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DEVELOPMENT OF A CONTROLLED DOSING SYSTEM FOR METHYL BROMIDE FUMIGATION OF MILLS AND GRAIN STORAGE STRUCTURES

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DEVELOPMENT OF A CONTROLLED DOSING SYSTEM FOR METHYL BROMIDE FUMIGATION OF MILLS AND GRAIN STORAGE STRUCTURES

by

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SUMMARY

A new microprocessor-controlled dosing system to fumigate flour mills using methyl bromide was tested at three mills. Concentration-time products (CTPs) high enough to control all stages of pest species were obtained at all three mills except at one gas sampling position at one of the mills which was located near a point of leakage. However, the CTP at this position was high enough to control all stages of insects in a bioassay that was placed at this position.

At the third site two mills were fumigated, one under control of the dosing system and the other using the traditional method. A saving in the amount of methyl bromide used was demonstrated in the mill fumigated using the dosing system even under the ideal weather conditions observed. In more windy conditions a greater saving would be expected.

INTRODUCTION

In 1992 methyl bromide was listed by the United Nations Environment Programme as an ozone depleting substance. In the ninth meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer in Montreal in September 1997 it was agreed that developed countries should reduce their consumption by 25% in 1999, by 50% in 2001, by 70% in 2003 and to phase out as of 2005 with an exemption for quarantine and pre-shipment uses and as yet undefined "critical agricultural uses".

In the seventh meeting of the Parties to the Montreal Protocol in Vienna (UNEP, 1995) decision VII/6 specifically states that "parties should endeavour to reduce methyl bromide emissions by encouraging producers and users to take appropriate measures to implement, inter alia, good agricultural practices and improved application techniques".

Flour mills can become infested with insect pests such as *Tribolium castaneum*, *Tribolium confusum*, *Cryptolestes turcicus* and *Ephestia kuehniella*. When this happens they are currently fumigated using methyl bromide. Fumigation of flour mills is one of the most difficult areas in which to find a suitable replacement for methyl bromide. Methyl bromide became the fumigant of choice for treating mills 35-40 years ago, because it had a rapid action, was a good penetrant, did not react with any structural materials as a gas, as well as being non-flammable and effective against a very wide range of pests. Methyl bromide, and the gas it replaced for this use, hydrogen cyanide, are both able to give acceptable results within 24 hours, although methyl bromide is a far better penetrant. For flour mills, the cost of production losses per day are likely to far exceed the cost of the fumigation itself, and so any alternative method considered also has to have a rapid action. At this time no obvious replacement exists. Furthermore, although structural fumigation is a minor use area in terms of the total methyl bromide market, more of the gas applied is emitted to the atmosphere from these treatments because there is little scope for sorption and reaction. There is thus a strong case for research to reduce methyl bromide doses and emissions from this area.

To control insect pests with methyl bromide a concentration-time product (CTP) of at least 200 g h m^{-3} throughout the mill is recommended (Anon, 1974). To achieve the CTPs necessary, fumigators apply high initial doses and top up the gas later in the fumigation. This often leads to over-dosing of some areas. A microprocessor-controlled dosing system has been developed at the Central Science Laboratory to increase the efficiency of the fumigation of flour mills with methyl bromide. In an early test at a flour mill the dosing system had shown promise as a more efficient means of fumigating flour mills by providing CTPs sufficient to control insect pests and at the same time minimising the need to over-dose (Wontner-Smith *et al*, 1994).

The dosing system has now been upgraded and tested on three further occasions.

MATERIALS AND METHODS

The microprocessor-controlled dosing system (Fig. 1) can serve up to sixteen separate areas. A sample of gas is drawn from each area in sequence via “nylon-6” gas sampling lines (2 mm bore) to the main cabinet of the system where the concentration of methyl bromide is measured by a thermal conductivity detector. The microprocessor compares the measured concentration level from every area with a pre-set threshold level. If a particular area is below the threshold level then it will receive methyl bromide for a programmed period (dose-time).

