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A TRACER INVESTIGATION OF VENTILATION IN AN AUTOMOBILE TUNNEL

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SUMMARY

Seven SF_6 tracer experiments were conducted during October and November, 1978 in the Bryn tunnels in Oslo. The purpose of these tests was to determine the amount of pollutants which, when exhausted from one tunnel, are recirculated into an adjoining, parallel tunnel. Under calm or low wind conditions, between 0.4% and 12% of tracer released in one tunnel was recirculated into the opposite tunnel.

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1 INTRODUCTION

Two parallel tunnels, each with one-way traffic, have been proposed for construction in Oslo. Ventilation air flow in each tunnel will be in the same direction as the traffic. As a result, polluted air from one roadway will be exhausted near the inlet for fresh air of the opposite roadway. In cases of calm meteorological conditions, the tunnel ventilation design may result in the build-up of high levels of carbon monoxide in the tunnels. These levels could exceed safety limits inside the tunnel and also act as a significant source of CO outside the tunnels.

The purpose of this work was to conduct SF_6 tracer tests in a similar, existing set of tunnels to determine how much, if any, of the exhaust air from one roadway enters the opposite roadway under certain dispersion conditions, and also to study the dispersion of the exhaust gas near the outlet of the tunnels.

2 EXPERIMENTAL PROCEDURE

Seven SF_6 tracer tests were conducted in the Bryn automobile tunnels during October 4, 27 and November 3, 1978. In each test, SF_6 was released in one tunnel continuously for 30 minutes at a steady rate from a height approximately 0.8 m above the road. The SF_6 flow rate was determined with a calibrated gas rotameter. The flow rate was checked at the end of each test with a soap film flow meter. The uncertainty in the flow rate is estimated to be less than ± 5%. Release data are shown in Table 1. Instantaneous air samples were collected periodically at two locations during and after the release. In addition, as many as 22 15-minute average samples were collected at various points in both tunnels during the last 15 minutes of each release. Release points and sampling locations used during these tests are shown in Figure 1.

Table 1: Tracer release data, wind velocity data, and traffic count data.

TEST	DATE	RELEASE PERIOD	RELEASE LOCATION [1]	RELEASE RATE m^3/s	$\bar{u}_A$ [2] m/s	$\bar{u}_B$ [2] m/s	$u_{ambient}$ [3] m/s	N_A [4] vehicles/h	N_B [4] vehicles/h
1	1.10.78	1206-1230	R1	$2.28\ 10^{-6}$	-	-	calm	460	320
2	27.10.78	0845-0915	R1	$1.99\ 10^{-6}$	4.7	3.7	calm	624	400
3	27.10.78	1020-1050	R1	$2.02\ 10^{-6}$	4.7	4.4	calm	390	503
4	27.10.78	1148-1220	R1	$2.02\ 10^{-6}$	2.8*	3.1*	calm	468	425
5	3.11.78	0915-0945	R2	$2.44\ 10^{-6}$	4.5	3.4	calm	520	408
6	3.11.78	1030-1100	R3	$2.48\ 10^{-6}$	3.9	4.2	calm	498	563
7	3.11.78	1215-1245	R4	$2.51\ 10^{-6}$	5.7	1.9	2-3	516	630

1) Shown in Figure 1.

2) The average tunnel air velocity was determined from several 1-minute observations collected at various points in the tunnel with hand-held anemometers.

3) Wind speed outside the tunnel, estimated from soap bubble measurements.

4) Traffic density averaged from either a 10-minute count or several 2 minute counts.

* The ventilation fans were operated during all tests except test 4.

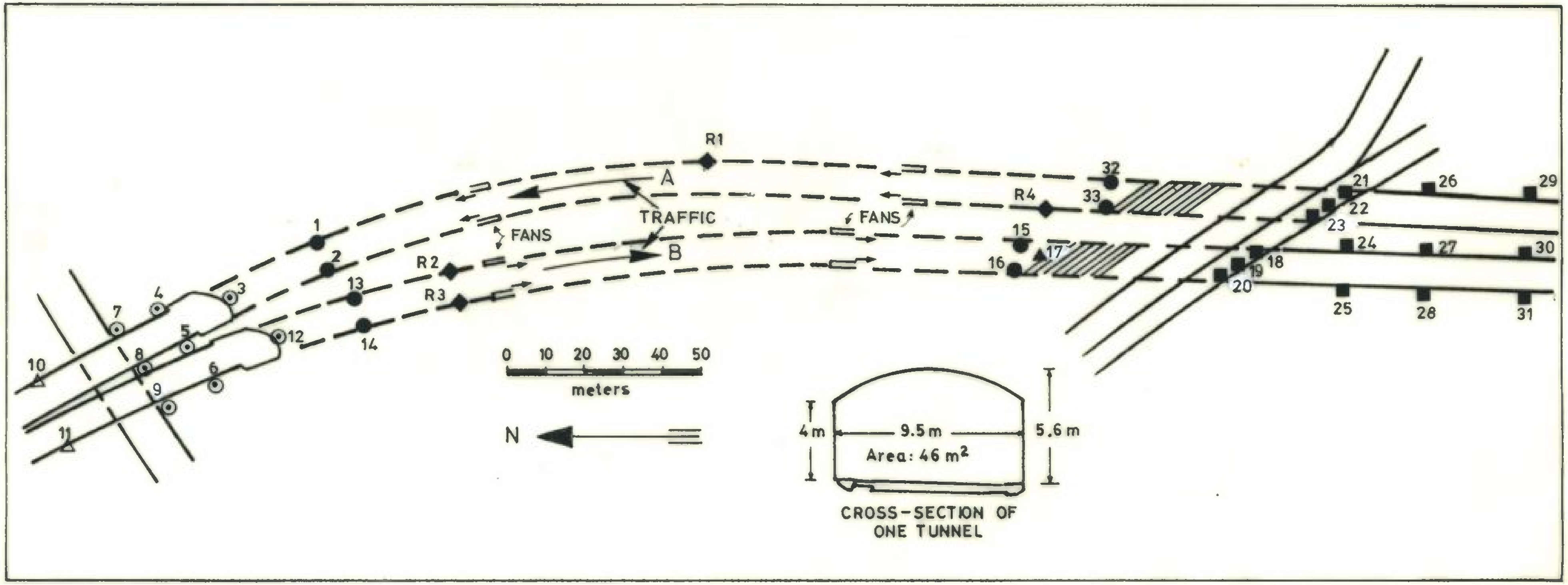


Figure 1: Map of the Bryn tunnels showing release points (◆) R1: Tests 1-4; R2: Test 5; R3: Test 6; and R4: Test 7 and sampling points for Test 1 (●, ⊙, ▲), Tests 2-4 (●, ⊙), Tests 5,6 (●, ■), and Test 7 (●, ⊙, △).

