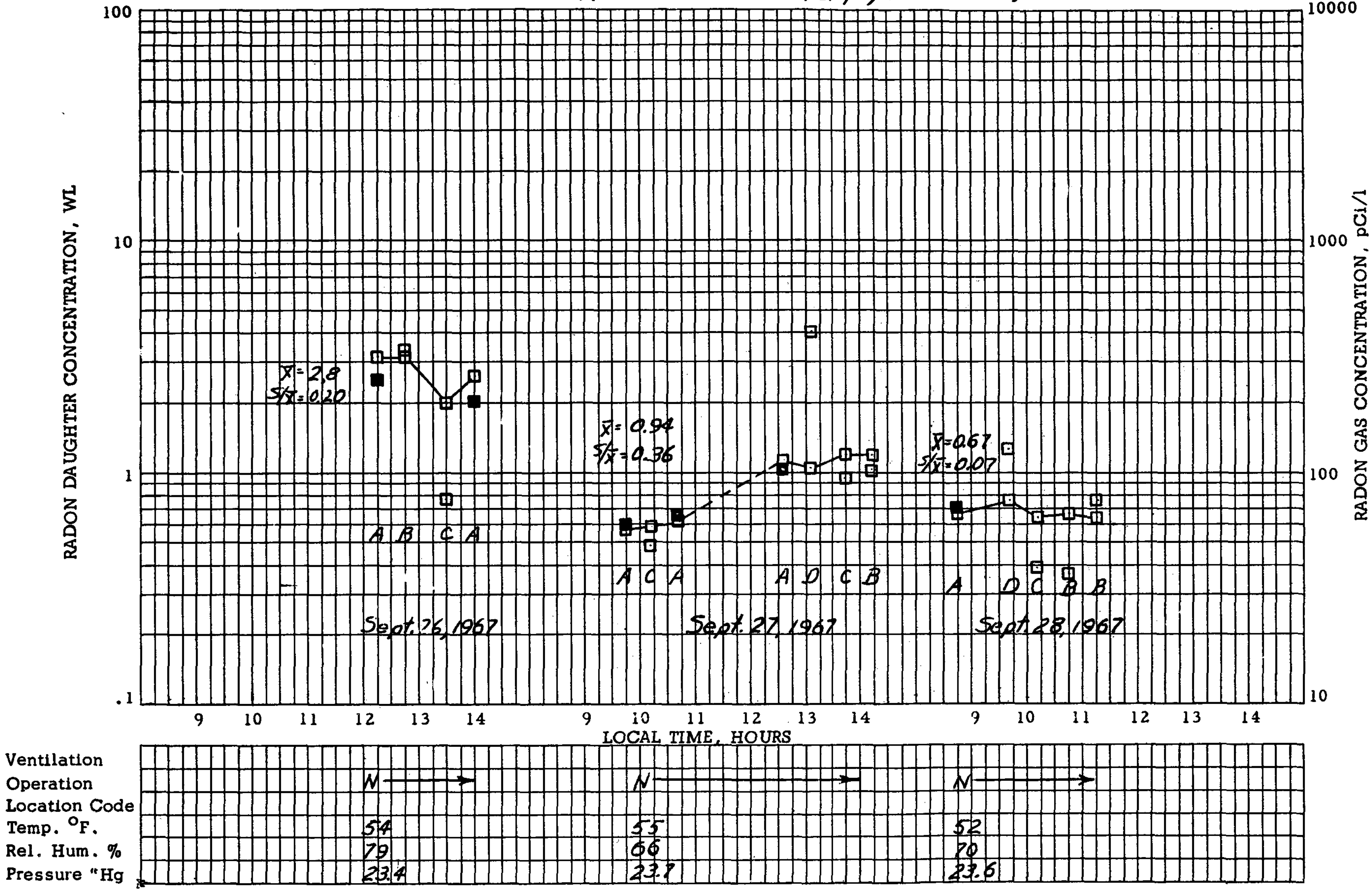
Temp, Rel Hum, Pressure - each usually measured once during day; values listed arbitrarily at start of sampling period.

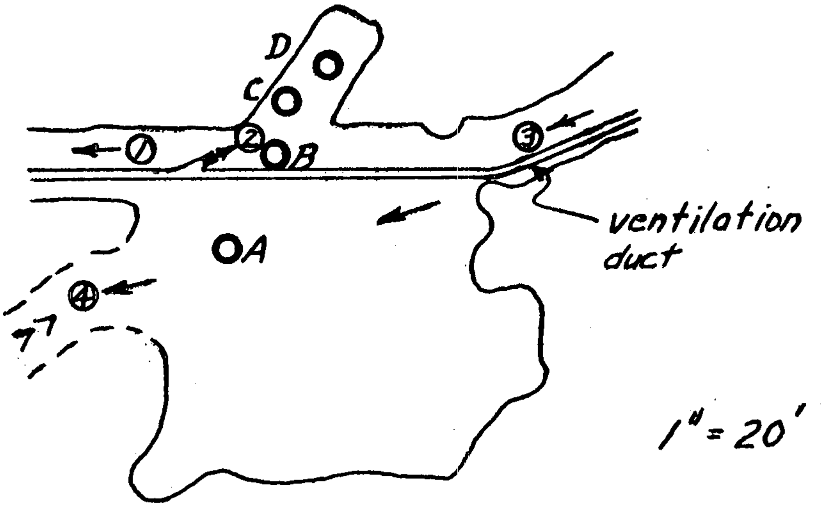


Mine - Location: A - 1, stope, fan station
Volume (ft^3): 2800 between C and door

Velocity (ft/min):	at C	9/26	80
		9/27	120
		9/28	100
Flowrate (ft^3/min):	through fan	9/26	4500
		9/27	5600
		9/28	5600

MINE: A LOCATION: 1 (stope, fan station)





Mine - Location: A - 2 stope
Volume (ft^3): 500 heading at D
6000 stope
Ventilation changes: 9/26 1235 air duct repaired

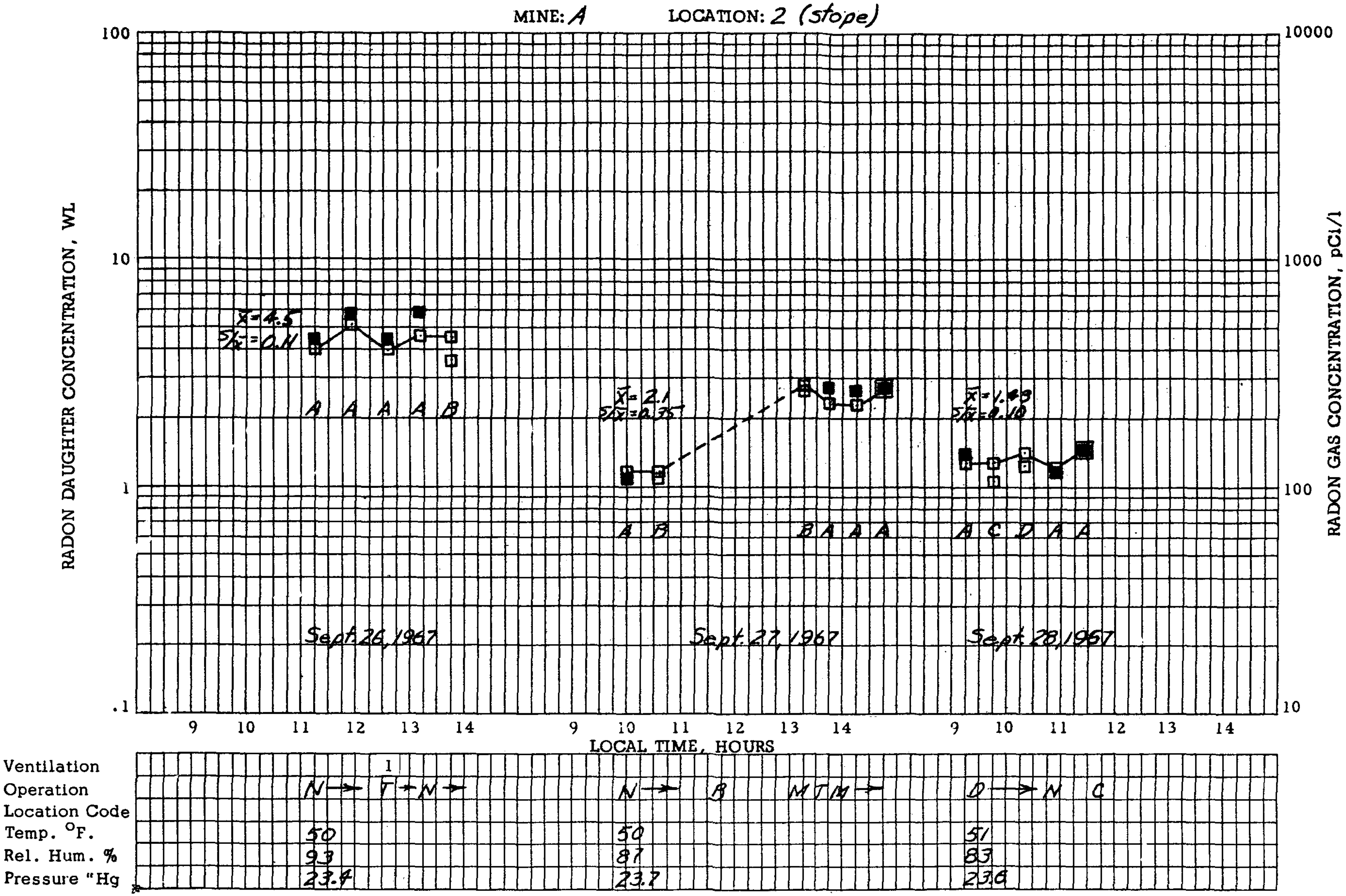
Velocity (ft/min): at ① 9/26 75
9/27 86
9/28 86

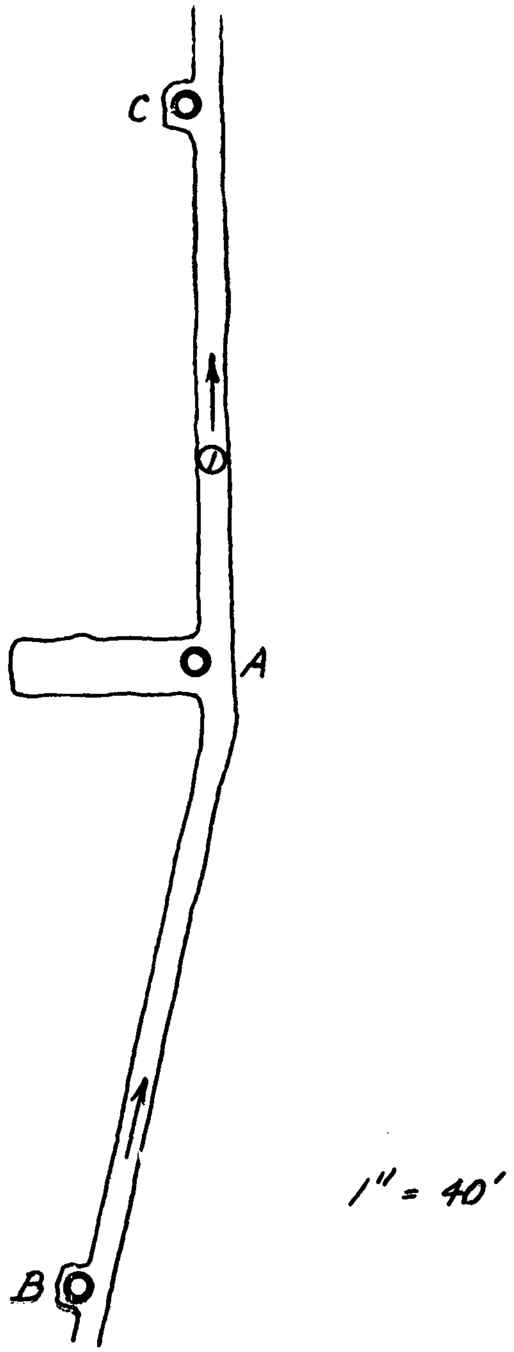
Flowrate (ft^3/min):

		①	②	③	④
9/26	1035	4200	2200	100	-
	1310	-	2600	-	-
9/27	1020	4900	2700	1100	200
9/28	0945	4500	4400	50	-
	1020	4900	2700	1100	-

Flowrate (change/min): at D 9/26 5.0
9/27 5.3
9/28 5.3

Ventilation note: 1. 9/26 1235 ventilation duct repaired


MINE: A
LOCATION: 2 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/1
100
10
1
.1
10000
1000
100
10
LOCAL TIME, HOURS
Sept. 26, 1967
Sept. 27, 1967
Sept. 28, 1967
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
50
93
23.4
50
87
23.7
51
83
23.6

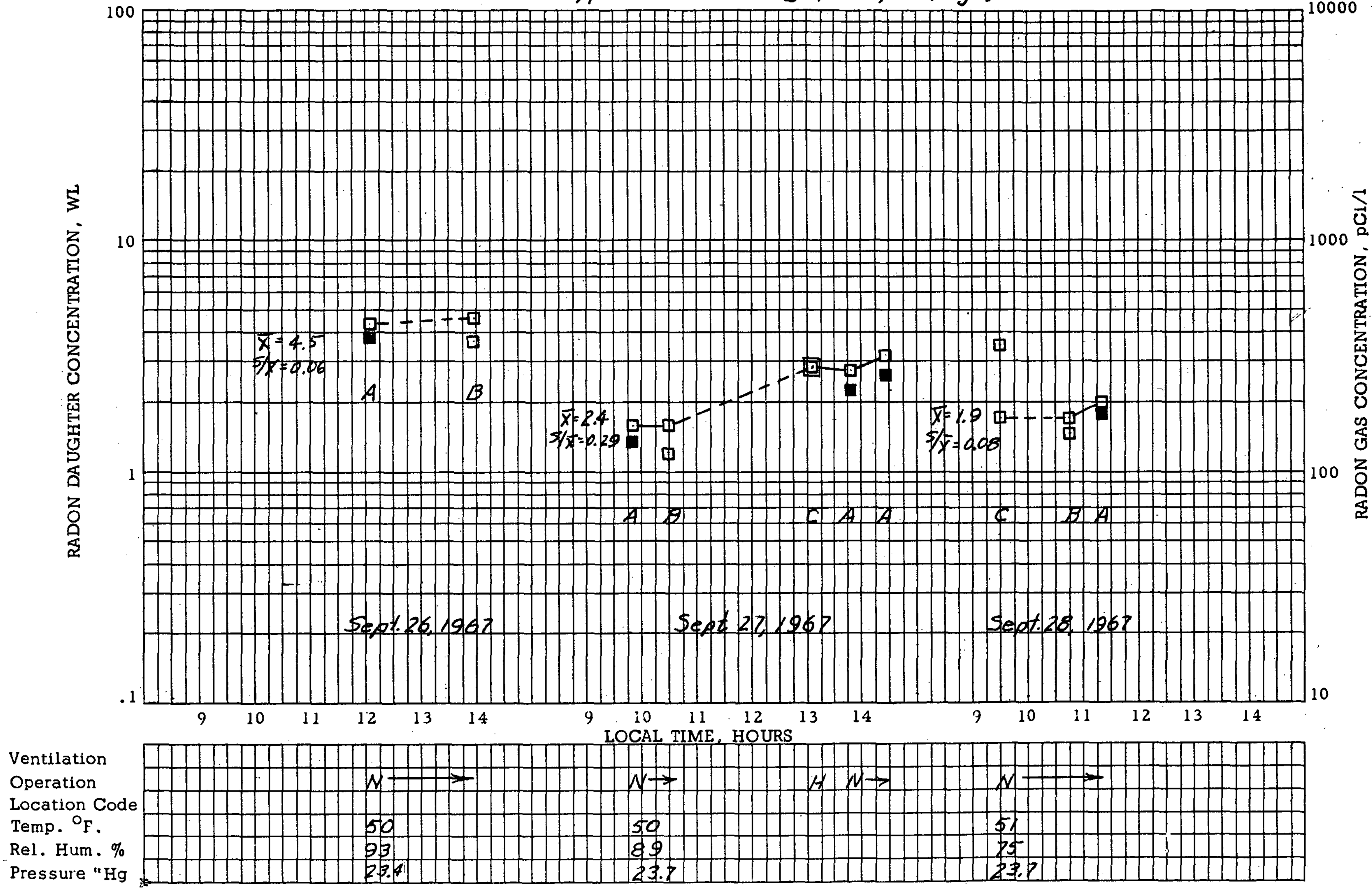


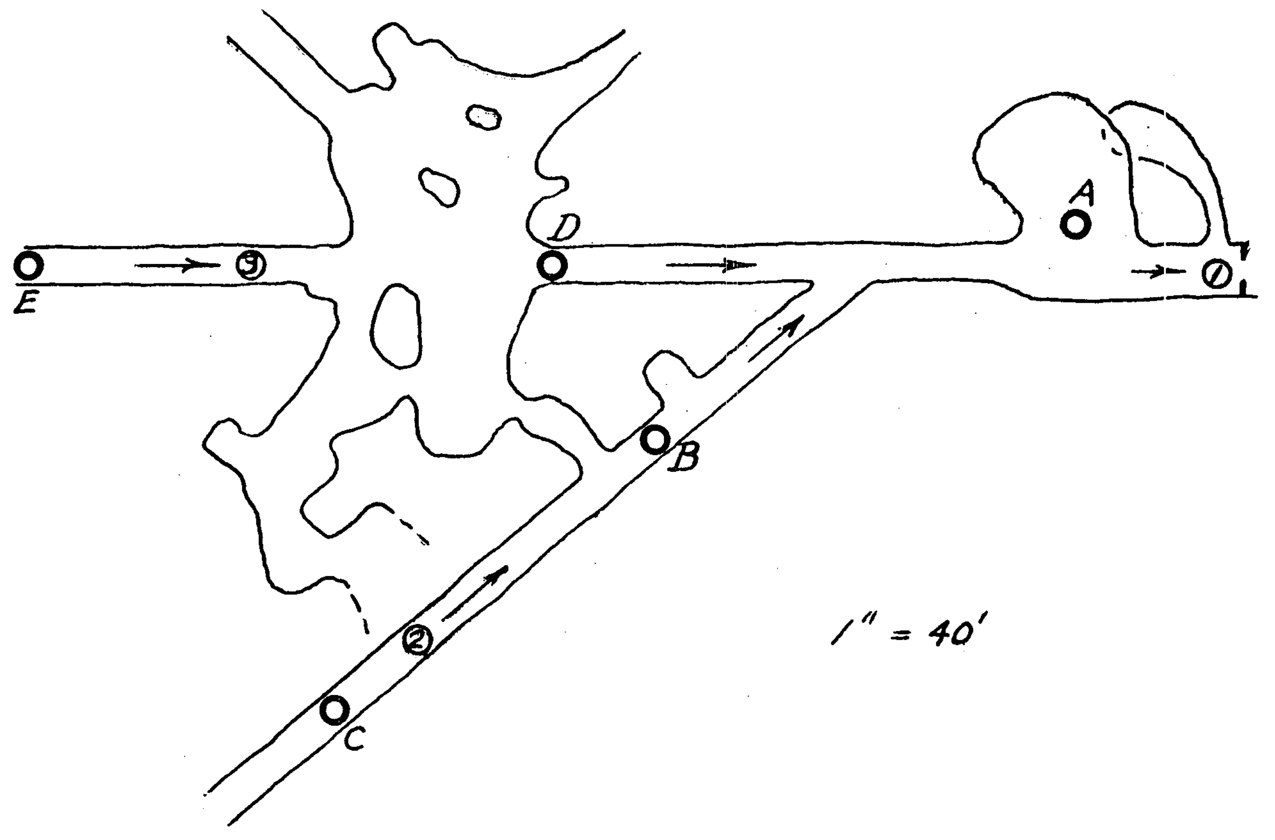
Mine - Location: A - 3 drift, haulage

Velocity (ft/min): at ① 9/26 - 110; 9/27 - 140; 9/28 - 140

Flowrate (ft^3/min): at ① 9/26 - 4500; 9/27 - 5900; 9/28 - 5900

MINE: A LOCATION: 3 (drift, haulage)



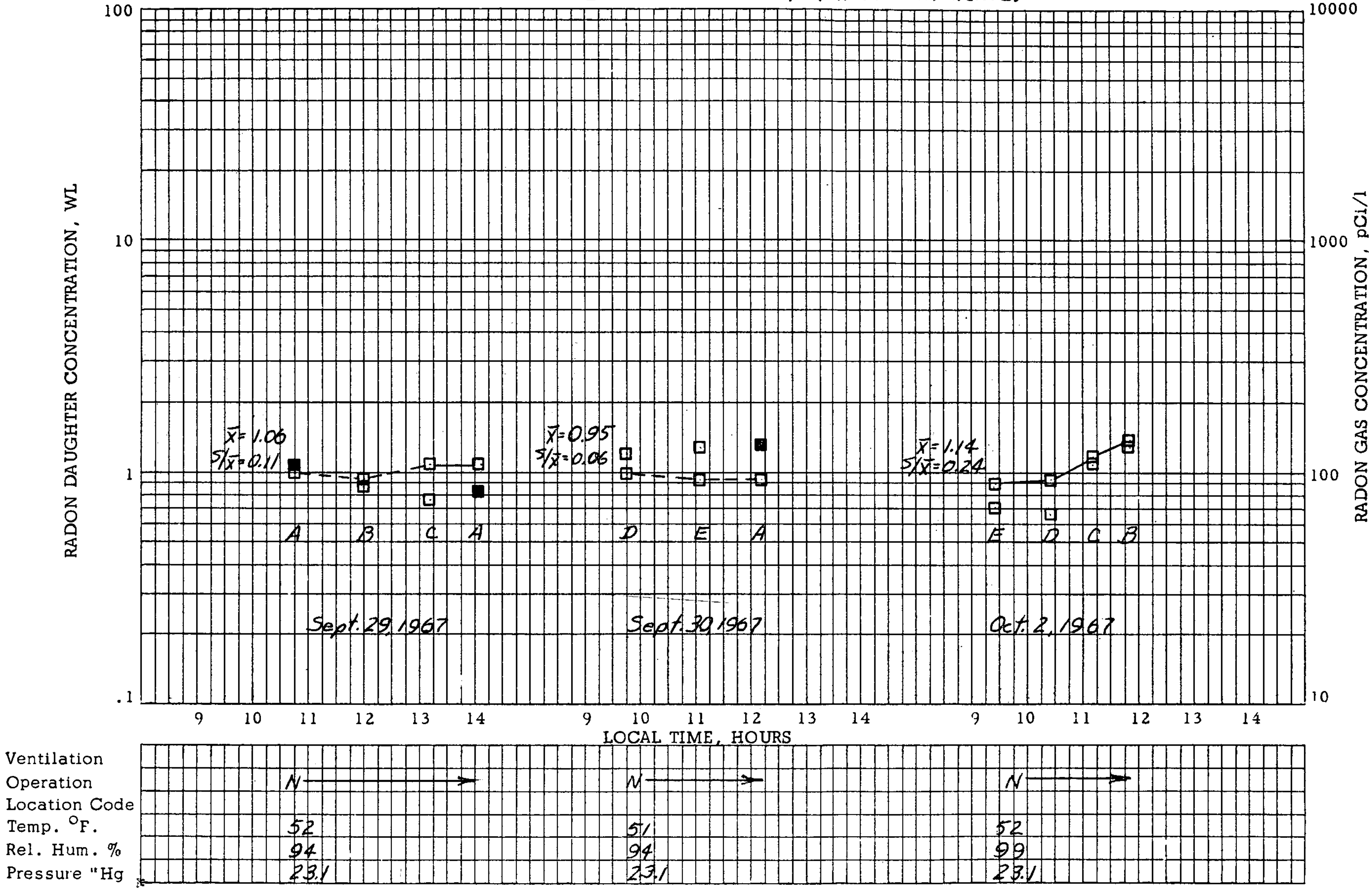


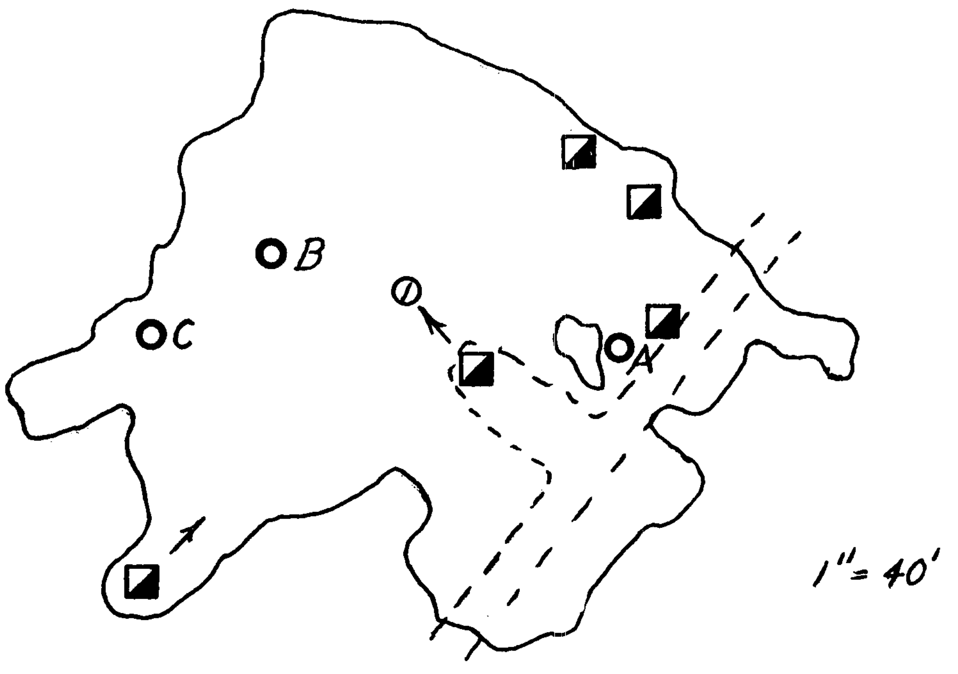
Mine - Location: B - 1, drift confluence

Velocity (ft/min):	①	②	③
9/29	1150	250	330
9/30	1150	250	330
10/2	720	190	180

Flowrate (ft^3/min):	①	②	③
9/29	34,500	16,000	18,500
9/30	34,500	16,000	18,500
10/2	22,000	12,000	10,000

MINE: B LOCATION: 1 (drift confluence)





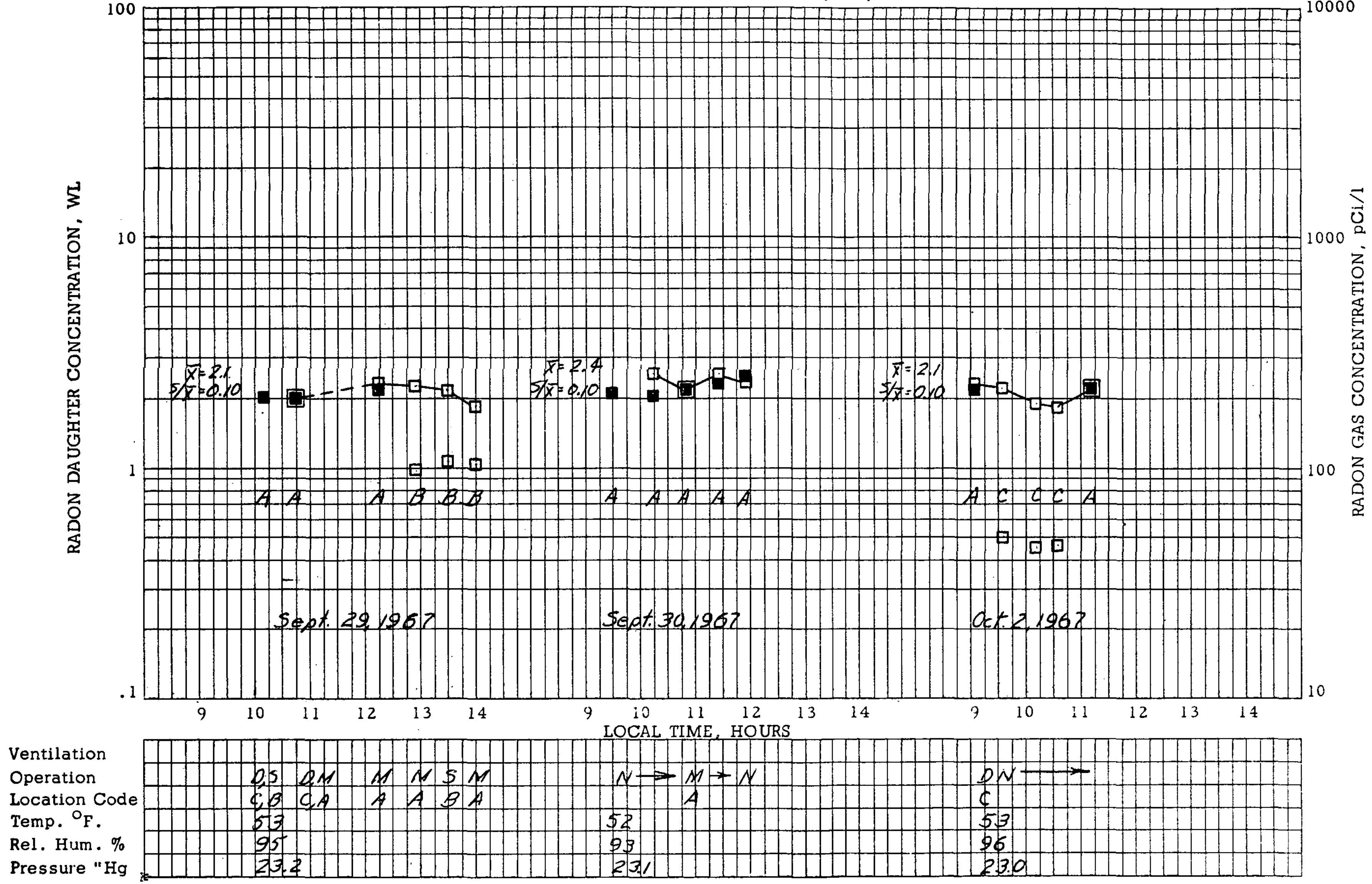
Mine- Location: B - 2, stope

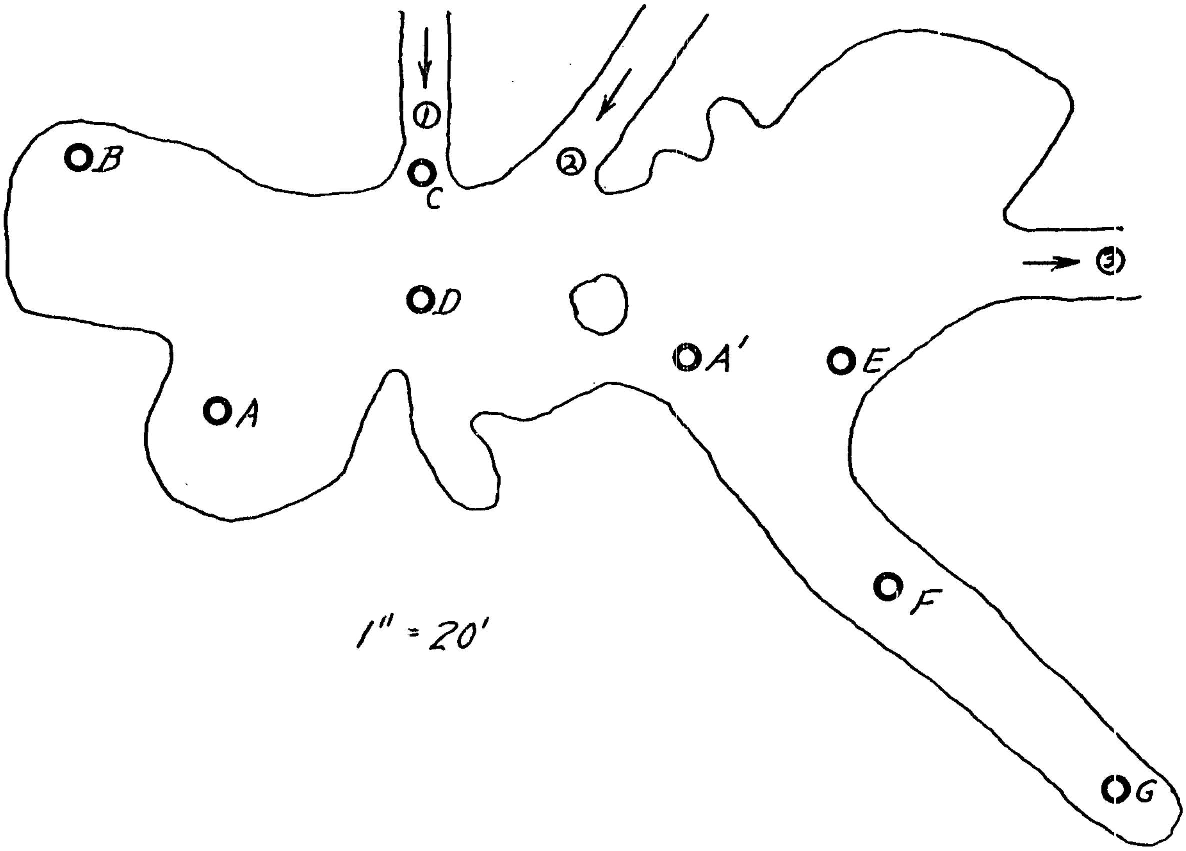
Volume (ft^3): 180,000

Flowrate (ft^3/min): at ① 200

Flowrate (changes/min): 0.01

MINE: B LOCATION: 2 (stope)



