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CARBON FIBER BEHAVIOR IN AN ENCLOSED VOLUME

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SUMMARY

The Contractor performed tests at Langley Research Center to evaluate the behavior of single carbon fibers existing in an enclosed space such as a room of a building. Three general phenomena were explored: the concentration decay rate of a fiber-charged room, the degree of uniform mixing of fibers within a room, and the effects of fibers being redisseminated off deposition surfaces within a room. The results were required in understanding the ratio of total indoor fiber exposure to total outdoor fiber exposure, a quantity essential to the risk analysis currently being conducted by the Graphite Fiber Risk Analysis Program Office at Langley. Results indicate that decay rate is predictable within acceptable limits and that homogeneous mixing can always be assumed. Some factors of redissemination are identified and effects discussed.

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

F	Total number of carbon fibers
m	Meters
s	Seconds
v_S	Fiber settling velocity, m/s
C	Instantaneous fiber concentration, F/m^3
E	Exposure F_S/m^3 , $E = \int C \; d(\text{Time})$
D	Deposition F/m^2 , $D = E \, v_S$
AETF	Airborne Exposure Transfer Function. Ratio of indoor to outdoor exposures.
Q_N	Rate of natural ventilation through an enclosure, volume air changes per second.
Q_{MU}	Rate of mechanically provided fresh air inlet rate, volume air changes per second.
Q_I	Rate of air infiltration through an enclosure, volume air changes per second.
Q_R	Rate of air movement from an enclosure, recirculated through a filter and returned to the enclosure, volume air changes per second.
η_F	Filter efficiency, number of fibers trapped by a filter in a duct divided by the total number of fibers transported by the duct.
η_I	Filtering efficiency of infiltration cracks and crevices, number of fibers trapped divided by the total of fibers trapped plus passed.
A	Floor area, m^2
V	Enclosure volume, m^3

1.0 Introduction

Carbon fiber exposure, E, is the generally accepted parameter for measurement of electrical equipment vulnerability. The NASA risk analysis involves calculation of probability of indoor equipment failure based upon expected exposure in the vicinity of the equipment, given a value of outdoor exposure. This transfer ratio, therefore must be known.

Reference 1 predicts the ratio of indoor to outdoor exposures as the AETF, where

$$\mathrm{AETF} = \frac{Q_N + (1-\eta_F)\ Q_{MU} + (1-\eta_I)\ Q_I}{Q_N + Q_{MU} + \eta_F\ Q_R + Q_I + \frac{v_s A}{V}}$$

Thus, the indoor exposure would depend only on outdoor exposure and ventilation rates, filter efficiencies, and the degree of fiber settlement during exposure.

This contractor report presents the results from testing designed to check the validity of both the settlement term $\frac{v_s A}{V}$ within the AETF and two of the assumptions explicit in the AETF model. The two assumptions are:

1. Fibers will mix homogeneously throughout a volume.

2. There is no redissemination of fibers, once deposited upon some surface.

As a basis for deriving a transfer function, Reference 1 and others have recognized that the concentration, C, of a fiber-charged, non-ventilated room must decay at a rate of $\frac{v_s A}{V}$ sec^{-1}.

More generally, for any given room,

$$C = (C_{\mathrm{Initial}})\, e^{-\left[(Q_{MU} + Q_N + Q_I + \eta_F\ Q_R + \frac{v_s A}{V}\quad (t_2 - t_1)\right]}$$

To confirm this behavior, testing was performed to measure the decay rate with very little ventilation (Q_N only) and over a wide range of room turbulence, checking to ascertain the homogenity of mixing during the tests.

The redissemination phenomenon does not lend itself well to comprehensive testing. Variables such as surface types and textures and air ventilation patterns obviously can only be crudely accounted for without substantial research. The test chamber's intentionally smooth epoxy painted surfaces no doubt encouraged redissemination during testing; the typicality of its turbulence patterns remains an unknown. However, these quick-look tests serve as a basis for support of the existing model and to provide some insight into redissemination.

2.0 Test Facility and Setup

Figure 1 is a simplified drawing of the NASA-LaRC fall chamber showing sensor placements and variable-speed turbulence fan locations. The recirculating airflow path that served to deliver fibers from the chopper into the chamber is shown schematically. As shown by the small arrows, air entered the bottom of the chopper duct, lifting fibers into the recirculating airstream, and dispensed them into the chamber. Recirculating air filters were present but are not shown.

The chamber's floor area was about 2.4m x 2.4m; its height about 3m. The recirculating air rate was measured to be sufficient for a volume air change about every 2000 seconds (about 17 times longer than for the settlement term in the AETF).

Ball sensors were used to count fibers, and thereby measure concentration. These sensors use charged metal balls that attract fibers and transfer a small amount of charge as fibers touch. This charge transfer is detected by electronics as a fiber and is counted. A known calibration factor multiplied by the count accumulated over a period of time (60 seconds for most of this testing) renders E. Then the average C for the period would be E divided by the period of time.

The ball sensors were supported on microphone stands, three placed at heights of 0.4m, 1.4m, and 2.3m, respectively, approximately at floor center, and a fourth in the SW corner at a height of 0.4m. This corner sensor was not used in all tests.

Airflow was controlled in two ways. The degree of turbulence within the chamber was varied by the speed of the two fans, which were resting on the floor, pointing upwards at about a 45° angle. Also, the recirculating airflow rate was cut off for some of the tests.

The turbulence velocities published herein are means for 12 readings taken at 4 locations in the chamber. These locations were at each of the three center balls and on the floor at floor center. At each location, measurements were made in the north-south, east-west, and up-down directions by a man in the chamber holding a hot wire anemometer, Hastings-Raydist model AB-27, whose resolution was 0.025 m/s (5 feet per minute). For each measurement, readings were subjectively averaged over a 5 second period.

As previously mentioned, the typicality of the chamber's specific air patterns has not been researched. Dead spots (areas of high floor deposition) were observed during testing, evidently because of standing air patterns that kept fibers swept clean in certain areas and eventually depositing them into the dead spots. Besides the minor trapping ability of the instrumentation cabling and the dead spots, practically no fiber sinks were present in the chamber.

In all tests, temperature was $21^{o}C$ to $27^{o}C$ and relative humidity was 30% to 45%, except during the test which produced the data of Figure 5 , relative humidity was about 60%. Parenthetically, this high humidity accompanied the highest observed clumping. All testing involved Thornel T-300 fibers of length 5mm and were conducted by the same experimenters, irregularly over a period of approximately three months.

3.0 Decay Rate Testing

Figure 2 shows the concentration decay of a fiber-charged chamber with a turbulence of 0.12 m/s, after 12 minutes of chopping at about 1 chop per second. The estimated exposure, E, was 5×10^{6} FS/m^3 prior to decay, and estimated deposition, $D = E\ v_s$ was 1.3×10^{5} F/m^2. The predicted slope of $\frac{v_s A}{V} = .0082$ sec^{-1} is shown as a solid line (vertical placement on the graph is arbitrary, the line serving only as a reference slope for data comparison). Over the 125 second period shown, the C decay rate was as predicted for each of the three sensors (the corner sensor not used here). The chopper and the recirculating fan were turned off at time zero.

As a note, in this and all other C graphs presented, logarithmic ordinates are used, greatly expanding the low C detail. Also, vertical and horizontal scales are as large as possible. Therefore, in some cases, graph resolution may exceed data accuracy. Further, air velocity and concentration data were rather irregular, especially low C, requiring a number of points to establish trends.

In Figure 3, time is extended to 1200 seconds for the same test as in Figure 2. The decay was as predicted until roughly 400 seconds, for all 3 sensors. From there on, redissemination caused the decay rate to decrease. Redissemination testing is discussed in Section 5.

Figures 2 and 3 show results for 0.12 m/s turbulence. As can be seen from the Appendix, this is roughly equivalent, though somewhat higher than the turbulence levels measured in a conveniently located room of a research building at Langley Research Center. To measure decay rates over a range of turbulence levels, a number of tests similar to the one just described was performed.