All samples were analyzed within 48 hours of a test using electron capture gas chromatography. This analytical technique allows detection of SF_6 at concentrations ranging from 10^{-6} parts SF_6/part air (10^6 parts per trillion, ppt) to 10^{-11} parts SF_6/part air (10 ppt). The uncertainty in the concentrations is estimated to be less than ±10%.

The average air velocity in each tunnel was determined from a series of 1 minute observations collected at various points in each tunnel with hand-held anemometers. The ventilation fans were on during every test except test 4. The wind speed outside the tunnels was estimated from soap bubble measurements. Tests 1-6 were conducted during calm or very low wind speed conditions. During test 7, winds were from the south at approximately 2-3 m/s. The average traffic density through each tunnel was determined from traffic counts taken during either a single 10-minute period or during several 2-minute periods. The results from all of these measurements are given in Table 1.

3 PRESENTATION AND DISCUSSION OF RESULTS

The SF_6 concentration data are presented in Figures 2-8. During tests 1-4, when SF_6 was released from point R1 near the center of tunnel A, concentrations observed near the outlet of tunnel A indicated that the tracer was not well-mixed across the tunnel. A similar non-uniform concentration distribution was observed during tests 5-7 when the release point was placed near the fresh air inlet of the tunnel. In spite of the turbulence generated by the traffic, it appears that gas released near the wall at one end of the tunnel did not become evenly distributed before leaving the tunnel.

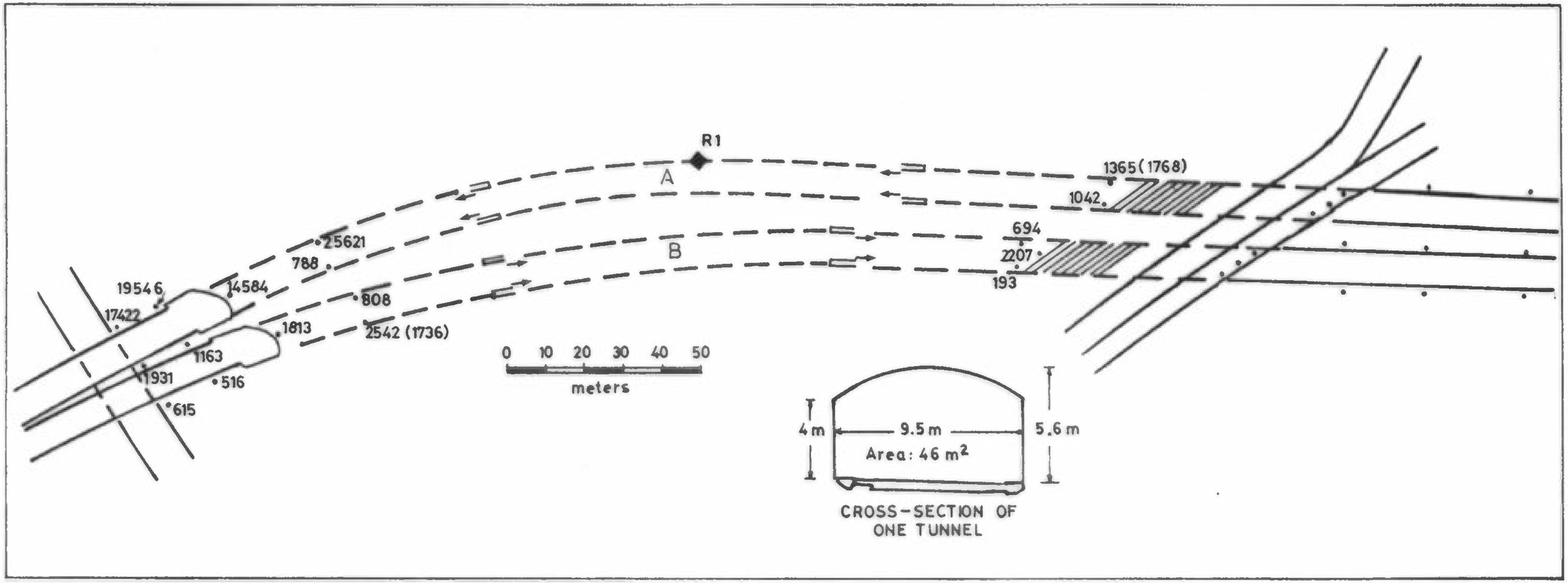
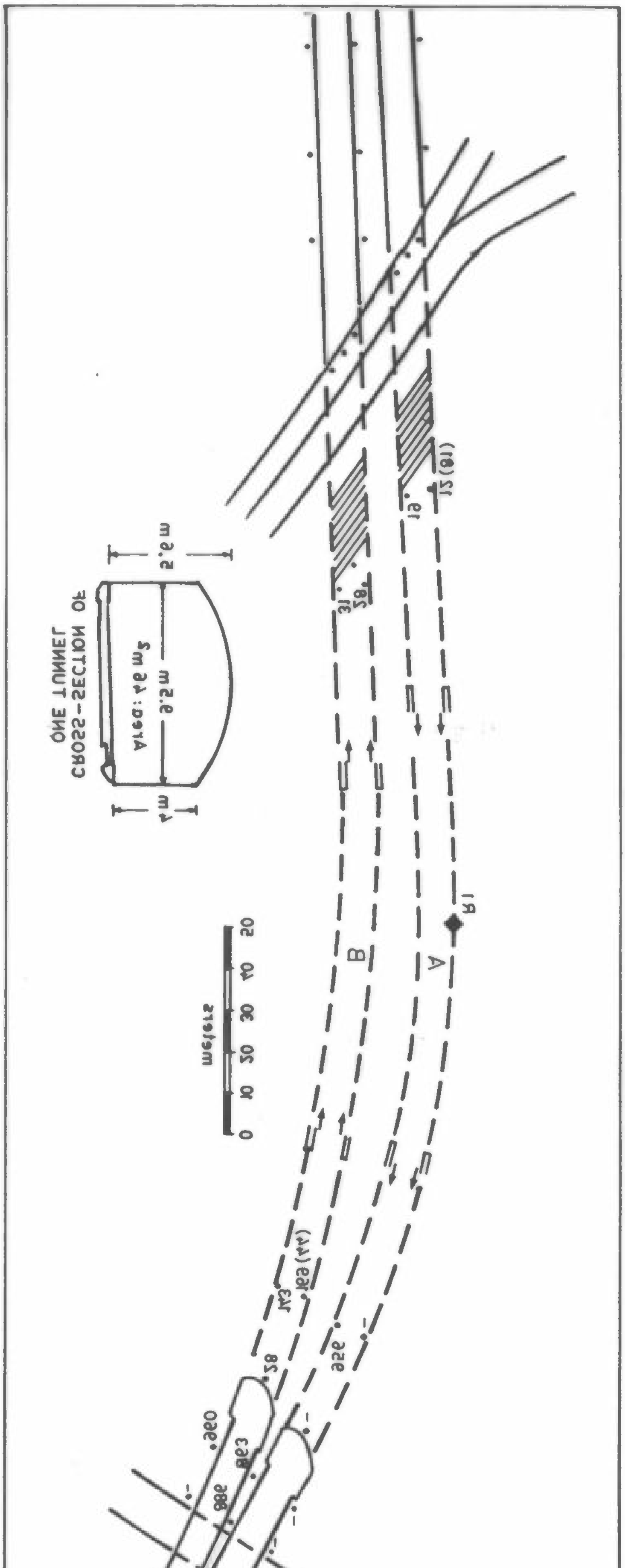
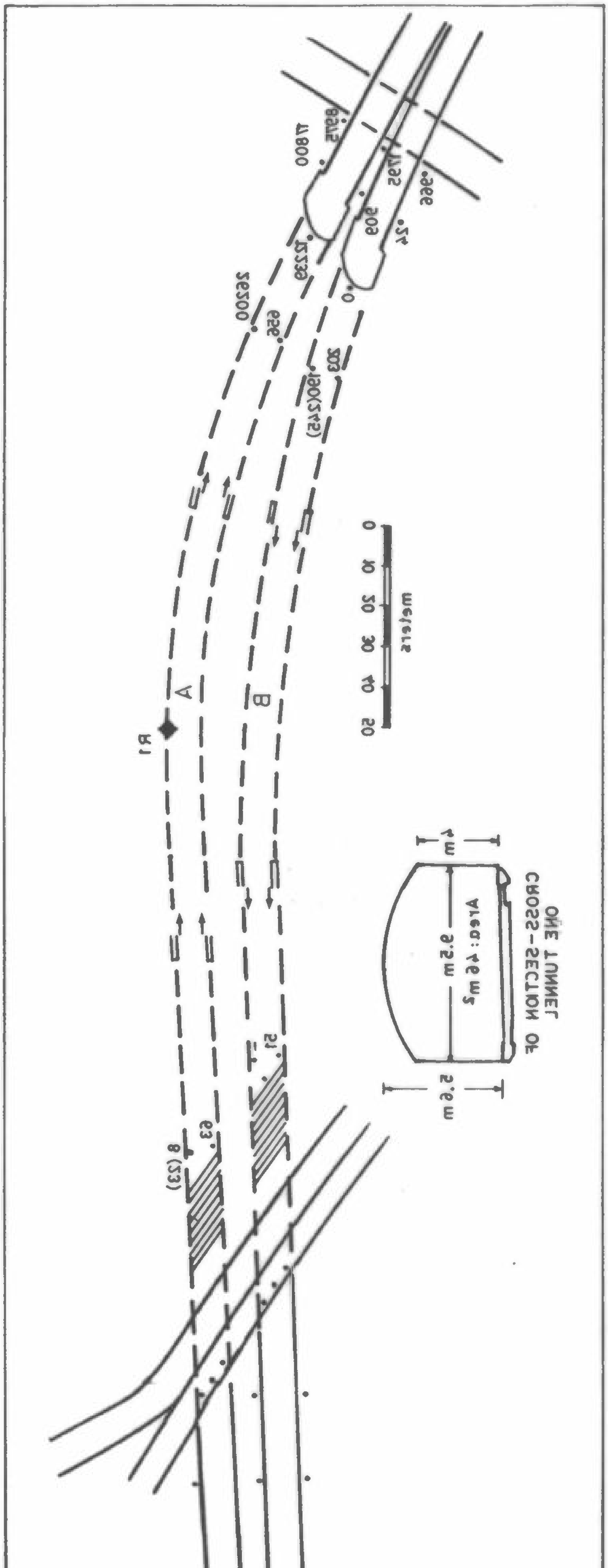