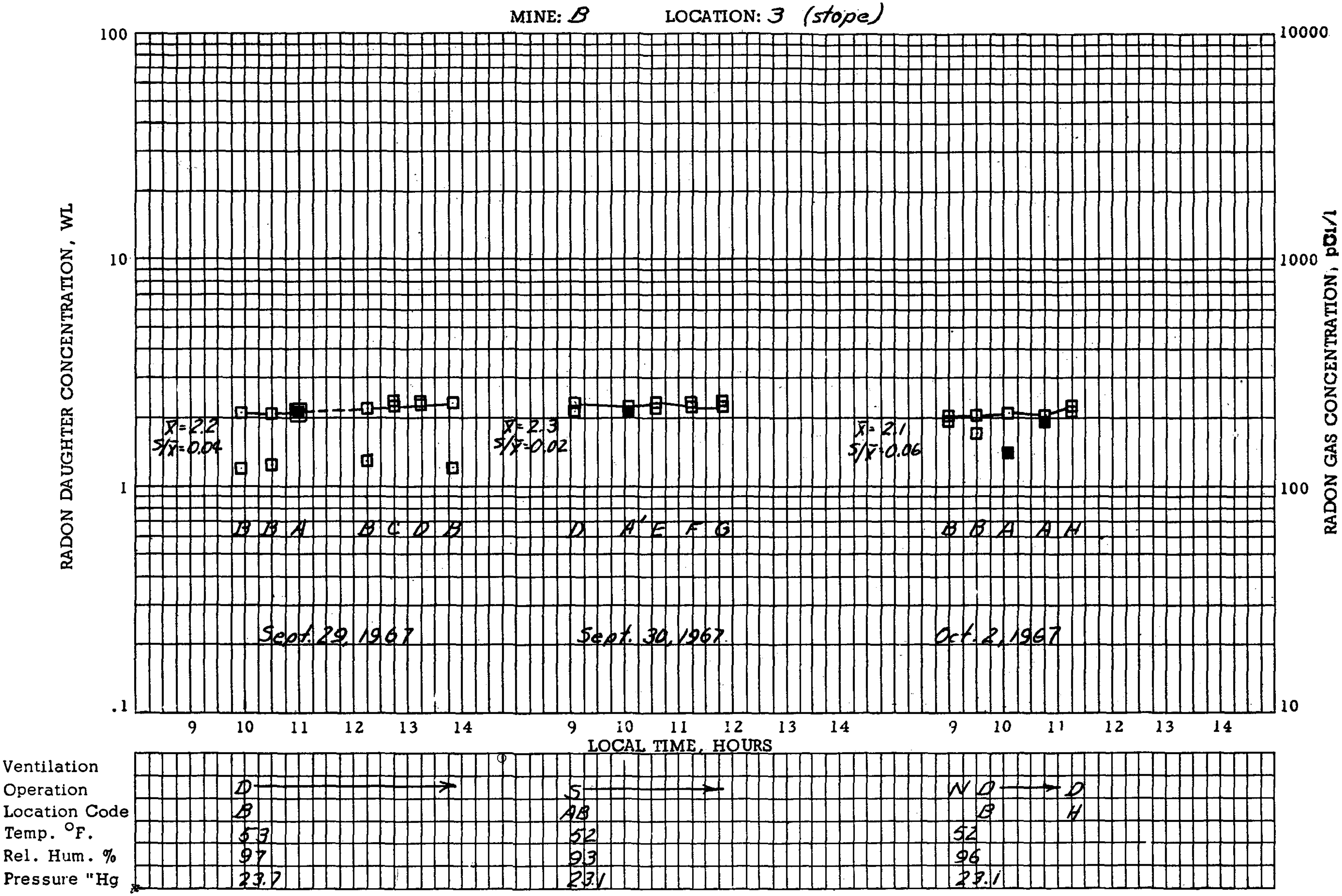


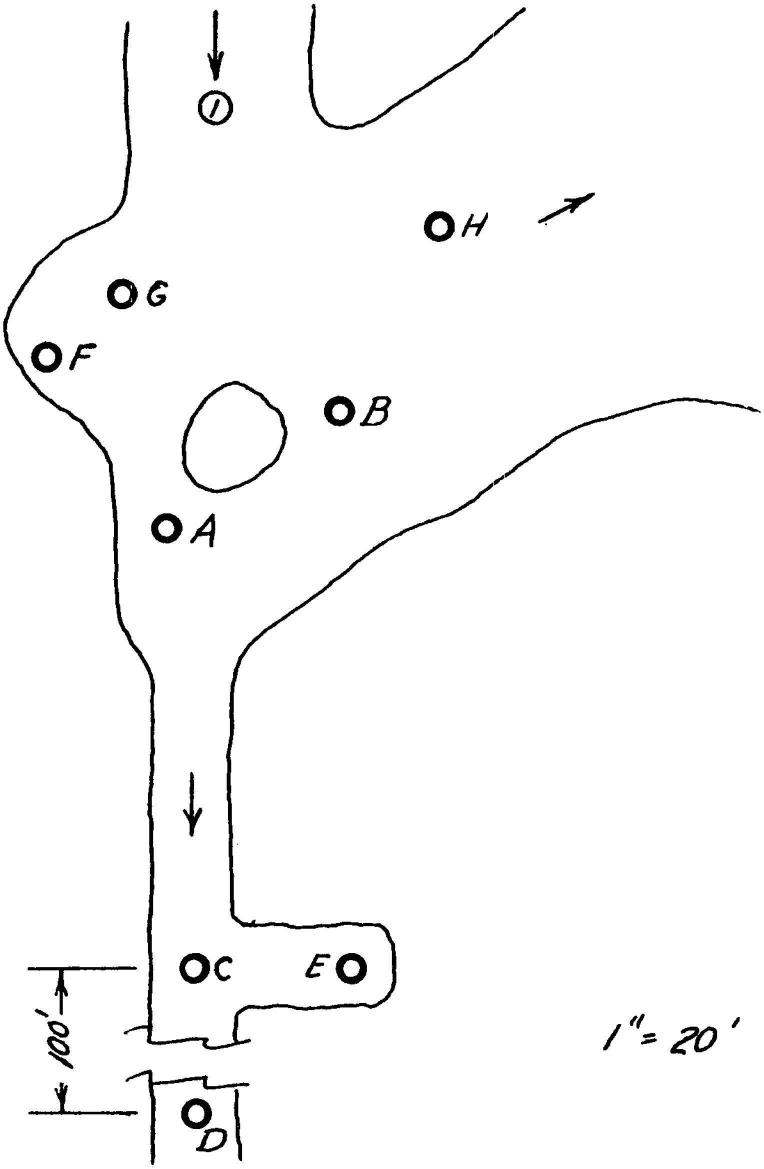
Mine - Location: B - 3, stope

Volume (ft^3): 14,000

Flowrate (ft^3/min): at ① 430
at ② 500
at ③ 1000

Flowrate (change/min): 2.5


MINE: B
LOCATION: 3 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
X̄ = 2.2
S/X̄ = 0.04
X̄ = 2.3
S/X̄ = 0.02
X̄ = 2.1
S/X̄ = 0.06
B B A B C D B
D A' E F G
B B A A H
Sept. 29, 1967
Sept. 30, 1967
Oct. 2, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
D
B
53
97
23.7
S
AB
52
93
23.1
N D
D
B
H
52
96
23.1

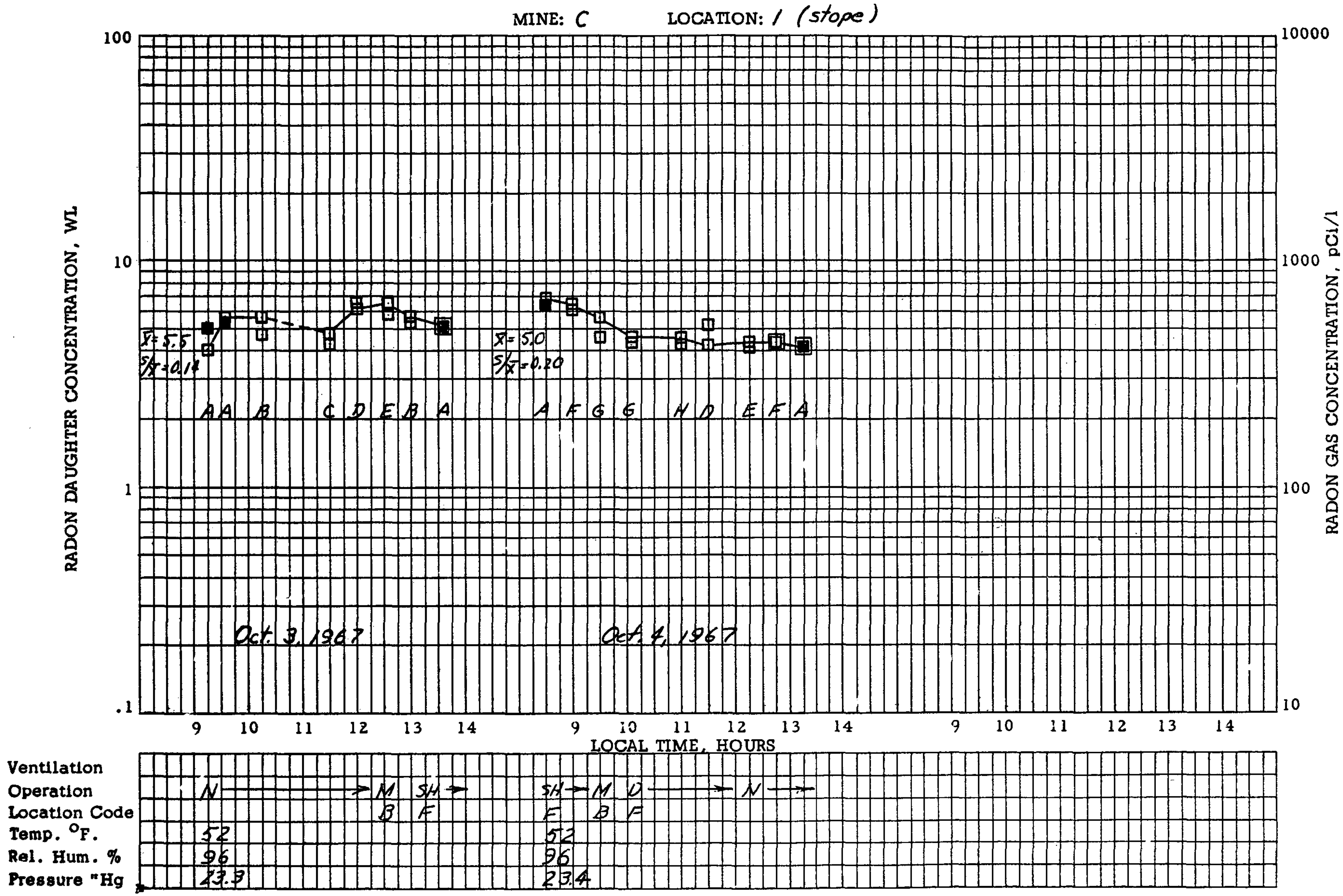


Mine - Location: C - 1, stope

Volume (ft^3): 13,000

Flowrate (ft^3/min): at ① 2000

Flowrate (changes/min): 0.2

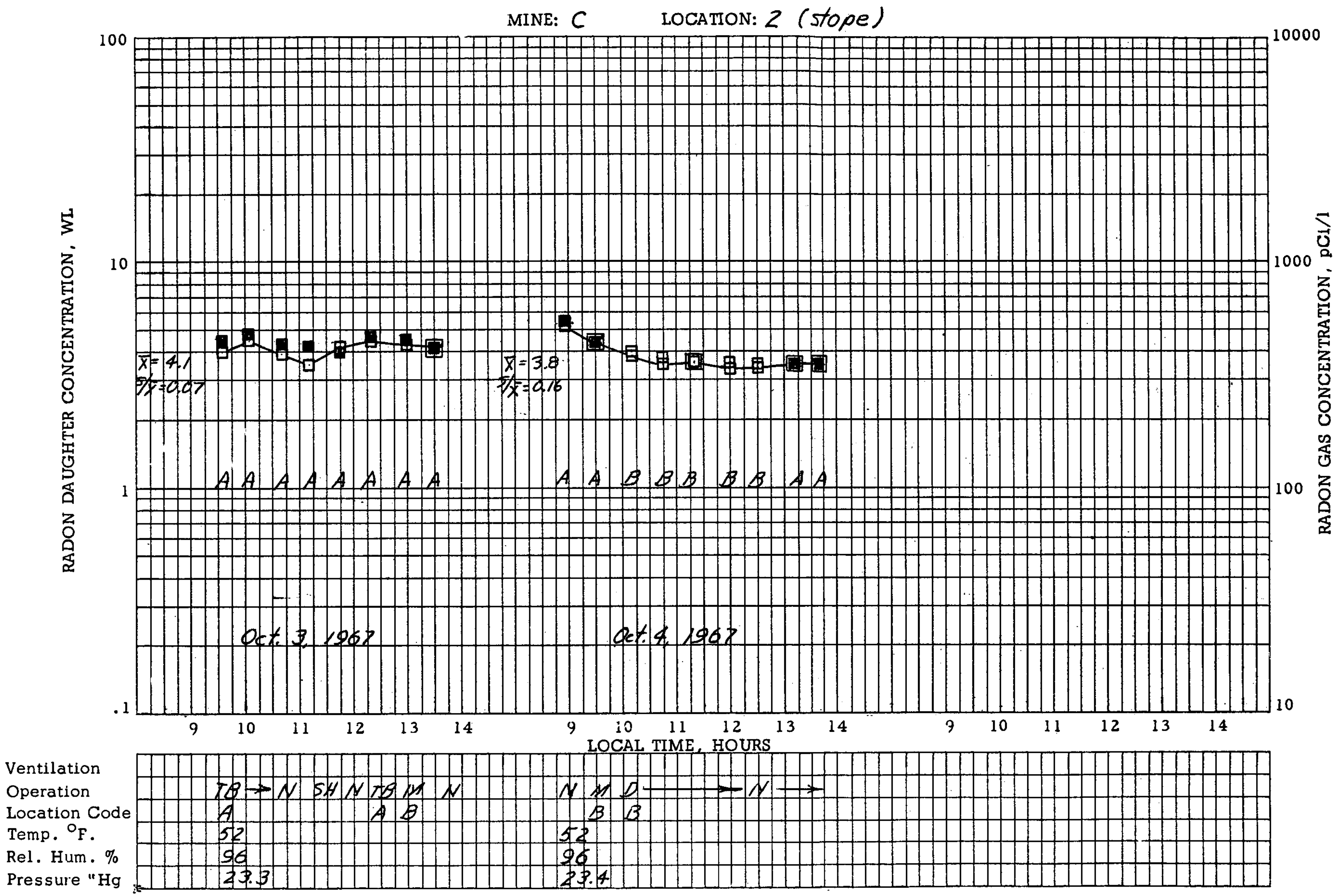

MINE: C LOCATION: 1 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
X̄ = 5.5
s/X̄ = 0.14
X̄ = 5.0
s/X̄ = 0.20
A A B C D E B A
A F G G H D E F A
Oct. 3, 1967
Oct. 4, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N M SH
B F
SH M D N
F B F
52
96
23.3
52
96
23.4

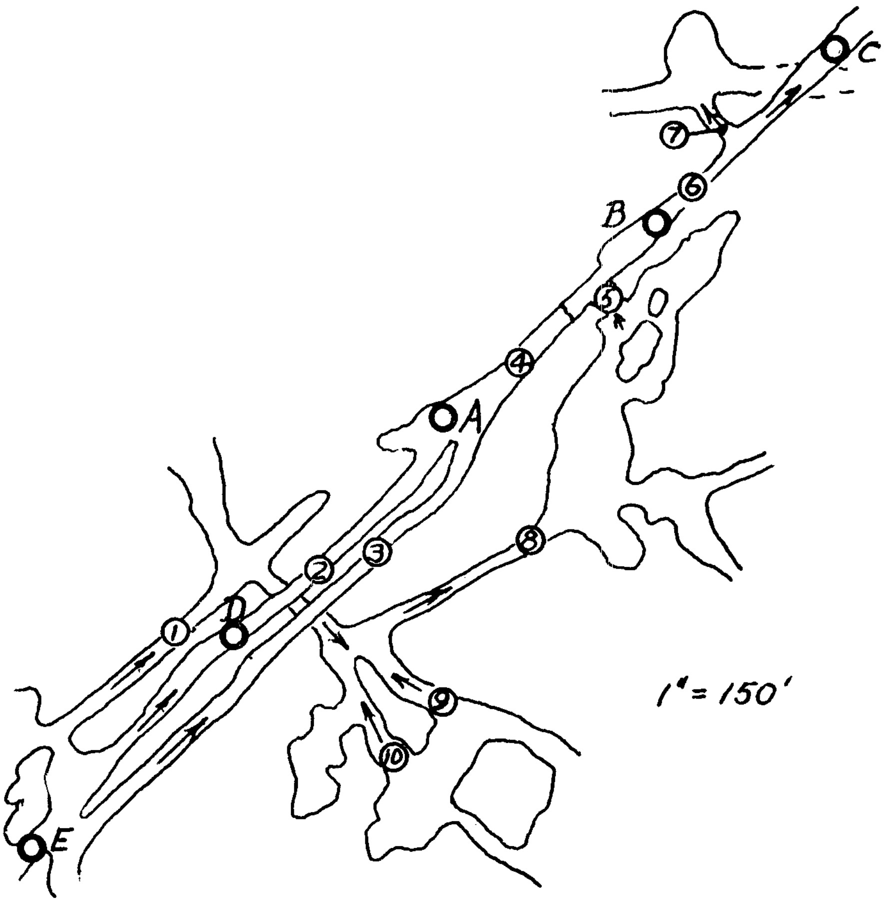
Mine - Location: C - 2, stope

Volume (ft^3): 200,000

Flowrate (ft^3/min): at ① 200
② 3500
③ 2500

Flowrate (change/min): .03


MINE: C LOCATION: 2 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
X̄ = 4.1
s/X̄ = 0.07
X̄ = 3.8
s/X̄ = 0.16
A A A A A A A A
A A B B B B B A A
Oct. 3, 1967
Oct. 4, 1967
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation TB → N SH N TB M N N M D → N →
Location Code A A B B B
Temp. °F. 52 52
Rel. Hum. % 96 96
Pressure "Hg 23.3 23.4



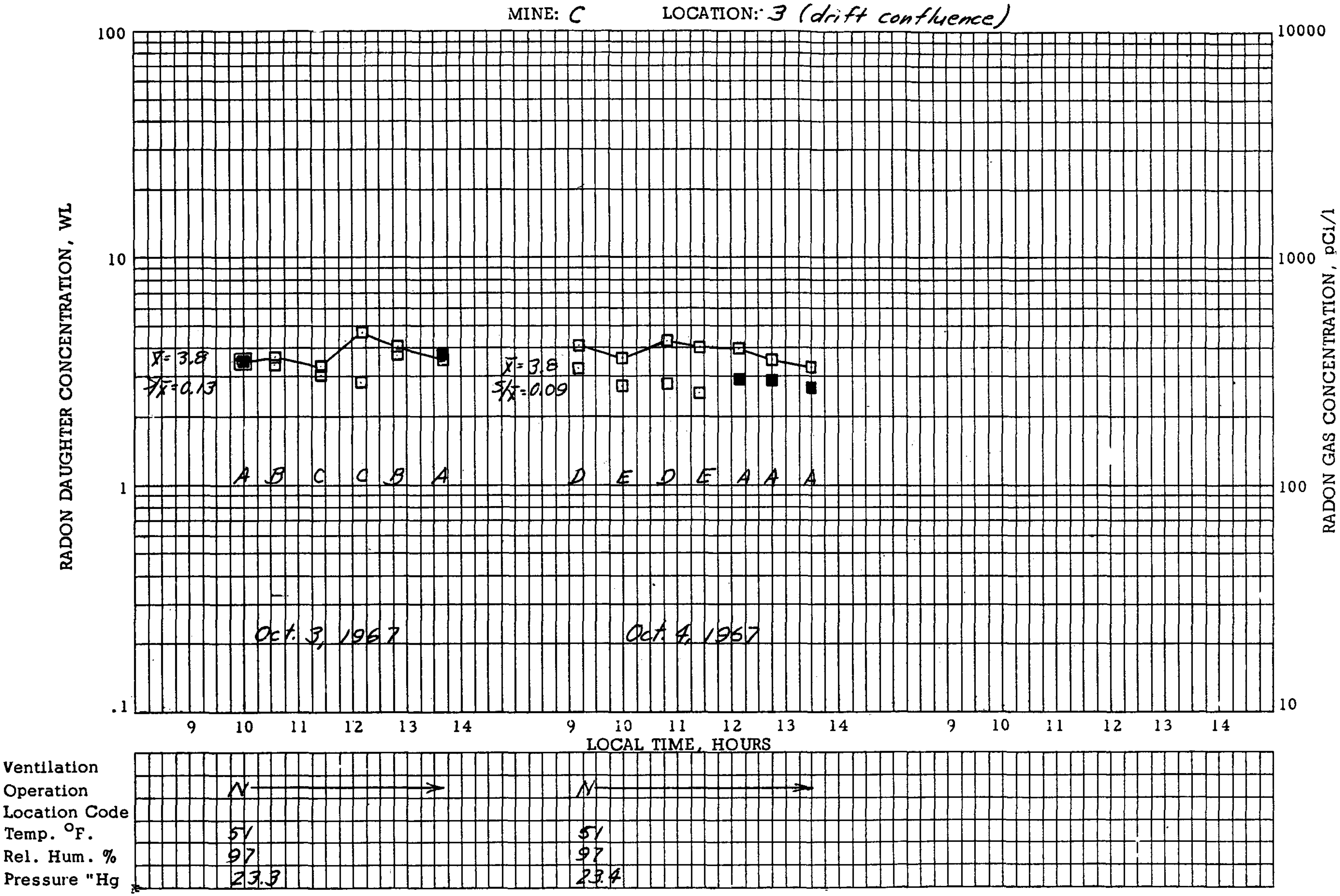
Mine - Location: C - 3, drift confluence

Velocity (ft/min):

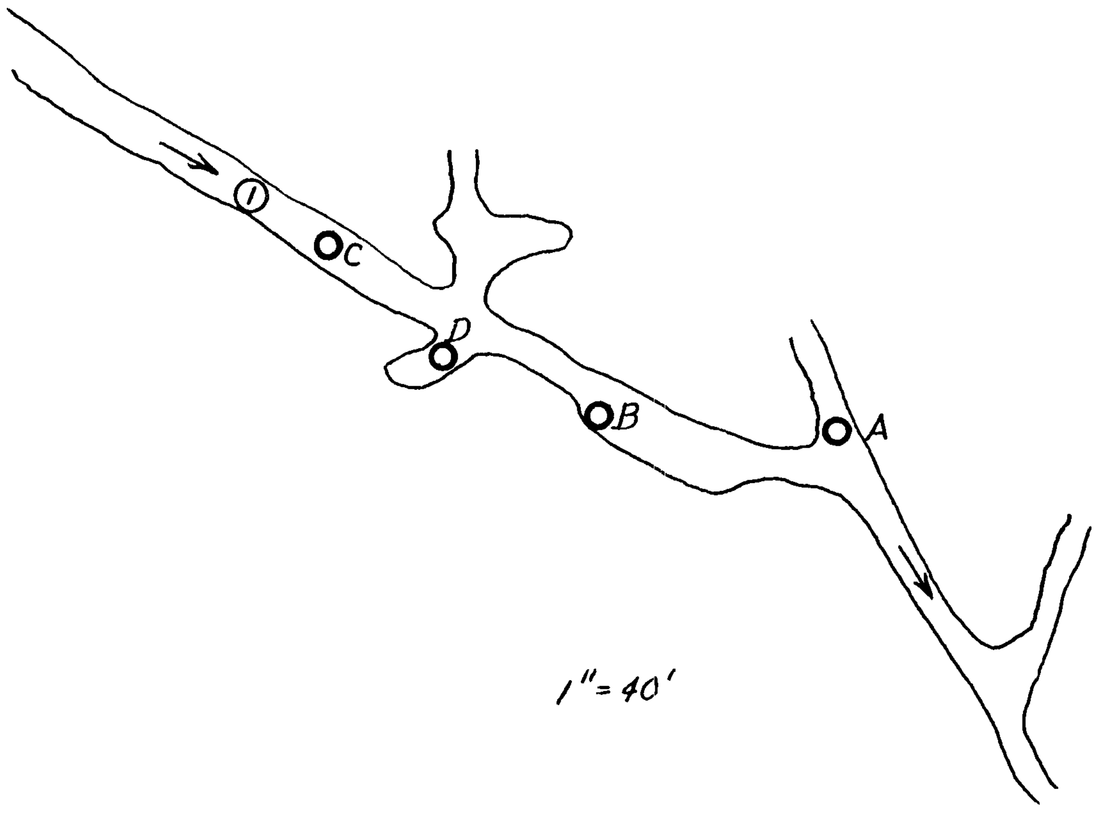
Point	Velocity	Point	Velocity
at ①	150	⑧	700
②	400	⑨	500
③	300	⑩	300
④	900		

Flowrate (ft^3/min):

Point	Flowrate	Point	Flowrate
at ①	11,000	⑥	34,000
②	20,000	⑦	500
③	13,000	⑧	39,000
④	27,000	⑨	23,000
⑤	500	⑩	16,000



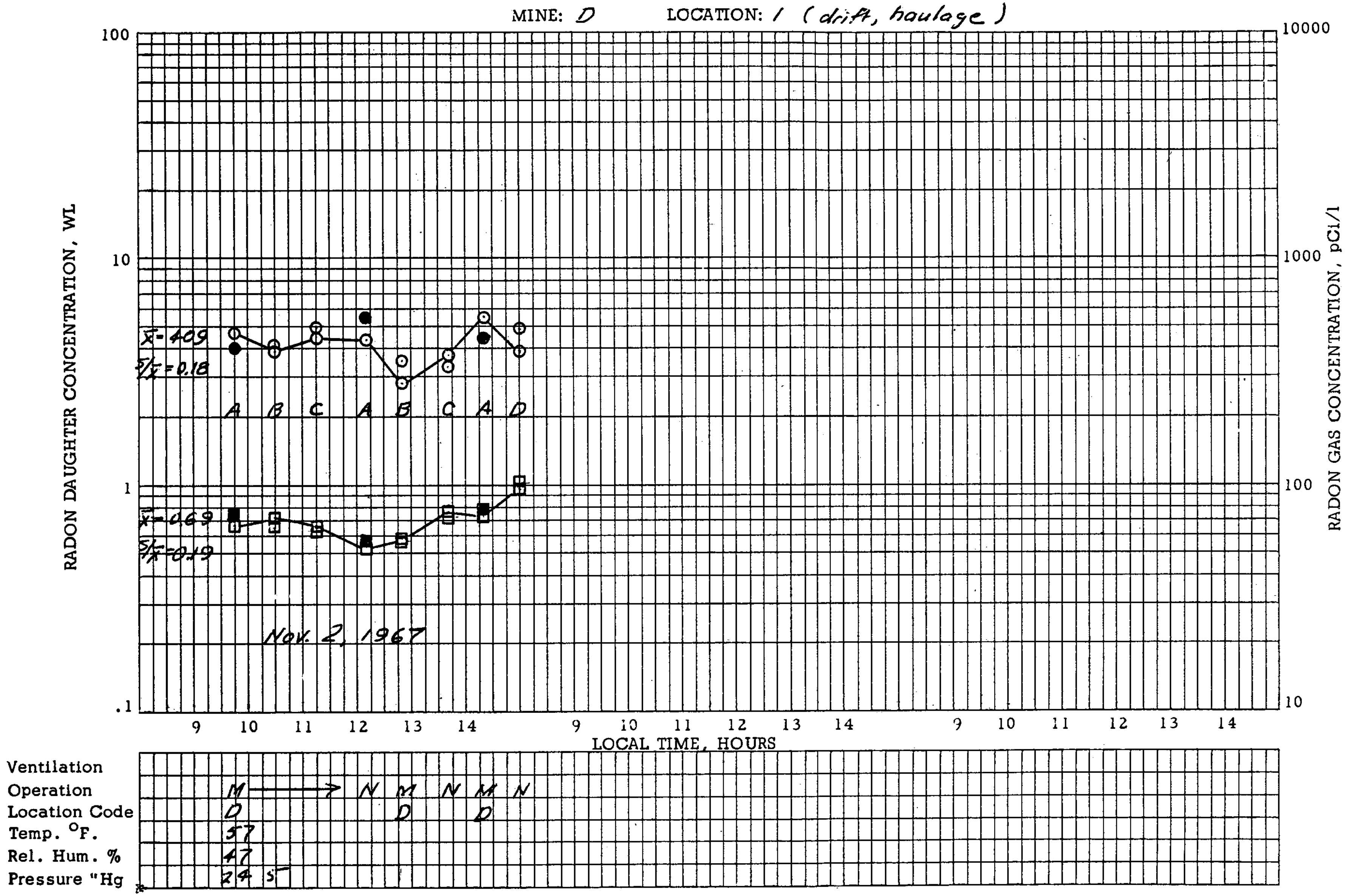
MINE: C
LOCATION: 3 (drift confluence)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 3.8
s/x̄ = 0.13
x̄ = 3.8
s/x̄ = 0.09
A B C C B A
D E D E A A A
Oct. 3, 1967
Oct. 4, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N
51
97
23.3
N
51
97
23.4

