VENTILATION SYSTEM PERFORMANCE

11th AIVC Conference, Belgirate, Italy
18-21 September, 1990

Paper 42

ERRORS IN THE MEASUREMENT OF LOCAL AND ROOM MEAN AGE USING TRACER GAS METHODS.

H.C. Sutcliffe, J.R. Waters

Coventry Polytechnic
U.K.

ERRORS IN THE MEASUREMENT OF LOCAL AND ROOM MEAN AGE USING TRACER GAS METHODS

H.C. SUTCLIFFE and J.R.WATERS

Coventry Polytechnic, U.K.

SYNOPSIS

Local and room mean ages of the air in a room may be measured by three versions of the tracer gas technique; which are the pulse method, the tracer step-up up method and the tracer decay method. The values of mean age obtained are of course subject to errors in the measurement of the tracer gas concentrations. The sensitivity of the three methods to errors in the tracer gas concentration is not the same, and in some cases can be very large. In order to examine this problem, test measurements have been carried out in a model room using the three different methods. The results obtained from these tests were then compared with each other, and with theoretical data, which was generated with differing levels of error. It has been found that the step-up method was the least reliable and local and room mean ages generated using this method varied substantially from mean ages measured using the other two tracer gas techniques.

1. INTRODUCTION AND OBJECTIVES

Local mean age, room mean age, and air change efficiency are now well established concepts in the assessment of ventilation systems. They are particularly useful in measuring the distribution of fresh air in ventilated rooms. The concepts themselves are normally defined for a mechanically ventilated room with one inlet and one exhaust duct (see, for example, Sutcliffe [1]). Nevertheless the definitions are such that all three concepts are independent of the means by which air enters and leaves the room. Thus, mechanical ventilation, natural ventilation, partial mechanical ventilation, and uncontrolled infiltration and exfiltration can all be included. However, the measurement of room mean age is most easily accomplished when there is only one inlet and one exhaust duct, and becomes progressively more difficult as the number of inlet and exhaust openings increases. Measurement is most difficult where the exhaust routes are not clearly defined. The most usual methods of measurement are by use of tracer gases in pulse, step-up or decay modes [1]. All three methods may be used where there is only one inlet and one exhaust, and where there is one inlet and several clearly defined exhausts. Where there are multiple inlets and multiple exhausts, it is still possible in principle to use all three methods, thought in practice only the decay method may be reliable. When there is a significant amount of infiltration and exfiltration, then only the decay method is feasible, and when exfiltration is present, only the local mean age can be measured.

The present study arose from an interest in measuring local mean age in industrial buildings. Ventilation in such buildings is often an arbitrary mixture of natural and mechanical ventilation, with a high proportion of uncontrolled air movement through doors, roof vents and leakage paths. Hence, in most cases, only the decay method would be valid. In order to determine the reliability of the decay method, a series of measurements were carried out in a mechanically ventilated model room. The local mean age and the room mean age were measured by all three tracer gas methods, and the measurements repeated several times at each of three ventilation rates. The objective was to compare the results obtained by the three methods and also to determine the repeatability of the measurements. Some calculations were also carried out using simulated data with varying degrees of random error.

2. THE MODEL AND THE MEASUREMENT PROCEDURE

The model consisted of a sealed wooden box of internal volume $0.96m^3$ with one inlet and one exhaust duct, and a variable speed fan in the inlet duct. Six points were sampled, one close to the inlet, one at the exhaust, and the other four distributed within the model as shown in figure 1.

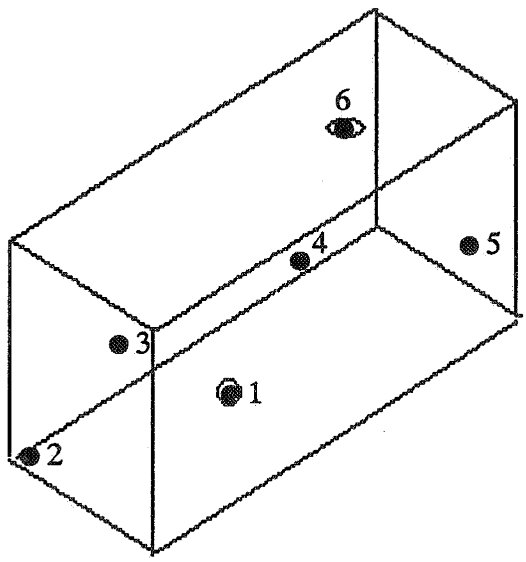

Figure 1. Positions of measurement points within the model

The tracer gas was sulphur hexafluoride, and tracer gas concentrations were measured by means of an on-line ECD chromatograph sampling at the rate of 1 sample per minute on all channels. For pulse tests, tracer gas was premixed with air to a convenient concentration and then injected by syringe into the inlet duct. For decay tests tracer gas was injected into the model, and brought to a uniform concentration by means of an internal fan, which was then switched off. For step-up tests, a mixture of sulphur hexafluoride in air was introduced into the inlet duct from a commercially supplied cylinder via control valves and regulators. The variable speed fan in the inlet duct had three speed settings, giving rise to three ventilation rates. These ventilation rates were measured by tracer decay tests with the internal mixing fan switched on, giving the results shown in table 1.