Figure 2: Fifteen minute average SF_6 concentrations, in ppt, observed during Test 1. The average of instantaneous concentrations are shown in parentheses. SF_6 was released from R1.


ONE TUNNEL
CROSS-SECTION OF
Area: 46 m2
9.5 m
5.5 m
4 m
meters
0 10 20 30 40 50
A
B
R1
12 (81)
19
31
28
956
28
743
169 (44)
960
863
886


ONE TUNNEL
CROSS-SECTION OF
Area: 46 m2
9.5m
5.6m
4m
meters
0 10 20 30 40 50
A
B
R1
8 (23)
63
51
26200
956
22239
17800
8575
190(245)
203
0
24
509
17795
966

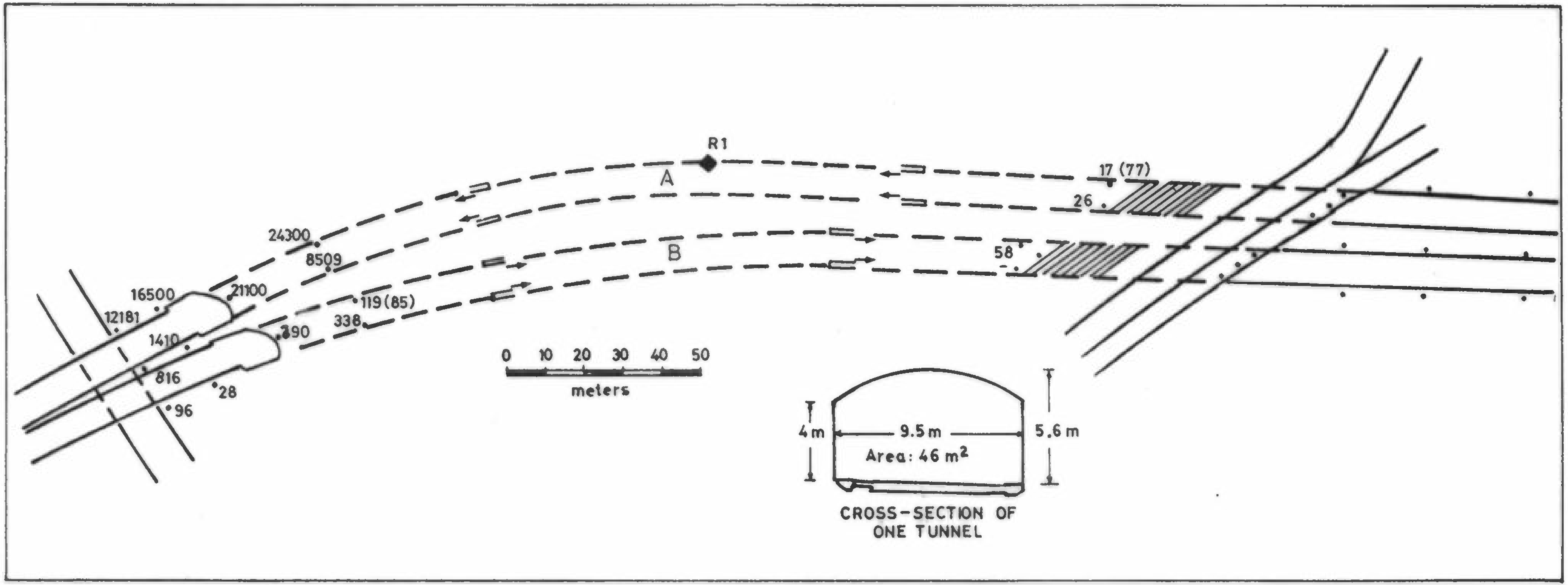


Figure 5: Fifteen minute average SF_6 concentrations, in ppt, observed during Test 4. The average of instantaneous concentrations are shown in parentheses. SF_6 was released from R1. All fans were off.

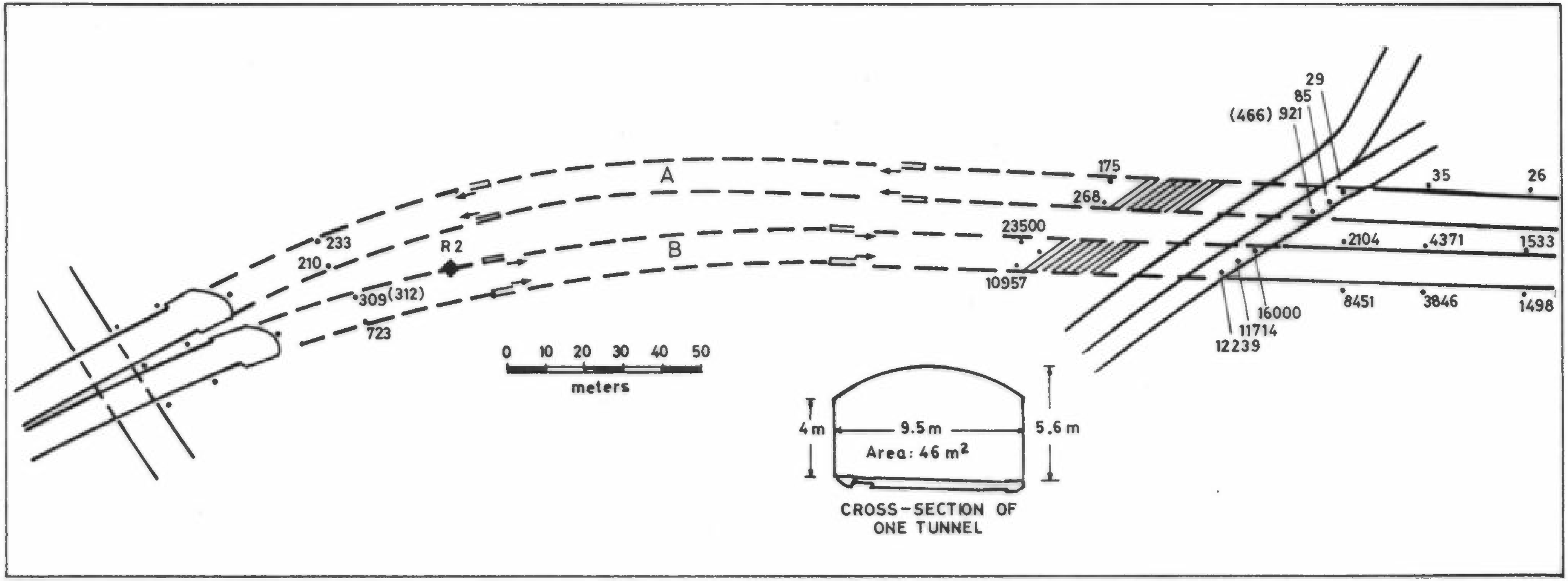


Figure 6: Fifteen minute average SF_6 concentrations, in ppt, observed during Test 5. The average of instantaneous concentrations are shown in parentheses. SF_6 was released from R2.

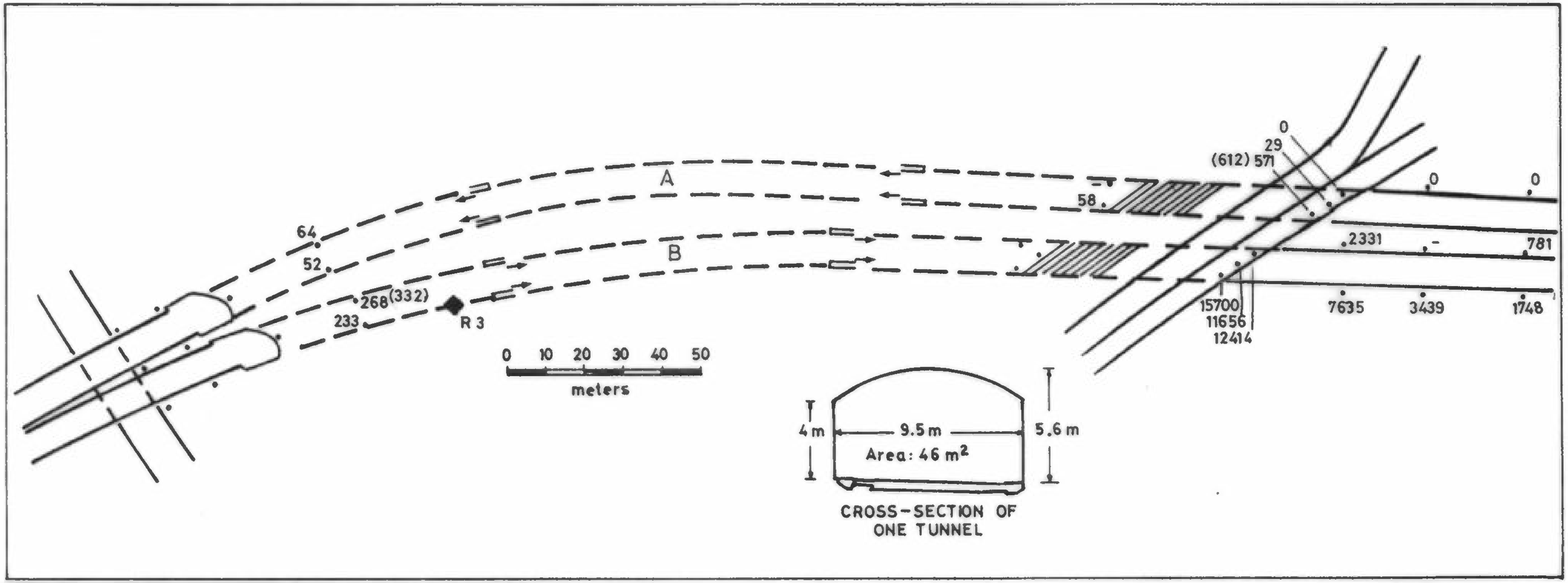


Figure 7: Fifteen minute average SF_6 concentrations, in ppt, observed during Test 6. The average of instantaneous concentrations are shown in parentheses. SF_6 was released from R3.