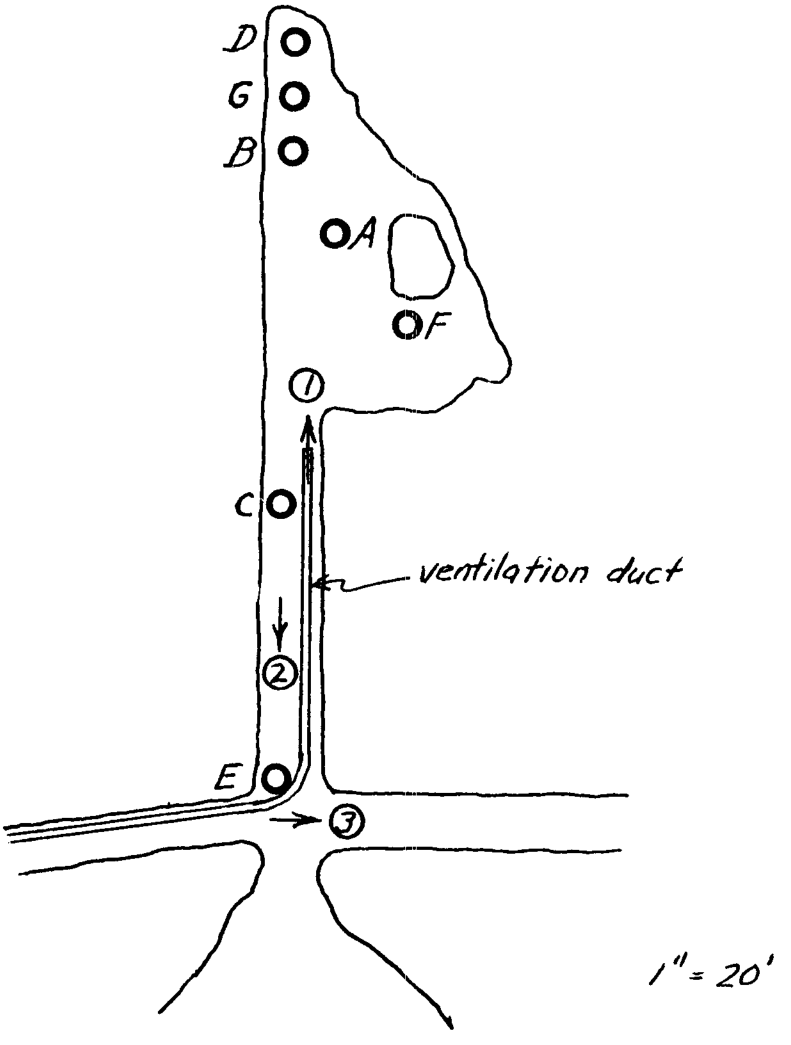


Mine - Location: D - 1, drift, haulage

Velocity (ft/min): at ① 440

Flowrate (ft^3/min): at ① 27,000


MINE: D
LOCATION: 1 (drift, haulage)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄=.409
s/x̄=0.18
A B C A B C A D
x̄=.069
s/x̄=0.19
Nov. 2, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
M → N M N M N
D D D
57
47
24.5

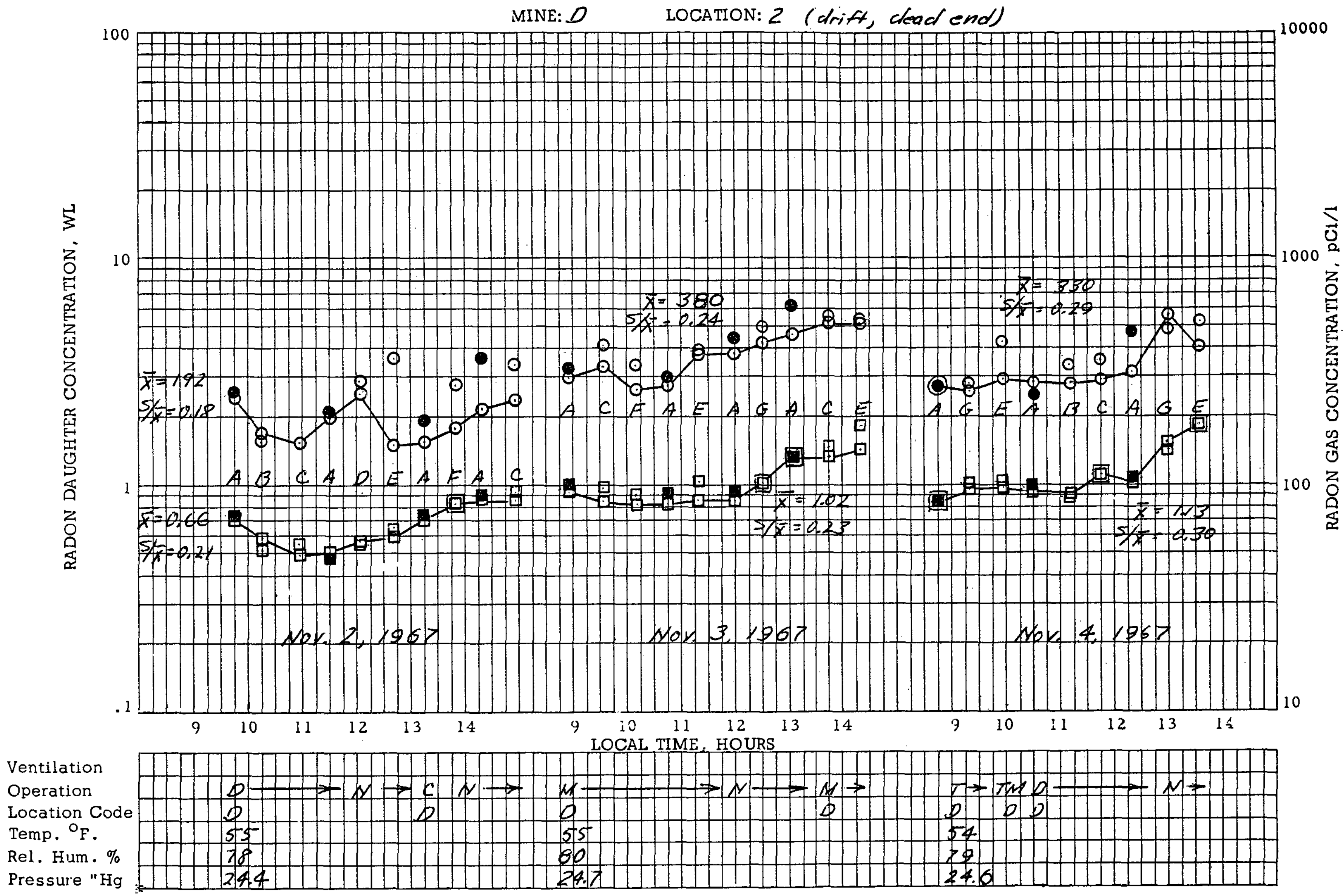


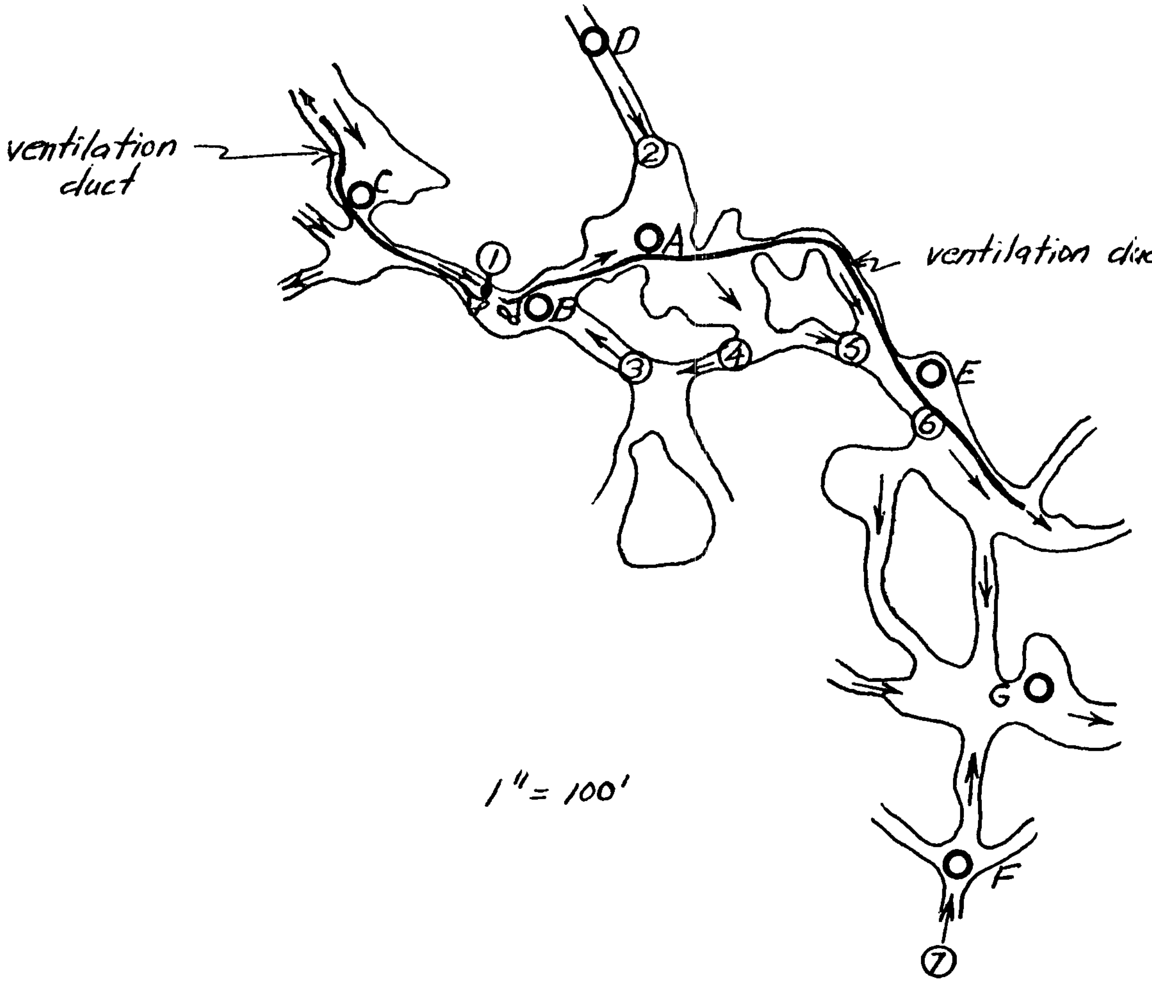
Mine - Location: D - 2, drift, dead end

Volume (ft^3): stope 6000

Velocity (ft/min): at ② 22

Flowrate (ft^3/min): at ① 900
③ 500 (leakage from duct)

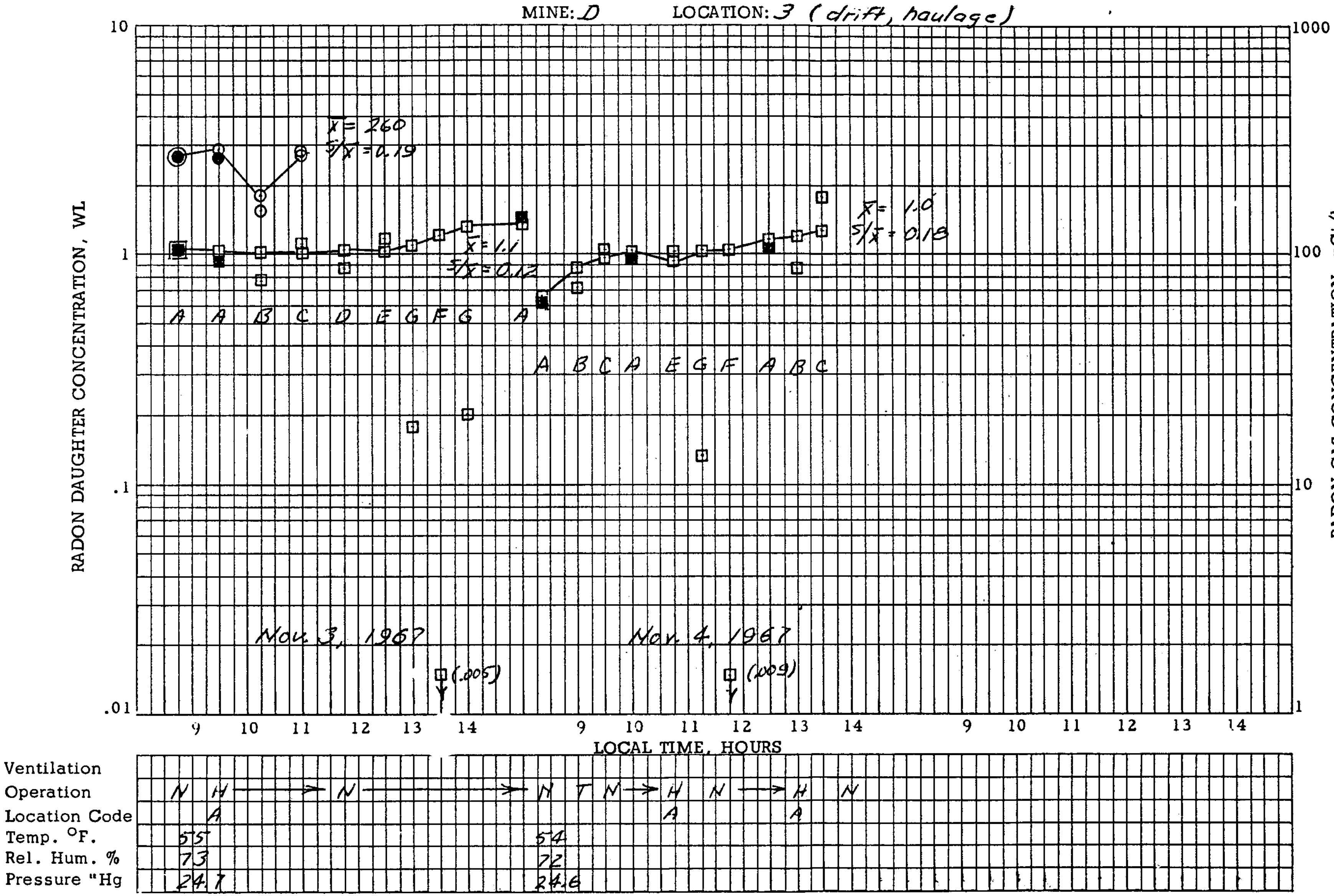

MINE: D
LOCATION: 2 (drift, dead end)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 192
S/x̄ = 0.18
x̄ = 0.66
S/x̄ = 0.21
x̄ = 380
S/x̄ = 0.24
x̄ = 1.02
S/x̄ = 0.23
x̄ = 330
S/x̄ = 0.29
x̄ = 113
S/x̄ = 0.30
A B C A D E A F A C
A C F A E A G A C E
A G E A B C A G E
Nov. 2, 1967
Nov. 3, 1967
Nov. 4, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
D → N → C N →
M → N → M →
T → TM D → N →
D D
D D
D D D
55
55
54
78
80
79
24.4
24.7
24.6

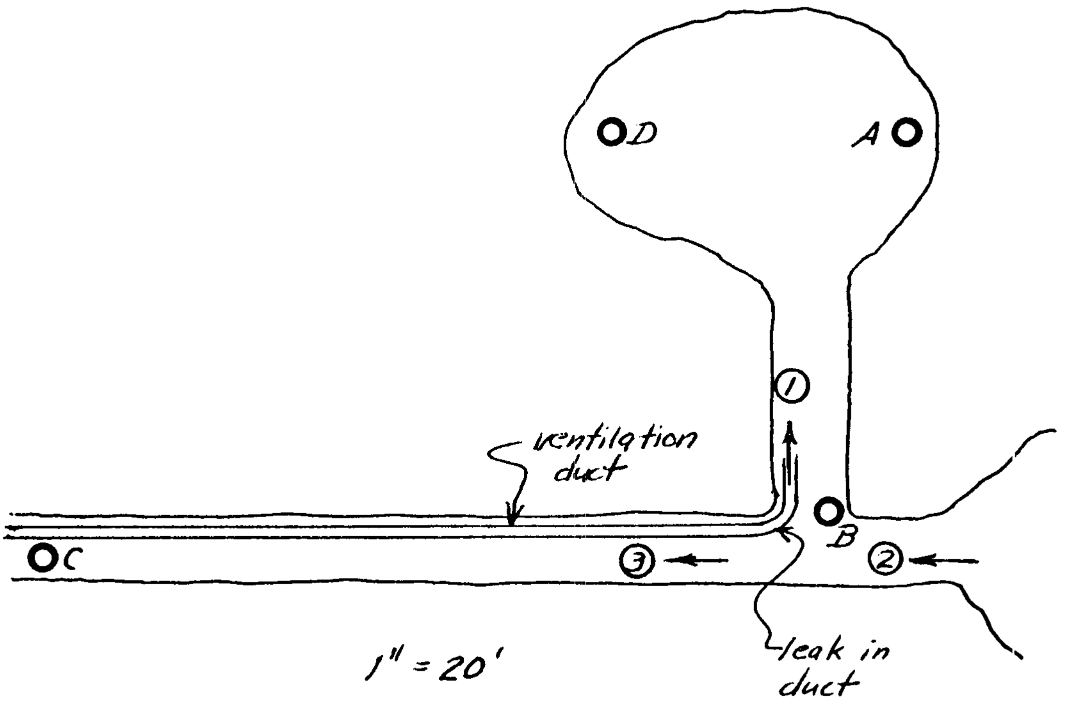


Mine - Location: D - 3, drift, haulage

Flowrate (ft^3/min): at

①	6300
②	1000
③	3000
④	3500
⑤	500
⑥	10,300
⑦	15,000


MINE: D
LOCATION: 3 (drift, haulage)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
10
1
.1
.01
1000
100
10
1
$\bar{x}$ = 260
s/$\bar{x}$ = 0.19
$\bar{x}$ = 1.1
s/$\bar{x}$ = 0.12
$\bar{x}$ = 1.0
s/$\bar{x}$ = 0.18
A A B C D E G F G A
A B C A E G F A B C
Nov. 3, 1967
Nov. 4, 1967
(.005)
(.009)
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N H → N → N T N → H N → H N
A A A
55
73
24.7
54
72
24.6



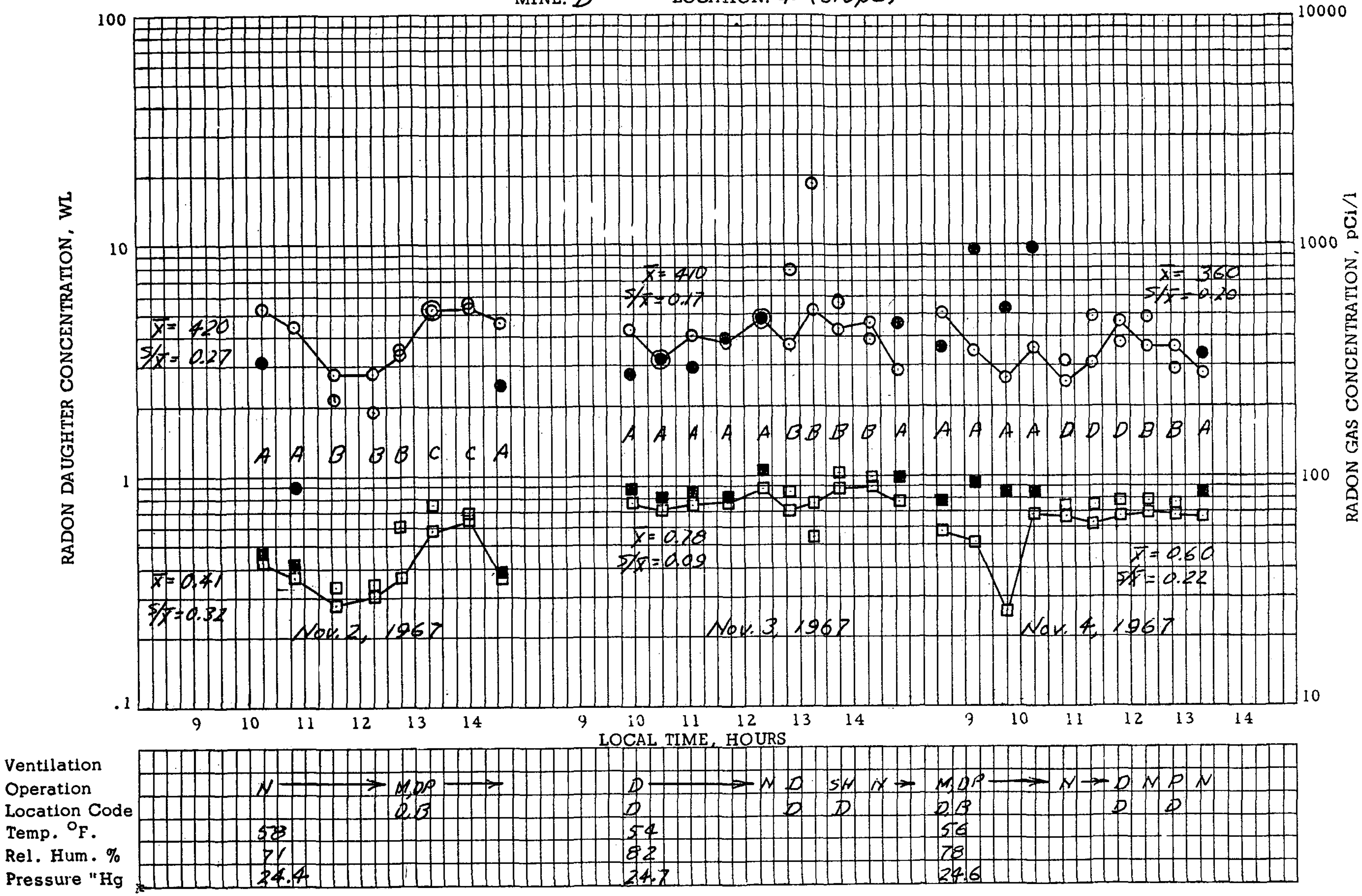
Mine - Location: D - 4, stope

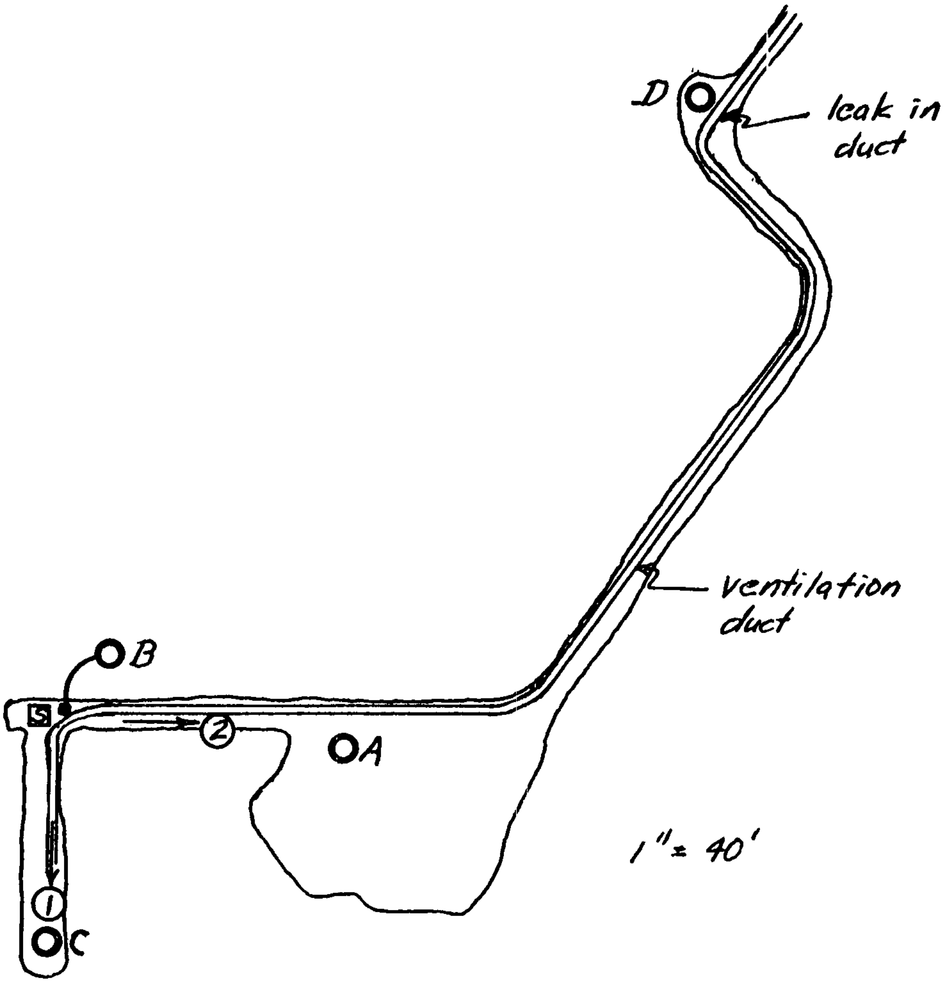
Volume (ft^3): stope 10,000

Flowrate (ft^3/min): at	①	1000
	②	200
	③	2500

Flowrate (change/min): stope 0.1

MINE: D LOCATION: 4 (stope)

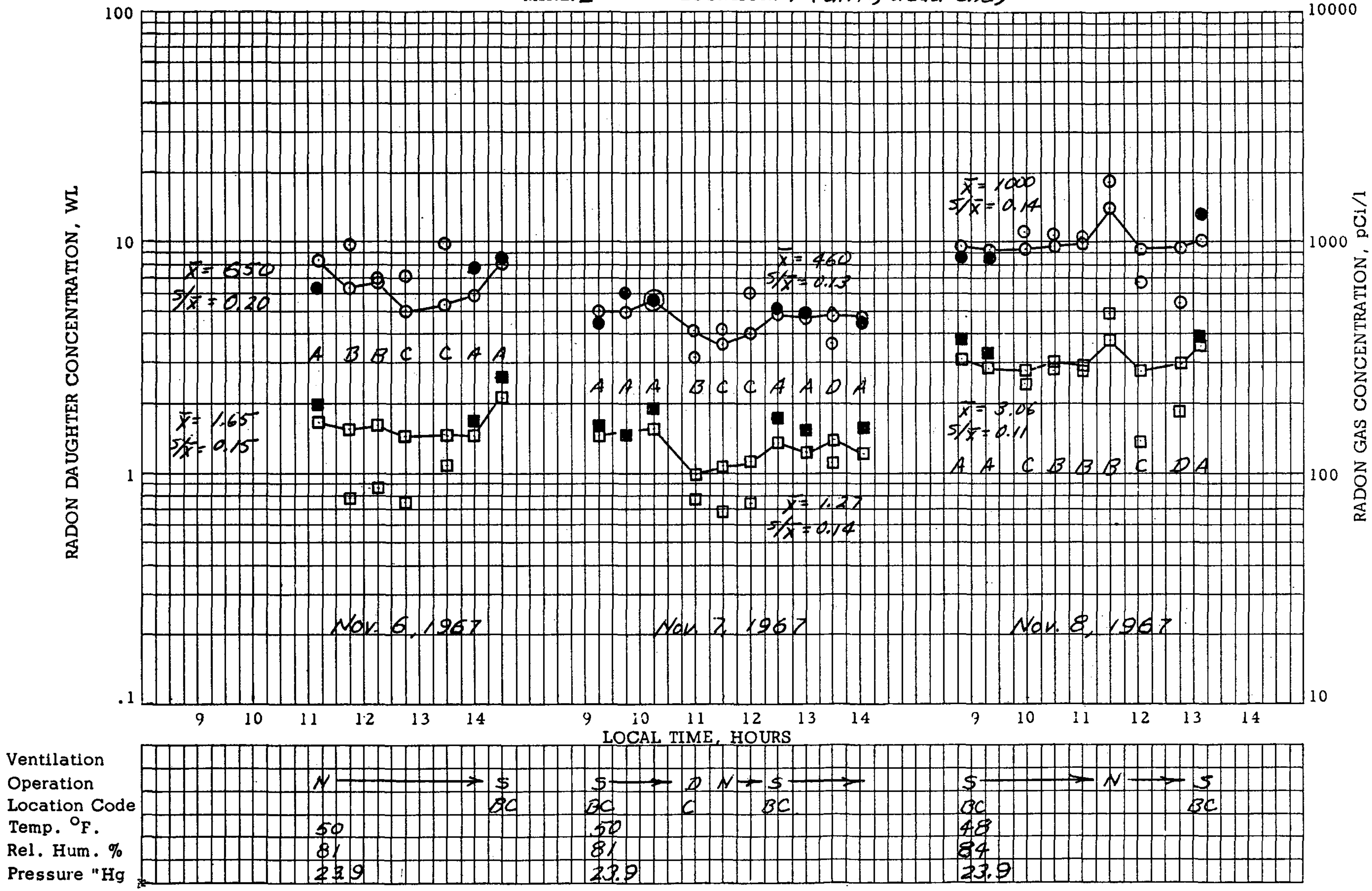


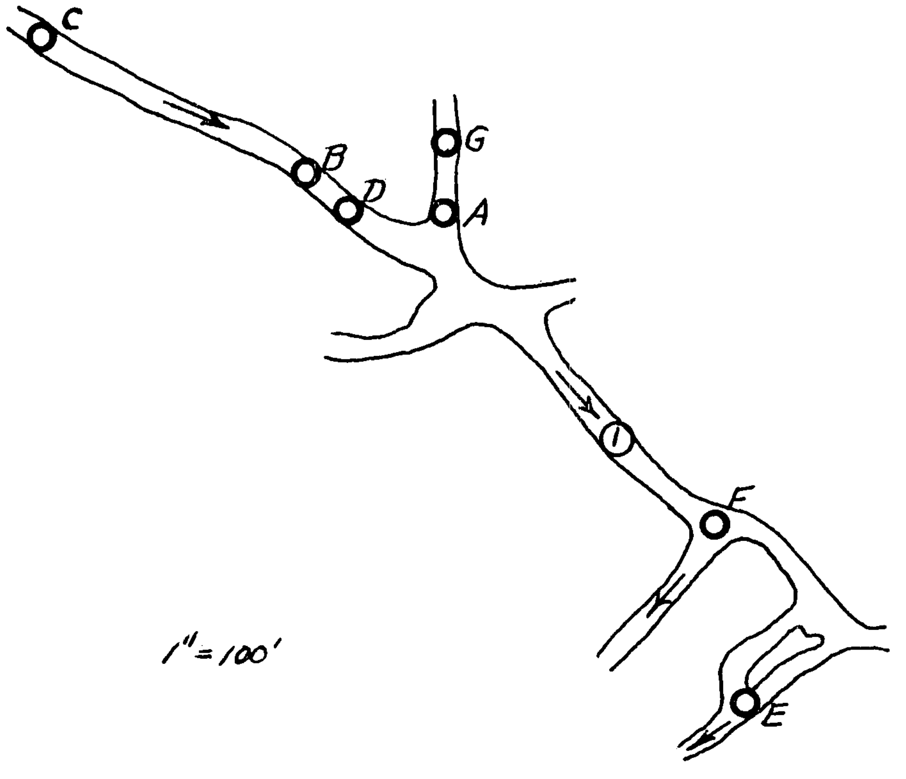


Mine - Location: E - 1, drift, dead end

Velocity (ft/min): at	②	11/16	12
		11/7	24
		11/8	20
Flowrate (ft^3/min): at	①		500
	②	11/6	600
		11/7	1200
		11/8	1000

MINE: E LOCATION: 1 (drift, dead end)