The methyl bromide is supplied via 9.5 mm nylon dosing lines which are opened and closed by a series of rack-mounted solenoid valves. The valves are controlled by the microprocessor in the main cabinet of the system to which they are connected via cables and interface with a gas manifold connected to a cylinder based supply of methyl bromide.

When every area has been sampled and dosing has occurred where necessary, the cycle is repeated. After a predetermined period the microprocessor terminates the sampling and dosing process. All variables are set using a Psion Organiser.

Since the early test (Wontner-Smith *et al.*, 1994) the dosing system has been upgraded to give more repeatable concentration readings by using a less powerful pump and a lower gas flow rate through the sensor. The programming of the system has been modified so that the amount of methyl bromide dosed at each dosing position is recorded by the system and the re-dosing threshold is more simple to set. Copper coils have been incorporated at the dosing system end of the dosing lines to aid vaporization.

In between small scale tests in the laboratory, the dosing system was tested at three separate mills (A, B and C). A fourth mill (mill D) was treated at the same site as mill C following the procedure normally used by the fumigation company.

In all trials, in addition to the sampling operation of the automated dosing system, the concentration of fumigant was monitored automatically from a mobile laboratory equipped with a Hewlett Packard 5890 series II gas chromatograph (GC). The GC was fitted with a flame ionisation detector, an automatic sampling loop, two 16 port stream selection valves and a 2 m x 3.1 mm OD glass-lined stainless steel column packed with Porapak QS. Samples of gas were drawn from the atmosphere in the fumigated area to the GC via "nylon-6" gas sampling lines (2 mm bore) using a Capex pump at a constant rate controlled by a mass flow controller. Wind speed and wind direction were monitored using a weather station positioned on the mill roof and temperature at various points in the mill were monitored using copper-constantan thermocouples.

At all three sites Igrox Limited had been contracted to carry out the fumigations and the initial dose was applied by Igrox via reinforced PVC dosing lines. The outlets of the dosing lines were split using plastic piping to which were joined lengths of perforated polythene lay-flat tubing to provide good initial gas distribution in the mills. "Hot gas" was supplied to the dosing lines via a vaporiser.

After application of the initial dose the concentration of methyl bromide was maintained by the dosing system.

Mill A

The mill included storage structures for receiving and holding the grain. These were in the form of bins which could be accessed from the top floor of a 5-storey building which also contained the mill. Both the bin area and the mill itself were to be fumigated. On the first four floors, gas sampling lines were fixed in sampling positions A, B, C and D (Fig. 2). On the top floor sampling position D was not used because the room on the bin side was only 56.6 m^3. An additional sampling line was dropped 3 m into one of the bins from the top floor.

Dosing lines for the initial dose were fixed on each of the first three floors of the mill. Floors 4 and 5 were dosed from the same line. On the bin side, all floors were dosed from the same line except floor 5 which had a separate line.

A mixing fan was placed on floor 1 (the ground floor) on the mill side under a shaft for a man hoist that went to floor 4. A large diameter piece of lay-flat tubing ran from the fan outlet to floor 4 so that gas could be taken from floor 1 to floor 4 to provide extra mixing of the gas.

A second set of gas sampling lines were fixed at sampling positions B and D on each floor for the dosing system. Nylon dosing lines (9.5 mm OD) with ceramic jets in the outlets were positioned on both sides on every floor. Lay-flat tubing of 3 to 5 m lengths was taped to the end of each dosing line and fixed across the room (Fig. 2). Lengths of plastic sheeting were fixed beneath the lay-flat tubing to protect the floors and machinery from any unvaporised liquid methyl bromide. The dose time was set at 5 seconds and the threshold concentration was set at the high level of 18 g m^{-3}. This was because the contract between Igrox Limited and the mill management involved maintaining the concentration of methyl bromide above 16 g m^{-3}, at all times, until a CTP of 200 g h m^{-3} had been achieved. The fumigation had then to be extended to give a total exposure time of 24 hours. The dosing system had not been designed to maintain such high concentrations and so a second dose was applied by Igrox Ltd after 5.3 hours to insure that the terms of the contract were met.

CTPs of at least 200 g h m^{-3} had been achieved at all the Igrox sampling positions after 12 hours. The threshold for the dosing system was then reduced to 12 g m^{-3} and the dose time was increased to 8 seconds.