Figure 4 is a somewhat random compilation of results from these tests. The labelling identifies whether the datum is from the top (T), middle (M), or bottom (B) ball, or from an average (A) of the three. The numbers correspond to the turbulence level present for each datum. The lengths of the lines indicate the period of time over which each point was measured. Though a busy graph with apparently scattered data, its message is that the decay rate was not dependent upon turbulence level. Further, upon close inspection, the predicted decay rate of 0.0082 sec^{-1} was again maintained within limits. As previously mentioned: C measurements required a number of data points to establish trends; low C measurements were the most irregular; at roughly 400 seconds (6 to 7 minutes), the decay rate decreased noticeably. Therefore the most accurate data of Figure 4 are those close enough to time zero to have been taken during highest C and over a period of time long enough for good data statistics, but short enough not to extend beyond 6 to 7 minutes. All such data is fairly well representative of predictions. Further evidence of predicted decay rates is shown in Figures 1 through 4 of Appendix 2, which gives details of Redissemination testing.

4.0 Mix Uniformity Testing

Testing confirmed that over a wide range of turbulence levels, instantaneous C was nearly equal at each of the three sensor locations (again the corner sensor was not used). Though Figure 5 is a composite of results for only two distinct tests, similar results were observed throughout the test series.

In Figure 5, the stratification of C over 20 minute periods is shown as a ratio of counts registered on each sensor, T for top, M for middle, B for bottom, divided by the total counts for all three sensors over the period, at each turbulence level. The 0.0086 m/s shown was the actual mean reading for a zero condition with the turbulence fans and recirculating fan off, defining average background. This background level was significantly below all other measurements.

The data shows good mixing throughout, except for the fact that, at the highest turbulence the top sensor was depleted of fibers for some reason, perhaps due to a standing vortex which bypassed that sensor.

5.0 Redissemination Testing

As pointed out in Section 1, some of the testing was directed toward verification of the assumption that there would be no significant redissemination of fibers off surfaces, once deposited. Verification is important because, theoretically, fibers could be deposited, re-entrained into the air, re-deposited, re-entrained, etc. many times before encountering a terminal sink of some kind. This could add tremendously to eventual exposure.

The testing performed was expected to be the most pronounced case for redissemination in that the fibers would have little tendency to cling to the chamber's smooth surfaces and turbulence levels could be made to equal and greatly exceed typical values for indoor enclosures. However, the typicality of the chamber's specific airflow patterns became a concern during testing. Therefore, it cannot be stated that results thus obtained would represent a worst case.

Testing was devised to measure the effects of redissemination on the long term E for the chamber. Ideally, two identical tests would have been performed; one with turbulence, one without. Then the long term E's could be compared. But since this would involve very low C measurements with a rather variable background, and would require unattainable chopping/dispensing constancy, another approach was taken. After an initial deposition, several redisseminations were made and each evaluated. Before each test, fibers were blown around the chamber with the exhaust of a shop vacuum cleaner and allowed to settle. E was accumulated for three fan-induced redisseminations and two occasions of a man walking or working in the chamber.

Appendix 2 gives the test details. The important test results are:

1. Redissemination can be a significant factor contributing to total E within an enclosure.

2. The effect of redissemination is to reduce the $\frac{v_s A}{V}$ term of the AETF.

3. In chamber testing, a single redissemination event generated an additional exposure about equal to 70% of the original exposure. After 5 events, the total redissemination exposure was about equal to the original exposure.

4. Even turbulence levels that would exist in a quiet room can cause redissemination off smooth surfaces.

5. The test chamber had standing turbulence patterns, creating dead spots, or areas of low velocity on the floor, in which fibers tended to accumulate.

To supplement these tests some observations were made of fibers lying on a smooth desktop, blown by a fan 2m away. Scissors-cut fibers of lengths 6mm and 25mm were dropped in singles and in clumps in random orientations. Observations were:

1. The long fibers were more easily redisseminated than the short ones.

2. Fibers lying most normal to airflow direction were most easily redisseminated.

3. The short fibers tended to clump in tufted fashion, the long ones tending toward parallel fiber clumps.

4. The tufted clumps were much more easily redisseminated than the parallel clumps and began to be moved at velocities of 0.3 m/s.

5. At 0.8 m/s all of the tufted clumps had been moved to new locations, some off the desk, but the long, parallel clumps still were not affected.

6. A large number of singles were seen to cling tenaciously at one or more points along their lengths, while vibrating in the wind.

7. After a blow of 2.5 m/s, some parallel clumps of the long fibers remained. There was no observable loss of singles of either length.

6.0 Conclusions

The AETF should be used in its present form until such time that more knowledge of fiber life and typical ventilation patterns may shed new light on redissemination.

The assumption of homogeneous mixing throughout a volume at any turbulence level has been verified within practical limits.

The concentration decay rate based on the settlement term, $\frac{v_sA}{V}$, of the AETF has been verified for an enclosure whose only deposition area is essentially the floor area. For real-world applications, deposition area will be greater than just the floor area, increasing the $\frac{v_sA}{V}$ term. However some degree of redissemination will typically occur, reducing the $\frac{v_sA}{V}$ term. Based on current information, these two effects are judged to be about self-cancelling, with a net zero effect on the AETF.

As a basis for any future considerations, some further redissemination factors have been identified. Obviously, deposition surface texture and "stickiness" would be important and would be quite variable. Also, though turbulence has been characterized herein as an average of 12 local velocity measurements, probably only peak surface velocities and patterns are important. Further, though no numbers were obtained, there seemed to be a non-linear relationship between deposition and redissemination levels. That is, a unit increase in deposition prior to redissemination seemed to cause a disproportionately larger increase in initial redissemination C levels.