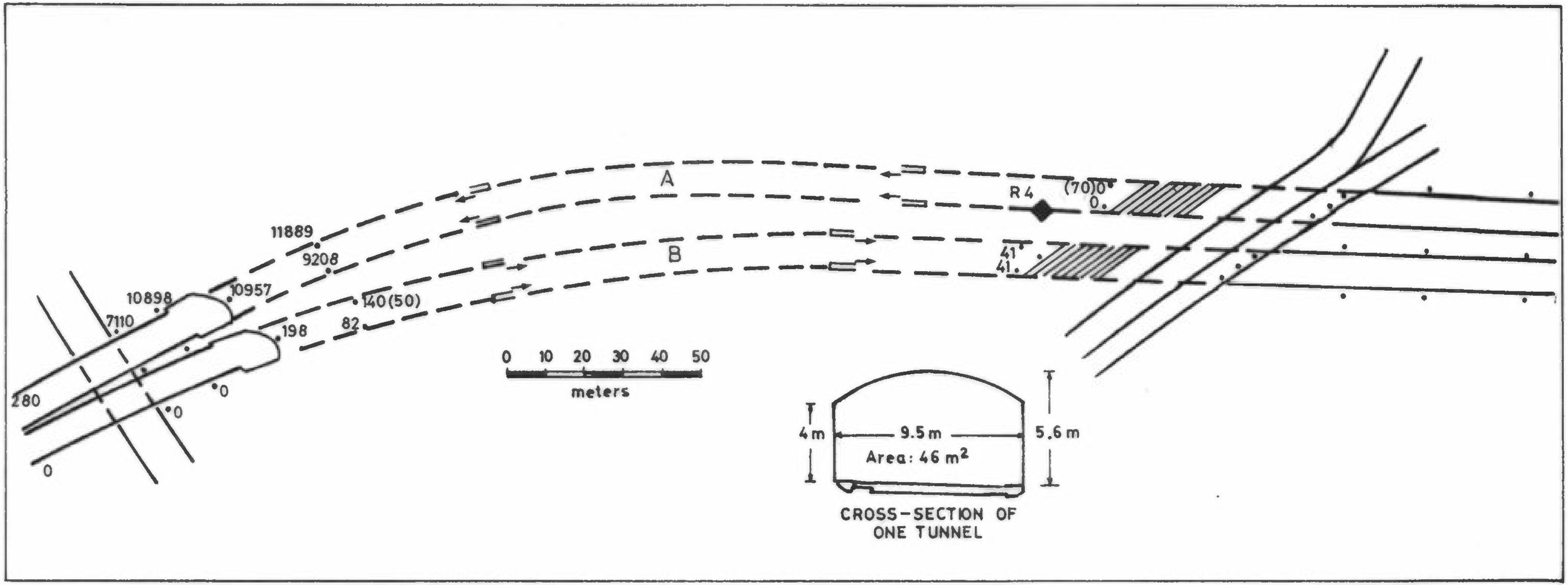


Figure 8: Fifteen minute average SF_6 concentrations, in ppt, observed during Test 7. The average of instantaneous concentrations are shown in parentheses. SF_6 was released from R4.

The skewed concentration pattern observed inside the release tunnel also appeared immediately outside the tunnel. The highest concentrations were measured along the same side of the road as the release point. In 5 of the tests, however, significant SF_6 concentrations were also detected along the side of the opposite road. These data show that the gas emitted from one tunnel is mixed across the opening of the opposite tunnel. Under calm conditions, this mixing is probably caused by the turbulence generated by the traffic itself and also by the turbulence associated with the parallel, but opposite streams of tunnel ventilation air.

The mixing of tracer across both roads resulted in the appearence of significant levels of SF_6 inside the tunnel not used for the release. During tests 1-4 and 7 where SF_6 was released in tunnel A, the SF_6 concentrations observed immediately inside tunnel B, did not show a distinct distribution pattern. During tests 5 and 6 where SF_6 was released inside tunnel B, the highest concentrations observed at the entrance to tunnel A occurred on the side of the tunnel closest to tunnel B. This pattern was repeated, with smaller differences in concentration, at points 32 and 33 in tunnel A.

Concentrations measured near the exhaust of the tunnel not used for the SF_6 release were generally less than those observed at the inlet of the same tunnel. Evidently, the SF_6 transported through the tunnel was further diluted by the action of vehicles traveling in the tunnel.

Air samples were collected in the tunnel upstream of the release point in order to determine if tracer was recirculated through both tunnels. In tests 2-4, and 7, the SF_6 concentrations observed at points 32 and 33 in tunnel A were measureably smaller than the concentrations observed at points 15 and 16 in tunnel B. However, during the remaining tests, the SF_6 concentrations at points 32 and 33 were approximately equal to or slightly higher than those found at points 15 and 16.

During tests 5,6 and 7 the sampling points were less than 15 m upstream from the release points, both of which were upstream of the first ventilation fans. In these cases, turbulent mixing caused by the traffic might explain the high concentrations.

Instantaneous air samples were collected at the inlet of the non-release tunnel and also in the tunnel upstream of the release point. Data for tests 1, 3 and 5 from the first point are shown in Figure 9 and data for the same tests from the second point are shown in Figure 10. The averages of the instantaneous data were in fair agreement with the data from the automatic 15-minute average samplers as indicated in Figures 2-8. However, the individual values given in Figures 9 and 10 show a large degree of fluctuation. Since the 1-minute average air velocities at a point were generally constant, it is possible that extremely high or low instantaneous SF_6 concentrations were closely related to the presence or absence of passing vehicles at the time of the measurements. Note also that the data from Table 1 do not suggest any correlation between the average air velocity and the average traffic count. It appears there is a relatively steady, long-term transport of air through the tunnel which is a function of the ventilation system and outside wind conditions. At the same time, it is possible that the transport of gas on a short-term basis, which can cause extremes of concentrations to occur, is a function of fluctuations in the traffic pattern. Tests designed to relate instantaneous tracer concentrations to instantaneous traffic patterns would be required to confirm this suggestion.