Mill B

The mill had four floors with an attic in the top floor and was part of a larger building with ante rooms on each floor between the mill and the rest of the building. The mill was sealed off from the ante rooms and treated as a separate unit except on floor 1 (the ground floor) where the ante room was treated as part of the mill.

Gas sampling lines were fixed at sampling positions 1 to 4 on the floor 4 (Fig. 3) and sampling positions 5 and 6 on floors 1 to 3 (Fig. 4). Extra gas lines were fixed at sampling position 7 on floor 2 and sampling position 8 on floor 1. The heights of the sampling positions are given in Table 10.

A bioassay was included in this treatment. Thirty-two cultures of the rust-red flour beetle, *Tribolium castaneum*, were started by placing twenty-five unsexed adult beetles on each of thirty-two jars containing 40 g of wholemeal flour plus 5% yeast. The jars were sealed by fine nylon mesh and a screw top. Adult beetles were kept on the flour so that they continued to lay eggs up to the time of fumigation. The culture schedule was planned so that at the time of the fumigation they contained all developmental stages including adult beetles, the naturally tolerant pupae and young eggs.

A pair of cultures remained in the laboratory and was maintained at a temperature similar to that in the mill. Pairs of cultures were placed in the mill in free space locations at sampling positions 1 to 4 on floor 4 (Fig. 3) and at sampling positions 5 to 7 on floors 1 to 3 (Fig. 4). The number of pupae in the controls was counted on the day the other cultures were placed in the mill after removing the original adults to prevent further oviposition. Thirty cultures containing an average of at least 533 pupae each were fumigated. The treated cultures were examined weekly to determine if any adult beetles emerged.

The initial dose was applied by Igrox Limited via dosing lines which had been fixed on each floor. The contract between Igrox and the mill management did not require high initial concentrations and so a second booster dose was not necessary.

A mixing fan was placed on floor 1 (the ground floor) and a large diameter piece of lay-flat tubing ran from the fan outlet to floor 4 so that gas could be taken from floor 1 to floor 4 to provide extra mixing of the gas if required. The fan was switched off half an hour after the initial dose and was not used again.

A second set of gas sampling lines were fixed at sampling positions 2, 3 and 4 on floor 4 and at sampling positions 5 and 6 on floors 1 to 3. These were connected to the dosing system. Nylon dosing lines (9.5 mm OD) with ceramic jets in the outlets were fixed at dosing positions A, B and C on floor 4 and dosing positions D and E on floors 1 to 3. Lay-flat tubing of 3 to 5 m lengths was taped to the end of each dosing line and fixed across the room (Figs 3 and 4). Lengths of plastic sheeting were fixed beneath the lay-flat tubing to protect the floors and machinery from any unvaporised liquid methyl bromide. The threshold concentration was set at 12 g m^{-3} and the dose time was set at 5 seconds.

Mills C and D

These two mills were part of the same building but were treated separately. Each mill had four floors.

Gas sampling lines were fixed at sampling positions A to D on each of the four floors (Fig. 5). An extra gas line was fixed at sampling position E on floor 1 (ground floor).

In both mills, the initial dose for floors 3 and 4 were supplied from the same dosing line. Floor 2 and floor 1 (ground floor) had separate dosing lines. The contract between Igrox and the mill management did not require high initial concentrations and a second dose was not necessary.

As at the previous mills, mixing fans were placed on floor 1 (the ground floor) of both mills and a large diameter piece of lay-flat tubing ran from the outlets of the fans to floor 4 to provide extra mixing of the gas if required. In mill C the fan was switched off half an hour after the initial dose and was not used again and in mill D the fan was left on for the whole exposure time.

A second set of gas sampling lines were fixed at sampling positions A and B on all floors of mill C. These were connected to the dosing system. Nylon dosing lines (9.5 mm OD) with ceramic jets in the outlets were fixed at dosing positions A and C on all floors and lay-flat tubing of 3 to 5 m lengths was taped to the end of each dosing line and fixed across the room (Fig. 5). Once again, lengths of plastic sheeting were fixed beneath the lay-flat tubing to protect the floors and machinery from any unvaporised liquid methyl bromide. The threshold concentration was set at 12 g m^{-3} and the dose time was set at 3 seconds.