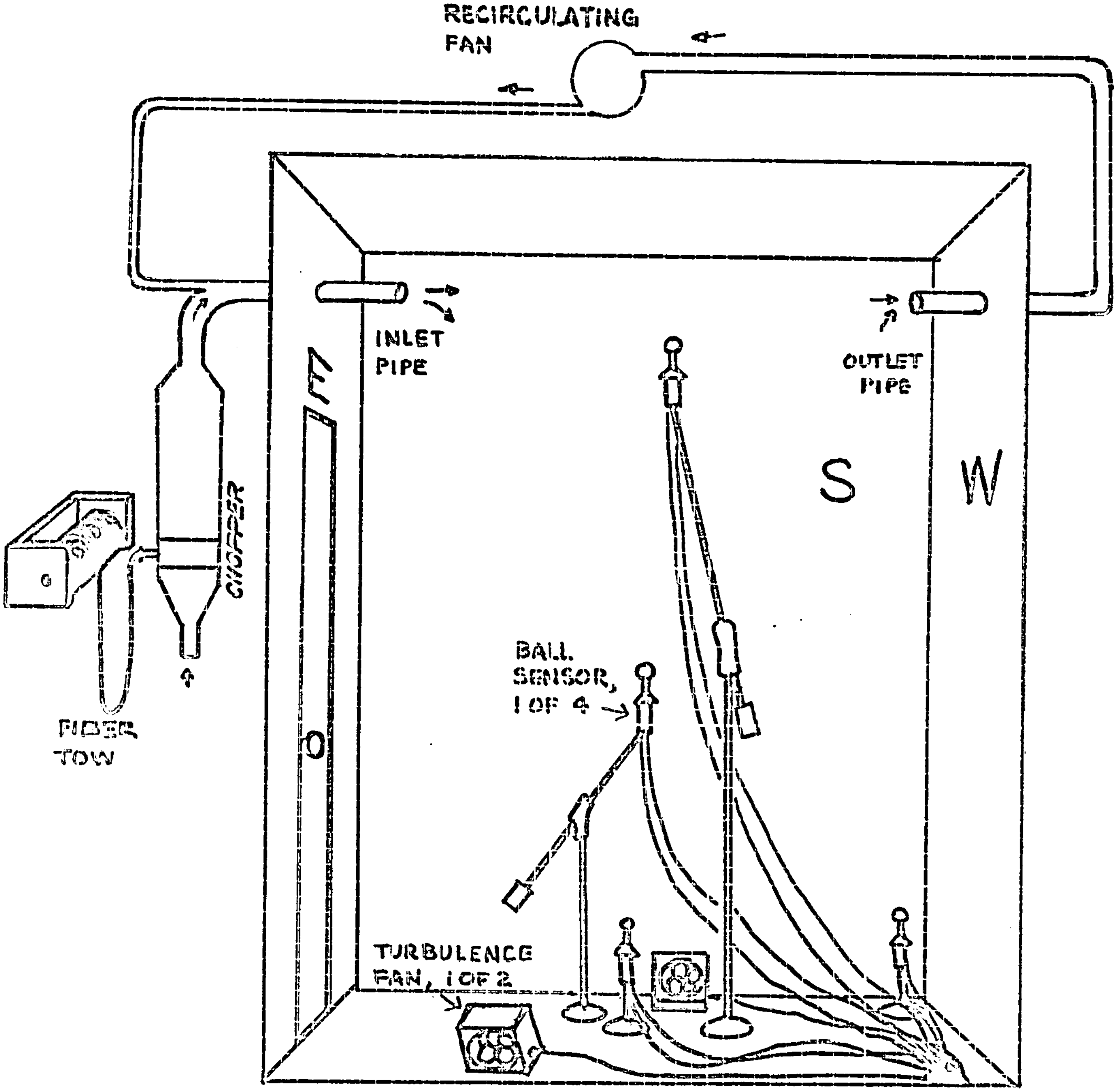

FIGURE 1

Test Facility and Setup

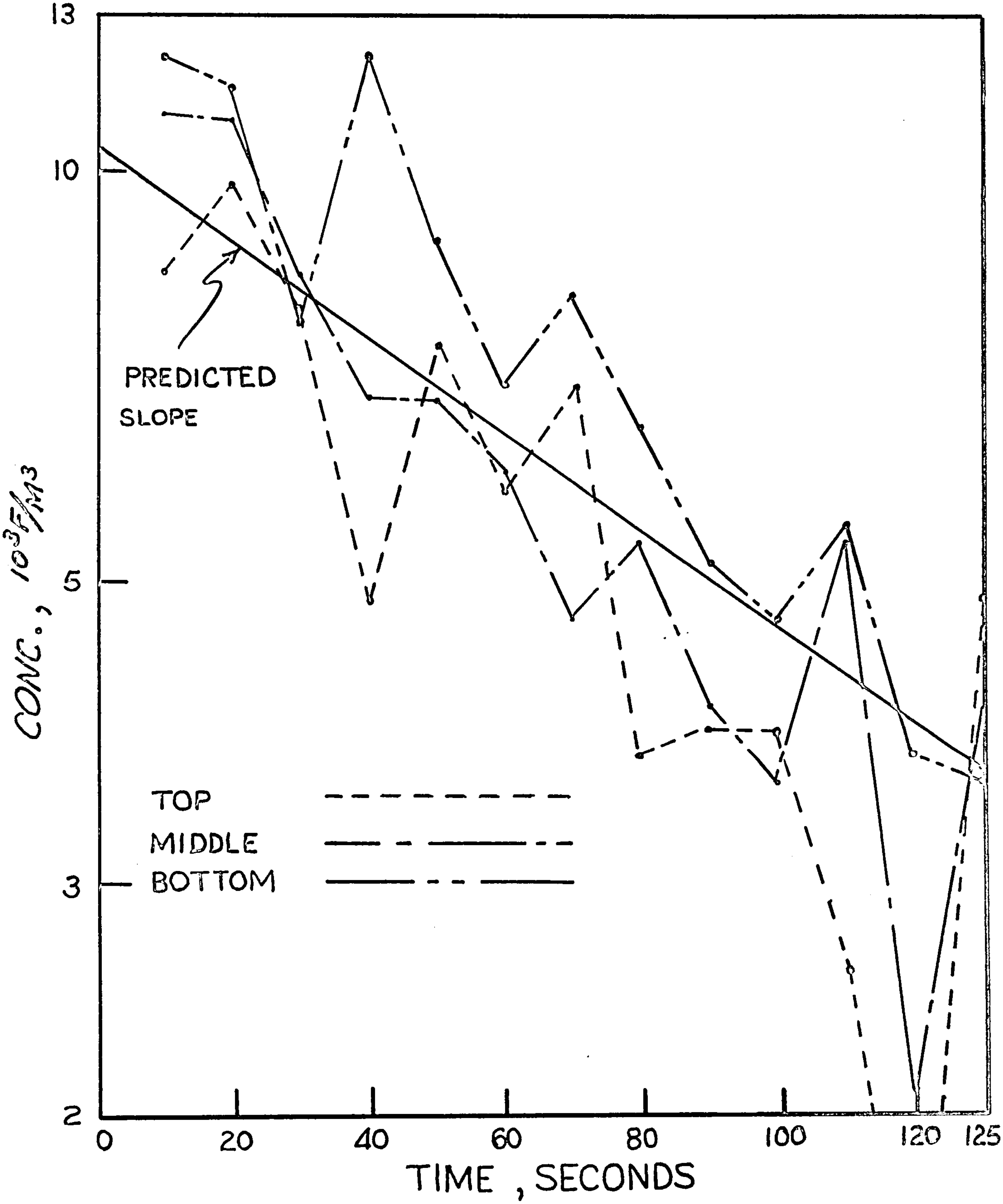

FIGURE 2

Initial Decay for 0.12 m/s Turbulence

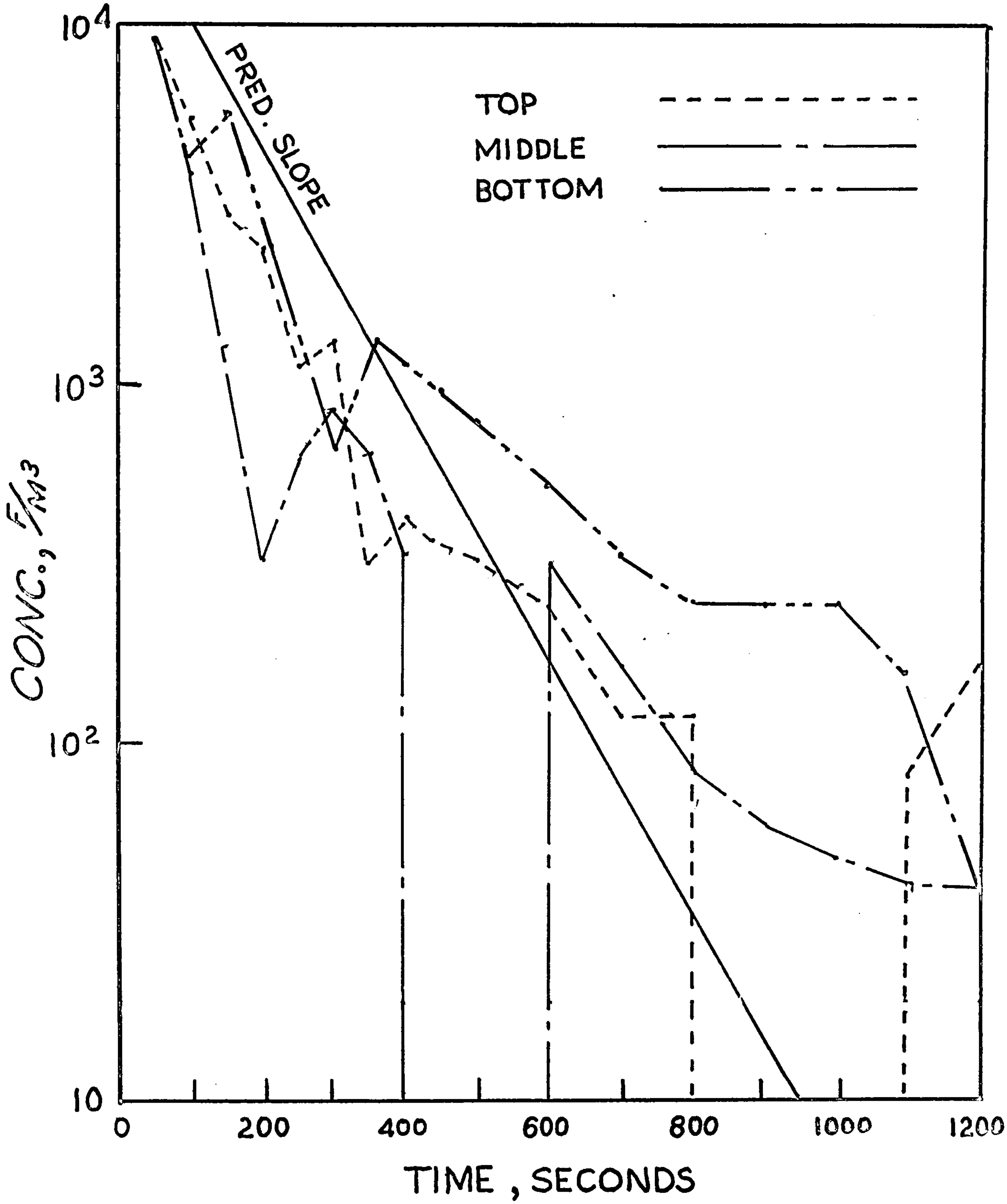

FIGURE 3

Intermediate Decay for 0.12 m/s Turbulence

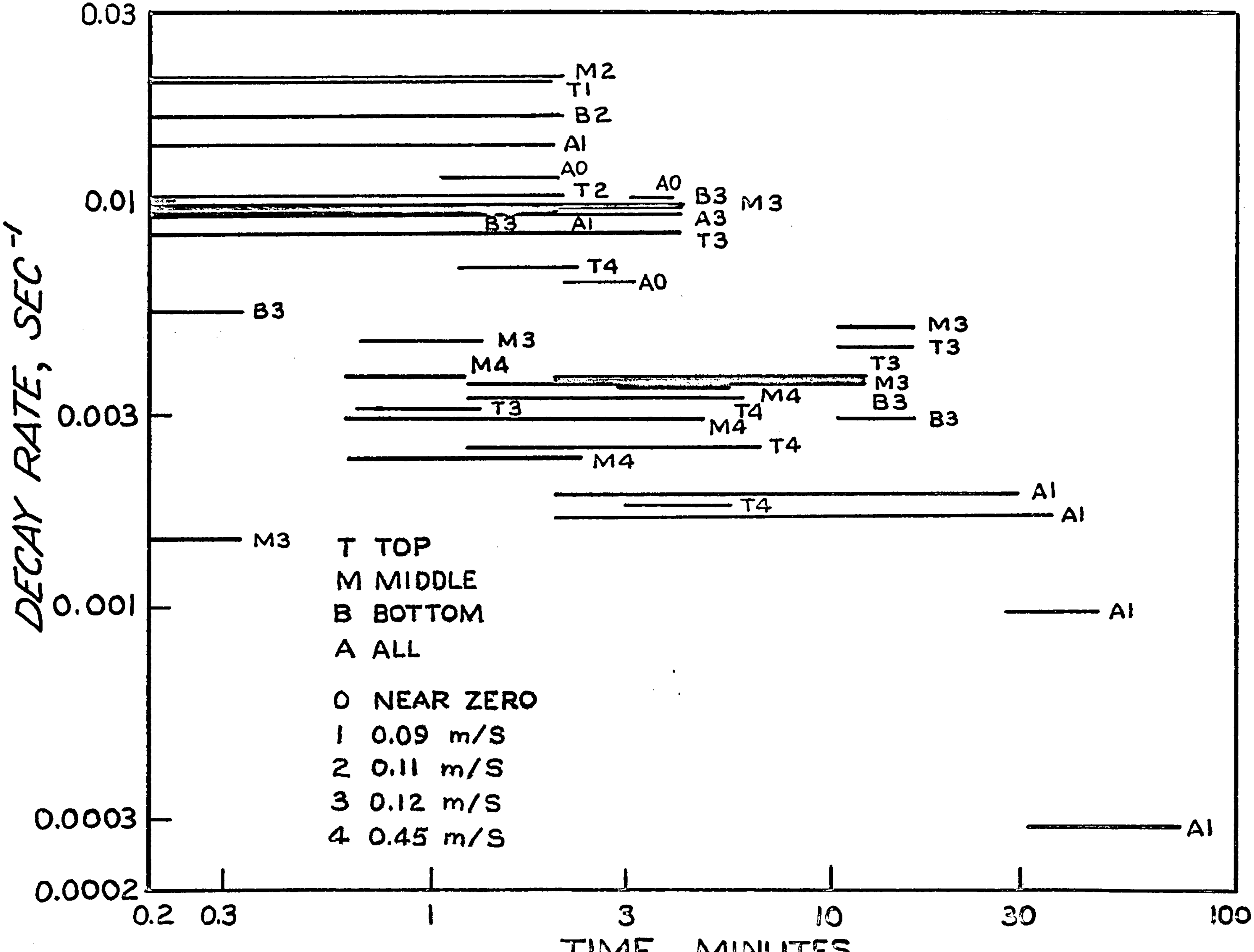

FIGURE 4

Compilation of Decay Rates for Five Turbulence Levels vs Time

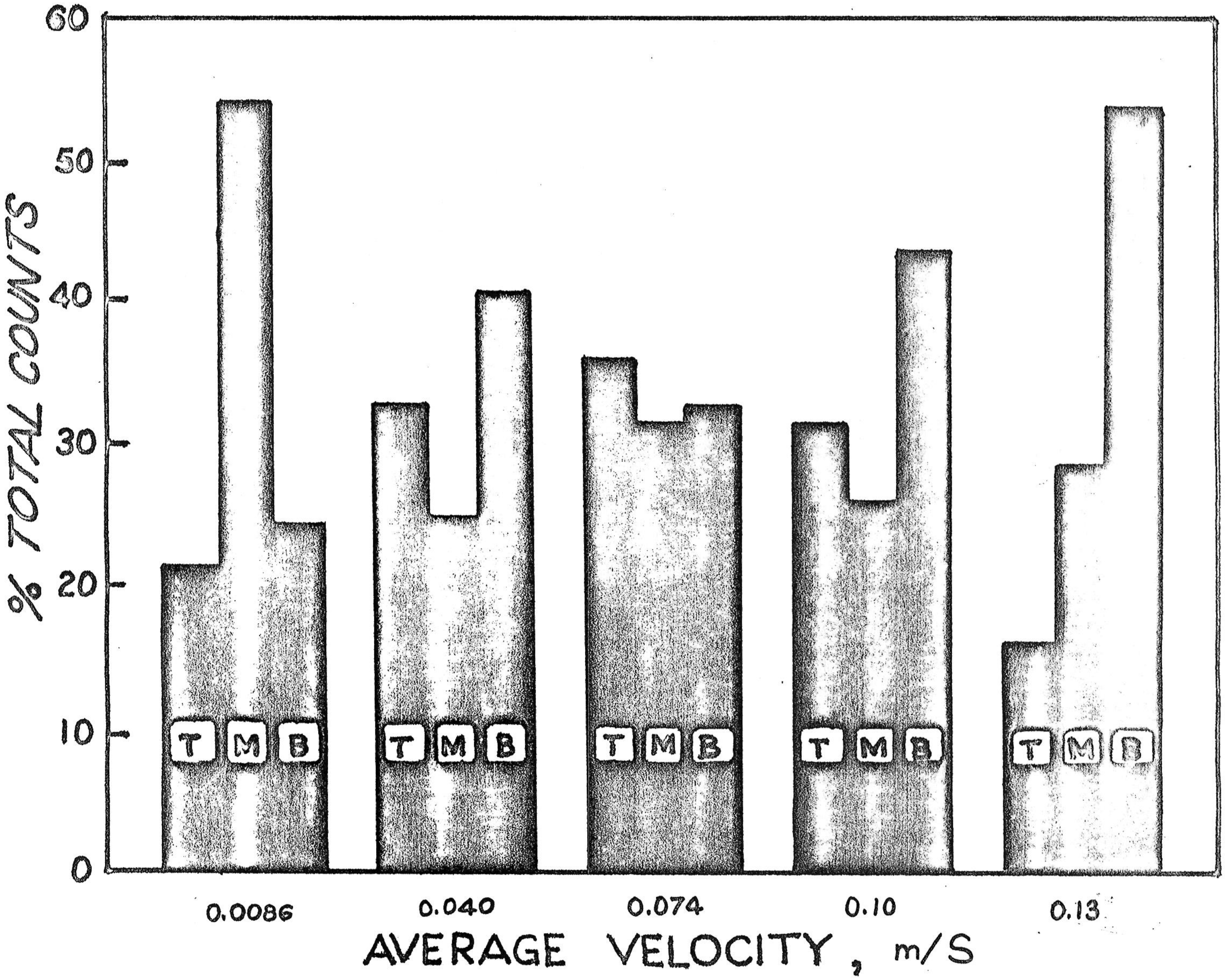

FIGURE 5

Fiber Mixing for Five Turbulence Levels

APPENDIX A

Room 09, Building 1293A, LaRC Air Velocity Measurements

Figure 1 below is an outline drawing of Room 09, Building 1293A, LaRC showing air conditioner outlets (4 each) and the air conditioner return register. The circled letters show locations where air velocity measurements were made with a hot