Table 1. Model Ventilation Rates

Fan Speed Setting	Air Flow Rate (l/min)	Air Change Rate (ach)	Nominal Time Constant (mins)
1	16.41	1.03	58.50
2	35.07	2.19	27.37
3	41.05	2.57	23.39

Pulse, decay and step up tests were typically continued for a period of 90 minutes, which included five or six minutes of measurement of the starting conditions. Thus each test typically produced 85 useful measurements of tracer gas concentration on each channel. Generally this ensured that the measurement period was comfortably in excess of one time constant, and that the measured tracer gas concentrations covered a range in excess of one decade.

3. ANALYSIS OF RESULTS

The local mean age, $\bar{\tau}_p$, was calculated using the usual equations, that is :-

1 Pulse method $$\bar{\tau}_p = \frac{\int_0^\infty t.C_p(t)\,dt}{\int_0^\infty C_p(t)\,dt}$$

2 Step-up method $$\bar{\tau}_p = \int_0^\infty \left(1 - \frac{C_p(t)}{C_s}\right) dt$$

3 Decay method $$\bar{\tau}_p = \int_0^\infty \frac{C_p(t)}{C(o)}\,dt$$

Similarly, for room mean age, $<\bar{\tau}>$, the equations used were :-

1. Pulse method $$<\bar{\tau}> = \frac{Q}{2V}\frac{\int_0^\infty t^2 C_e(t)\,dt}{\int_0^\infty C_e(t)\,dt}$$

2. Step-up method $$<\bar{\tau}> = \frac{Q}{V}\int_0^\infty t\left(1 - \frac{C_e(t)}{C_s}\right) dt$$

3. Decay method $$<\bar{\tau}> = \frac{Q}{V}\int_0^\infty t\frac{C_e(t)}{C(o)}\,dt$$

The integrals were evaluated in two parts. The first part was found directly from the data set by summation up to and including the final reading. The remaining, unmeasured, part of the integral was treated as an end correction and evaluated on the assumption that the remainder of the time evolution of concentration followed a single exponential law with decay constant, The value of λ was determined separately for each curve by first examining the plot of the natural logarithm of concentration (or (C_s - C(t)) in the case of step-up) versus time, determining visually the time at which the plot became essentially a straight line, and then performing a least squares fit on the relevant data points to find the gradient. If t_f is the time of the final measured data point, and $C(t_f)$ the concentration value, the end corrections are then as follows :

$$\int_{t_f}^{\infty} C(t)\,dt = \frac{C(t_f)}{\lambda}$$

$$\int_{t_f}^{\infty} t.C(t)\,dt = \frac{C(t_f)}{\lambda}\left(t_f + \frac{1}{\lambda}\right)$$

$$\int_{t_f}^{\infty} t^2.C(t)\,dt = \frac{C(t_f)}{\lambda}\left(t_f^2 + \frac{2t_f}{\lambda} + \frac{2}{\lambda^2}\right)$$

Clearly the magnitudes of the end corrections are large whenever the decay constant is small, and when this is the case, errors in determining λ from the gradient of the log plot are likely to be large. In the case of the step-up test, $C(t_f)$ is replaced by $(C_s - C_p(t_f))$ and since both C_s and $C_p(t_f)$ are subject to error, the error in their difference could become highly significant, contributing even more to the error in the end correction. Thus the end correction may not only be large, but it may also be subject to a large error.

4. RESULTS OF MEASUREMENTS

Table 2 is a complete summary of the results of the measurements of local mean age.

Table 2. EXPERIMENTAL DATA, Local Mean Ages (Mins)

Method	No of Tests	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
				Fan Speed 1			
Pulse	4	91.0± 9.6	74.1± 6.8	82.5±10.6	92.9± 3.3	77.6± 4.1	76.7±12.9
StepUp89	3	18.3±10.5	59.3±26.2	51.2±11.5	91.5±24.8	46.9± 4.7	78.3±12.3
StepUp90	8	0.0± 0.0	71.8±16.9	75.3±14.3	85.6+10.4	70.8± 8.6	74.7± 5.9
Decay	5	84.8±10.2	80.7± 3.6	93.5± 8.3	93.4± 4.5	92.9± 9.3	95.0± 6.3
				Fan Speed 2			
Pulse	3	29.9± 6.9	36.9± 1.7	34.3± 3.2	52.0± 2.3	31.1± 2.6	26.4± 1.8
StepUp89	3	63.4±25.8	29.6±13.7	32.7± 9.2	59.4±10.3	33.3± .1	63.9±11.4
StepUp90	5	0.0± 0.0	28.7± 3.4	37.2± 2.4	42.5± 3.5	32.3± 4.5	33.0± 2.1
Decay	6	29.6± 3.3	28.9± 2.1	30.9± 3.1	34.1± 3.9	35.0± 6.1	33.7± 3.3
				Fan Speed 3			
Pulse	3	31.8± 1.5	52.2±13.2	39.0± 4.7	54.8± 4.4	30.1± 2.2	29.9± 2.2
StepUp89	4	28.6±25.2	19.2± 3.1	29.6± 5.3	58.5±11.8	30.9± 1.9	60.1± 8.5
StepUp90	5	0.0± 0.0	42.0± 9.8	45.1± 6.3	53.7± 6.6	34.4± 7.5	30.3± 9.1
Decay	4	32.8± 4.1	33.3± 6.0	41.0±10.4	43.3±10.0	40.5± 7.5	37.6± 6.1