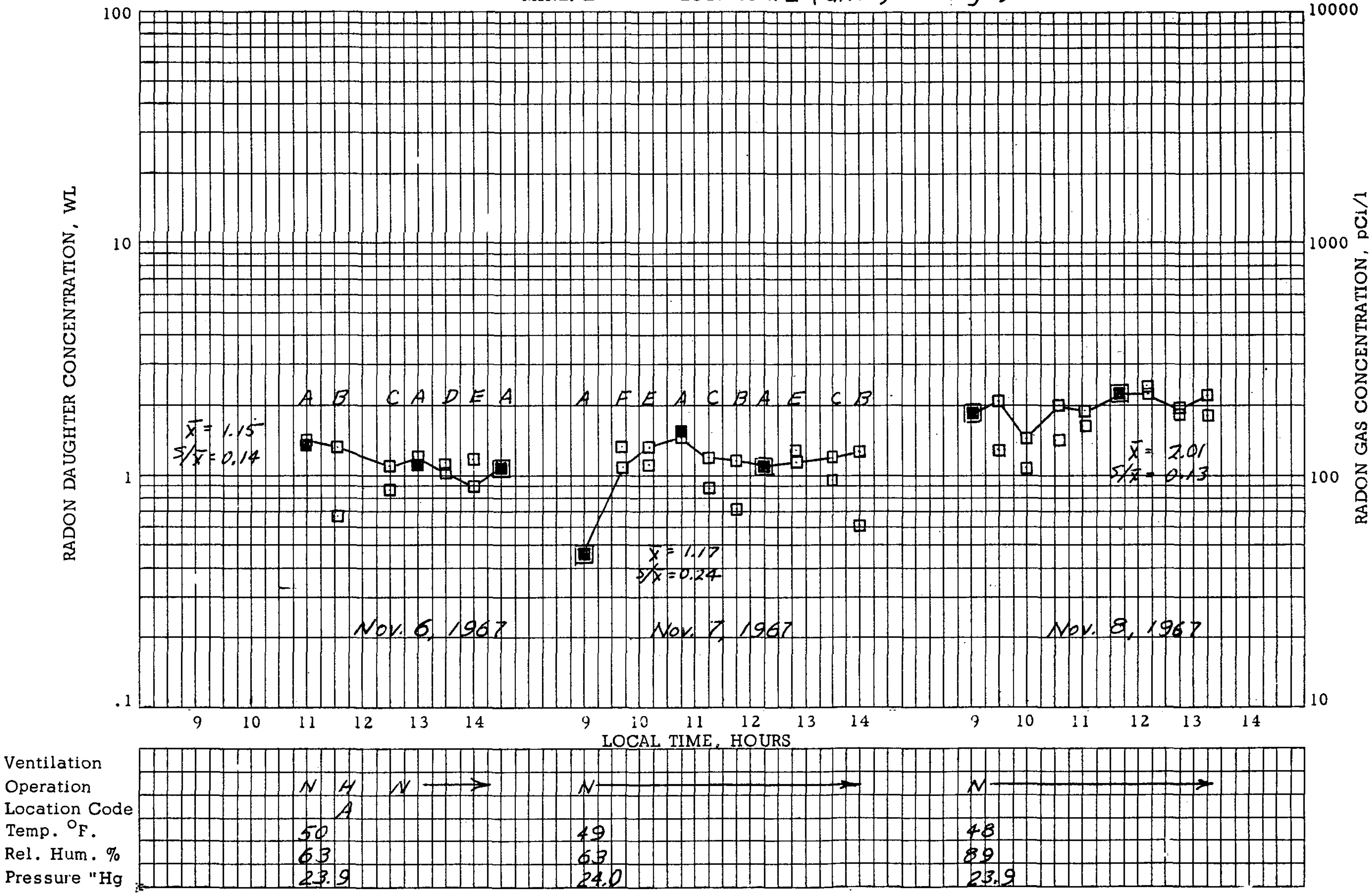


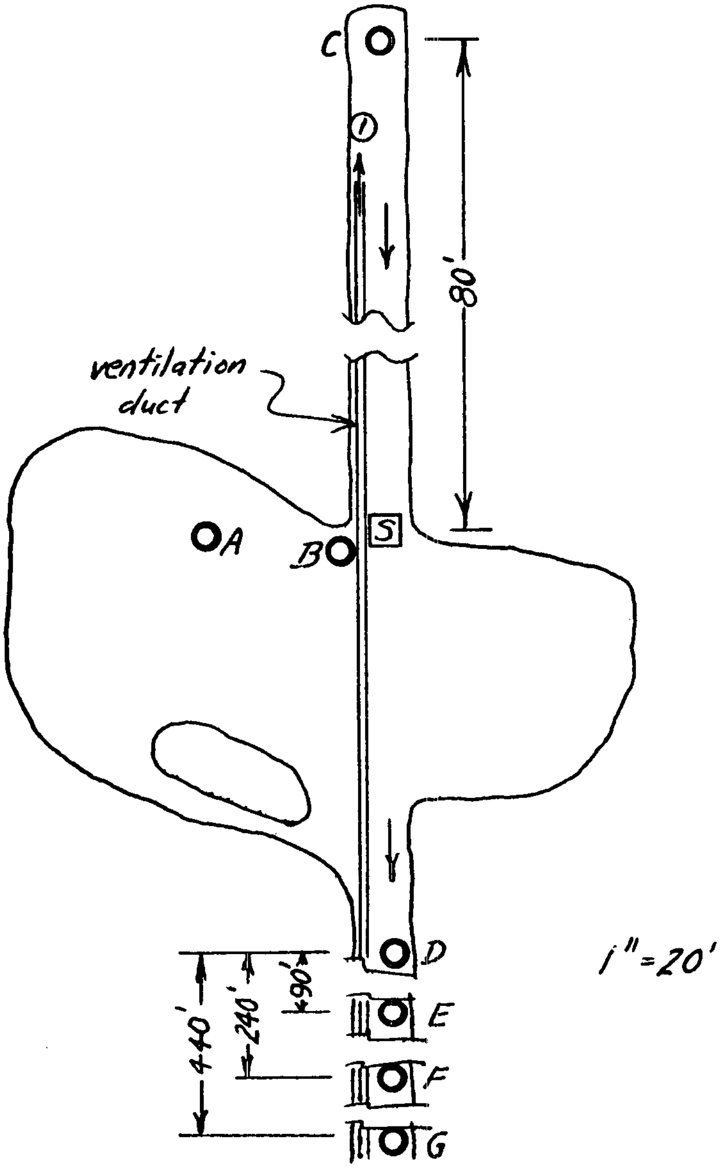
Mine - Location: E - 2, drift, haulage

Velocity (ft/min): at ① 60

Flowrate (ft^3/min): at ① 3000

MINE: E LOCATION: 2 (drift, haulage)

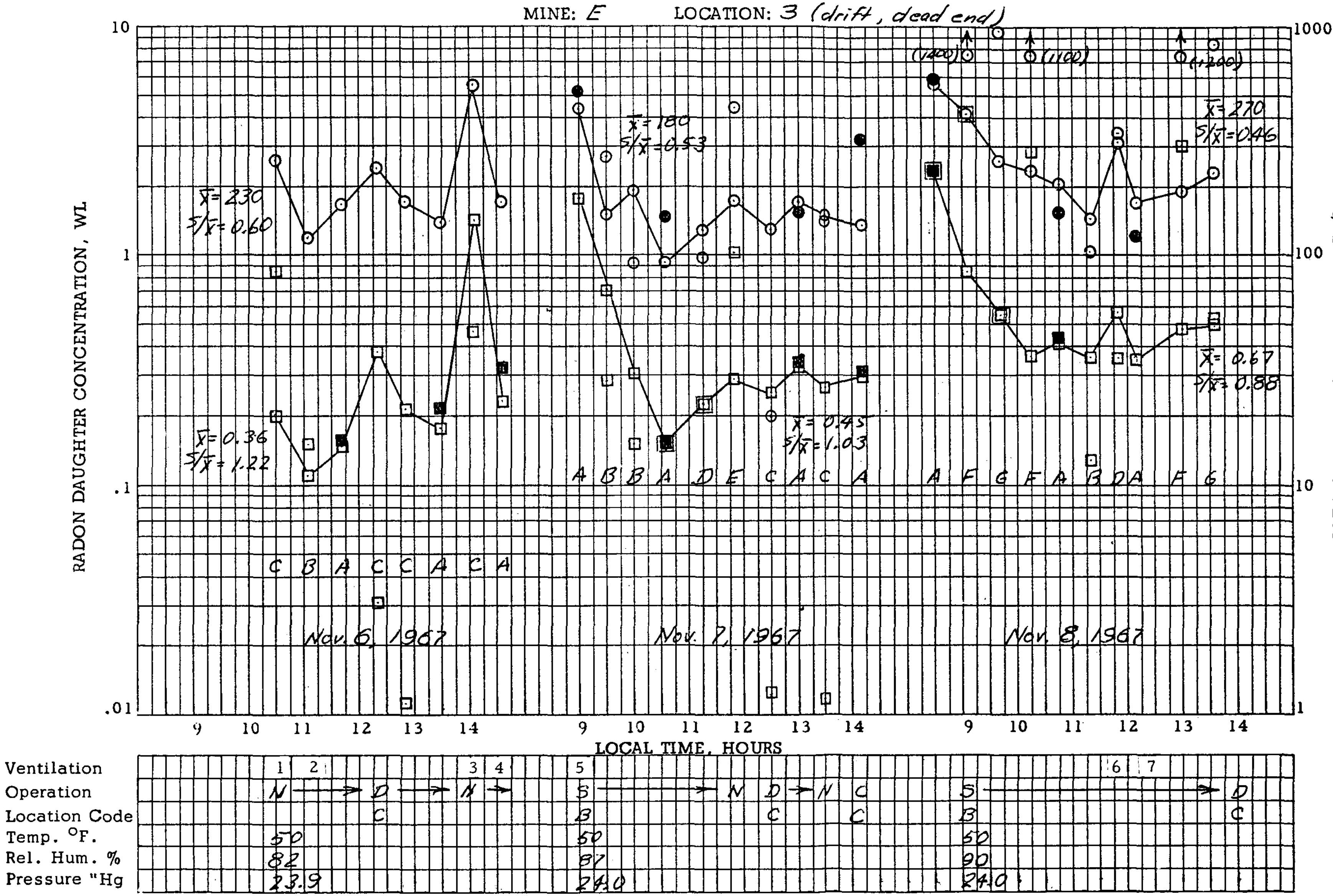


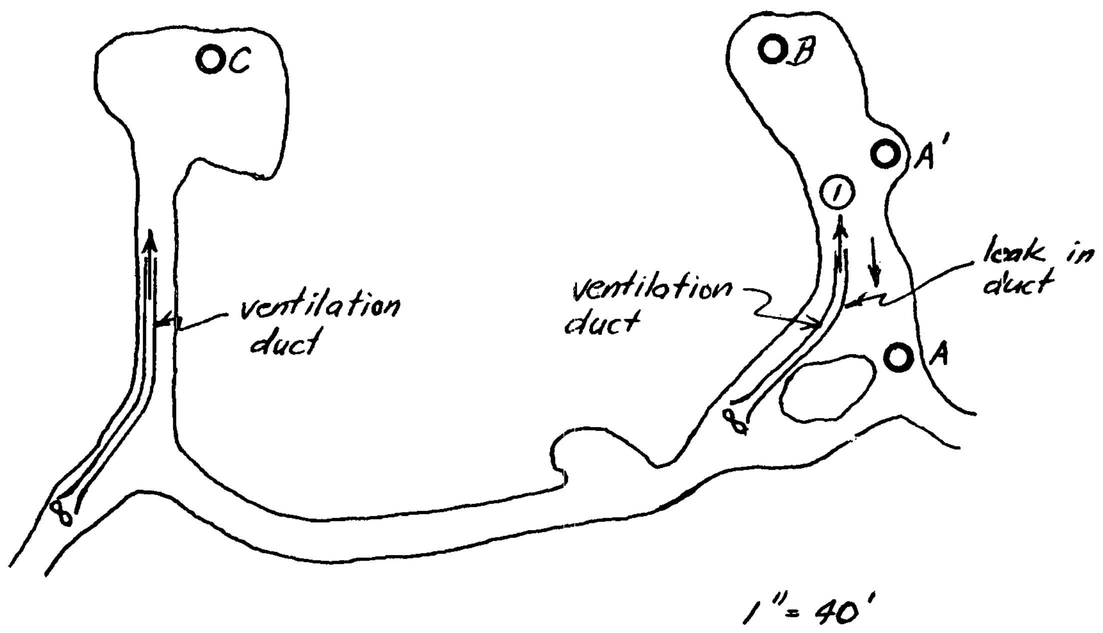


Mine - Location: E - 3, drift, dead end
Volume (ft^3): stope 10,000
Flowrate (ft^3/min): at ① 3000

Ventilation Notes:

1.	11/6	1030	ventilation duct venting at D
2.		1105	ventilation duct extended to ①
3		1405	ventilation turned off
4.		1435	ventilation turned on
5.	11/7	0900	ventilation turned on venting at ①
6.	11/8	1150	ventilation intermittent
7.		1225	ventilation resumed


MINE: E
LOCATION: 3 (drift, dead end)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
10
1
.1
.01
1000
100
10
1
LOCAL TIME, HOURS
Nov. 6, 1967
Nov. 7, 1967
Nov. 8, 1967
x̄ = 230
s/x̄ = 0.60
x̄ = 0.36
s/x̄ = 1.22
x̄ = 180
s/x̄ = 0.53
x̄ = 0.45
s/x̄ = 1.03
x̄ = 270
s/x̄ = 0.46
x̄ = 0.67
s/x̄ = 0.88
(1400)
(1100)
(1200)
C B A C C A C A
A B B A D E C A C A
A F G F A B D A F G
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
1 2 3 4 5 6 7
N → D → N →
S → N D → N C
S → D
C
B
C
C
B
C
50
50
50
82
87
90
23.9
24.0
24.0

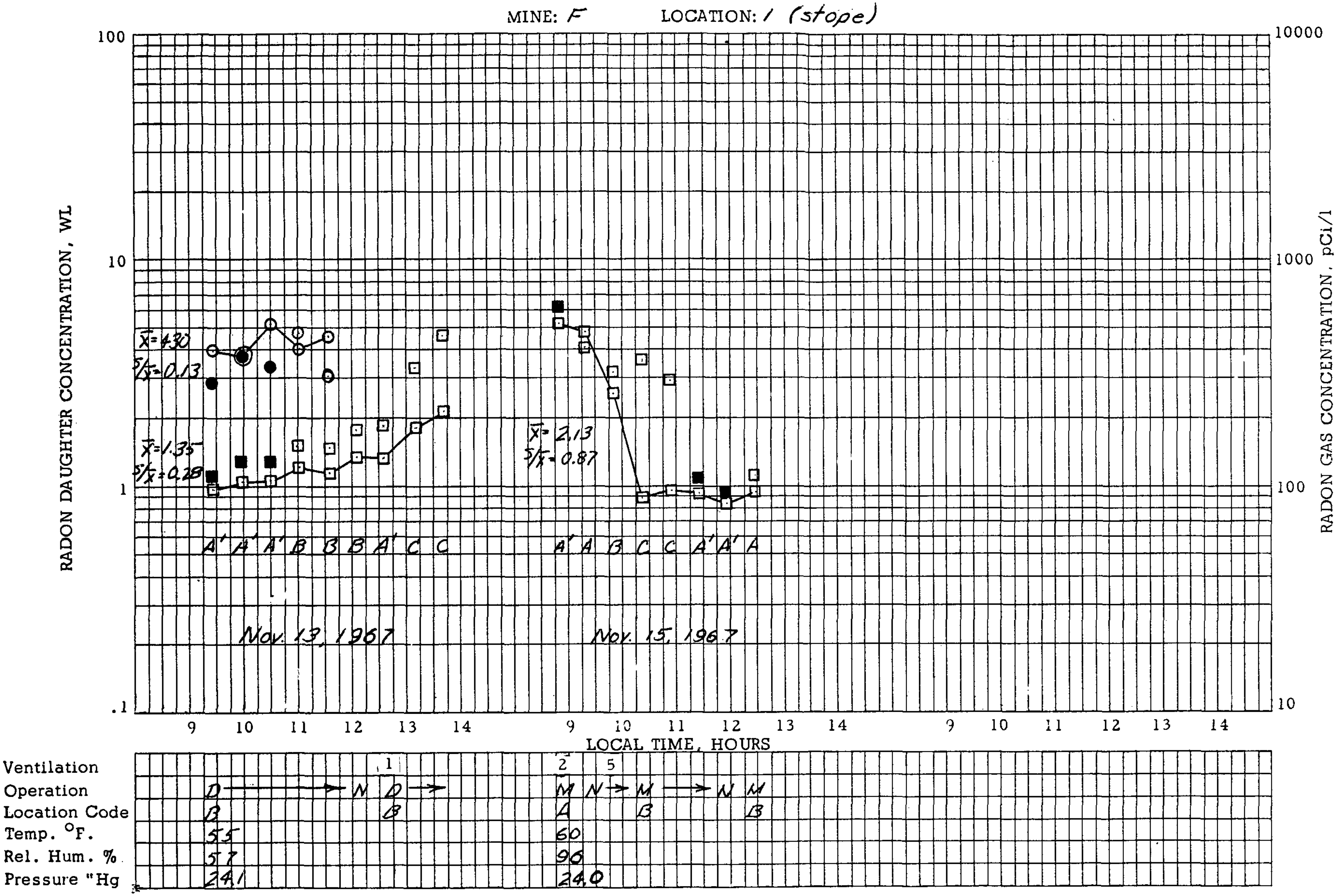


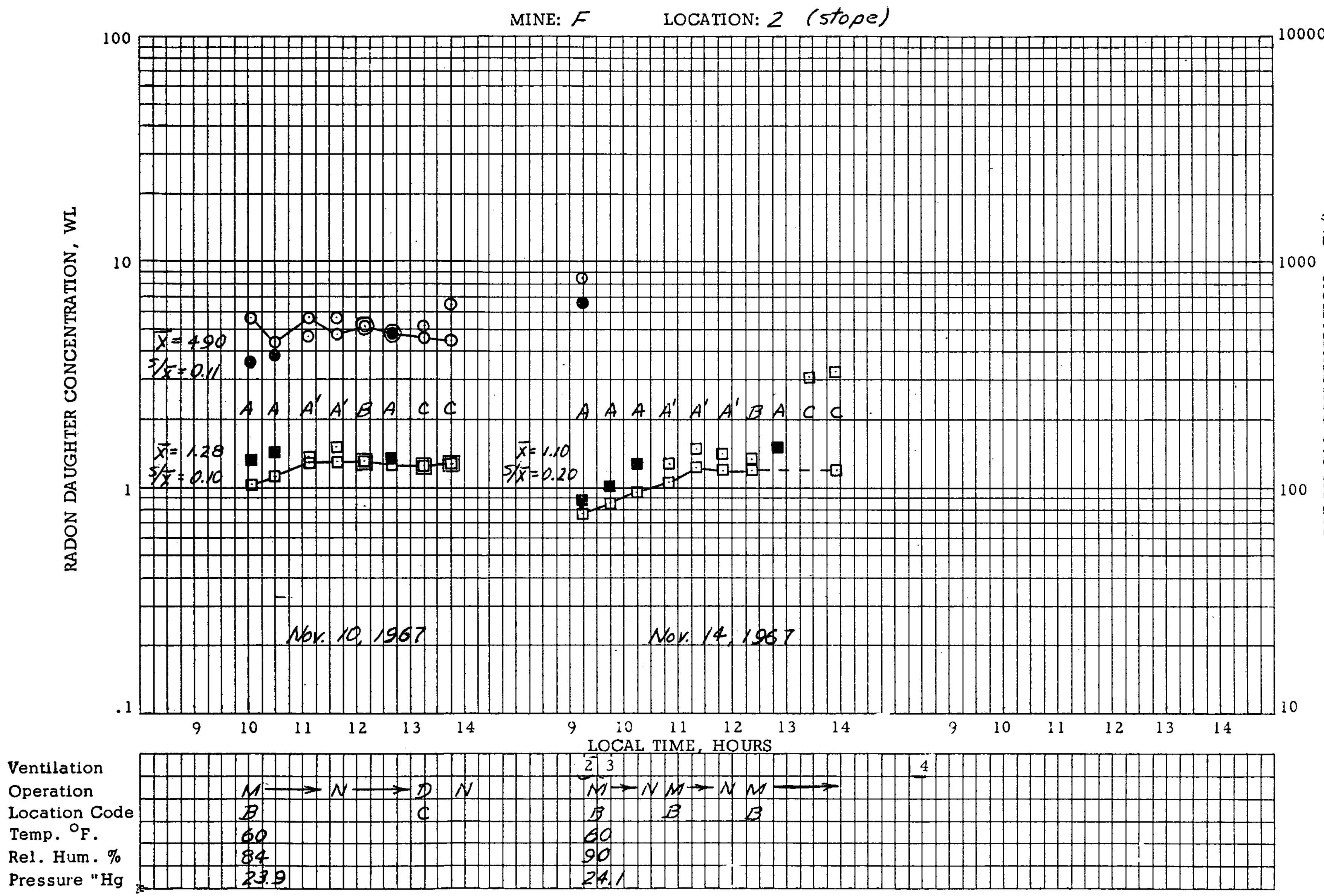
Mine - Location: F - 1, F - 2, stope

Flowrate (ft^3/min): at	①	11/10	1600 (leak in duct)
		11/13	1600
		11/14	3000 (leak repaired)
		11/15	3000

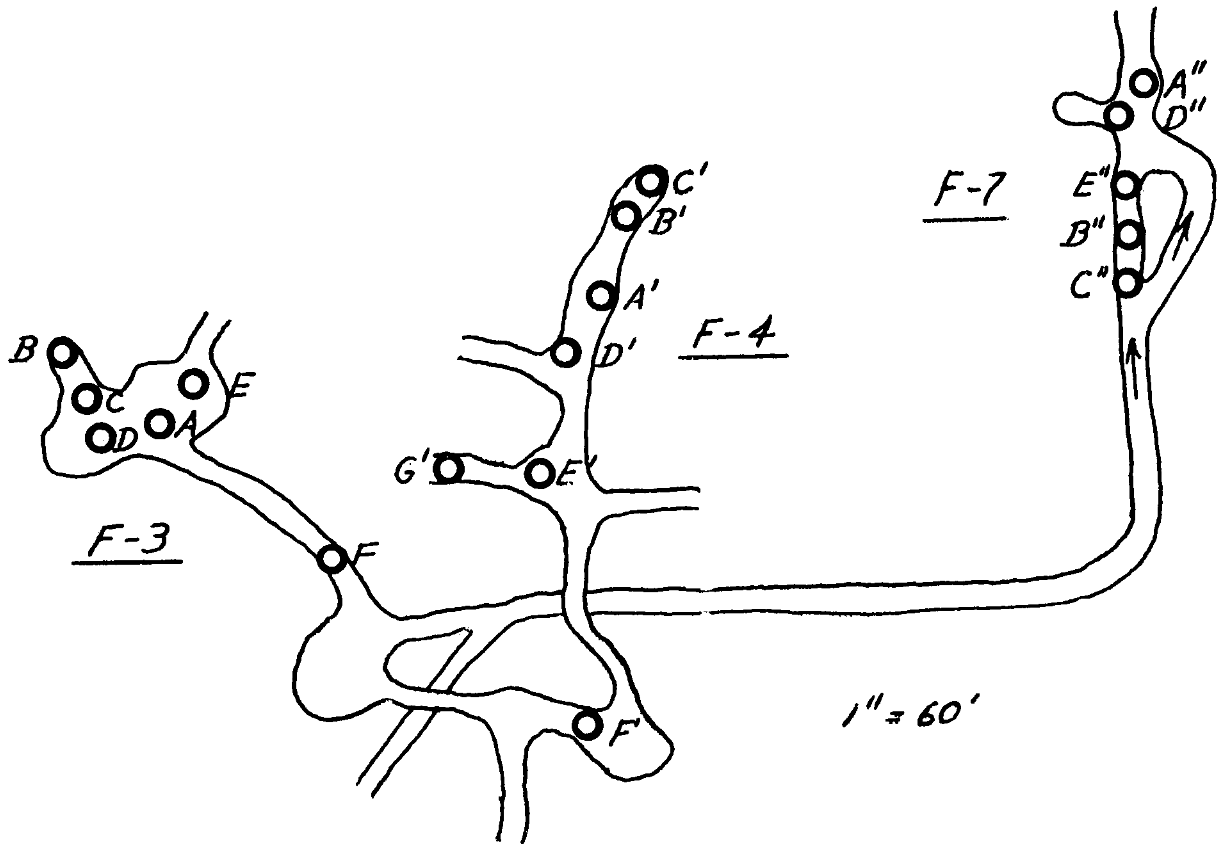
Ventilation Notes:

1. 11/13 1240 ventilation off, power failure
2. 11/14; 11/15 fan ventilating "C" burned out
3. leak in ventilation duct near "A" repaired
4. 1530 ventilation duct damaged at "A" by blast
5. 11/15 0950 ventilation leak repaired


MINE: F
LOCATION: 1 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/1
LOCAL TIME, HOURS
Nov. 13, 1967
Nov. 15, 1967
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg



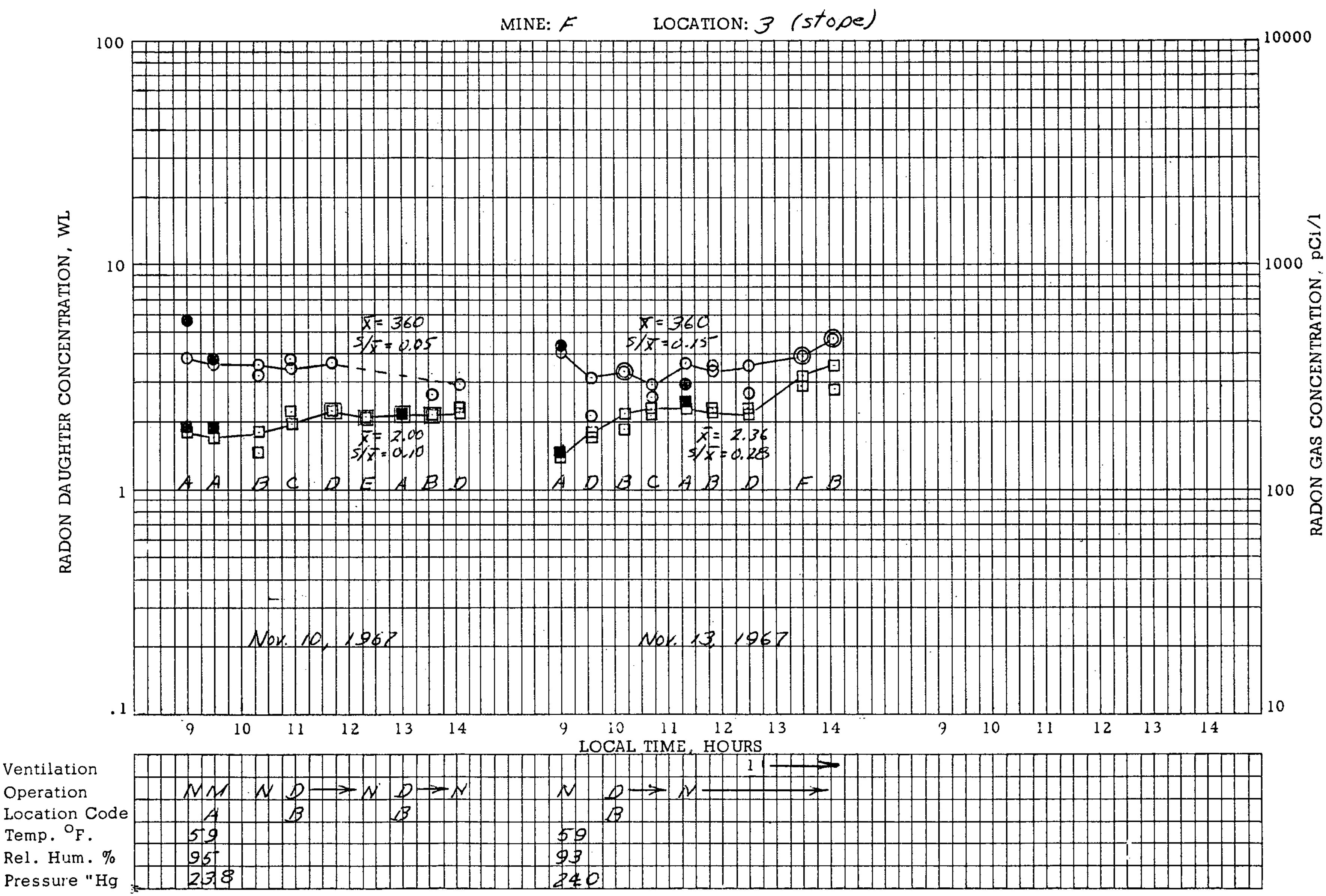
MINE: F
LOCATION: 2 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/1
100
10
1
.1
10000
1000
100
10
x̄ = 4.90
s/x̄ = 0.11
x̄ = 1.28
s/x̄ = 0.10
x̄ = 1.10
s/x̄ = 0.20
A A A' A' B A C C
A A A A' A' A' B A C C
Nov. 10, 1967
Nov. 14, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
2 3 4
M → N → D N
M → N M → N M →
B C
B B B
60
84
23.9
60
90
24.1



Mine - Location: F - 3 stope
F - 4 stope
F - 7 drift

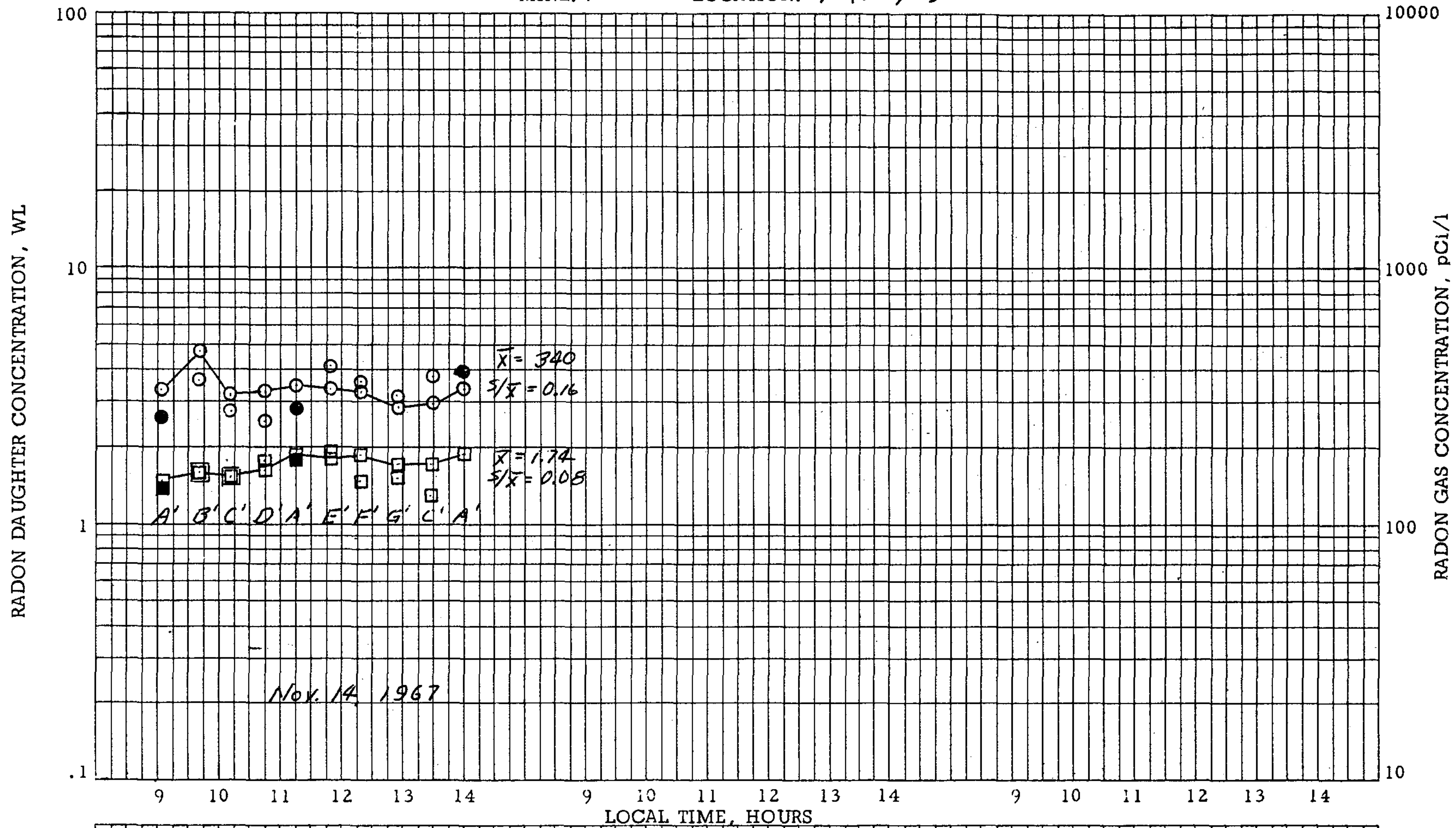
Ventilation Note:

1. 11/13 1230 power failure, ventilation off

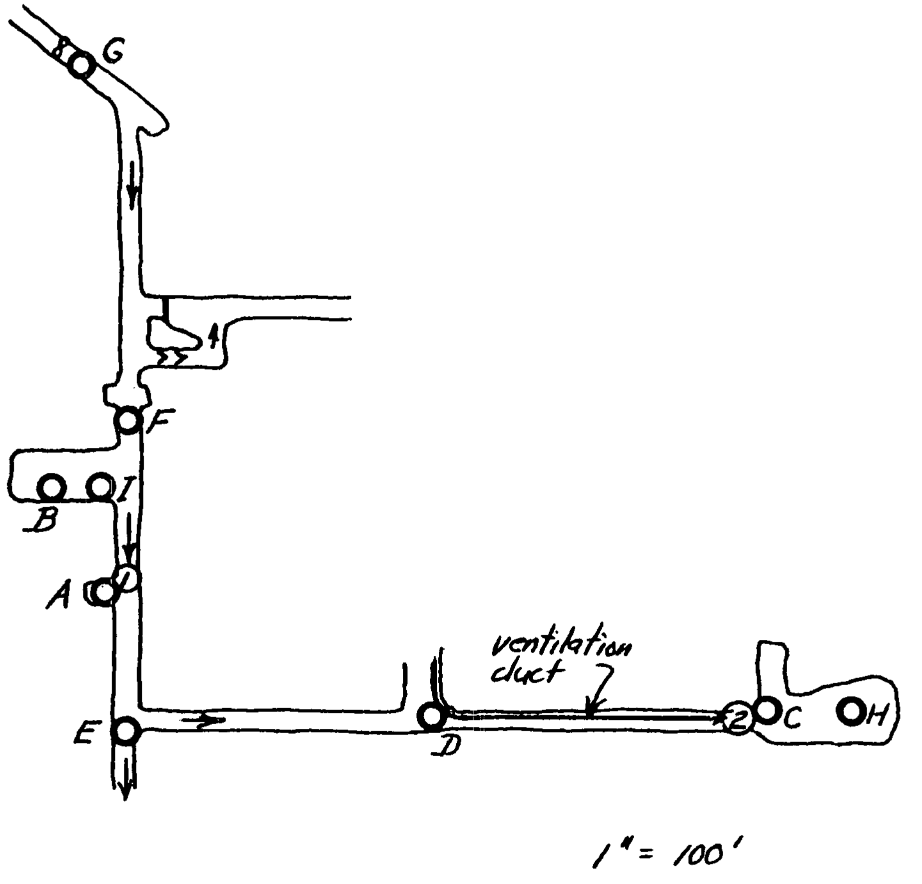


MINE: F LOCATION: 3 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 360
s/x̄ = 0.05
x̄ = 2.00
s/x̄ = 0.10
x̄ = 360
s/x̄ = 0.15
x̄ = 2.36
s/x̄ = 0.28
A A B C D E A B D
A D B C A B D F B
Nov. 10, 1967
Nov. 13, 1967
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
NM N D N D N
A B B
59
95
238
N D N
B
59
93
240

MINE: F LOCATION: 4 (stope)



Ventilation	
Operation	M N D → N ——→
Location Code	A' C'
Temp. °F.	59
Rel. Hum. %	92
Pressure "Hg	23.9



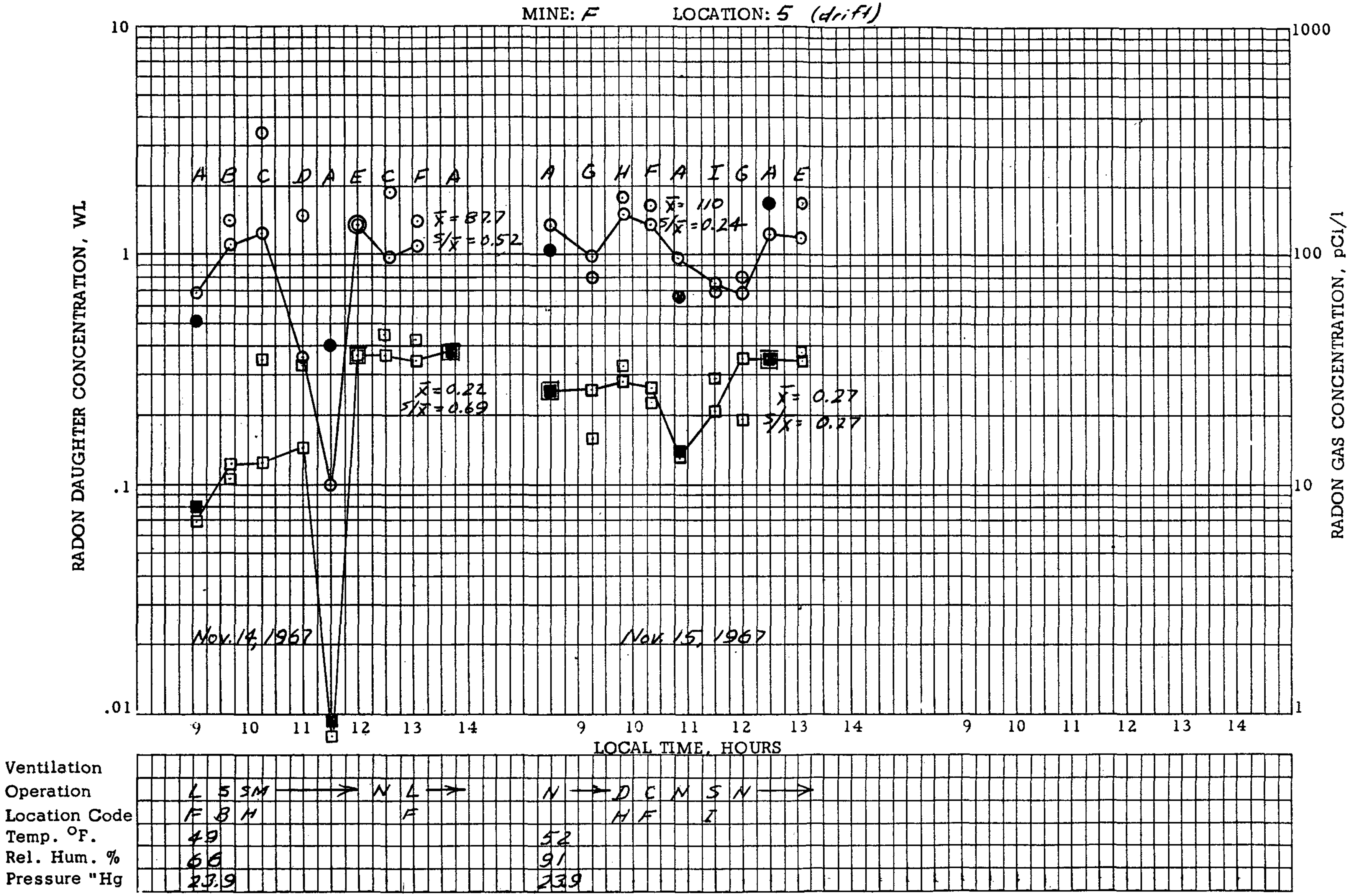
Mine - Location: F - 5, drift

Volume (ft^3): stope C-H 9500

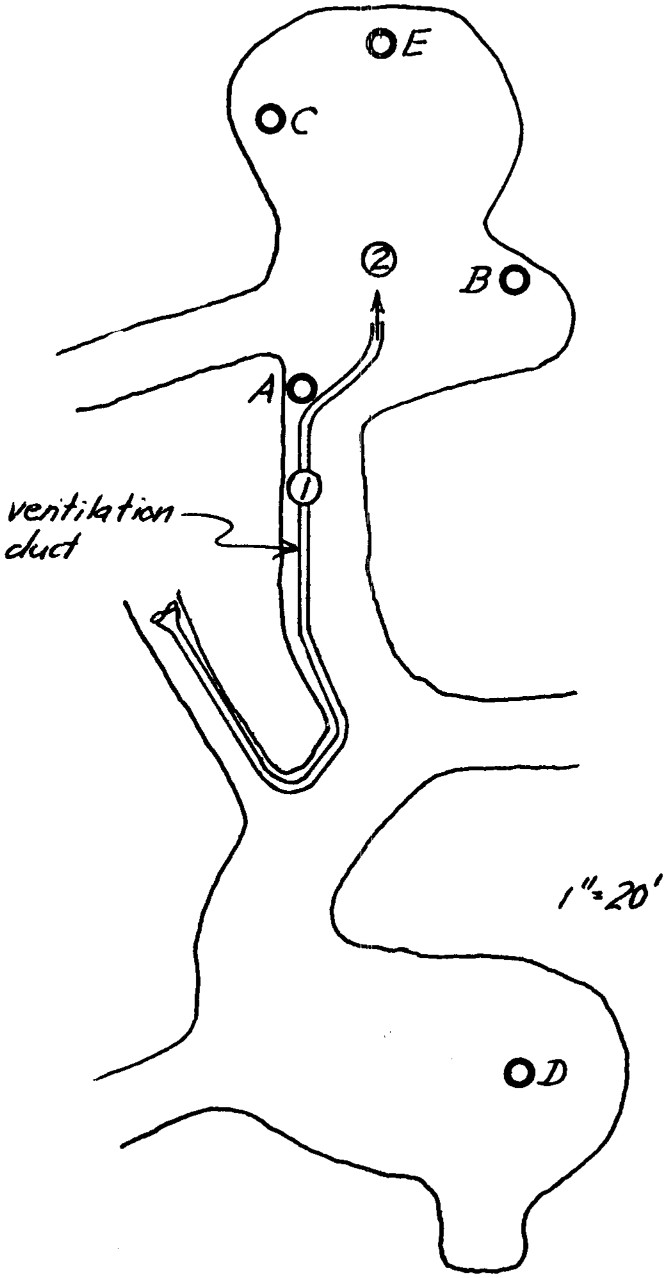
Velocity (ft/min): at ① 11/14 100
11/15 180

Flowrate (ft^3/min): at ① 11/14 5000
11/15 9000
② 13,000

Ventilation Note: Fresh air entering at "G"



MINE: F
LOCATION: 5 (drift)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
10
1
.1
.01
1000
100
10
1
A B C D A E C F A
A G H F A I G A E
$\bar{x}$ = 87.7
s/$\bar{x}$ = 0.52
$\bar{x}$ = 110
s/$\bar{x}$ = 0.24
$\bar{x}$ = 0.22
s/$\bar{x}$ = 0.69
$\bar{x}$ = 0.27
s/$\bar{x}$ = 0.27
Nov. 14, 1967
Nov. 15, 1967
9 10 11 12 13 14 9 10 11 12 13 14 9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
L S SM → N L →
N → D C N S N →
F B H
F
H F I
49
52
66
91
23.9
23.9

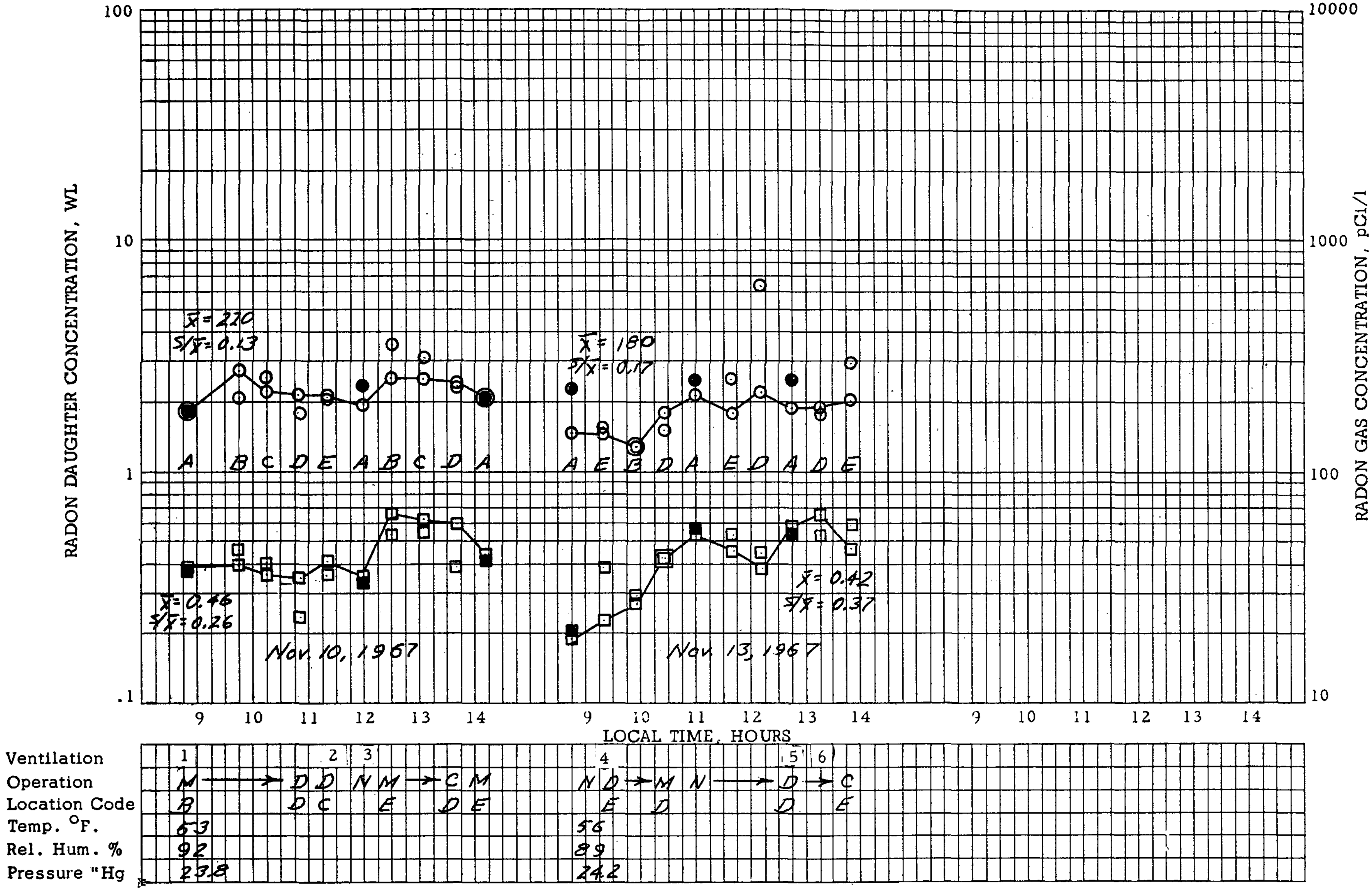


Mine - Location: F - 6, stope
Volume (ft^3): stope BCE 6000
Flowrate (ft^3/min): at ① 11/10, 9000; at ② 11/13, 7000 (duct extended)
Flowrate (change/min): stope BCE, 11/10, 1.5; 11/13, 1.2

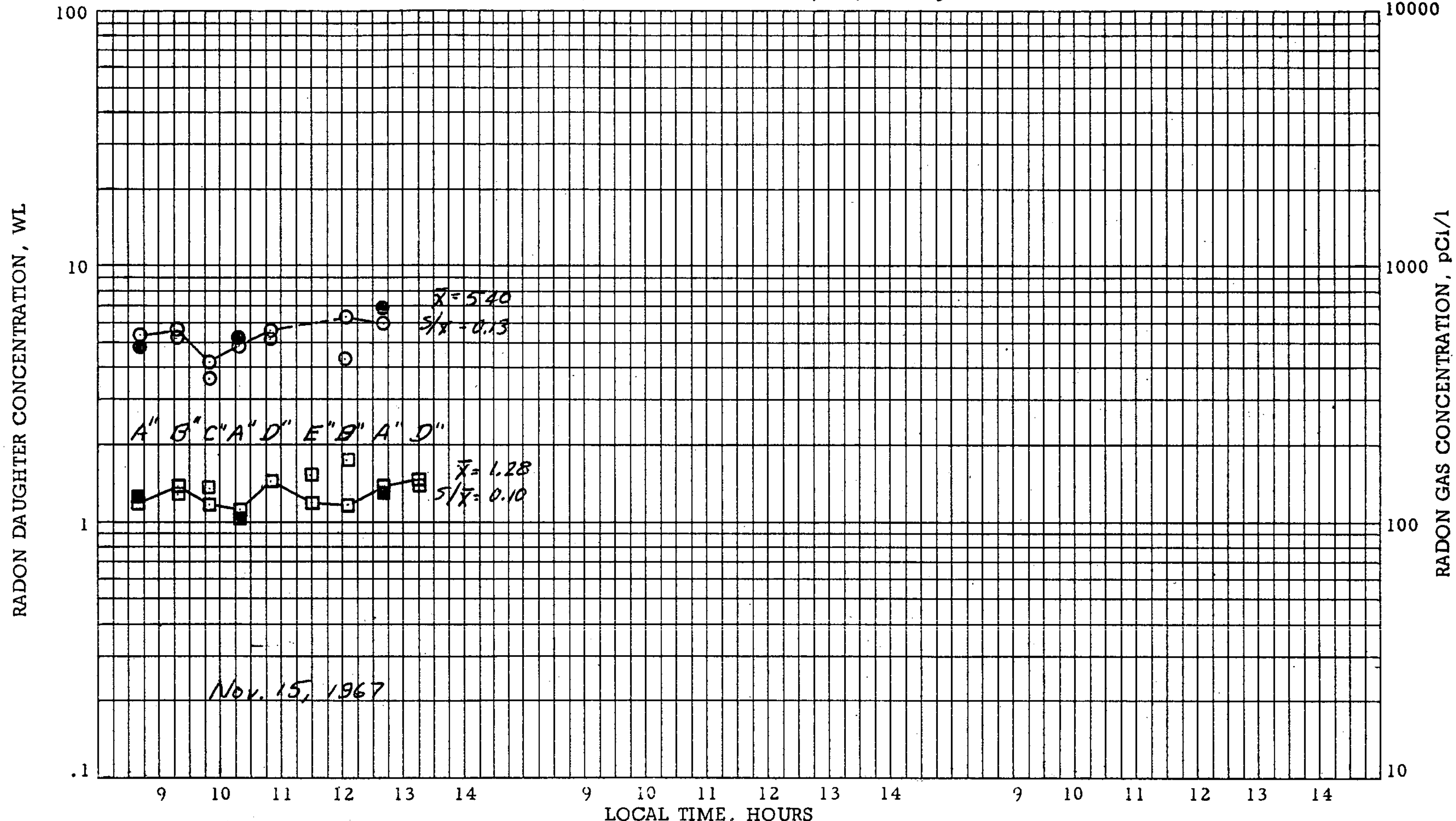
Ventilation Note:

1. 11/10 0850 ventilation duct discharging at ①
2. 1120 ventilation off
3. 1200 duct extended to ② , ventilation on
4. 11/13 0925 ventilation duct discharging at ①
5. 1245 ventilation off
6. 1315 ventilation on at ①

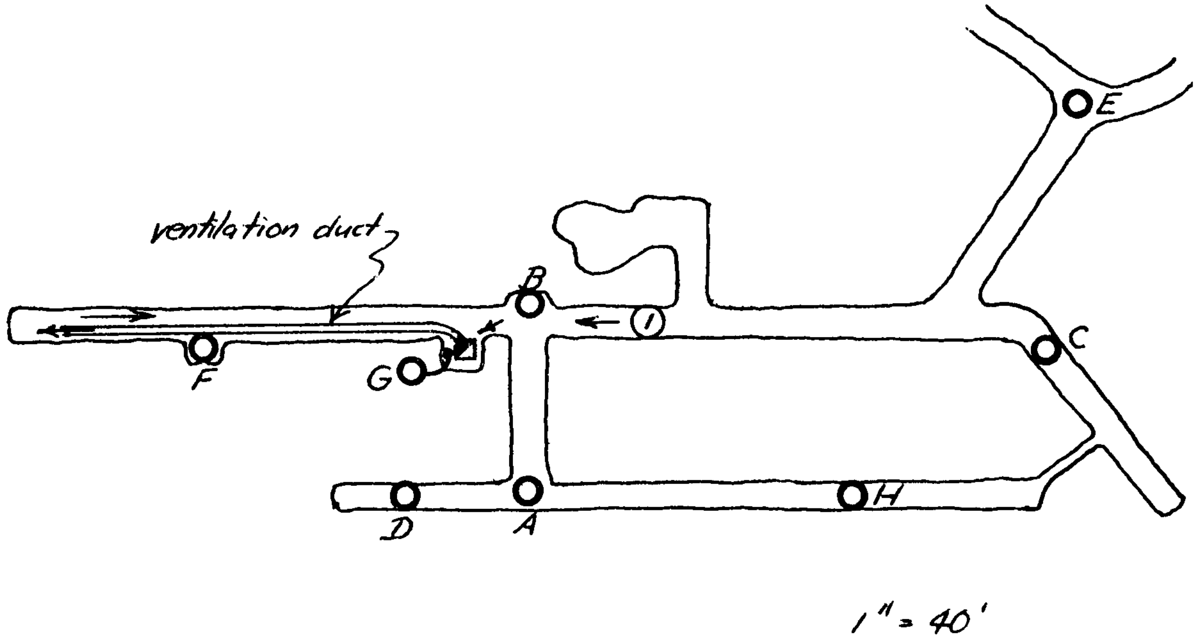
MINE: F LOCATION: 6 (stope)



MINE: F LOCATION: 7 (drift)



Ventilation	
Operation	HD →
Location Code	
Temp. °F.	60
Rel. Hum. %	94
Pressure "Hg	23.9

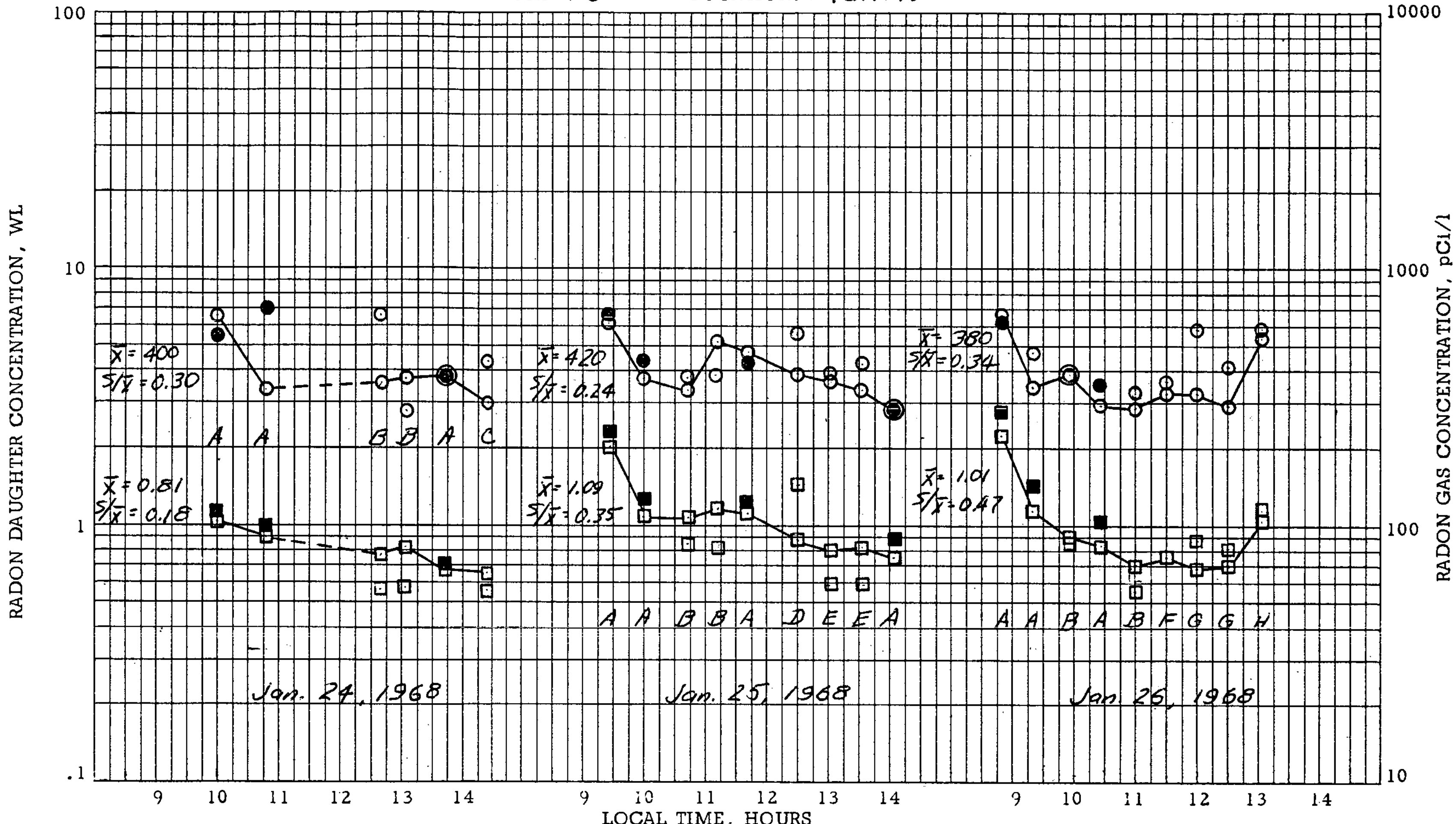


Mine - Location: G - 1, drift

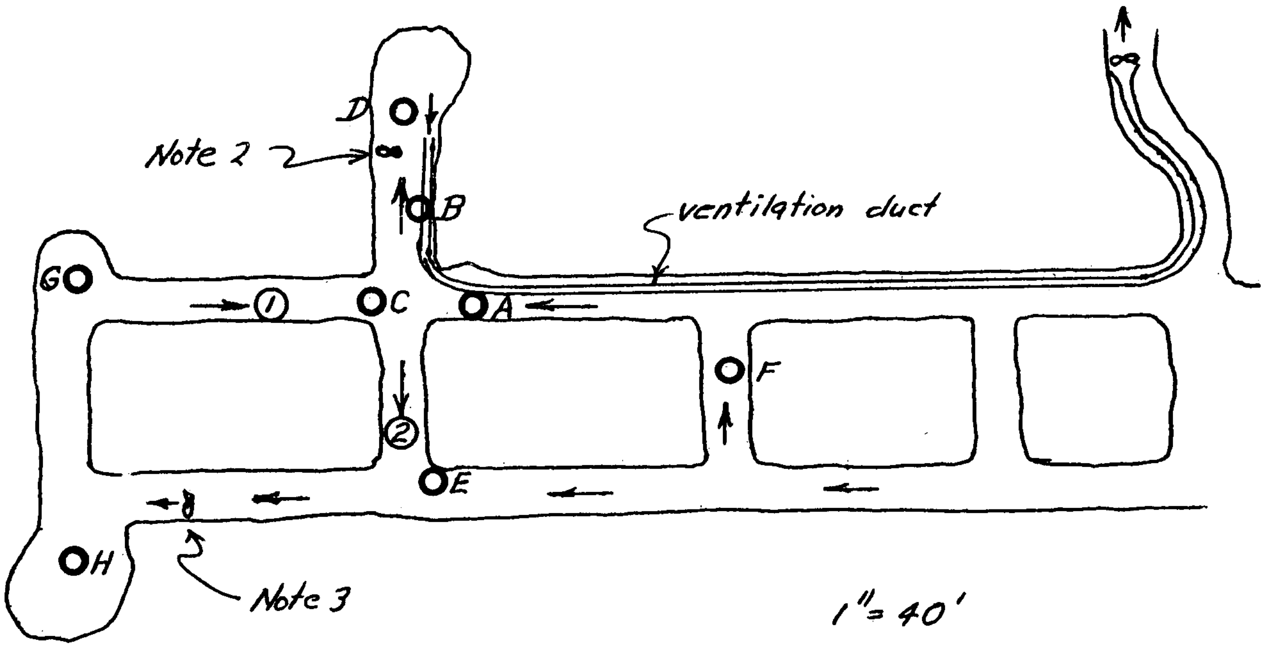
Velocity (ft/min): at ① 175

Flowrate (ft^3/min): at ① 14,000

MINE: G LOCATION: 1 (drift)



Ventilation Operation	N H; N → D →	N → H D → H → N	N → B N M → N M
Location Code	B; C	C D E	F F F
Temp. °F.	63	63	62
Rel. Hum. %	81	81	76
Pressure "Hg	23.7	23.7	23.9



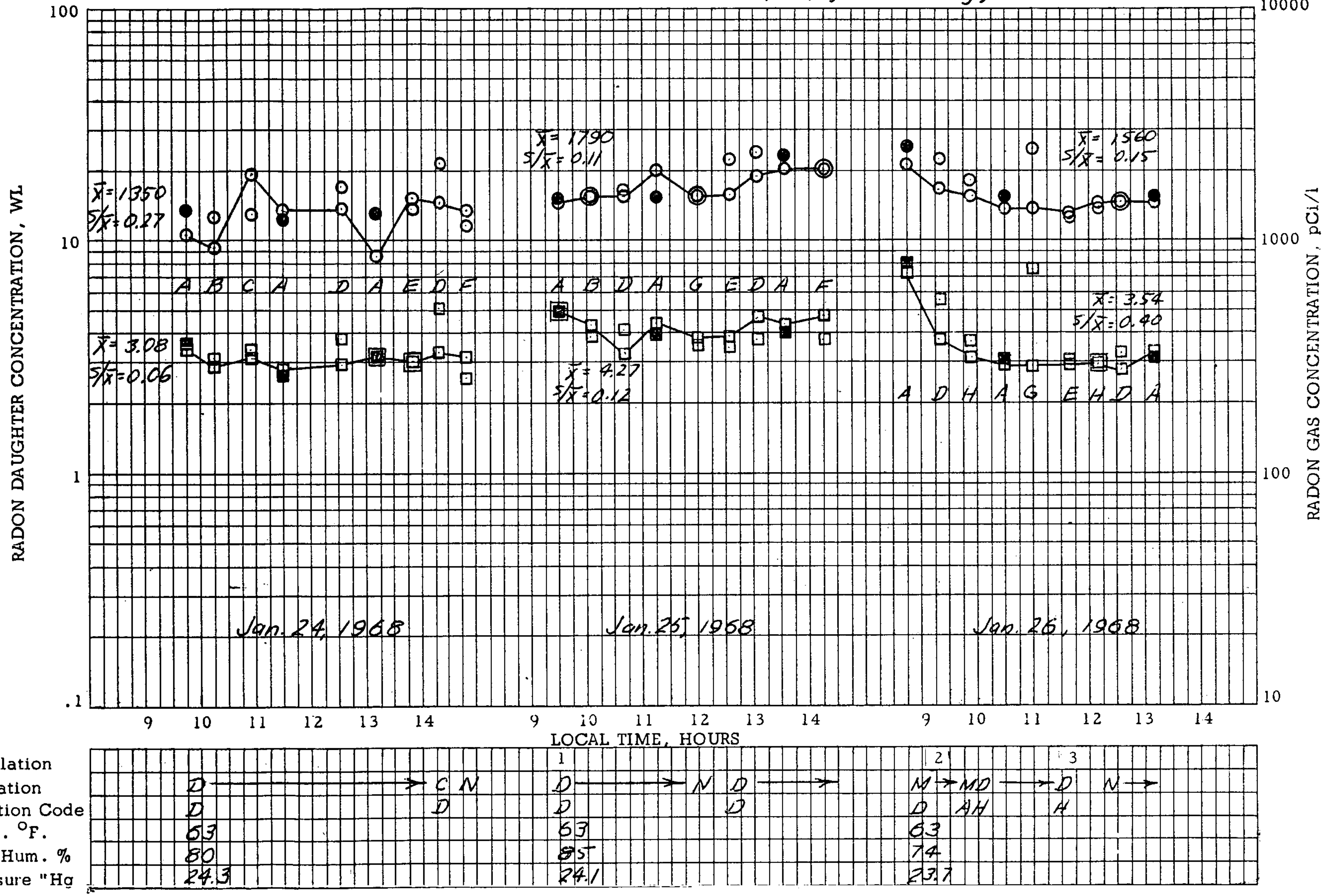
Mine - Location: G - 2, drift, near heading
Volume (ft^3): heading 22,000