The SF_6 data collected in the release tunnel, downstream of the release, can be used to calculate the average air flow rate and velocity through the tunnel according to

$$\bar{C} = \frac{Q_{SF_6}}{Q_{Air}} \quad \text{or} \quad Q_{Air} = \frac{Q_{SF_6}}{\bar{C}} \qquad (1)$$

where $\bar{C}$ is the average SF_6 concentration observed in a cross-section of the tunnel, Q_{SF_6} is the average SF_6 release

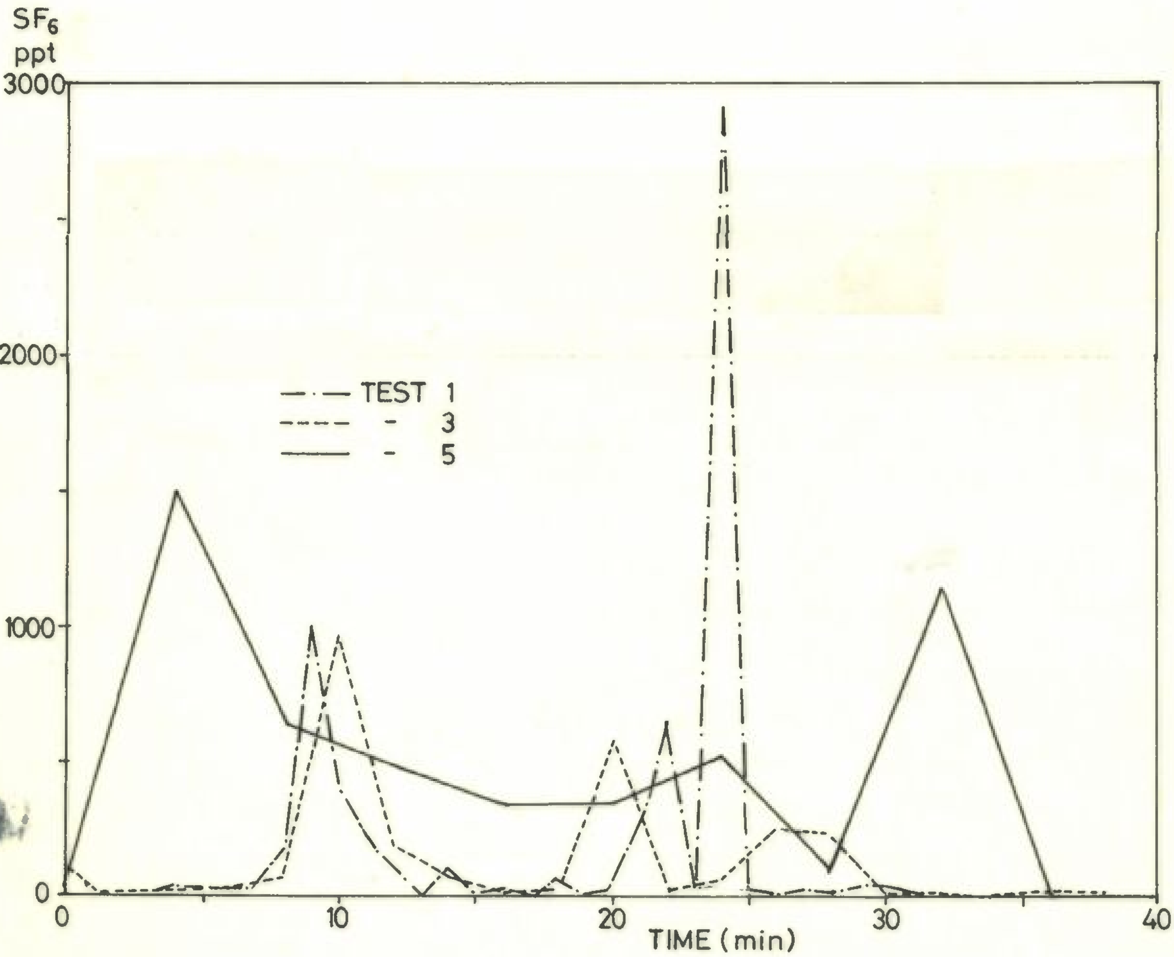


Figure 9: Instantaneous SF_6 concentrations observed at point 13 during Test 1 and Test 3 and at point 33 during Test 5. These points were each located in the entrance to the tunnel not used for the SF_6 release.