Each result is the average of the number of tests indicated, and the standard deviation is also given. The results for step-up tests are given in two separate sets because a number of improvements to the experimental technique were introduced for the second (Stepup 90) set. These were introduced because it was observed that the results for the first set (Stepup 89) were often inconsistent, as shown by large values of the standard deviation, and by some large discrepancies with respect to the pulse and decay methods. Three improvements were introduced, all three aimed at improving the stability and mixing of the tracer gas in the inlet duct. These improvements were :

1. The introduction of a high quality flow controller in the tracer gas inlet stream, with a claimed control capability of 1 part in 5000;

2. The introduction of a flow straightener immediately downstream of the fan in order to stabilise the flow in the inlet duct;

3. A six port injection device to distribute the injected tracer uniformly across the inlet duct according to the probable velocity profile in the duct.

It can be seen that these improvements reduced the standard deviations of the step-up test, and brought the local mean ages more into line with those obtained by the pulse and decay methods. Figures 2, 3 and 4 show the same information as table 2, and the inconsistencies of the first set of step-up tests are clear. Channel 1 was found to be difficult to analyse because its proximity to the inlet duct made it sensitive to turbulence in this region, so that the recorded tracer gas concentration did not follow a smooth curve. Hence results for channel 1 are particularly unreliable, and indeed for the second set of step-up tests channel 1 was not analysed.

Table 3 is a complete summary of the results for room mean age. These results are plotted in figure 5, and the inconsistency of the first set of step-up tests is even more marked.

Table 3. EXPERIMENTAL DATA, Room Mean Ages (Mins)

Method	No of Tests	Fan1	No of Tests	Fan2	No of Tests	Fan3
Pulse	4	72.3±18.9	3	19.0± 1.9	3	23.5± 3.7
StepUp89	3	119.3±23.8	3	119.4±23.8	4	191.4±43.0
StepUp90	8	60.4± 9.1	5	25.0± 3.6	5	34.8±14.6
Decay	5	95.2± 6.6	6	32.3± 3.3	4	38.9± 9.0

5. RESULTS OF SIMULATIONS

In order to explore the effect of random error in the measured tracer gas concentrations, sets of simulated data with different levels of error were prepared. Unfortunately, it is not easy to produce theoretically exact tracer gas curves which match those produced experimentally in the model. Hence the simulations were carried out for the case when the air in the model is fully mixed, in which case the equation for the curve at each point is the same, and follows a simple exponential law. Also the pulse and decay methods produce identical results. The air flow rate was chosen to give a nominal time constant of 33.3 minutes, approximately equivalent to fan speed 2 of the experimental data set. Error was introduced into the data by means of a random error generator with a normal distribution and with a standard deviation set to a fixed percentage of the maximum value in the data set. Results were obtained for 1%, 2%, 5% and 10% levels of error, and four sets of data were generated for each level of error, corresponding to four independent tests. The results were analysed in exactly the same way as the experimental results. Table 4 is a summary of the results for local mean age, and Table 5 a summary for room mean age.

Table 4. SIMULATED DATA, Local Mean Ages (Mins)

% Error	No of Tests	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
				Step-Up Tests			
1	4	34.6± .3	34.5± .3	34.1± .3	34.4± .2	34.2± .3	34.3± .5
2	4	33.9± .7	34.1± .9	34.2± .3	34.6± .5	35.0± .4	35.0± .5
5	4	34.2± .5	33.9±1.5	33.2±1.2	36.2+1.6	32.7±1.3	33.4±1.3
10	4	32.9±2.2	35.7±3.9	33.4±2.9	35.6±5.0	35.4±4.0	35.9±3.9
				Decay Tests			
1	4	33.4± .2	33.7± .3	33.2± .5	33.2± .4	33.8± .4	33.2± .3
2	4	33.5± .8	33.4± .9	34.0± .8	33.1± .8	33.7±1.1	33.1± .5
5	4	33.6± .9	32.6±1.1	32.0±1.3	32.8±1.8	33.9± .9	33.8±1.0
10	4	31.7±2.7	37.0± .2	31.6±1.4	30.6±1.1	36.3±5.0	32.7±1.8