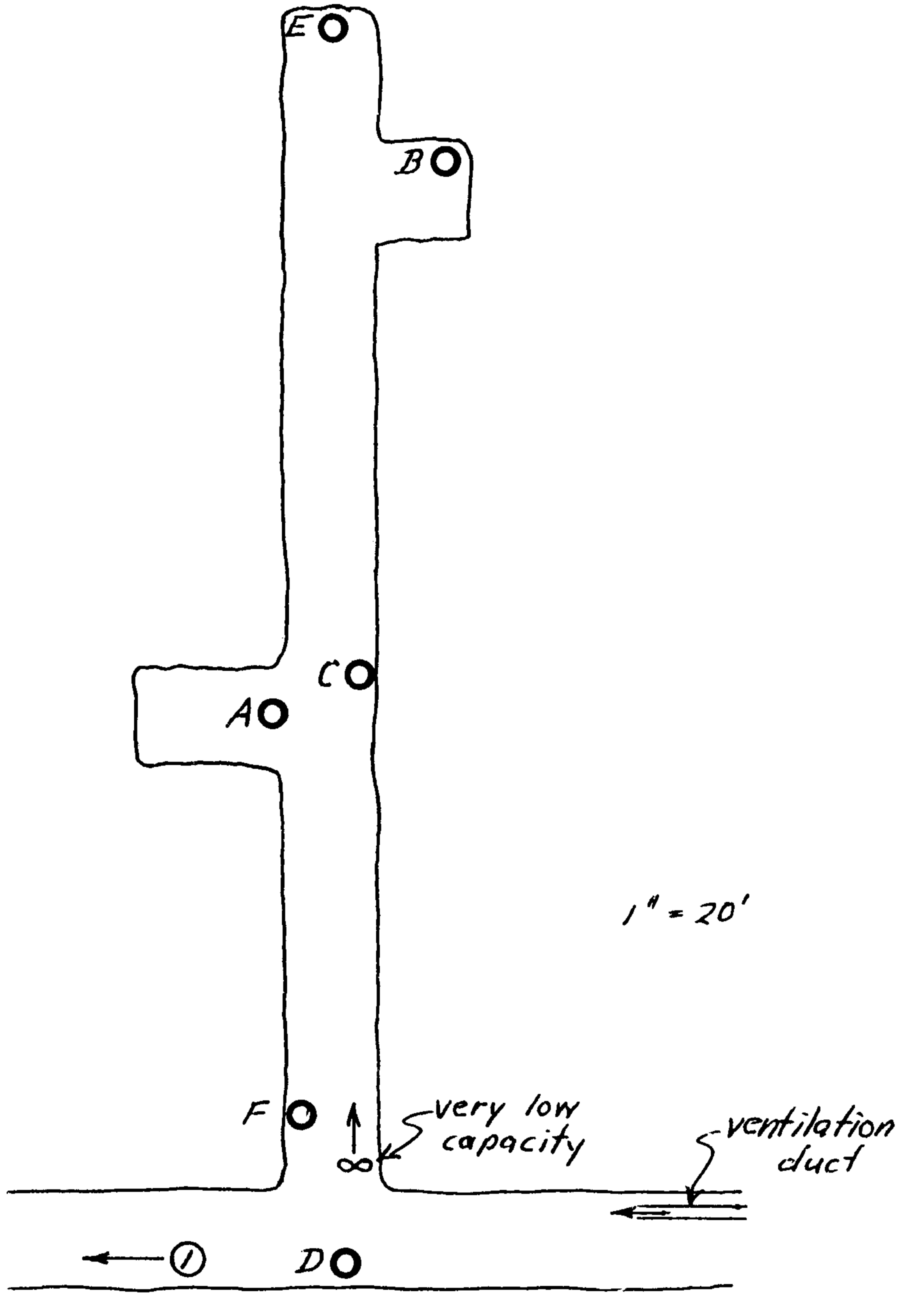
Flowrate (ft^3/min): at	A	6000
	B	12,000
	①	8000
	②	2000
	F	200

Ventilation Notes:

1. 1/25 0930 ventilation duct extended 10' into stope near "D"
2. 1/26 0920 fan installed in stope "D" to blow air out of stope
3. 1140 fan installed near "H"

MINE: G LOCATION: 2 (drift, near heading)

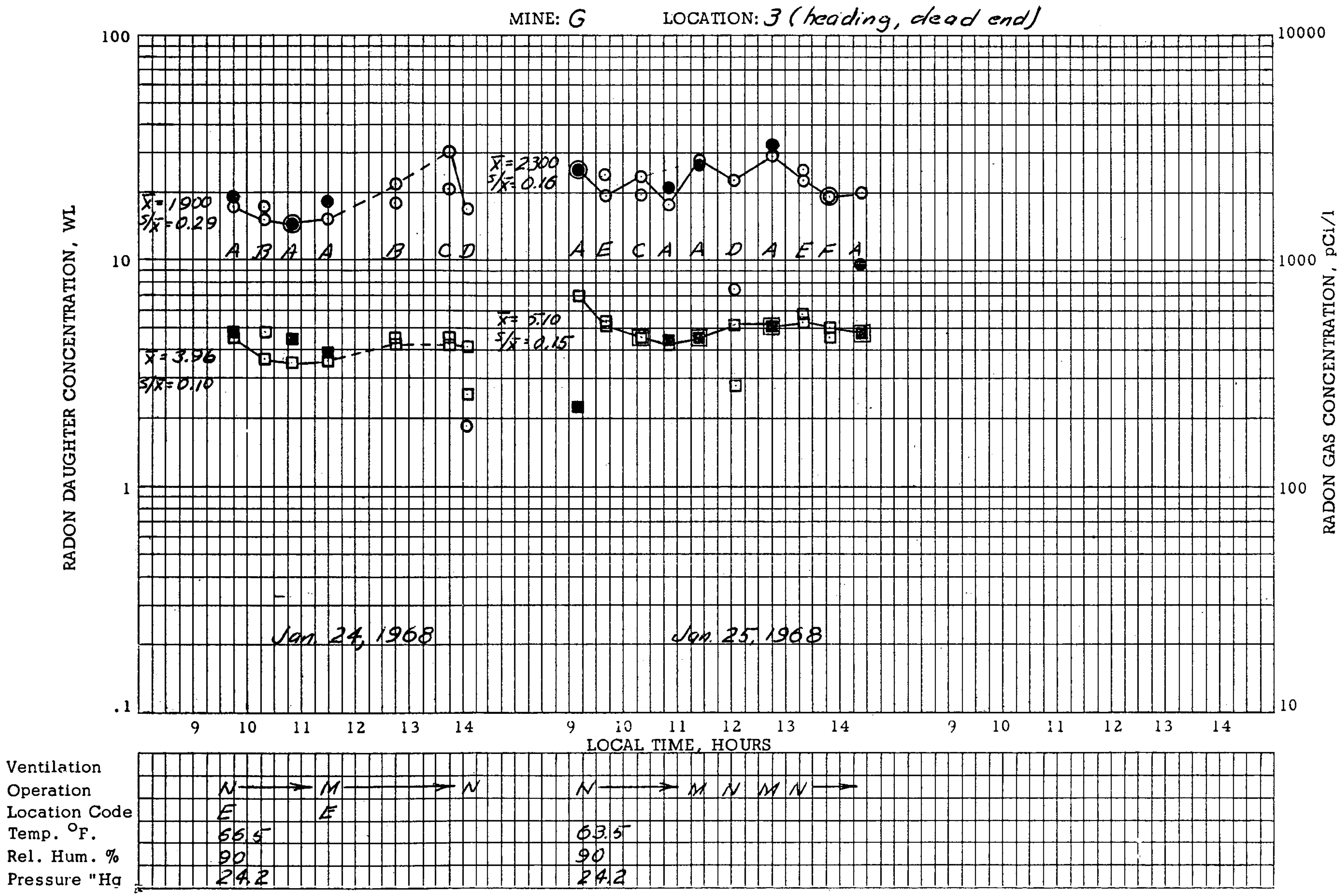




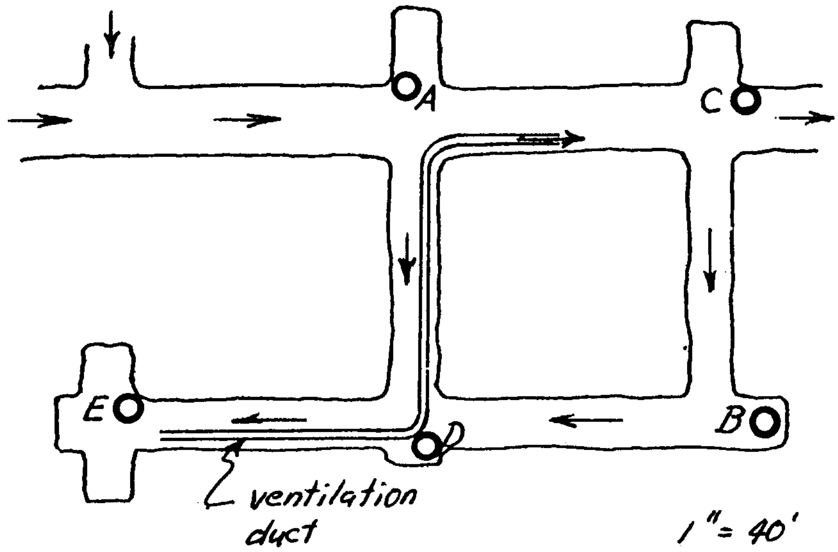
Mine - Location: G - 3, heading, dead end

Volume (ft^3): stope 800

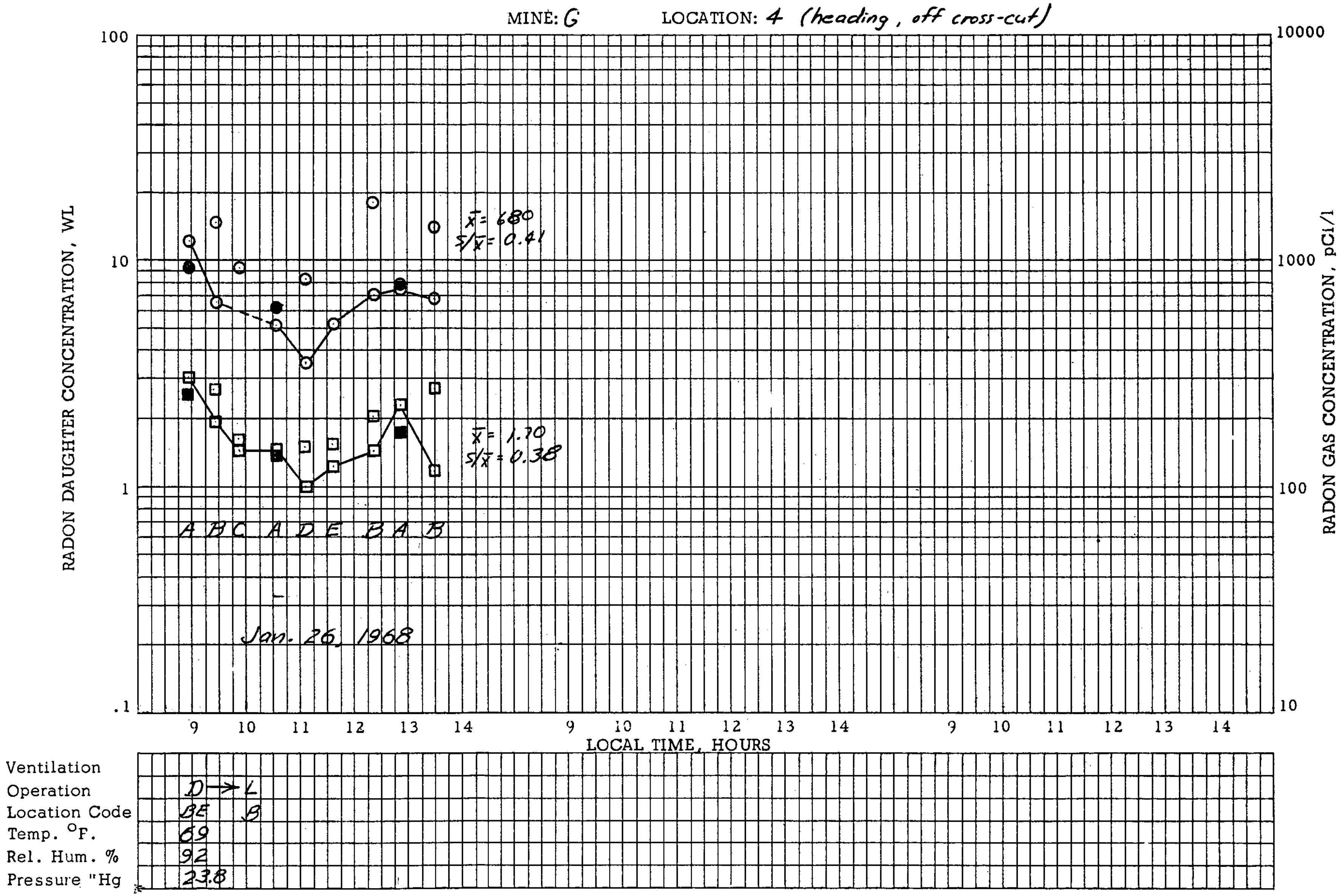
Flowrate (ft^3/min): at ① 38,000
in stope - convection only

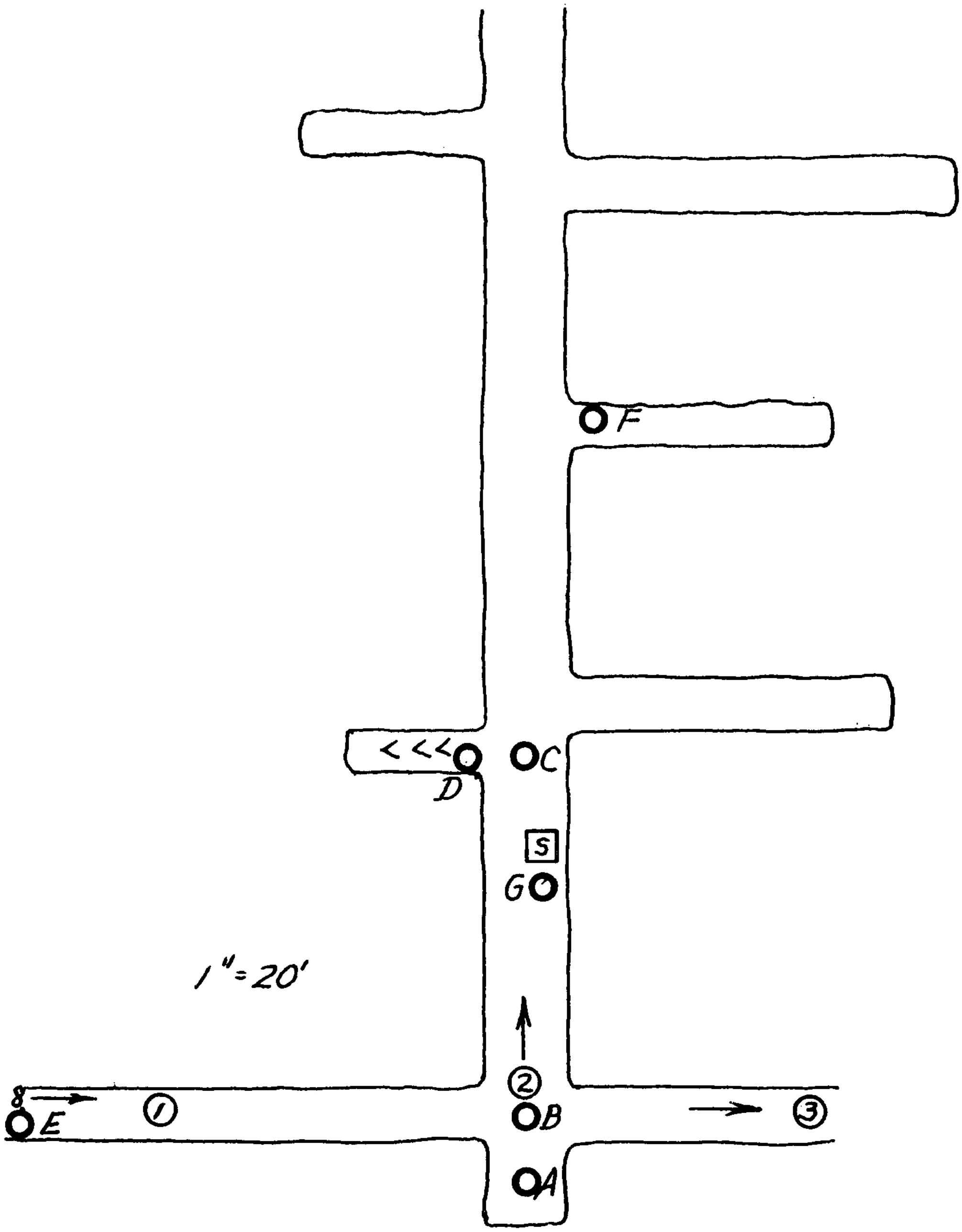


MINE: G
LOCATION: 3 (heading, dead end)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 1900
s/x̄ = 0.29
x̄ = 3.96
s/x̄ = 0.10
x̄ = 2300
s/x̄ = 0.16
x̄ = 5.10
s/x̄ = 0.15
A B A A B C D
A E C A A D A E F A
Jan 24, 1968
Jan 25, 1968
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N → M → N
E E
66.5
90
24.2
N → M N M N →
63.5
90
24.2



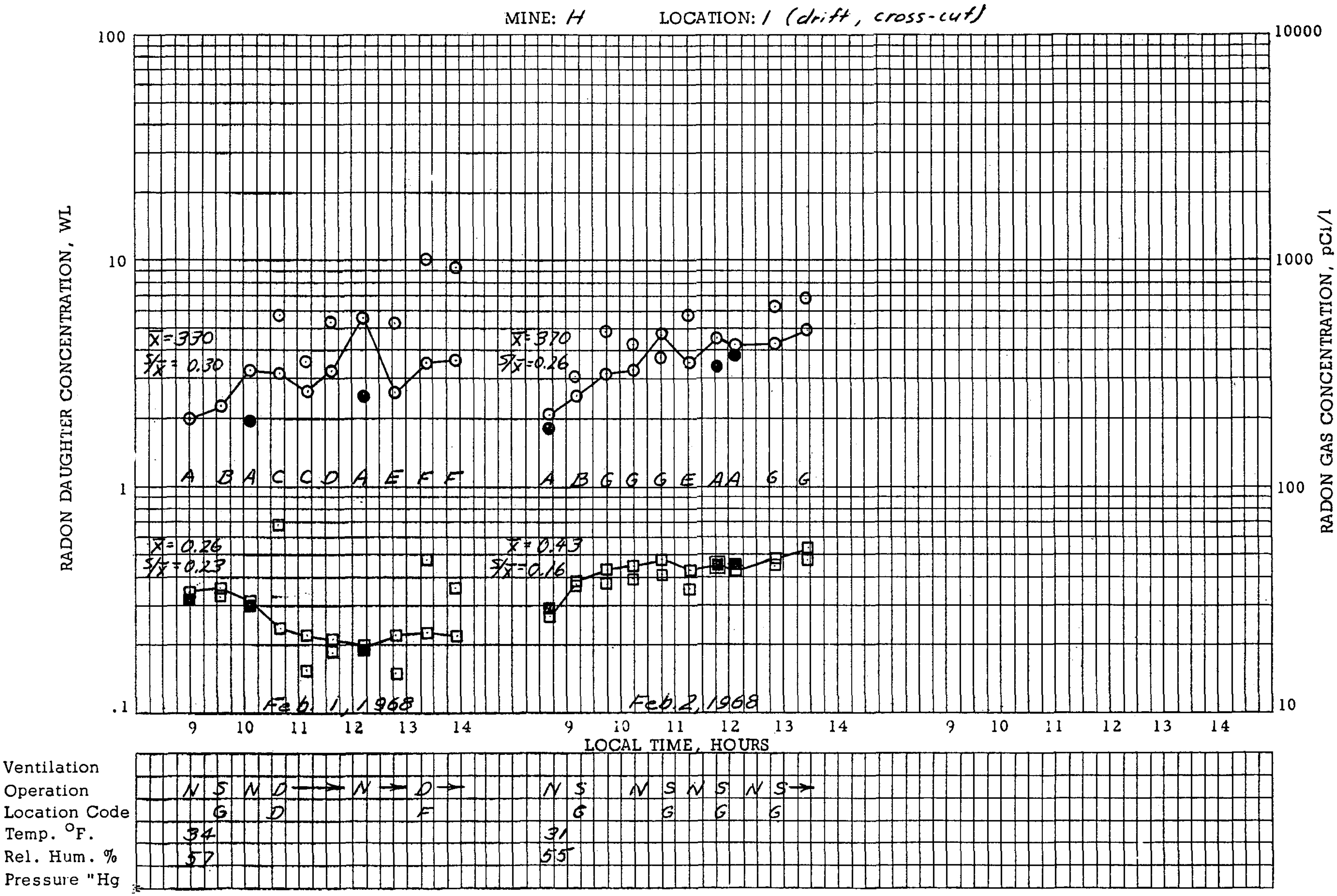
Mine - Location: G - 4, heading, off cross-cut

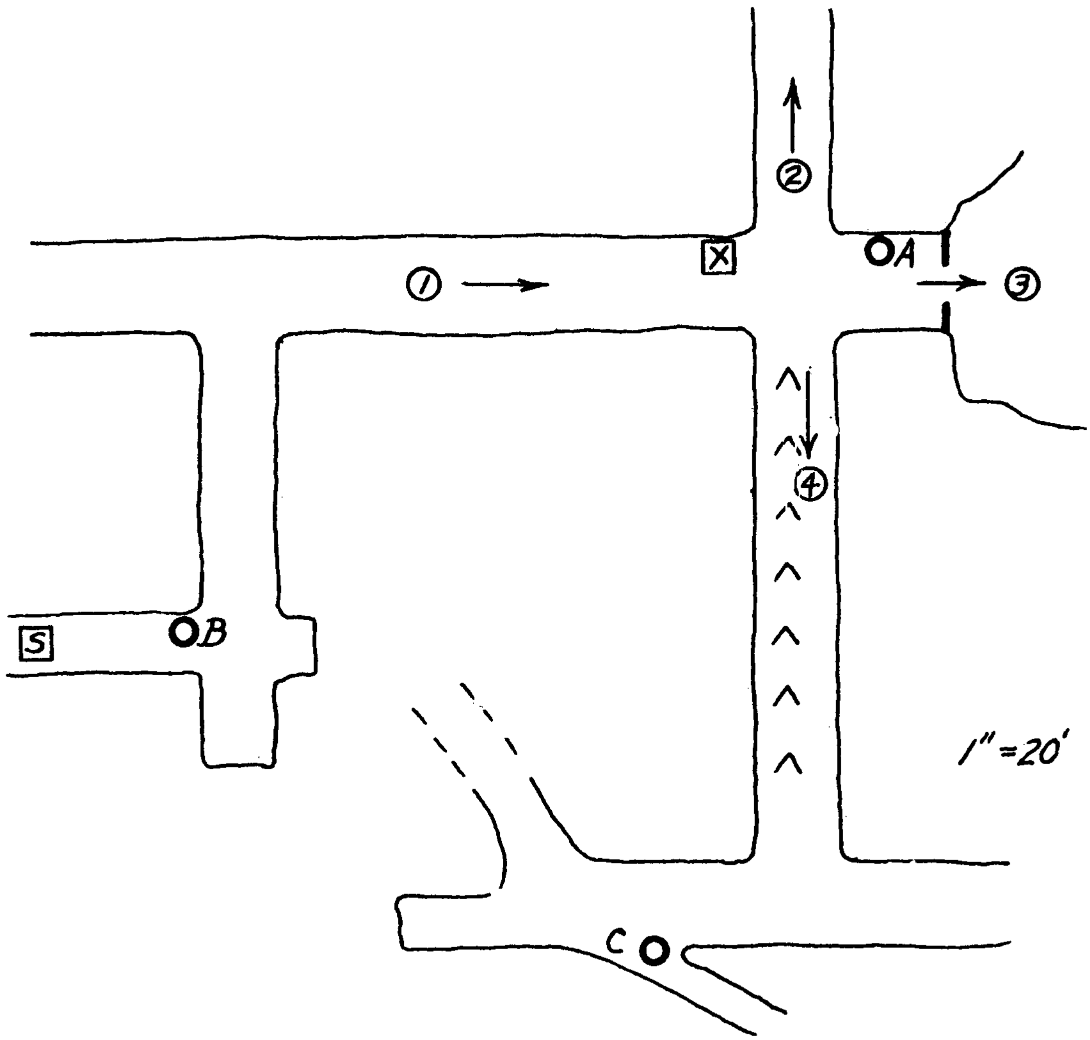

MINE: G
LOCATION: 4 (heading, off cross-cut)
RADON DAUGHTER CONCENTRATION, WL
100
10
1
.1
RADON GAS CONCENTRATION, pCi/l
10000
1000
100
10
x̄ = 680
s/x̄ = 0.41
x̄ = 1.70
s/x̄ = 0.38
A B C A D E B A B
Jan. 26, 1968
9 10 11 12 13 14 9 10 11 12 13 14 9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
D → L
Location Code
BE B
Temp. °F.
69
Rel. Hum. %
92
Pressure "Hg
23.8



Mine - Location: H - 1, drift, cross-cut

Flowrate (ft³/min): at	①	②	③
2/1	36,000	26,000	10,000
2/2	34,000	29,000	-

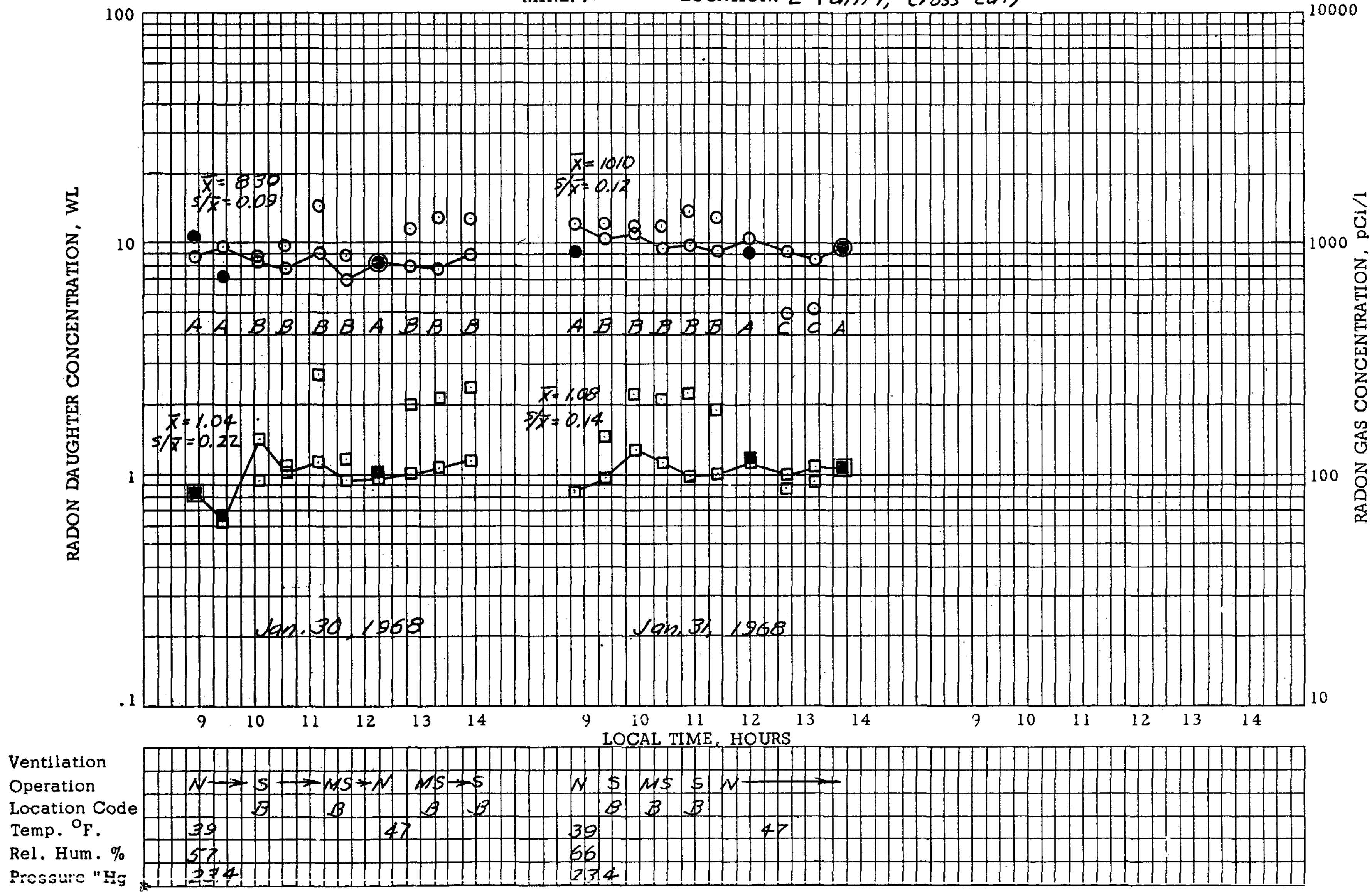

MINE: H
LOCATION: 1 (drift, cross-cut)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 370
s/x̄ = 0.30
x̄ = 370
s/x̄ = 0.26
A B A C C D A E F F
A B G G G E A A G G
x̄ = 0.26
s/x̄ = 0.23
x̄ = 0.43
s/x̄ = 0.16
Feb. 1, 1968
Feb. 2, 1968
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N S N D → N → D →
G D F
34
57
N S N S N S N S →
G G G G
31
55