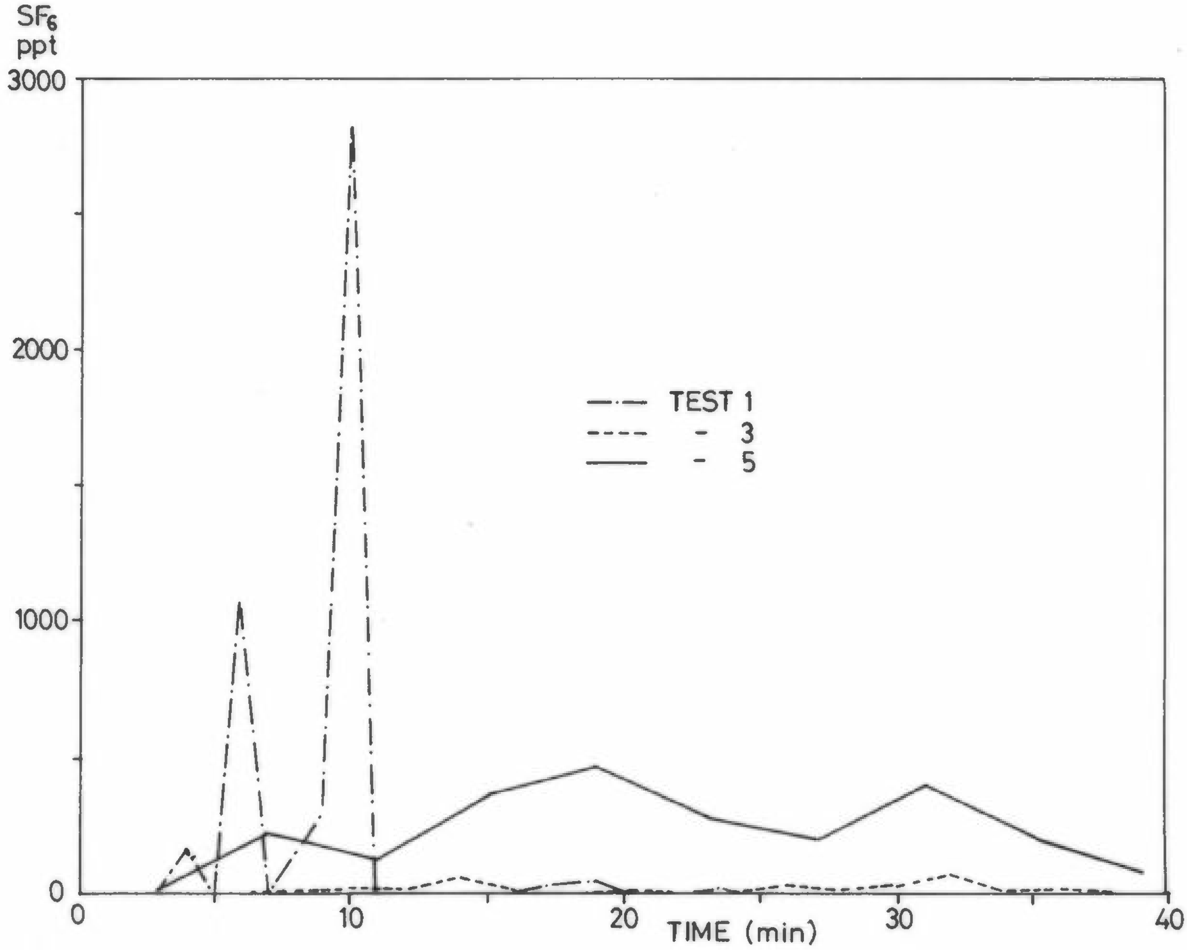


Figure 10: Instantaneous SF_6 concentrations observed at point 32 during Test 1 and Test 3 and at point 13 during Test 5. These points were each located upstream of the tracer release location.

rate, and Q_{Air} is the average air flow rate. The average air velocity is given by

$$\bar{u}_{calc} = \frac{Q_{Air}}{A} \qquad (2)$$

where A, the cross-sectional area, equals 46 m^2.
The results for these calculations are given in Table 2.
The anemometer measurements were all performed along the walls of the tunnels. It might be expected that the air velocity is greatest in this region because of the locations of the ventilation fans. This could explain the fact that values of $\bar{u}$ are systematically larger than $\bar{u}_{calc}$. The data collected with the anemometer measurements are given in Appendix A. Because the tracer data involves a phsyical process which takes place over the length and width of the tunnel, the air velocities based upon the tracer data may be more representative than those obtained from anemometer data.

It should be noted that during test 7, ambient winds of about 3 m/s were from the south, a direction roughly parallel to the tunnels. The air velocity data collected in the tunnels show that the air velocity in tunnel A was increased relative to previous tests, and the air velocity in tunnel B was decreased relative to previous tests. At times when no traffic was present in tunnel B, conditions were almost completely calm. This observation suggests that during conditions with winds parallel to the tunnel, the ventilation of one tunnel may be seriously impaired by operating the ventilation fans.

The average percent of released SF_6 which was recirculated through the non-release tunnel is given:

$$F_{SF_6} = \frac{\bar{C}_R \cdot A \cdot \bar{u}}{Q_{SF_6}} \cdot 100\% \qquad (3)$$

Table 2: Determination of air flow rates, velocities, and SF_6 recirculation.

TEST	1) $\bar{C}$	2) Q_{Air}	3) $\bar{u}_{calc.}$	4) $\bar{u}$	$\bar{u}_{calc}/\bar{u}$	5) $\bar{C}_R$	6) $\bar{u}$	7) F_{SF_6}
	ppt	m^3/s	m/s	m/s		ppt	m/s	%
1	13664	167	3.6	-	-	1721	3.6	12
2	-	-	-	4.7	-	113	3.7	1.0
3	13032	155	3.4	4.7	.72	114	4.4	1.1
4	17970	112	2.4	2.8	.86	282	3.1	2.0
5	17229	142	3.1	3.4	.91	221	4.5	1.9
6	16779	148	3.2	4.2	.76	58	3.9	0.4
7	10685	235	5.1	5.8	.88	140	1.9	0.5

1.) $\bar{C}$ is the average of the SF_6 concentrations observed at points 1, 2, and 3 for tests 1-4, and 7, and the average of the SF_6 concentrations observed at points 15 and 16 for tests 5 and 6.

2.) $Q_{Air} = \frac{Q_{SF_6}}{\bar{C}}$ where Q_{SF_6} is the average SF_6 release rate and Q_{Air} is the average total air flow rate.

3) $\bar{u}_{calc} = \frac{Q_{air}}{A}$ where A is the cross-sectional area of the tunnel.

4) $\bar{u}$ is the average air velocity determined from several 1-minute anemometer measurements.

5) $\bar{C}_R$ is the average of the SF_6 concentrations observed at points 12, 13, and 14 for tests 1-4 and 7, and the average of the SF_6 concentrations observed at points 32 and 33 for tests 5 and 6.

6) $\bar{u}_R$ is the average air velocity in the tunnel where $\bar{C}_R$ is measured.

7) $F_{SF_6} = \frac{\bar{C}_R \cdot A \cdot \bar{u}_R}{Q_{SF_6}} \cdot 100\%$ F_{SF_6} is the percent of released SF_6 which was recirculated.

ere $\bar{C}_R$ is the average SF_6 concentration measured in vertical cross-section at the sampling points nearest the entrance to the non-release tunnel. The results of this calculation are listed in Table 2. For test 1, it was assumed that the air velocity taken from the tracer data for tunnel A also existed in tunnel B. For tests 1-4, and 7, $\bar{C}_R$ was calculated with data from points 12,13, and 14. For tests 5 and 6, $\bar{C}_R$ was based upon data from points 32 and 33; values of $\bar{u}$ for these tests were taken from the averages for point 33, given in Appendix A.

The results indicate that while as much as 12% of the released SF_6 was recirculated during test 1, no more than 2% was recirculated in any of the following experiments. There was no discernable net air movement outside the tunnels during test 1 which would account for the relatively large degree of recirculation. It is suggested that in future tests, recording anemometers be positioned outside above each end of each tunnel. Although no air velocity data are given in Table 1 for test 1, soap bubble measurements indicated that the air velocity in both tunnels was between 3 and 4 m/s, which is similar to velocities measured in subsequent tests. The traffic data also show no significant deviations in test 1 when compared to data for tests 2-7. The data for all tests suggest that under calm and low wind conditions the amount of pollutants which might be recirculated from one tunnel to the next is of order 1% to 10%. Note, however, that none of the tests were conducted during conditions with measureable winds blowing across the exit of the SF_6 release tunnel towards the entrance of the adjoining tunnel. These conditions could cause a larger amount of recirculation to occur. Additional tracer tests would be necessary to quantify the amount of recirculation which might occur during these "worst-case" situations.

These results can be used to estimate the contribution of pollutants released in one tunnel to pollutants levels observed in the parallel tunnel. For example, if the average concentration of CO at the exit of tunnel A is 200 ppm, then the contribution to tunnel B could be between 2 ppm and 20 ppm. Thus, if measured levels in tunnel B also equaled 200 ppm, between 180 ppm and 198 ppm of CO would result from CO emissions inside tunnel B.