Table 5. SIMULATED DATA, Room Mean Ages (Mins)

Percentage Error	No of Tests	Step-Up Tests	Decay Tests
1	4	34.2± 1.6	32.8± .5
2	4	36.7± 1.6	33.2± .6
5	4	32.7± 4.3	35.1± 1.7
10	4	43.4±13.6	29.8± 1.9

As an illustration, the results for local mean age for Channel 5 are plotted in figure 6, and the results for room mean age in figure 7. Overall the standard deviations appear to be lower for the results obtained from decay tests. Also, because in a fully mixed room all channels should give the same result, all the local mean age results can be combined, giving a global mean and standard deviation over 24 independent tests at each error level for both step-up and decay tests. These results are shown in table 6.

Table 6. SIMULATED DATA, Global Local Mean Ages (Mins)

Percentage Error	No of Tests	Step-Up Tests	Decay Tests
1	24	34.3± .4	33.4± .4
2	24	34.5± .7	33.5± .9
5	24	33.9±1.7	33.1±1.4
10	24	34.8±3.9	33.3±3.5

When evaluating the simulated data for the step-up tests, it was assumed at first that the value of the tracer gas concentration in the inlet duct, Cs, which is also the asymptotic value C (infinity) within the room, is known exactly (a value of 200 vpb was used). The effect of an error in this assumption was also explored, by re-calculating with different values of C (infinity). These results are shown in table 7 for local mean age, in which the global for 24 tests is shown. Table 8 gives room mean age for four sets of results

Table 7. SIMULATED DATA, Local Mean Ages (Mins)
Step-Up Tests, Effect of Error in C(infinity)

	Error on data				
C(inf)	0%	1%	2%	5%	10%
180	25.3±0.0	26.3± .2	26.5± .5	27.2±1.4	29.4±2.3
190	29.2±0.0	30.2± .3	30.3± .6	30.4±1.4	31.5±2.6
200	33.4±0.0	34.3± .4	34.5± .7	33.9±1.7	34.8±3.8
210	37.7±0.0	38.6± .4	38.8± .8	38.0±2.2	38.8±4.2
220	42.1±0.0	43.0± .5	43.2± .9	42.4±2.4	42.0±5.0

Table 8. SIMULATED DATA, Room Mean Ages (Mins)
Step-Up Tests, Effect of Error in C(infinity)

	Error on data				
C(inf)	0%	1%	2%	5%	10%
180	27.2± 0.0	29.6± .6	31.2± 1.4	28.5± 2.6	34.7± 4.7
190	29.5± 0.0	30.5± 1.5	32.9± 1.4	32.3± 2.2	40.7± 5.9
200	33.4± 0.0	34.2± 1.6	36.6± 1.5	32.6± 4.2	42.5±13.1
210	37.7± 0.0	38.5± 1.7	40.8± 1.6	36.5± 3.9	46.3±13.9
220	42.2± 0.0	42.9± 1.7	45.2± 1.6	40.8± 3.7	52.3±14.4

6. DISCUSSION

It must first be pointed out that the visual appearance of the tracer gas concentration versus time graphs, whether they originated from measured or simulated data, gave little indication of the likely quality of the results obtained from them. The graphs themselves, and the results, would always appear plausible. The exploration of the effect of error is therefore of some importance. Although limited to the case of a fully mixed room, the results from the simulated data show several interesting features. These are :

1. As errors in the data increase, step-up tests become less reliable than decay test.
2. The un-reliability of the step-up tests becomes more pronounced when the error in C (infinity) is also included.

3. Step-up tests are only marginally worse than decay tests when evaluating local mean ages, but are much worse when evaluating room mean age.

It is difficult to draw similarly precise conclusions from the results of the experimental data because at least some of the variability is due to turbulence in the model as well as small differences in experimental conditions between tests. Nevertheless, the results tend to support the conclusions drawn from the simulated data. The poor results of the first set of step-up tests confirm the importance of accurate control and measurement of the tracer concentration in the inlet duct. Comparison of the second set of step-up tests with the pulse and decay tests shows again that when measuring local mean age, step-up is marginally worse than the other methods, but when measuring room mean age, step-up is much worse.

The poor performance of step-up tests that have been found here may be partly explained by the difficulty in estimating the end correction. Even though tracer gas measurements were continued well beyond one time constant, the end correction was often of similar order of magnitude to the principal measurement of area. This is illustrated in table 9.