wire anemometer. At most of these locations, measurements were made at three heights above the floor: 0.3 M, 1.8 M, and at the ceiling (about 2.6 M). All were made with the air-conditioner running normally.

Table 1 is a compilation of measurements taken and their calculated averages. Notice that the average room velocity is generally at least double the typical fiber settling velocity of 0.025 m/s.

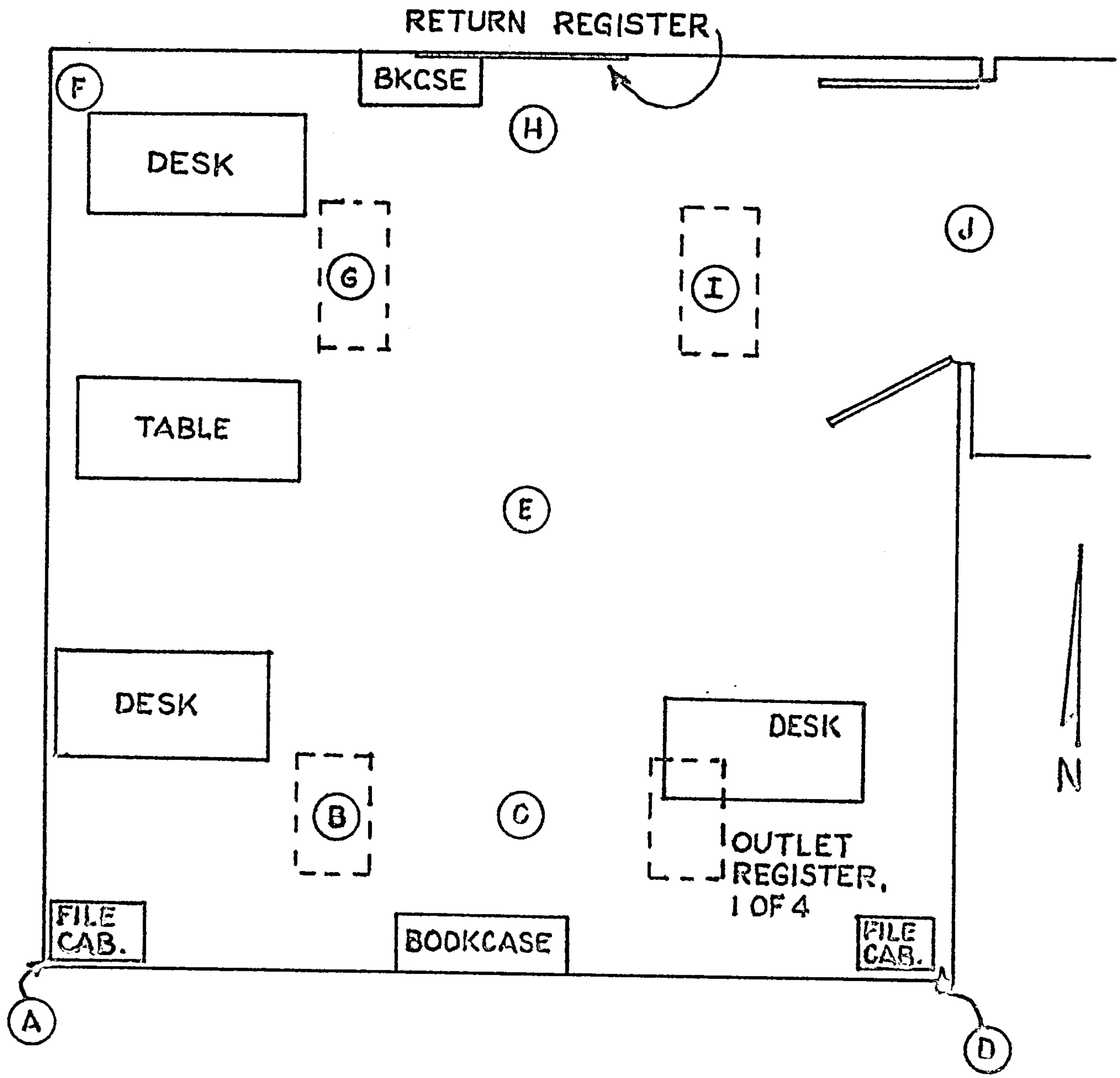

FIGURE A-1

Outline Drawing of Room 09, Building 1293A, LaRC

	0.3 M HEIGHT			1.8 M HEIGHT			CEILING		
	N/S	E/W	U/D	N/S	E/W	U/D	N/S	E/W	U/D
A				0.025	0.025		0.14	0.025	
B	0.088	0.025	0.025	0.025	0.076	0.10	0.025	0.20	
C	0.13	0.025	0.025	0.076	0.063	0.12	0.18	0.025	
D			0.064	0.025	0.025	0.41	0.025	0.025	
E	0.038	0.025	0.11	0.025	0.025	0.025	0.025	0.025	
F	0.025	0.025		0.025	0.025		0.025	0.025	
G	0.063	0.10		0.088	0.13		0.18	0.025	
H	0.038	0.10		0.025	0.076		0.038	0.10	
I	0.025	0.13		0.025	0.025		0.076	0.051	
J	0.025	0.20		0.025	0.063		0.038	0.025	
MEAN HORIZ.	0.053			0.040			0.064		
MEAN VERT.	0.057			0.162					

TABLE A-1

Air Velocity Measurements and Means

APPENDIX B

Details of Redissemination Testing

Prior to redissemination testing, T-300 fibers of 5mm length were chopped and dispensed into the chamber until an exposure of 53.8×10^6 Fs/m^3 had been accumulated. This provided a calculated deposition of $D = Ev_s = 1.3 \times 10^6$ F/m^2 upon the chamber floor. Next, fibers were dispersed uniformly over the chamber floor by blowing them around with air blasts, and then allowed to settle.