The effect of a roof ventilation outlet in the tunnel upon the transport and recirculation of pollutants can be examined with the data from tests 5 and 6. In test 5, the flux of SF_6 past points 18,19 and 20 was equal to 78% of the SF_6 released. It has been assumed that the air velocity calculated from the tracer data inside tunnel B also existed at the exit of tunnel B. If it is assumed that no SF_6 was lost upstream of points 15 and 16, then it appears that approximately 22% of the SF_6 was vented through the opening in the tunnel roof immediately downstream of points 15 and 16. This figure could be an underestimate of the loss through the roof since the air velocity used in the calculation may be larger than the actual air velocity. Data given in Appendix A for tests 5 and 6 indicate that the air velocity inside tunnel A is approximately 2 times higher than the air velocity measured at the entrance to tunnel A. If this were true for tunnel B, the SF_6 flux observed at points 18,19, and 20 would be 30%, and the flux through the roof vent would be 61%.

Similar calculations for test 6 yield an SF_6 flux through the exit of tunnel B ranging from 79% to 39% and a corresponding flux through the roof vent ranging from 21% to 61%. A roof vent thus appears to cause a significant loss of gas from the tunnel. However, since the SF_6 fluxes recirculated through tunnel A during these tests were similar to those observed in other tests, some of the recirculation may occur through the roof vents. Further measurements would be necessary to specify the amount of recirculation which might take place through the roof vents.

4 SUMMARY

The purpose of these experiments was to quantify the amount of pollutants which, when released in one automobile tunnel, are recirculated into an adjoining, parallel tunnel. It appears that under calm or low wind conditions, between 0.4% and 12% of tracer released in one of the Bryn tunnels is recirculated into the other Bryn tunnel. The uncertainty in the maximum value is estimated to be 12 ± 3%. The recirculation is apparently associated with turbulent mixing of the exhaust gas from one tunnel across the entrance of the second tunnel. Between 21% and 61% of the gas appears to be exhausted through a large vent in the roof of the tunnels. However, the data do not suggest that this causes a significant decrease in the amount of recirculation. This, in turn, indicates that recirculation of air through the roof vents also occurs.

Tracer data can be used to determine the total air flow rate through a tunnel and the corresponding air velocity. Average air velocities determined with the tracer data in these tests were in good agreement with the average air velocities determined from 1 and 2 minute wind observations. This work demonstrates that tracer techniques offer a simple relatively inexpensive means of quantitatively studying the ventilation of automobile tunnels.

APPENDIX A

AIR VELOCITY DATA

TEST	TUNNEL	LOCATION	AVERAGING TIME (min)	u (m/s)
1		-	-	-
2	A	R1	2	5.0
		R1	2	5.0
		32	2	4.4
		R1	2	4.3
				$\bar{u}_A$ = 4.7
	B	13	1	3.6
		13	1	3.9
		13	1	3.5
		13	1	3.8
				$\bar{u}_B$ = 3.7
3	A	R1	1	5.0
		R1	1	4.9
		opposite R1	1	4.3
		opposite R1	1	4.8
		R1	1	4.5
				$\bar{u}_A$ = 4.7
	B	13	1	4.0
		13	1	4.3
		13	1	5.0
		13	1	4.3
		13	1	4.2
		13	1	4.4
				$\bar{u}_B$ = 4.4
4	A	R1	1	2.3
		R1	1	3.3
(FANS WERE OFF DURING TEST 4)		opposite R1	1	2.4
		opposite R1	1	1.8
		32	1	2.6
		R1	5	3.1
				$\bar{u}_A$ = 2.8
	B	13	1	2.9
		13	1	2.9
		13	1	3.2
		13	1	3.2
		13	1	3.3
		13	1	3.3
				$\bar{u}_B$ = 3.1

	TUNNEL	LOCATION	AVERAGING TIME (min)	u (m/s)	
	A	23	1	1.9	
		23	1	5.3	
		23	1	1.5	
		33	1	4.2	
		23	1	2.0	
		33	1	4.0	
				$\bar{u}_A$ = 3.2	$\bar{u}_A$ at point 23=1.8 $\bar{u}_A$ at point 33=4.5
	B	R2	1	3.9	
		R2	1	3.3	
		R2	1	3.2	
		R3	1	3.7	
		50 m from R2, between fans	1	2.8	
		R2	1	3.2	
				$\bar{u}_B$ = 3.4	
6	A	23	1	3.5	
		33	1	4.2	
		23	1	3.5	
		33	1	3.5	
		23	1	1.5	
		33	1	4.0	
		23	1	2.0	
		33	1	3.8	
				$\bar{u}_A$ = 3.3	$\bar{u}_A$ at point 23=2.6 $\bar{u}_A$ at point 33=3.9
	B	R3	1	3.4	
		R3	1	4.3	
		R3	1	3.9	
		R2	1	3.7	
		opposite R1 in tunnel B	1	5.6	
		R3	1	4.0	
				$\bar{u}_B$ = 4.2	
7	A	R4	1	4.3	
		R4	1	4.9	
		opposite R4	1	6.0	
		opposite R1	1	6.5	
		opposite R1	1	7.0	
		R4	1	5.4	
		R4	1	5.8	
				$\bar{u}_A$ = 5.7	
	B	13	1	3.9	
		opposite R1, in tunnel B	1	2.2	
		13	1	2.7	
		opposite R1, in tunnel B	1	1.0	
		13	1	.7	
		opposite R1, in tunnel B	1	.5	
		13	1	2.2	
		opposite R1, in tunnel B	1	1.8	

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REFERAT (maks. 300 anslag, 5-10 linjer)

Syv sporstoffundersøkelser er utført i oktober og november 1978 for å registrere ventilasjonen i Bryntunnelen i Oslo. Hensikten med undersøkelsene var å bestemme mengden av forurensninger, som når de slippes ut i et tunnelløp, trekkes med ventilasjonsluften inn i det andre tunnelløpet. Ved vindstille eller liten vind ble mellom 0.4 og 12% av sporstoffutslippet registrert i det andre tunnelløpet.

TITTEL

ABSTRACT (max. 300 characters, 5-10 lines)

Seven SF_6 tracer experiments were conducted during October and November, 1978 in the Bryn tunnels in Oslo. The purpose of these tests was to determine the amount of pollutants which, when exhausted from one tunnel, are recirculated into an adjoining, parallel tunnel. Under calm or low wind conditions, between 0.4% and 12% of tracer released in one tunnel was recirculated into the opposite tunnel.

**Kategorier: Åpen - kan bestilles fra NILU A
Må bestilles gjennom oppdragsgiver B
Kan ikke utleveres C