Table 9. Average size of end correction expressed as a Percentage of the Measured Area

Method	No of Tests	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
				Fan Speed 1			
Pulse	4	62.3	45.0	54.5	64.7	48.6	48.0
StepUp89	3	49.5	74.4	49.8	115.5	25.1	92.0
StepUp90	8	0.0	128.8	52.8	58.0	43.0	59.5
Decay	5	79.4	67.2	73.0	72.6	74.4	78.3
				Fan Speed 2			
Pulse	3	8.9	11.6	9.2	19.5	8.0	6.0
StepUp89	3	273.1	26.1	10.5	43.5	5.3	103.3
StepUp90	5	0.0	37.3	27.6	21.6	13.2	24.0
Decay	6	9.1	8.2	8.8	9.3	7.8	8.7
				Fan Speed 3			
Pulse	3	10.8	25.2	13.9	23.8	8.7	9.1
StepUp89	4	162.8	6.5	7.3	62.5	3.4	93.0
StepUp90	5	0.0	23.4	21.1	19.8	16.2	45.1
Decay	4	23.0	18.0	25.4	25.2	20.3	21.0

7. CONCLUSIONS

The original objective was to determine whether or not the decay method is more or less reliable than other methods in determining local and room mean ages. The results suggest that the decay method may be slightly better than the pulse and step-up techniques and it was found to be the easiest method to use from a practical point of view. It was also discovered that the step-up method can give rise to large errors, due to uncertainties in the value of C (infinity) and the effect that the end corrections can have upon the final answers. These errors were especially predominant in the measurement of the room mean age. measurement of room mean age.