Two turbulence fans, located on opposite sides of the floor, each pointing upwards at about 45^o rendered average velocity readings of 0.20 m/s (mean for a total of 12 velocity measurements at 4 locations). Ball sensors were located at heights of 0.4m, 1.4m, and 2.3m in the center of the chamber and another located in a corner at a height of 0.4m. The recirculating airflow which was used to dispense fibers into the chamber was left on during all but one phase of the tests. Its airflow rate was sufficient for a volume air change about every 2000 seconds.

Figure 1 shows the results of the first fan-induced redissemination. The decay slope predicted by $\frac{v_s A}{V}$ is shown as a solid line for data comparison. Data is shown for two sensors only (the middle and bottom sensors at floor center) because the other two sensors fouled during the test.

The data is shown in three pieces. The first shows the early decay for the first 6 minutes after the fans were turned on, in good agreement with predicted. The second piece shows the C level at about 135 minutes, the relatively high C evidence of continued redissemination at that time. At 140 minutes the fans were unplugged, reducing turbulence to nearly zero, the only source being the recirculating airflow. Electrical background (inadvertent counting of noise) had been measured just prior to chopping and found to be equivalent to roughly 2 F/m^3. Therefore the C level shown in the third piece at 152 minutes must have been redissemination sustained, surprisingly, by the meager airflow of the recirculating system, unless due to new fibers inadvertently released into the chamber during the test. Total E accumulated for this redissemination up to 152 minutes was 36.6×10^6 Fs/m^3.

After another background measurement (about 6 F/m^3), the fibers were again dispersed over the chamber floor with the exhaust of a shop vacuum cleaner, and the fans turned on, at time zero of Figure 2, still at a turbulence of 0.20 m/s. Data from all four sensors were accumulated, the count contributing about 8×10^6 Fs/m^3 to the previous E. Data was as expected.

The process was repeated again, this time with bridal veil, a nylon mesh that acts as a fiber filter, wrapped over the end of the inlet pipe. This insured that fibers that might be lodged in the dispensing duct would not be dislodged during the test. Also, the instrumentation cables were raised off the floor to reduce trapping efficiency at this time. The fans were turned on at time zero in Figure 3. Again the concentration decayed at the predicted rate for the first few minutes (average for three sensors, the corner data lost), then deviated. Again, the long term C level (after 75 minutes) was maintained, this time definitely not due to inadvertent fiber dispensing, and so, indicative of the presence of some re-dissemination. The data point at 1 minute is the average for the bottom and middle sensors only, because data collection was begun before fibers had begun to strike the top sensor. Total E accumulated during this test was 3.8×10^6 Fs/m^3. At 75 minutes, a man entered the chamber and walked a total distance of about 4m inside the chamber.

Figure 4 begins at time 78 minutes, when the man exited the chamber. Results were as expected; E increased by 2.5×10^6 FS/m^3. During a second trip into the chamber a man performed some brief work, generating another E of 5.1×10^6 Fs/m^3, bringing the total E for the five redisseminations to 55.9×10^6 Fs/m^3, approximately equal to the original E that generated the deposition.

On a later date, with a clean chamber, one final test was performed to determine for sure if the tiny air currents caused by the recirculating airflow could cause significant redissemination. The results are shown in Figure 5. After a calculated 5×10^5 F/m^2 ($E = 19.7 \times 10^6$ Fs/m^3) deposition was accumulated, the chopper was stopped and fibers allowed to settle for about 15 minutes before data collection was begun at time zero with the recirculating fan and turbulence fans off, the bridal veil still used over the inlet pipe.

The huge C increase at time 30 minutes, when the recirculating fan (Q_N) was again turned on indicates definite redissemination. Actually the recirculating fan was left on, the airflow controlled by a valve, to reduce the effects of any possible fan noise pickup in the instrumentation system.

The rest of Figure 5 shows definite C responses to airflow step changes. C gradually diminished at a rate much lower than that predicted by $\frac{v_s A}{V}$, as fibers eventually found their way into dead spots on the floor, at a rate specific to the chamber's geometry and turbulence conditions.