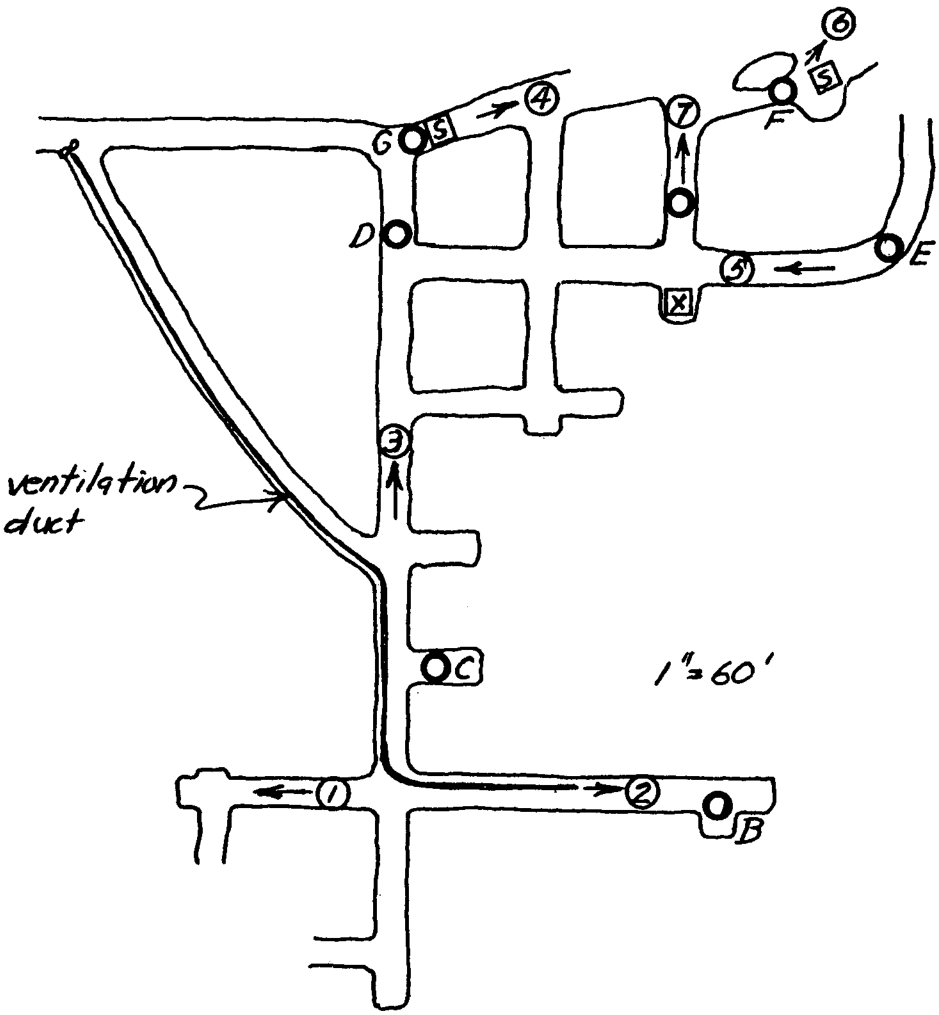


Mine - Location: H - 2, drift, cross-cut

Flowrate (ft^3/min): at	①	②	③	④
1/30	21,000	4000	3000	14,000
1/31	22,000	-	4000	-

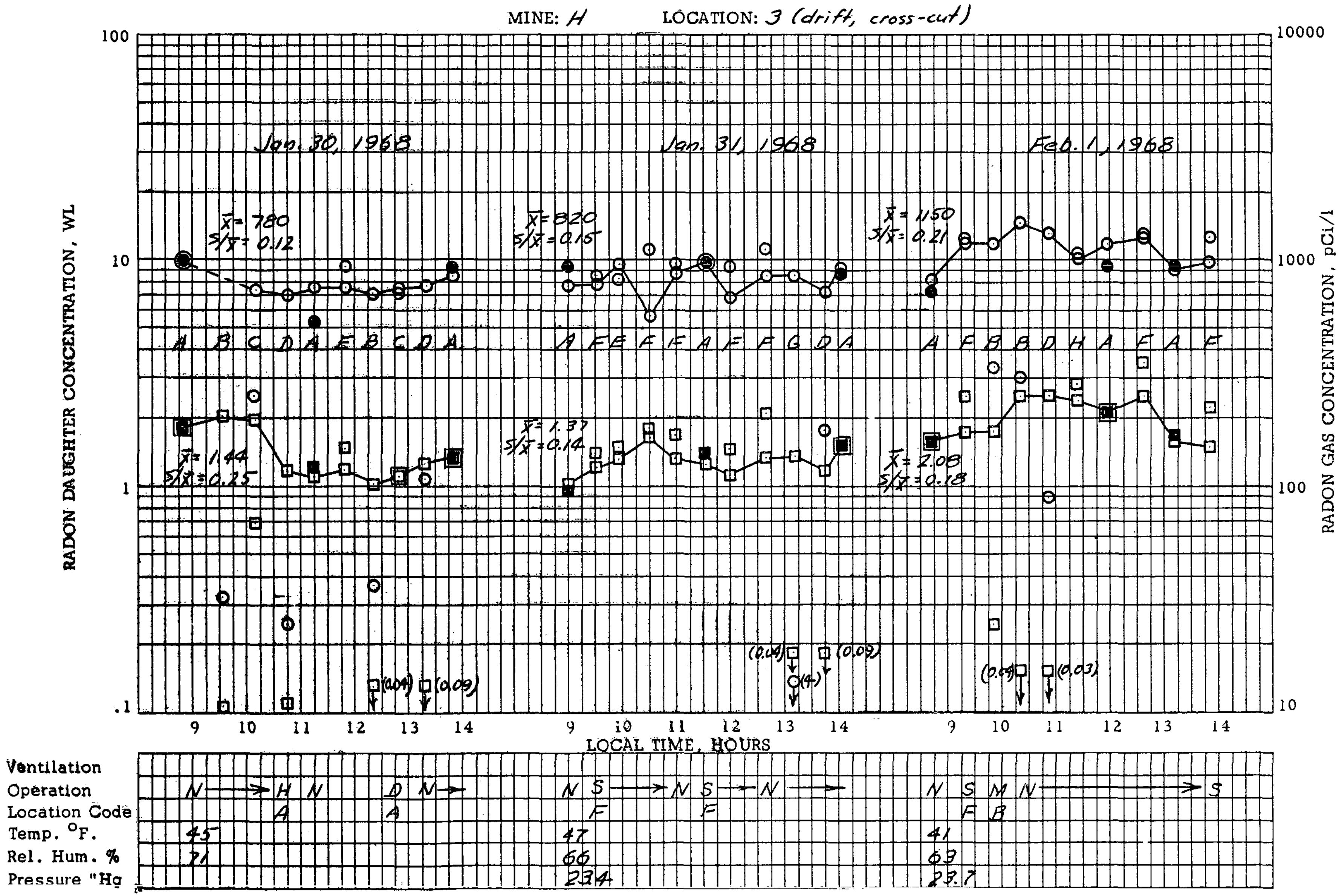
MINE: H LOCATION: 2 (drift, cross-cut)

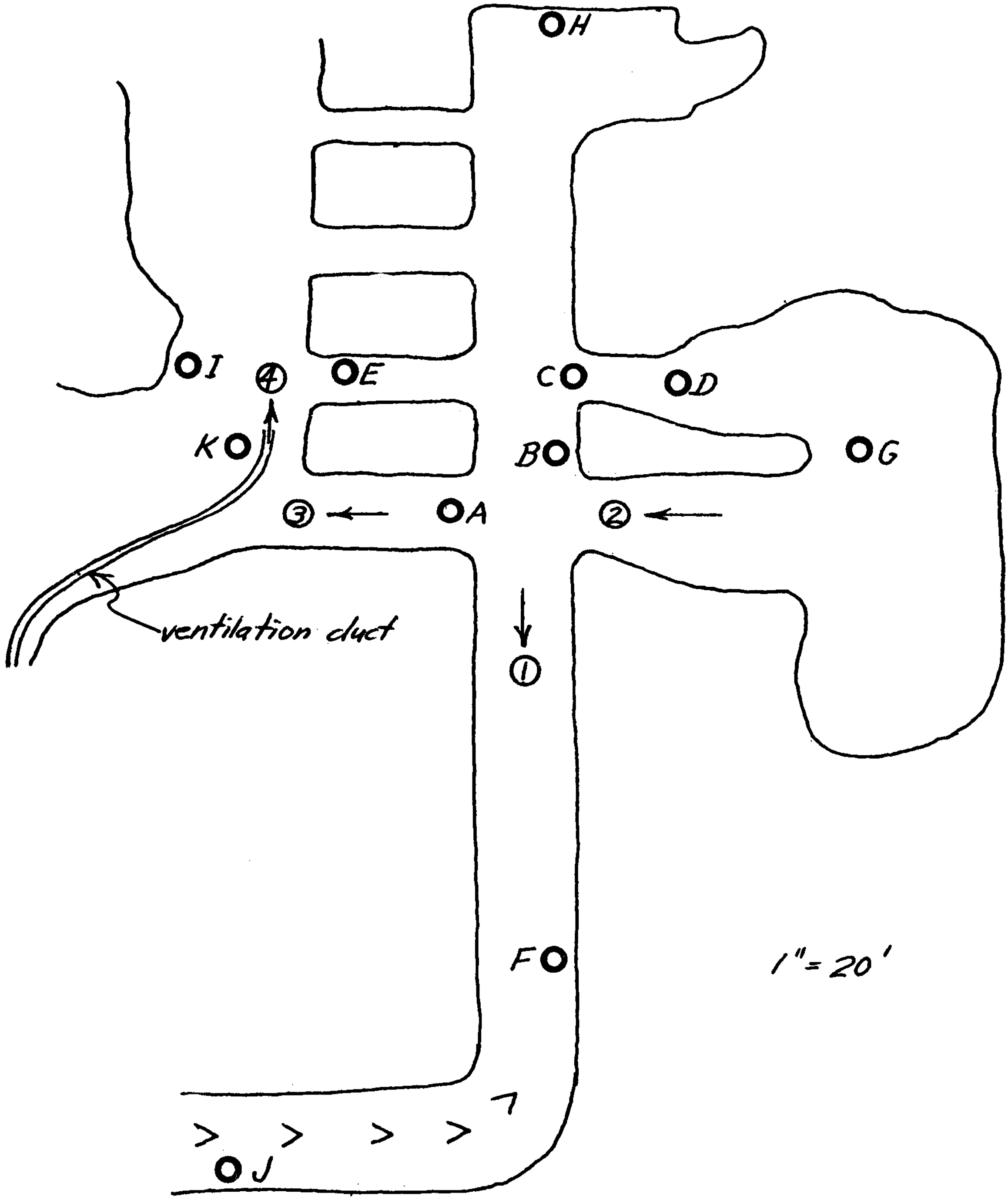




Mine - Location: H - 3, drift, cross-cut

Flowrate (ft^3/min): at			
	①	3000	
	②	6000	
	③	300	
	④	16,000	
	⑤	36,000	
	⑥	2000	
	⑦	1/30	9000
		1/31	10,000
		2/1	12,000


MINE: H LOCATION: 3 (drift, cross-cut)
Jan. 30, 1968
Jan. 31, 1968
Feb. 1, 1968
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg

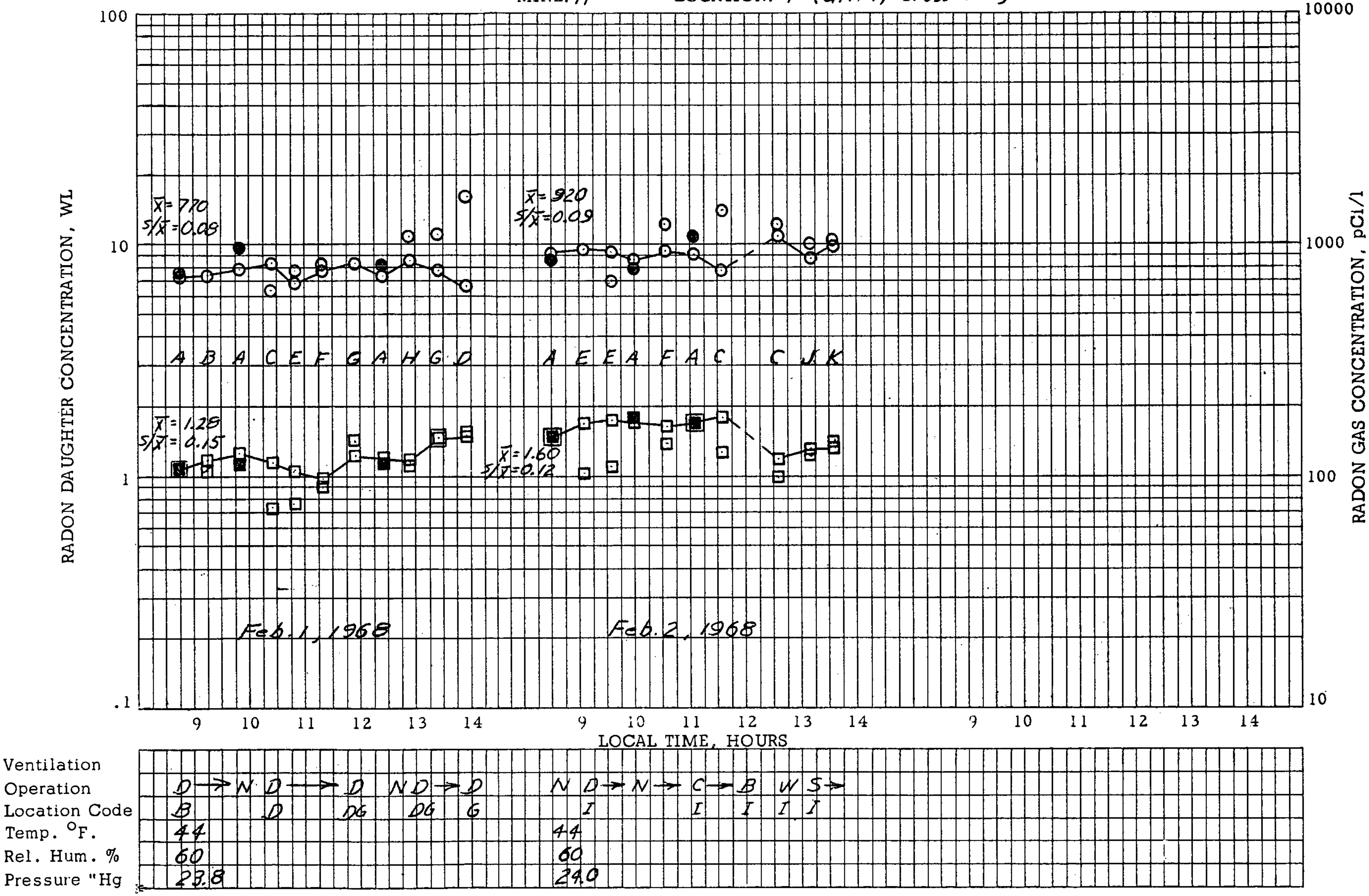


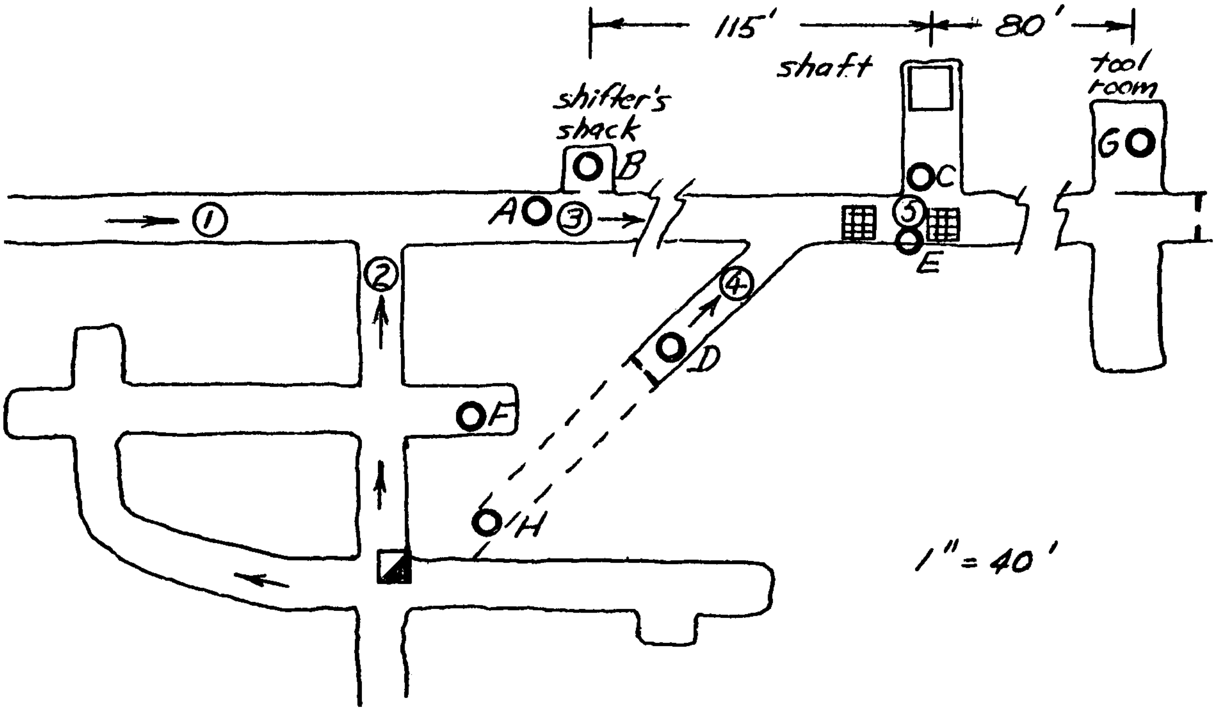
Mine - Location: H - 4, drift, cross-cut

Flowrate (ft^3/min): at

①		6000
②		2000
③		2000
④	2/1	11,000
	2/2	12,000

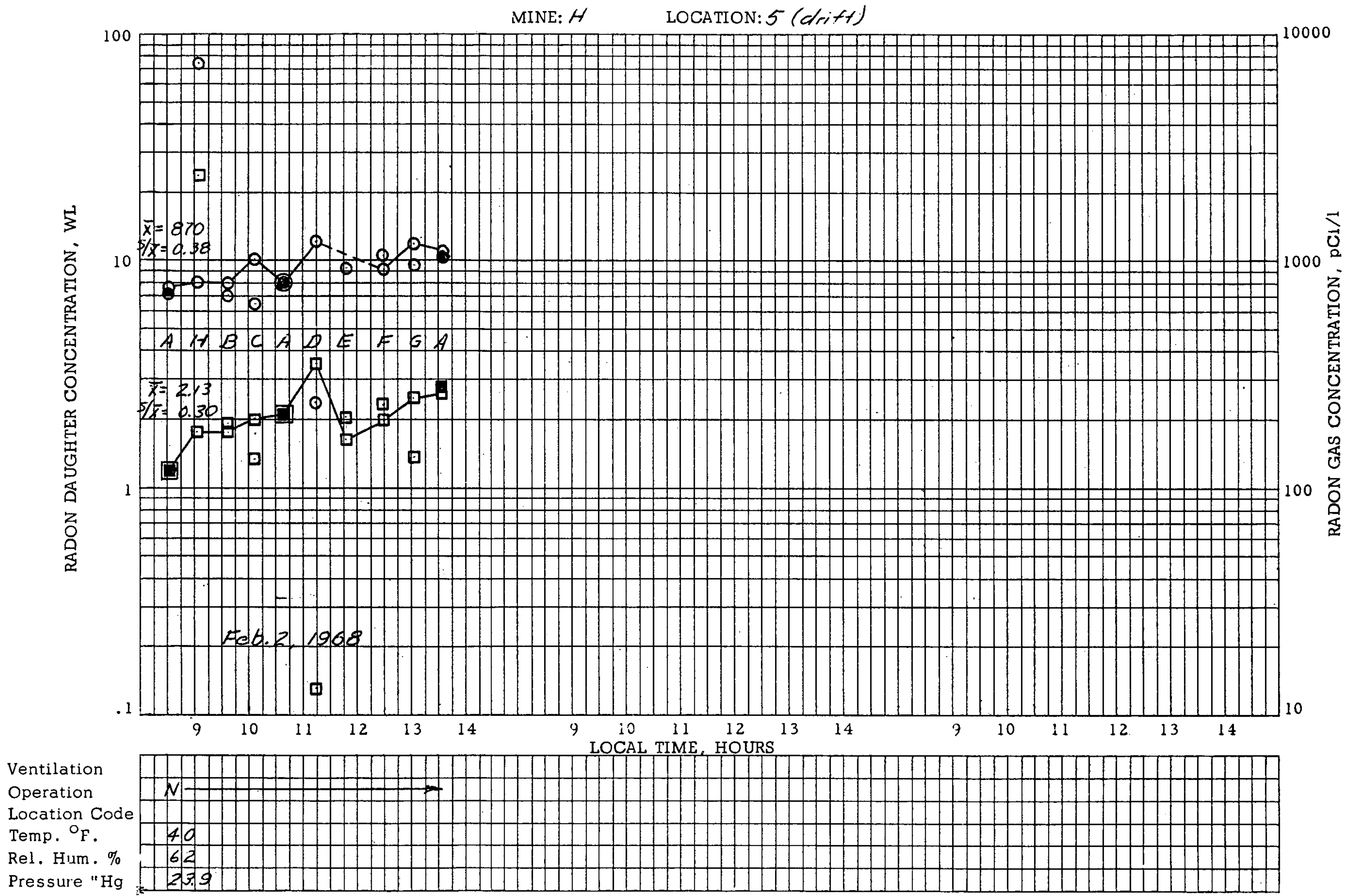
MINE: H   LOCATION: 4 (drift, cross-cut)



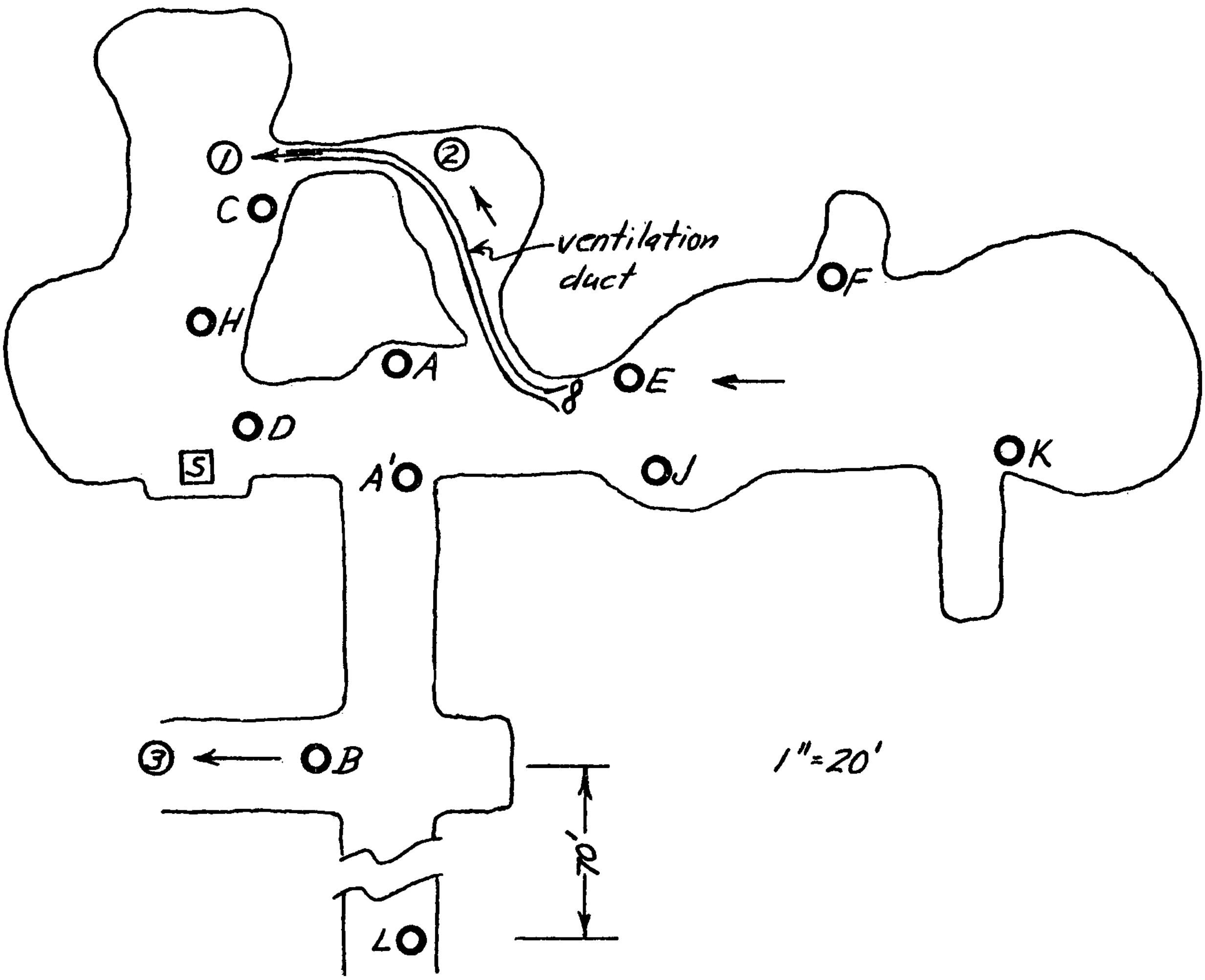


Mine - Location: H - 5, drift

Flowrate (ft^3/min): at		
	①	3000
	②	7000
	③	10,000
	④	5000
	⑤	15,000 (into grizzlies and shaft)



MINE: H
LOCATION: 5 (drift)
100
10
1
.1
10000
1000
100
10
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
x̄ = 870
s/x̄ = 0.38
A H B C A D E F G A
x̄ = 2.13
s/x̄ = 0.30
Feb. 2, 1968
9 10 11 12 13 14 9 10 11 12 13 14 9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
N
40
62
23.9

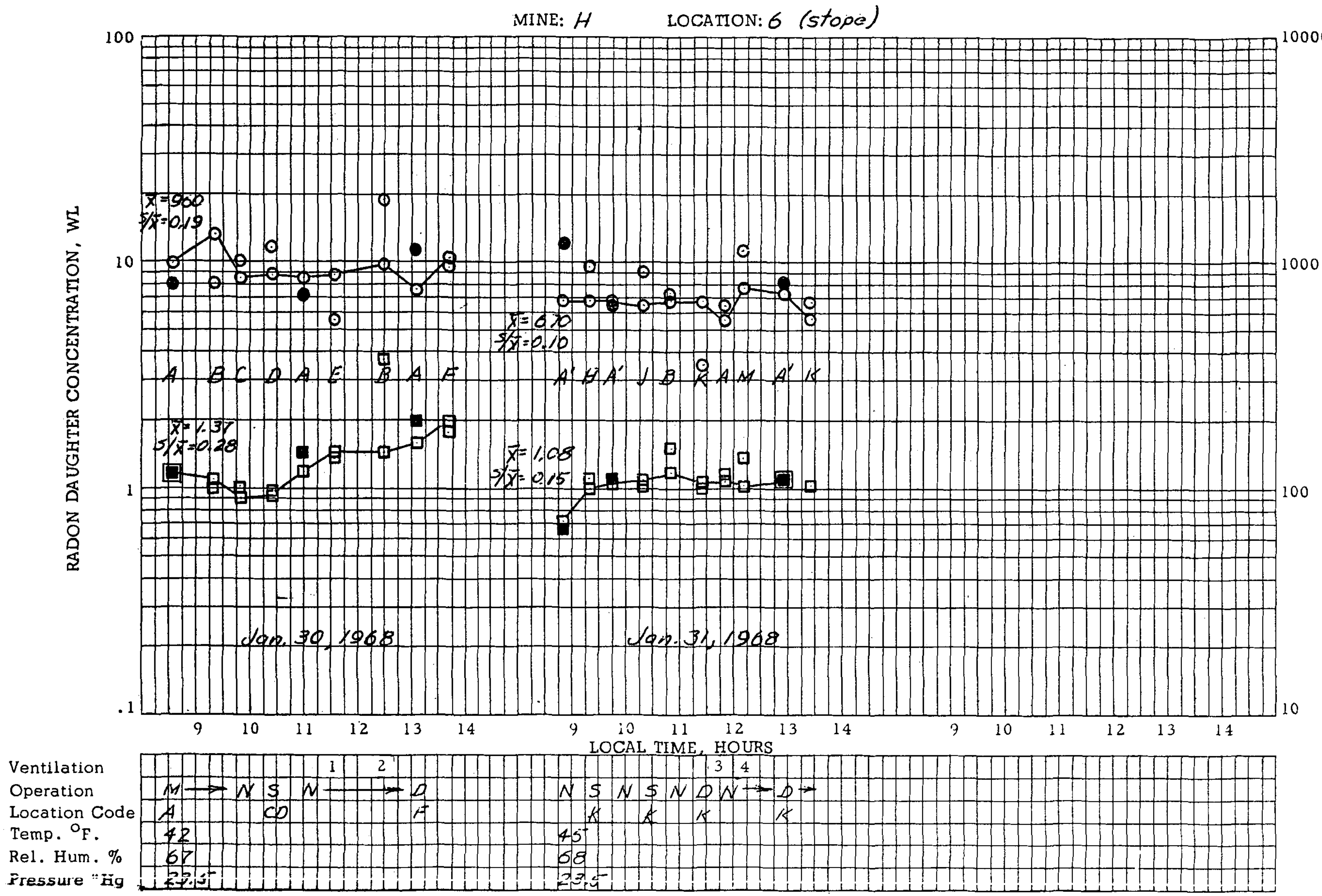


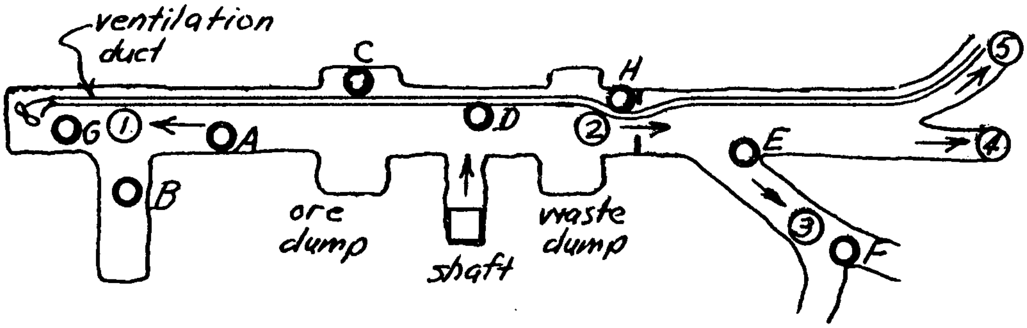
Mine - Location: H - 6, stope
Volume (ft^3): stope 19,000

Flowrate (ft^3/min): at		
	①	3000
	②	2000
	③	2000

Ventilation Notes:

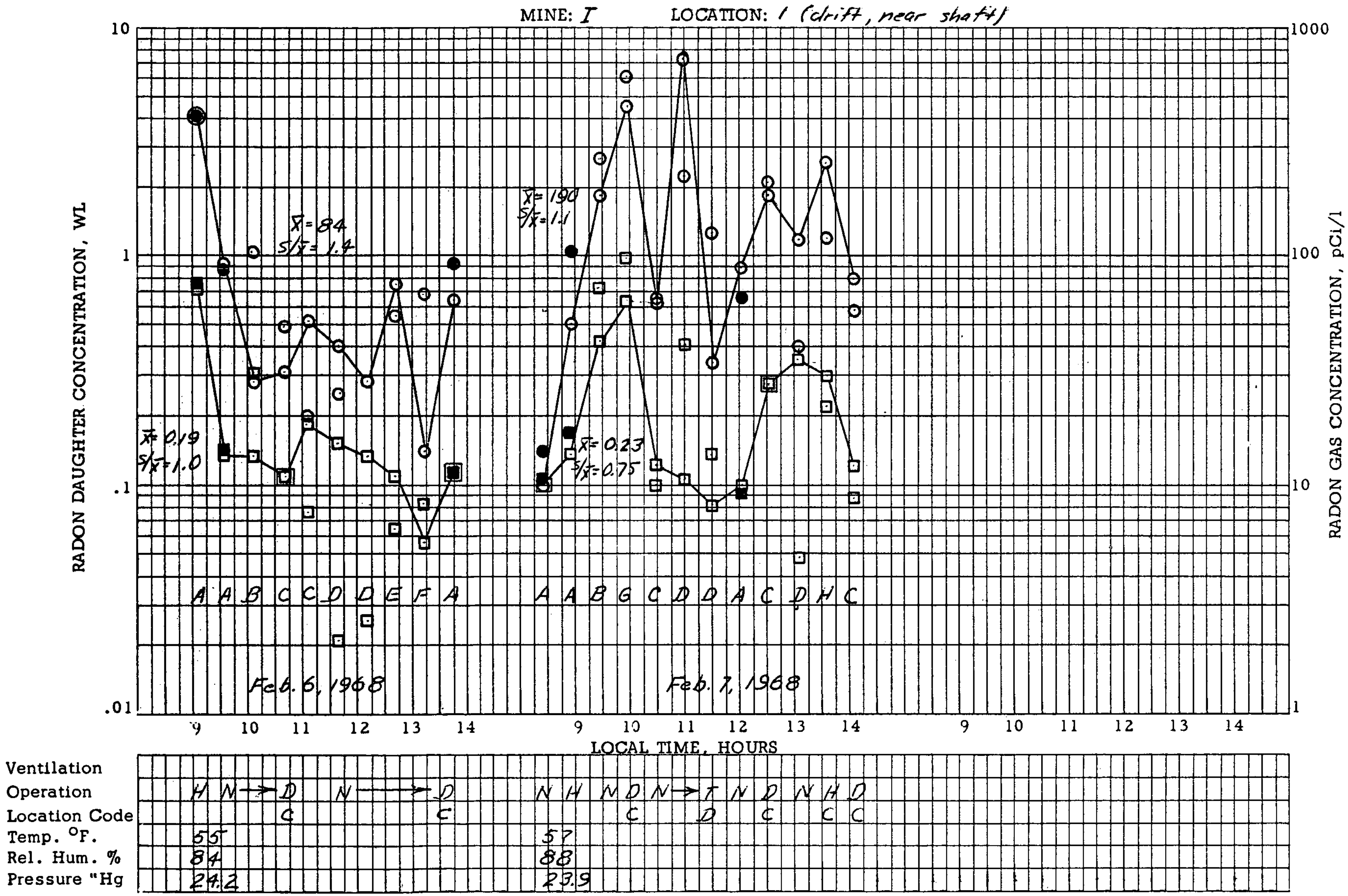
1.	1/30	1135	ventilation off
2.		1230	ventilation on
3.	1/31	1148	ventilation off
4.		1210	ventilation on

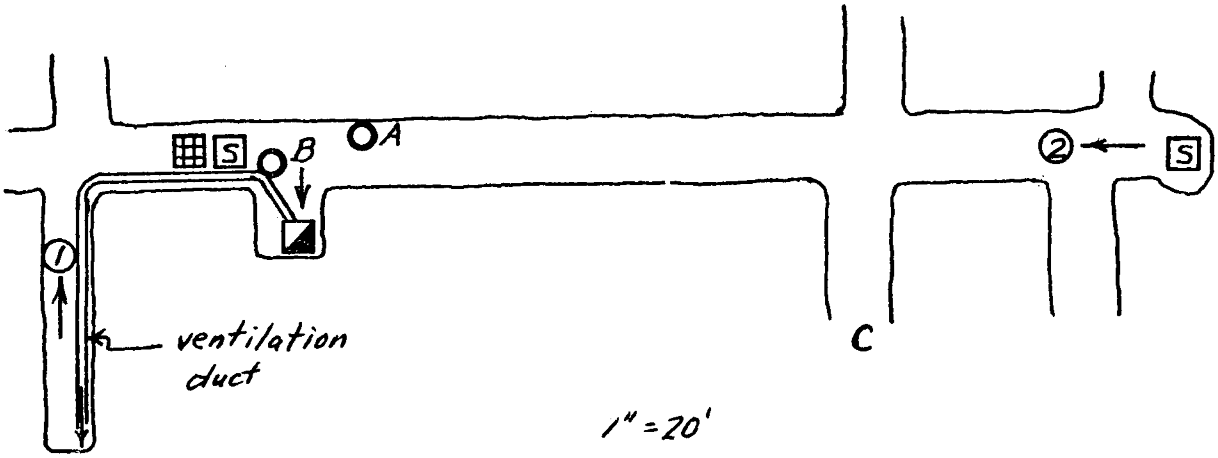

MINE: H LOCATION: 6 (stope)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
$\bar{x}$=9.60
s/$\bar{x}$=0.19
$\bar{x}$=1.37
s/$\bar{x}$=0.28
$\bar{x}$=6.70
s/$\bar{x}$=0.10
$\bar{x}$=1.08
s/$\bar{x}$=0.15
A B C D A E B A F
A' H A' J B K A M A' K
Jan. 30, 1968
Jan. 31, 1968
9 10 11 12 13 14 9 10 11 12 13 14 9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
1 2 3 4
M N S N D N S N S N D N D
A CD F K K K K
42 45
67 68
23.5 23.5



Mine - Location: I - 1, drift, near shaft

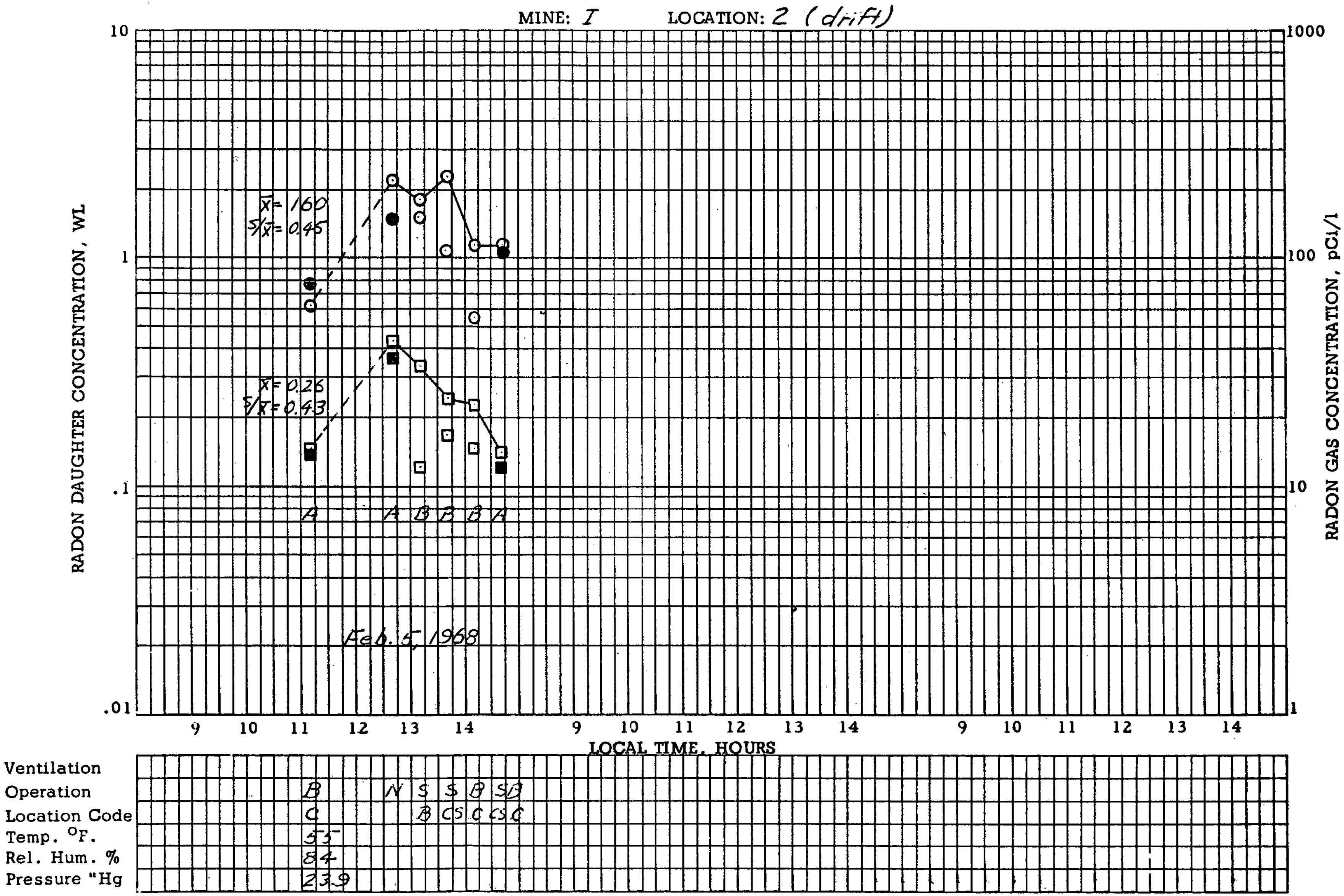
Flowrate (ft^3/min):	at	①	②	③	④	⑤
	2/6	5000	72,000	42,000	10,000	20,000
	2/7	3000	66,000	35,000	9000	22,000


MINE: I
LOCATION: 1 (drift, near shaft)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
10
1
.1
.01
1000
100
10
1
x̄ = 84
s/x̄ = 1.4
x̄ = 0.19
s/x̄ = 1.0
x̄ = 190
s/x̄ = 1.1
x̄ = 0.23
s/x̄ = 0.75
A A B C C D D E F A
A A B G C D D A C D H C
Feb. 6, 1968
Feb. 7, 1968
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
H N → D N → D
C C
N H N D N → T N D N H D
C D C C C
55
84
24.2
57
88
23.9

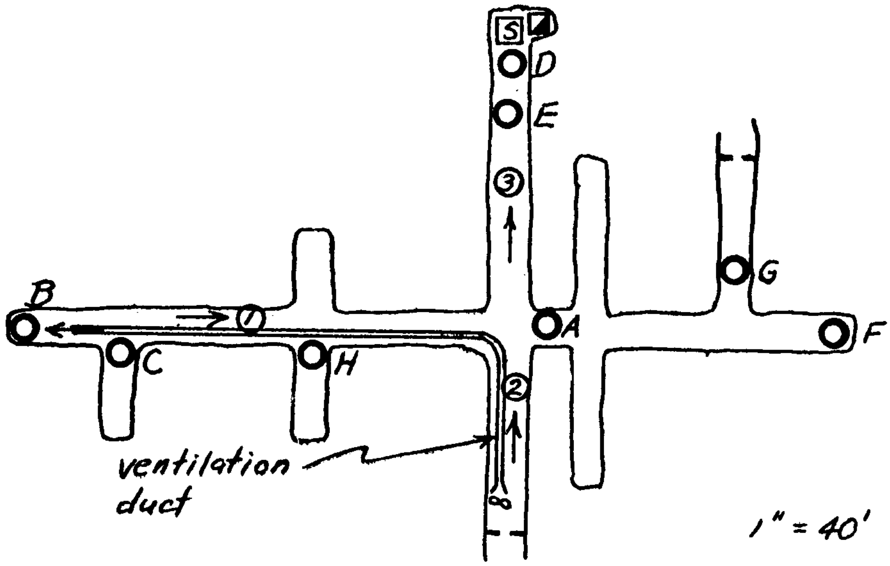


Mine - Location: I - 2, drift

Flowrate (ft^3/min): at ① 3000
② 3000

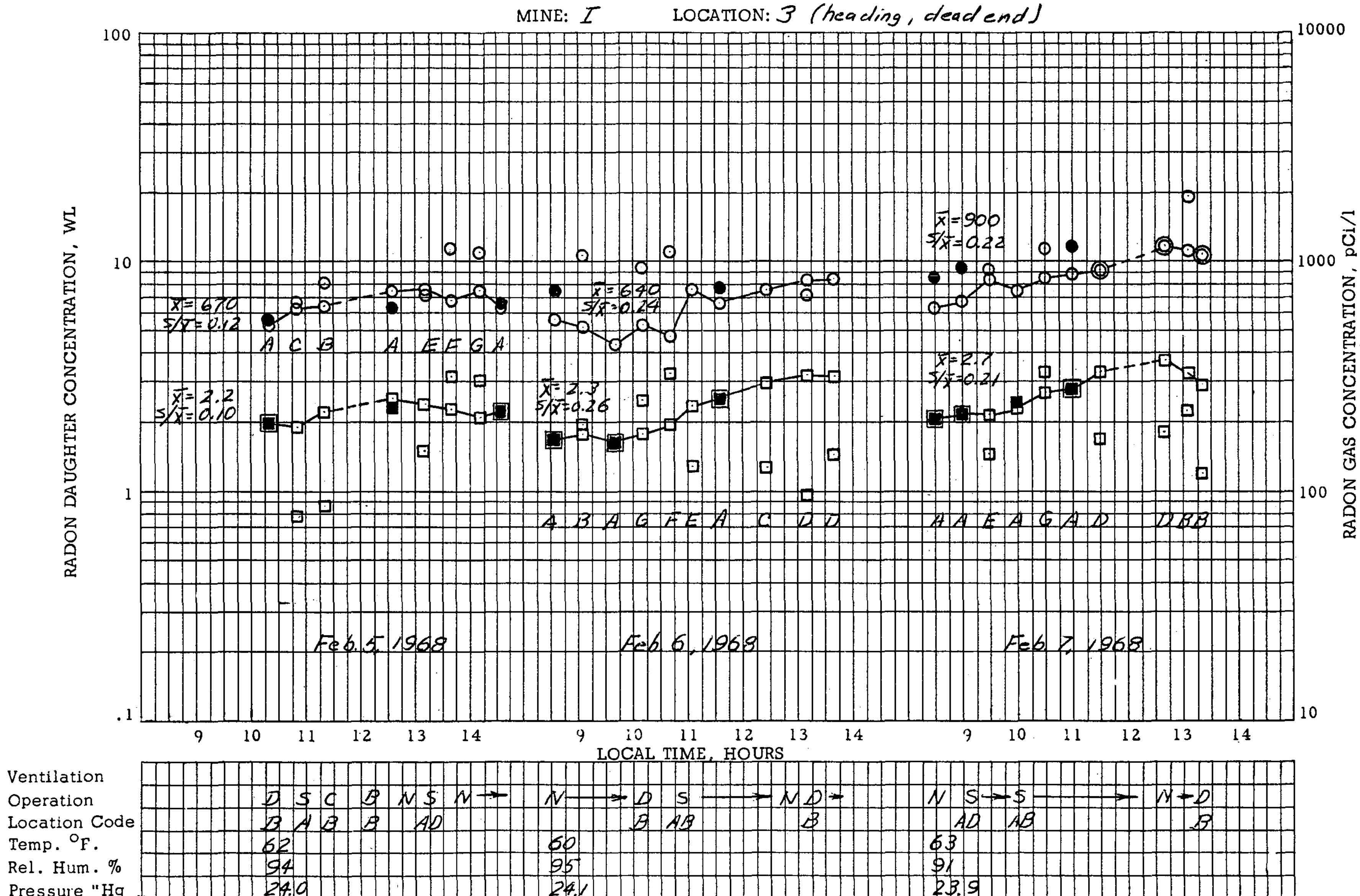


MINE: I
LOCATION: 2 (drift)
10
1
.1
.01
1000
100
10
1
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
x̄ = 1.60
s/x̄ = 0.45
x̄ = 0.26
s/x̄ = 0.43
A A B B B A
Feb. 5, 1968
9 10 11 12 13 14 9 10 11 12 13 14 9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation B N S S B SB
Location Code C B CS C CS C
Temp. °F. 55
Rel. Hum. % 84
Pressure "Hg 23.9

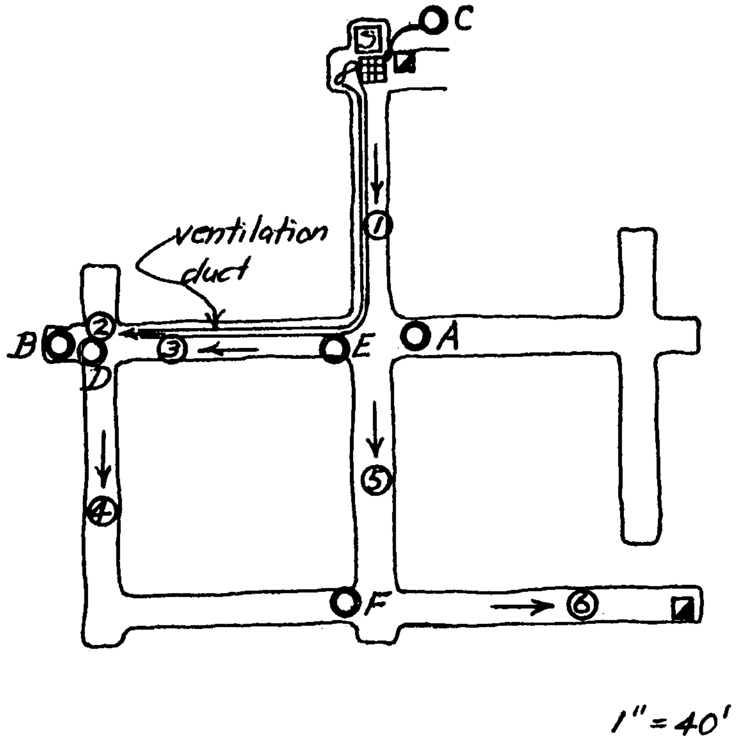


Mine - Location: I - 3, heading, dead end

Flowrate (ft^3/min): at		①	②	③
	2/5	5000	1000	6000
	2/6	5000	2000	7000
	2/7	3000	-	5000



MINE: I
LOCATION: 3 (heading, dead end)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
100
10
1
.1
10000
1000
100
10
x̄ = 670
s/x̄ = 0.12
x̄ = 2.2
s/x̄ = 0.10
x̄ = 640
s/x̄ = 0.24
x̄ = 2.3
s/x̄ = 0.26
x̄ = 900
s/x̄ = 0.22
x̄ = 2.7
s/x̄ = 0.21
A C B A E F G A
A B A G F E A C D D
A A E A G A D D B B
Feb. 5, 1968
Feb. 6, 1968
Feb. 7, 1968
9 10 11 12 13 14
9 10 11 12 13 14
9 10 11 12 13 14
LOCAL TIME, HOURS
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg
D S C B N S N →
N → D S → N D →
N S → S → N → D
B A B B AD
B AB B
AD AB B
62
94
24.0
60
95
24.1
63
91
23.9

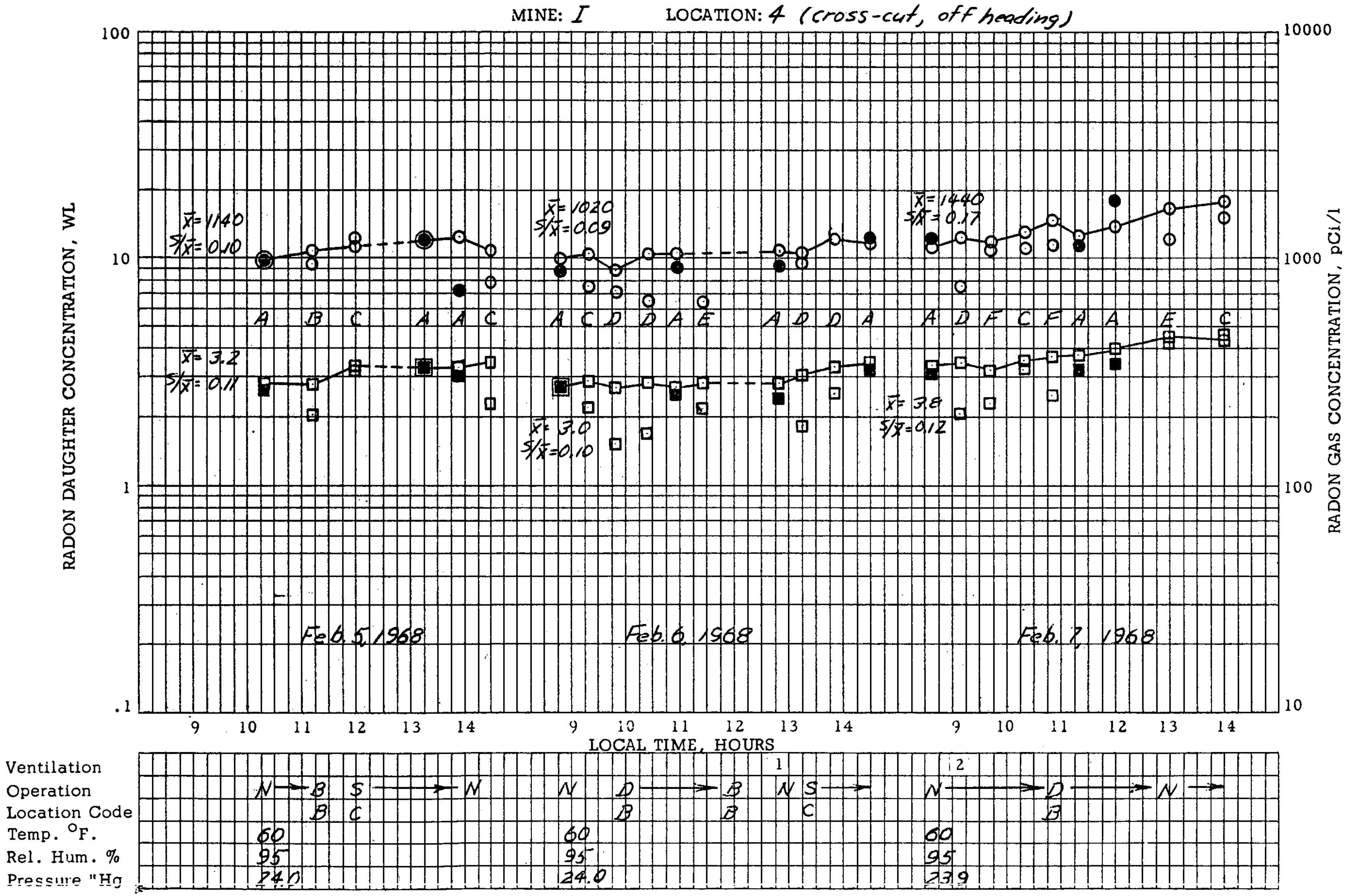


Mine - Location: I - 4, cross-cut, off heading

Flowrate (ft^3/min): at	①	②	③	④	⑤	⑥
2/5	18,000	6000	2000	8000	16,000	26,000
2/6	20,000	-	2000	5000	-	26,000
2/7	20,000	-	1000	5000	-	20,000

Ventilation Notes:

1. 2/6 1248 ventilation off in duct
2. 2/7 0910 ventilation on in duct


MINE: I
LOCATION: 4 (cross-cut, off heading)
RADON DAUGHTER CONCENTRATION, WL
RADON GAS CONCENTRATION, pCi/l
LOCAL TIME, HOURS
Feb. 5, 1968
Feb. 6, 1968
Feb. 7, 1968
Ventilation
Operation
Location Code
Temp. °F.
Rel. Hum. %
Pressure "Hg

APPENDIX B

DAILY AVERAGE RADON DAUGHTER RATIOS

Mine - Location	Ra-A / Rn	s	Ra-B / Rn	s	Ra-C / Rn	s	Ra-B / Ra-A	s	Ra-C / Ra-A	s
A - 1							.41	.087	.24	.084
							.27	.025	.20	.047
							.35	.046	.24	.044
A - 2							.72	.080	.54	.12
							.55	.048	.37	.12
							.62	.12	.42	.14
A - 3							.75	.076	.52	.17
							.62	.17	.38	.15
							.46	.015	.27	.042
B - 1							.63	.19	.49	.16
							.70	.28	.50	.21
B - 2							.65	.13	.47	.16
							.63	.043	.40	.053
							.62	.092	.41	.10
B - 3							.66	.039	.46	.036
							.54	.051	.38	.092
							.60	.061	.43	.071
C - 1							.73	.096	.52	.071
							.60	.035	.50	.082
C - 2							.86	.13	.66	.16
							.75	.12	.55	.15
C - 3							.96	.073	.84	.16
							.75	.14	.51	.15

Mine - Location	Ra-A / Rn	s	Ra-B / Rn	s	Ra-C / Rn	s	Ra-B / Ra-A	s	Ra-C / Ra-A	s
D - 1	.41	.18	.19	.053	.097	.026	.50	.14	.30	.20
D - 2	.69	.21	.39	.082	.23	.051	.57	.095	.35	.091
	.55	.11	.29	.036	.18	.035	.54	.092	.34	.096
	.75	.16	.38	.052	.21	.044	.52	.086	.29	.071
D - 3	.78	.12	.47	.11	.28	.085	.62	.12	.38	.14
D - 4	.31	.084	.093	.017	.055	.017	.31	.061	.19	.086
	.39	.089	.21	.029	.14	.026	.56	.075	.35	.067
	.37	.10	.18	.044	.11	.043	.51	.11	.31	.12
E - 1	.51	.16	.28	.033	.17	.032	.57	.16	.38	.19
	.64	.10	.30	.022	.16	.033	.48	.075	.26	.067
	.57	.082	.35	.026	.20	.026	.63	.13	.36	.097
E - 3	.40	.23	.13	.080	.069	.032	.35	.054	.20	.073
	.62	.17	.23	.12	.13	.12	.38	.22	.23	.25
	.63	.16	.23	.08	.12	.073	.37	.10	.20	.11
F - 1	.43	.099	.29	.053	.18	.017	.76	.11	.51	.11
F - 2	.54	.059	.29	.047	.17	.039	.54	.089	.32	.079
F - 3	.73	.31	.58	.082	.42	.085	.80	.14	.53	.11
	.98	.23	.73	.16	.49	.11	.75	.092	.51	.067
F - 4	.77	.16	.59	.096	.41	.11	.79	.20	.56	.21
F - 5	.27	.17	.23	.15	.22	.16	.65	.30	.50	.35
	.42	.27	.26	.13	.24	.10	.53	.22	.48	.29

Mine - Location	Ra-A Rn	s	Ra-B Rn	s	Ra-C Rn	s	Ra-B / Ra-A	s	Ra-C / Ra-A	s
F - 6	.47	.14	.21	.047	.13	.034	.43	.11	.26	.10
	.40	.22	.23	.085	.18	.052	.63	.17	.45	.18
F - 7	.39	.13	.25	.031	.18	.043	.70	.15	.51	.18
G - 1	.51	.091	.22	.040	.12	.040	.44	.081	.25	.090
	.53	.093	.28	.046	.16	.042	.54	.11	.32	.13
	.57	.066	.28	.069	.16	.048	.49	.11	.29	.082
G - 2	.74	.19	.25	.079	.11	.039	.34	.040	.15	.037
	.68	.062	.26	.048	.11	.028	.37	.047	.17	.033
	.56	.047	.25	.064	.10	.030	.45	.11	.18	.060
G - 3	.56	.087	.24	.048	.11	.032	.43	.072	.20	.056
	.52	.065	.26	.049	.11	.031	.49	.094	.22	.068
G - 4	.51	.14	.30	.076	.15	.033	.56	.08	.28	.08
H - 1	.27	.099	.091	.052	.038	.022	.32	.087	.13	.045
	.30	.049	.13	.019	.065	.017	.43	.060	.22	.057
H - 2	.32	.084	.13	.035	.077	.017	.41	.063	.25	.058
	.32	.067	.11	.020	.056	.017	.34	.061	.18	.065
H - 3	.36	.11	.70	.04	.11	.038	.55	.16	.31	.15
	.47	.15	.19	.052	.083	.023	.41	.074	.19	.051
	.30	.077	.20	.028	.14	.034	.71	.18	.49	.18
H - 4	.62	.087	.16	.035	.066	.015	.25	.034	.11	.025
	.61	.11	.18	.038	.064	.014	.29	.027	.11	.029

Mine - Location	Ra-A / Rn	s	Ra-B / Rn	s	Ra-C / Rn	s	Ra-B / Ra-A	s	Ra-C / Ra-A	s
H - 5	.48	.046	.25	.045	.13	.033	.50	.068	.27	.061
H - 6	.39	.13	.15	.063	.087	.041	.37	.081	.19	.052
	.48	.11	.16	.035	.090	.018	.32	.046	.19	.042
I - 1	.74	.30	.33	.16	.20	.16	.48	.21	.34	.30
	.49	.20	.17	.085	.11	.088	.35	.15	.22	.17
I - 2	.48	.23	.18	.056	.094	.043	.45	.22	.26	.21
I - 3	.60	.085	.38	.038	.22	.028	.63	.040	.37	.065
	.67	.11	.41	.047	.24	.028	.62	.056	.36	.075
	.58	.064	.34	.037	.20	.036	.59	.053	.35	.075
I - 4	.47	.092	.31	.041	.19	.014	.68	.066	.43	.094
	.48	.29	.33	.094	.24	.095	.62	.09	.40	.09
	.45	.071	.29	.022	.19	.016	.67	.075	.43	.051

APPENDIX C

ORE DUST CONCENTRATIONS

Mine - Location	Date	Concentration α dpm
A - 1	9/26	22
	9/27	18
		28
A - 2	9/26	0.2
		5.3
	9/27	2.5
		8.5
	9/28	7.7
A - 3	9/26	8.7
		7.7
	9/27	11
		8.4
	9/28	7.0
B - 1	9/29	3.8
		2.5
	9/30	1.1
	10/2	1.1
B - 2	9/29	1.4
		24
		0.8
	9/30	4.5
		2.5
	10/2	0.2
		1.4
		6.0
B - 3	9/29	5.7
		14
		4.1
	9/30	3.6
		1.1
	10/2	2.5
		6.3

Mine - Location	Date	Concentration α dpm
C - 1	10/3	1.4
		1.7
	10/4	2.0
		0.9
		2.4
C - 2	10/3	2.7
		1.0
	10/4	0.05
		1.7
C - 3	10/3	6.2
		3.6
	10/4	2.9
D - 1	11/2	1040
D - 2	11/4	8.2
D - 3	11/3	19
	11/4	17
D - 4	11/2	18
	11/3	23
	11/4	73
E - 1	11/6	26
	11/7	19
	11/8	24
E - 2	11/6	15
	11/7	14
	11/8	21
E - 3	11/6	8.4
	11/8	7.6

Mine - Location	Date	Concentration α dpm
F - 1	11/13	6.8
	11/15	17
F - 2	11/10	5.8
	11/14	21
F - 3	11/13	8.0
F - 4	11/14	5.6
F - 5	11/14	4.6
		5.0
F - 6	11/13	1.6
F - 7	11/15	5.2
G - 1	1/24	3.5
	1/25	2.3
	1/26	1.1
G - 2	1/24	1.0
	1/25	1.7
	1/26	2.4
G - 3	1/24	1.9
		9.6
	1/25	2.6
G - 4	1/26	6.3
H - 1	2/1	5.4
	2/2	2.8
H - 2	1/30	8.1
	1/31	17
H - 3	1/30	14
	1/31	15
	2/1	4.6

Mine - Location	Date	Concentration α dpm
H - 4	2/1	0.7
	2/2	1.4
I - 1	2/6	1.2
	2/7	4.8
I - 2	2/5	3.6
I - 3	2/5	0.7
	2/6	0.9
	2/7	1.4
I - 4	2/5	2.0
	2/6	2.6