8. REFERENCES

1. Sutcliffe, H.C. : "A Guide to Air Change Efficiency", AIVC, Technical Note 28, February 1990.

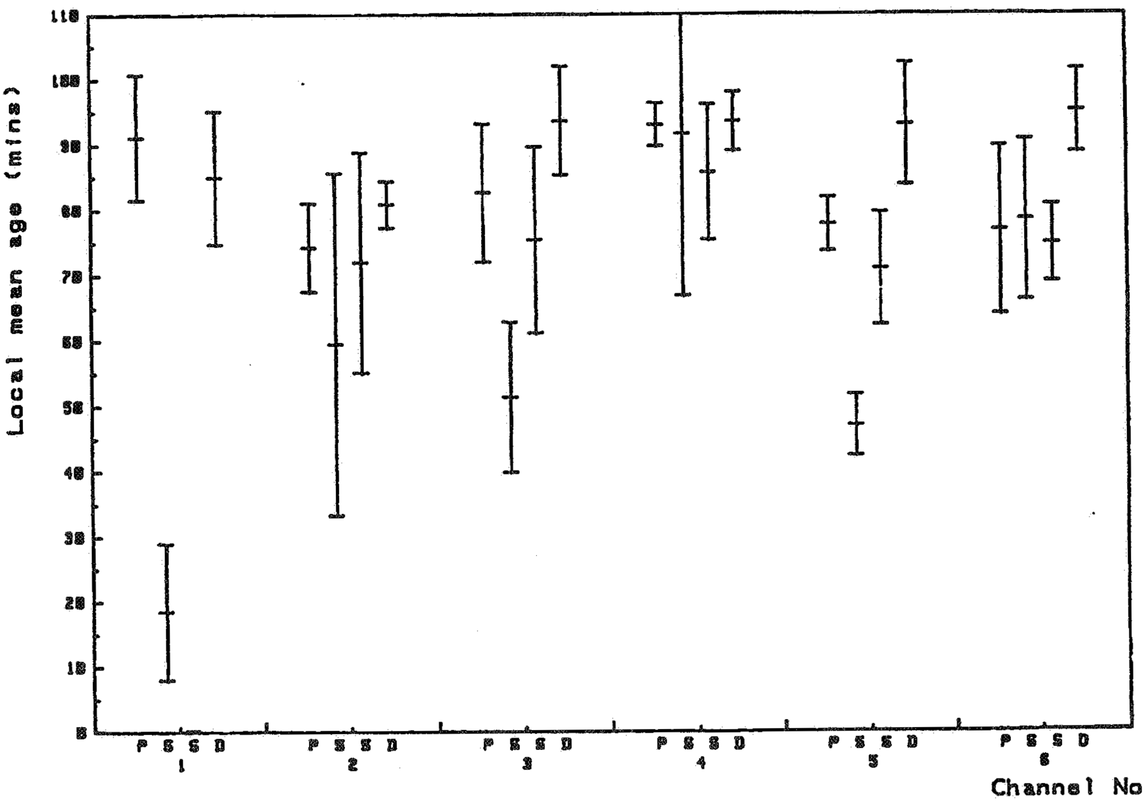

Figure 2. Local mean ages(mins), Fan Speed 1

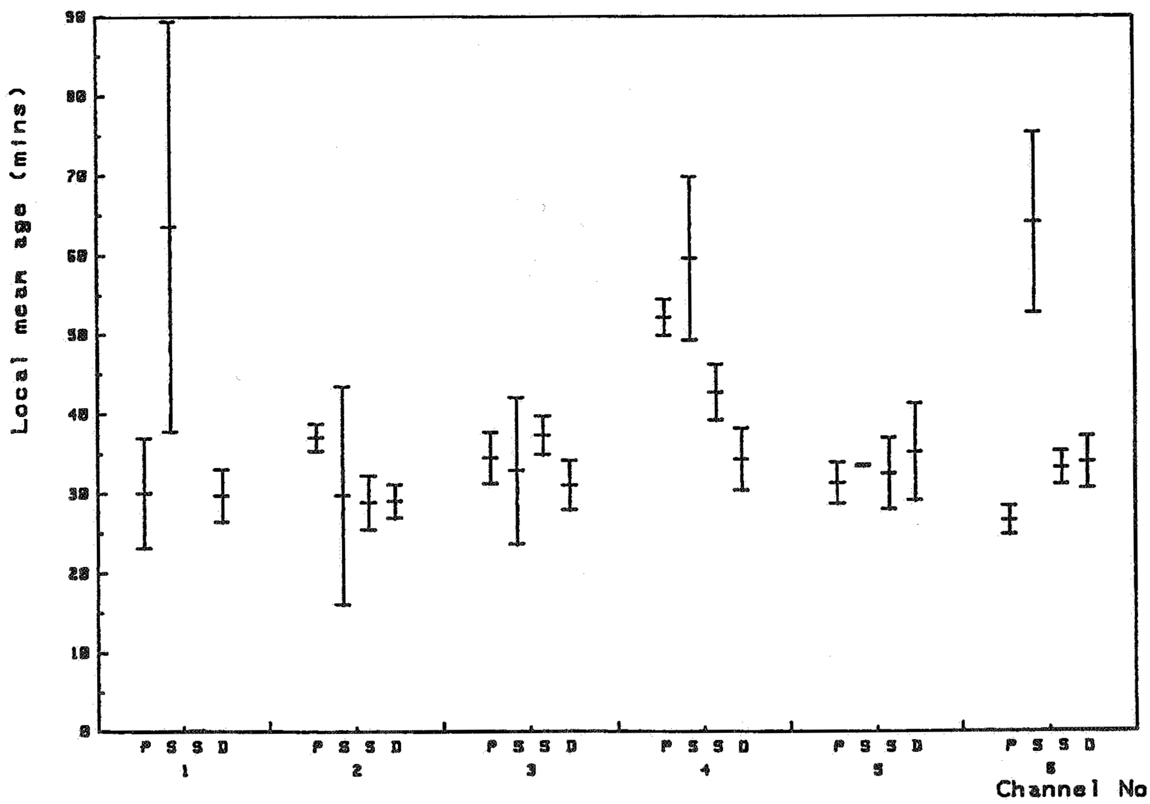