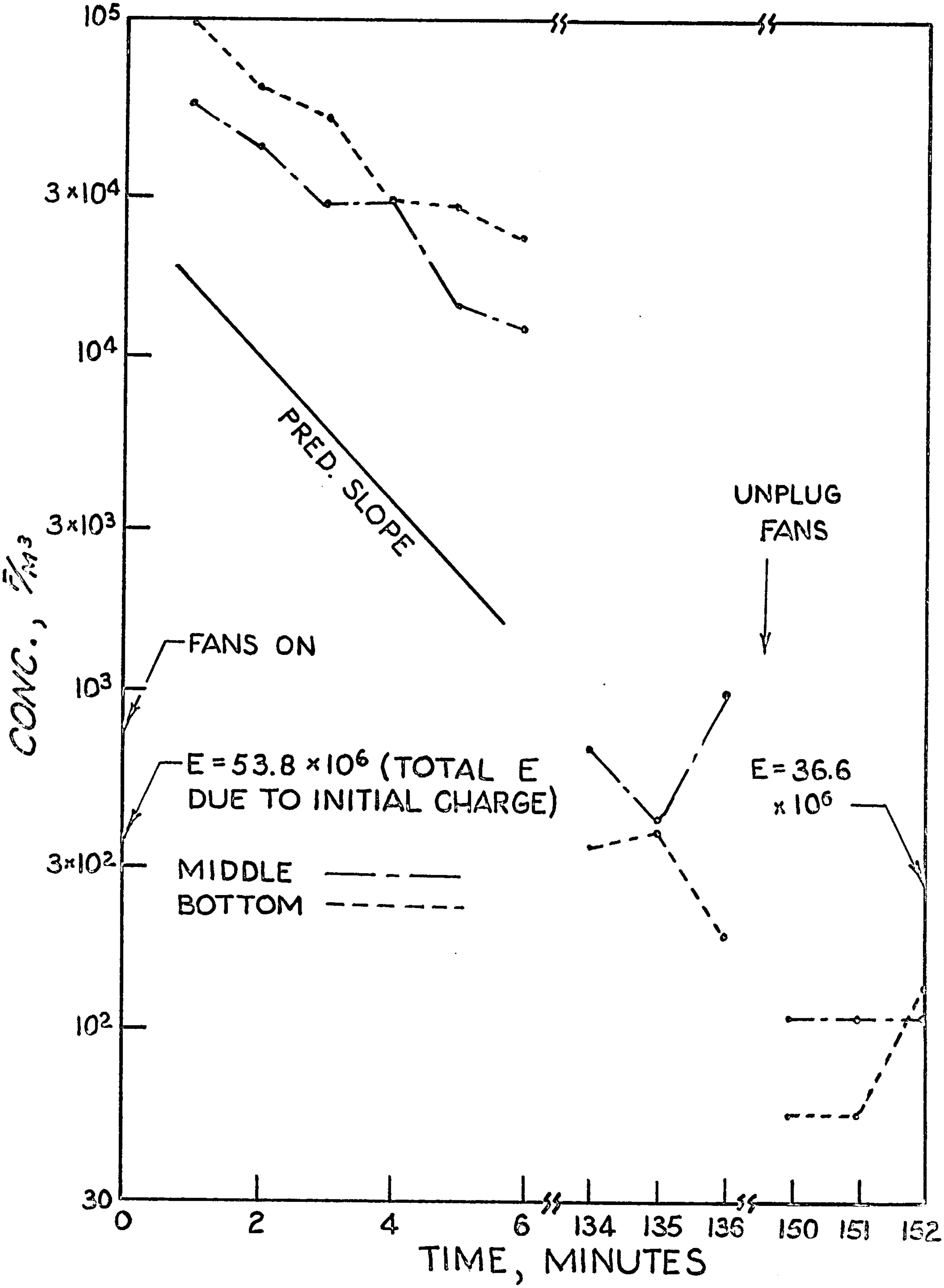

FIGURE B-1
Effects of First Fan-Induced Redissemination

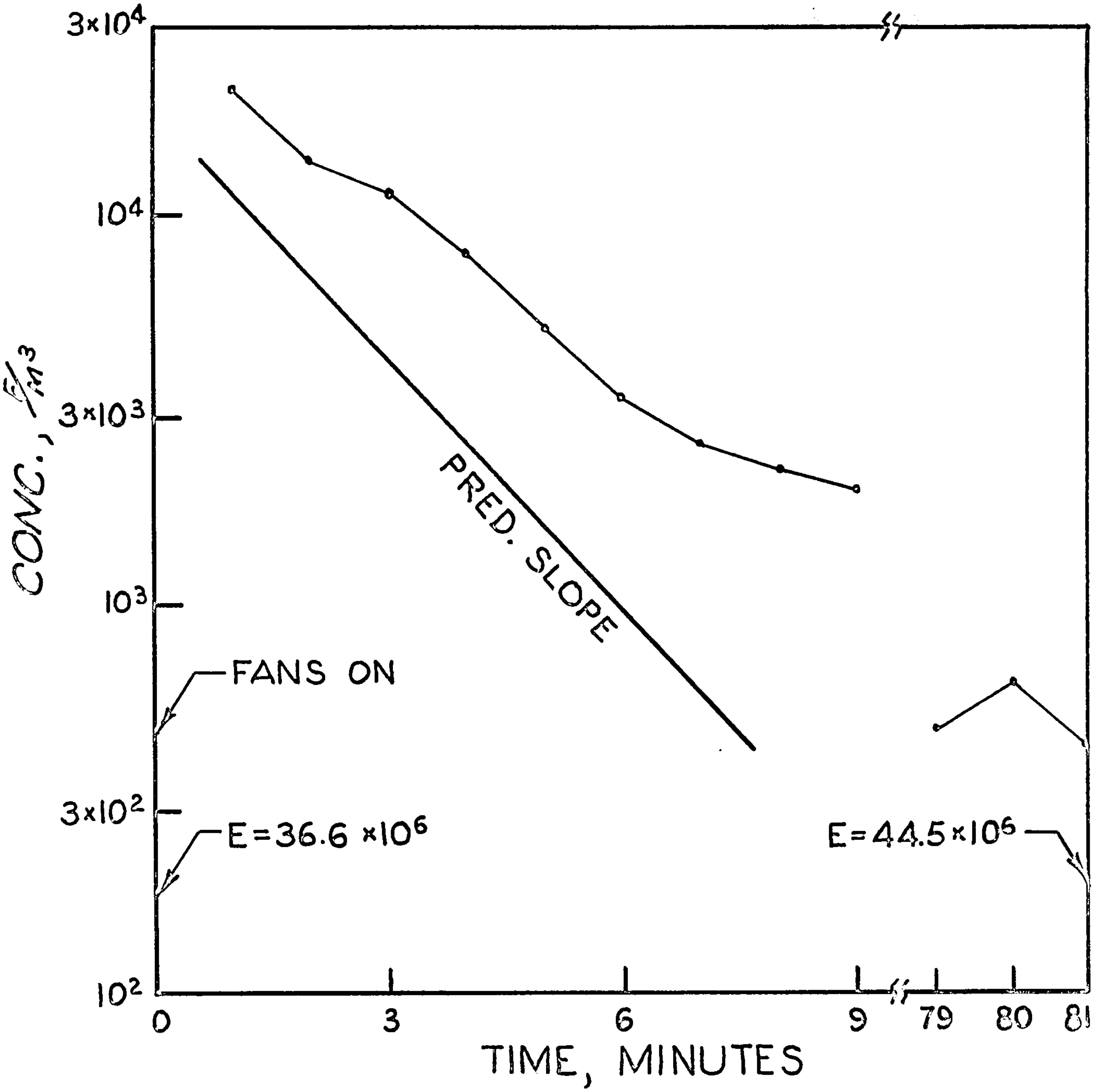

FIGURE B-2

Effects of Second Fan-Induced Redissemination

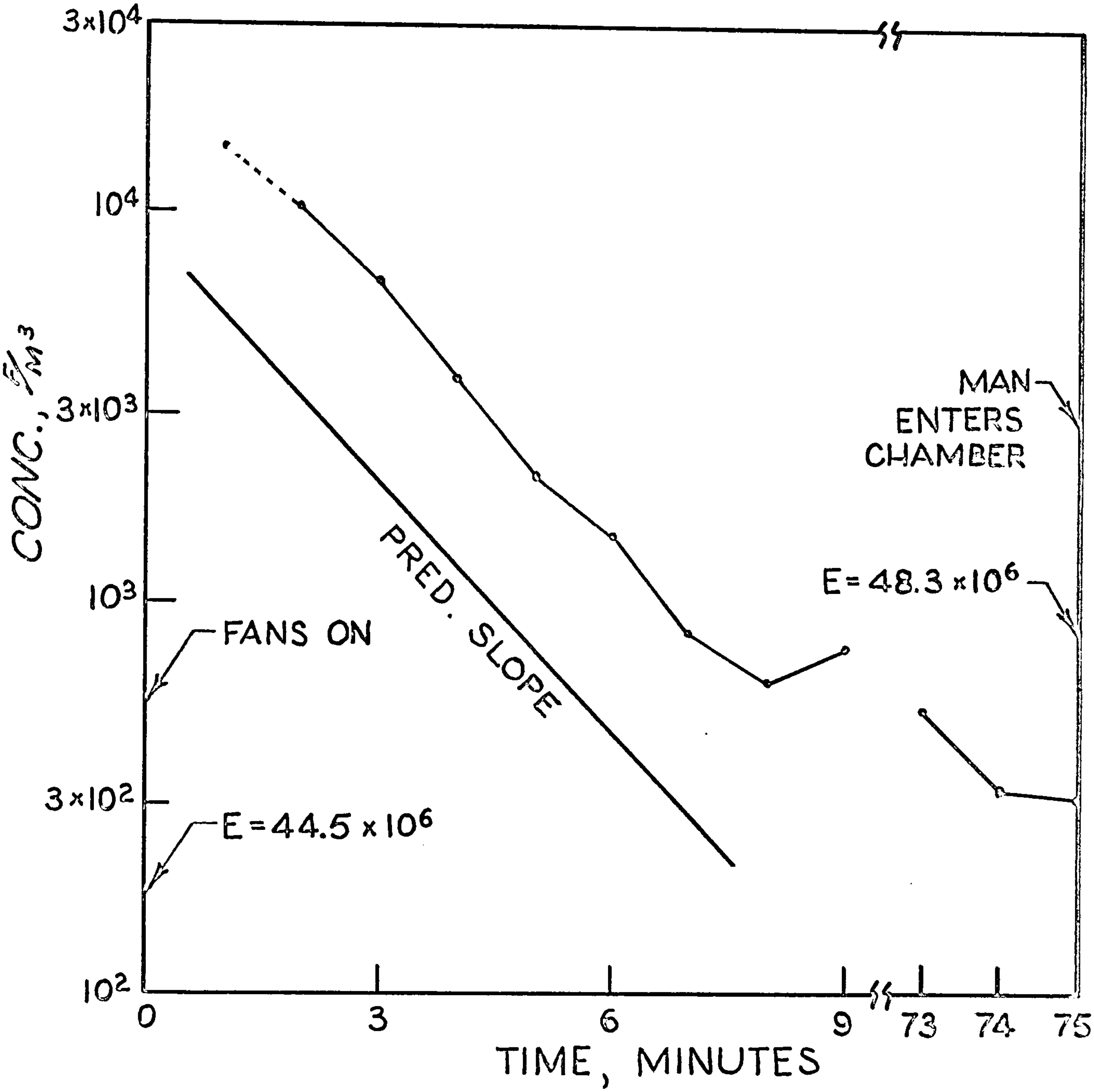

FIGURE B-3

Effects of Third Fan-Induced Redissemination

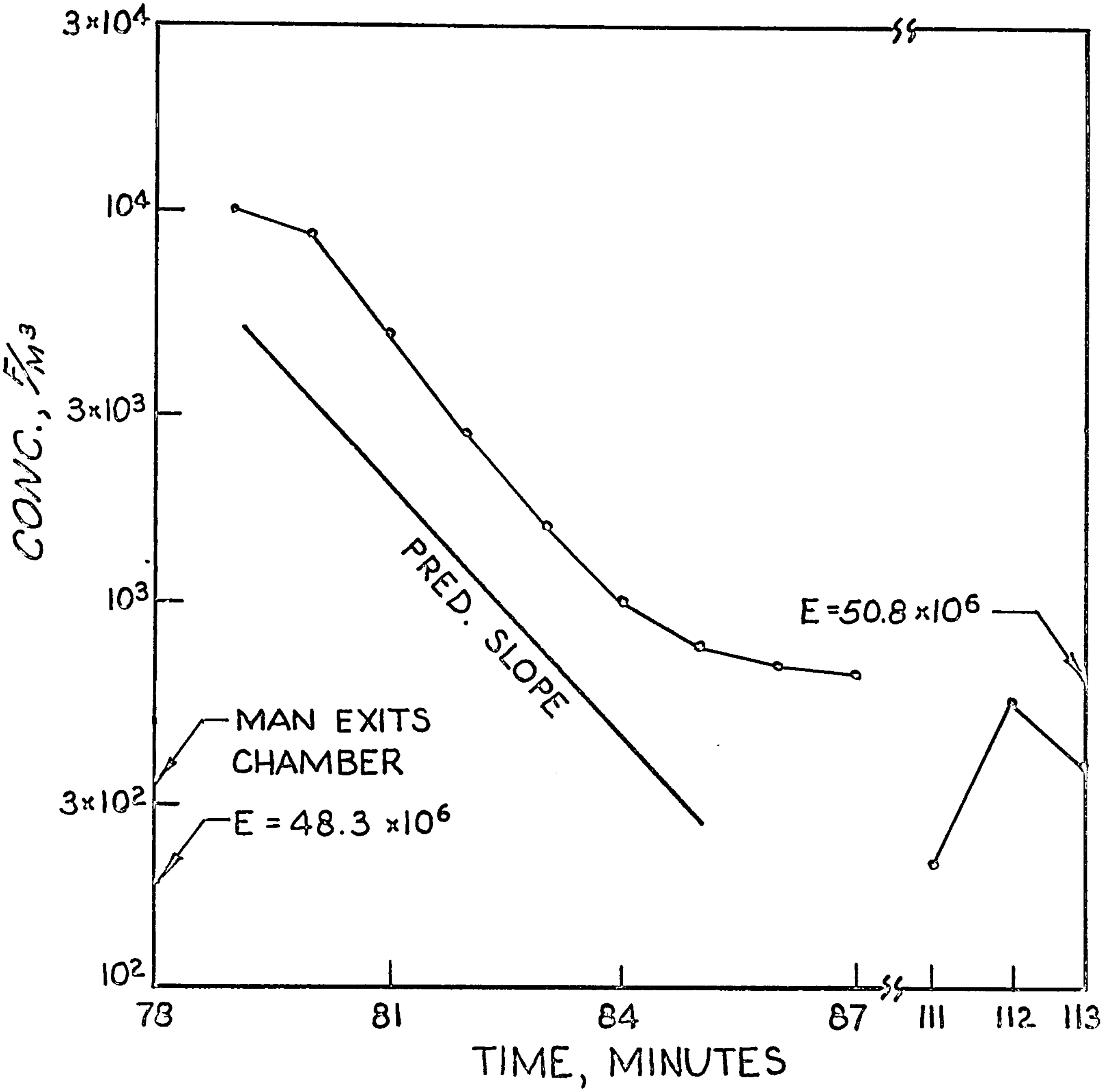

FIGURE B-4