Figure 3. Local mean ages(mins), Fan Speed 2

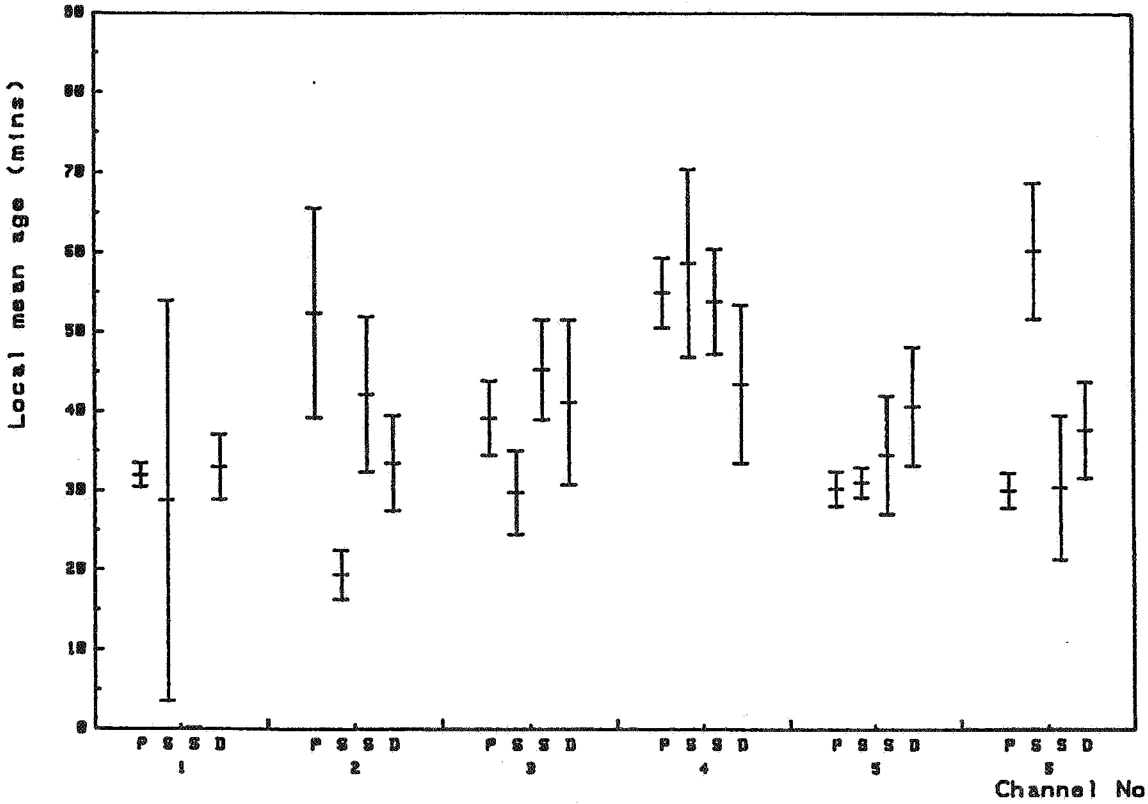

Figure 4. Local mean ages(mins), Fan Speed 3

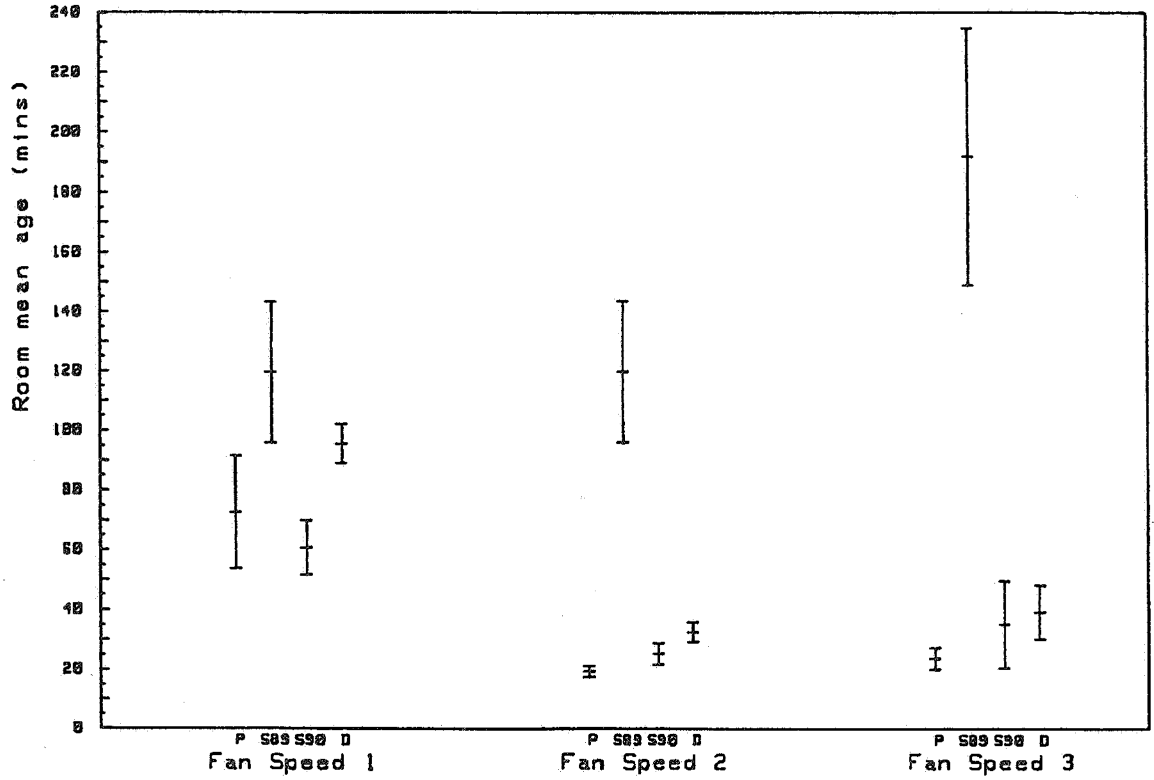

Figure 5. Room mean age (mins)

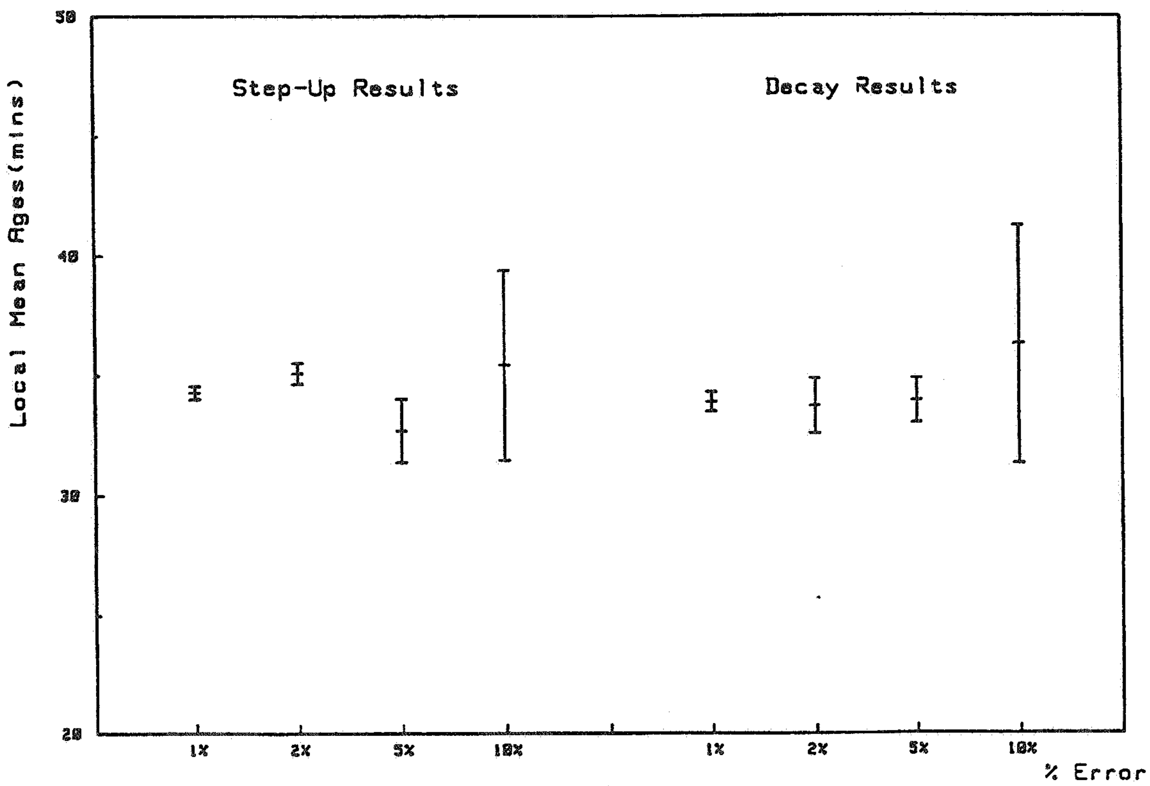

Figure 6. Local mean age(mins), Channel 5

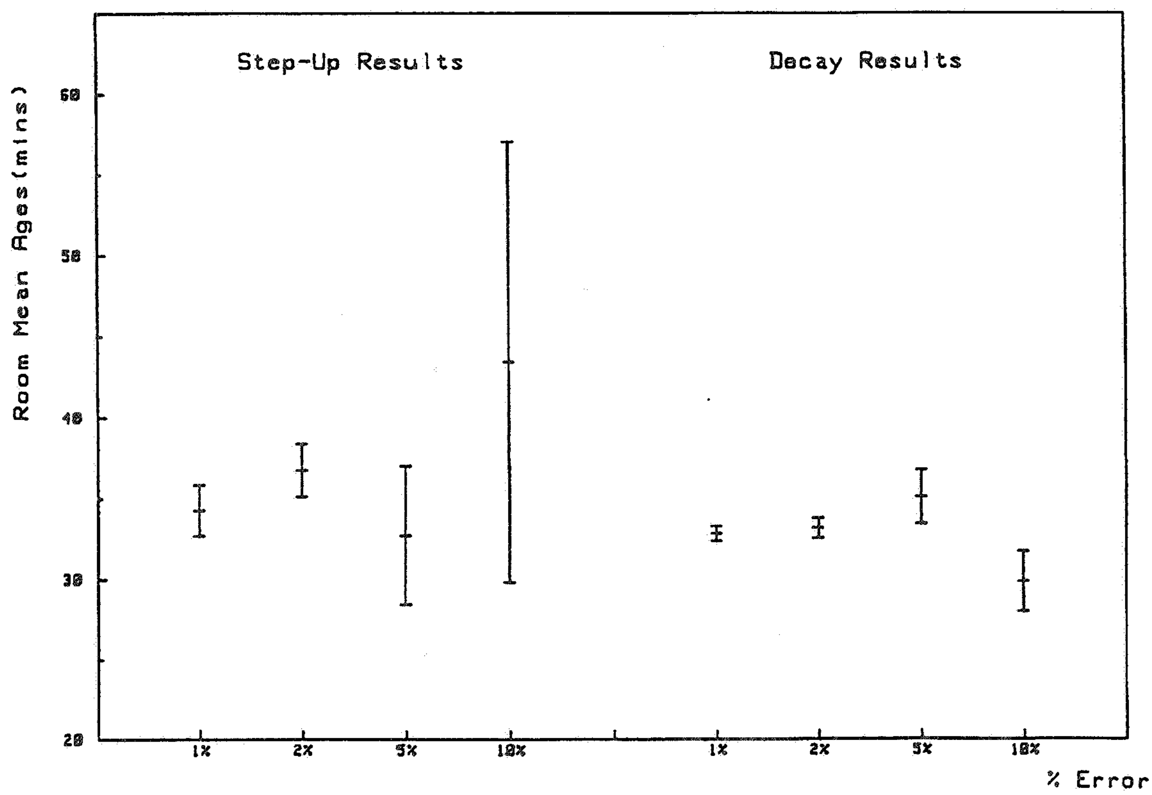

Figure 7. Room mean age(mins)