Effects of Brief Human Traffic in Chamber

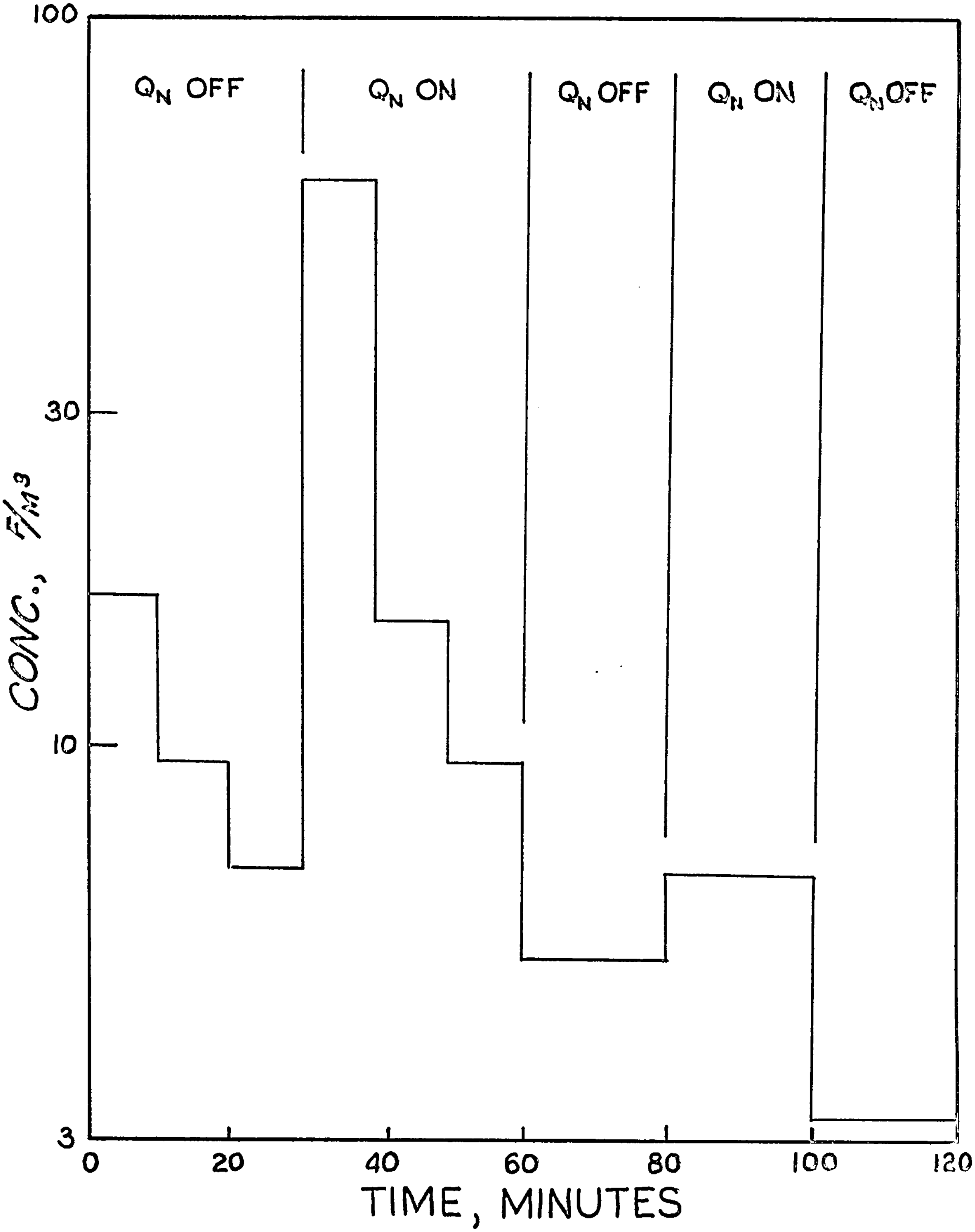

FIGURE B-5

Redissemination Effects for Near-Zero Turbulence

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1. An Assessment of the Risks Presented by the Use of Carbon Fiber Composites in Commercial Aviation, Arthur D. Little, Incorporated. NASA CR-158989, 1979.