RESULTS

Figures 6 to 10 show the concentration of methyl bromide against time at mill A, figures 11 to 14 show the same for mill B, figures 15 to 18 for mill C and figure 19 shows the same for mill D.

The theoretical CTP is that which would be obtained over the exposure period if the total dose had been applied at the start of the trial and there had been no leakage. For the sake of comparison the exposure time was taken as 24 hours for all trials.

Tables 1 to 8 give the dosage rates, theoretical CTPs and the amount of methyl bromide delivered to each dosing position by the dosing system at the four mills. The total theoretical CTP was 1050 g h m^{-3} at mill A, 1181 g h m^{-3} at mill B, 685 g h m^{-3} at mill C and 781 g h m^{-3} at mill D. The higher value obtained at mills A and B shows that more methyl bromide was used per unit volume.

Table 9 gives the CTPs obtained at mill A along with results from a similar trial undertaken at the same mill in 1994 (Wontner-Smith *et al.*, 1994). The CTPs were much greater than 200 g h m^{-3} which shows the high degree of overdosing that was necessary because of the unusual contract between Igrox and the mill management. The average CTP was about the same as in 1994 but the lower standard deviation shows that CTPs were more even. This is true even on the bin side where no mixing fan was used.

Table 10 shows the CTPs obtained at mill B. All CTPs except one were over 200 g h m^{-3} and the average CTP was 262 g h m^{-3} only 67% of the value obtained at mill A and the standard deviation was only 28.9 g h m^{-3}, 38% of the value obtained at mill A. The lower average deviation shows the more even gas distribution obtained when the dosing system is used to control the whole of the top up dose compared with the partial use of the system at mill A. There was no survival of pupae or other developmental stages in the bioassay even at the position where 200 g h m^{-3} was not achieved. In the two control jars 508 live insects were counted from one and 729 from the other.

Table 11 shows the CTPs obtained at mill C. These are similar to the results obtained at mill B. All CTPs were over 200 g h m^{-3}, the average CTP from 9 positions was 281 g h m^{-3} and the standard deviation was only 15.5 g h m^{-3}.

Table 12 shows the CTPs obtained at mill D. The average CTP from the 4 sample positions was 300 g h m^{-3}, 6.8% higher than at mill C which was treated at the same site and at the same time under the control of the dosing system.

Table 13 shows the average temperature in the mills and the average wind speed at the three sites. Figure 20 shows the wind speed against time at the three sites.

DISCUSSION

CTPs of over 200 g h m^{-3} were obtained everywhere in all trials except at one position at mill B which was located within a few inches of a bulkhead to the outside, a probable point of leakage. The CTP at this position was high enough to control all stages of insects in the bioassay jars placed at this position. All other sampling positions gave CTPs above the recommended minimum.

Figure 21 shows the theoretical CTPs and the average CTPs obtained at the four mills. The theoretical CTP at mill B was similar to the theoretical CTP at mill A but the average CTP at mill B was lower than at mill A. This shows a higher degree of leakage at mill B. The theoretical CTPs at mills C and D were much lower than at the other two sites. This shows that a lower amount of methyl bromide per unit area was needed. This was probably because the weather conditions over the exposure period were very still. At no time did the wind speed exceed 3 m s^{-1} (Fig. 20).

The lowest average CTPs were obtained at mills B and C where a low initial dose was used and the dosing system controlled the top-up dose. This demonstrates that the dosing system was delivering the correct amount of methyl bromide under good conditions at mill C and the relatively leaky conditions at mill B.

Mills C and D were treated at the same site and at the same time. Because of the calm weather conditions the initial dose was adequate to provide high enough CTPs in mill D without any top-up gas. The lower initial dose at mill C meant that top-up gas was required. This was delivered by the dosing system. At mill D the theoretical and average CTPs were both higher than at mill C which shows that the dosing system provided a small saving of methyl bromide even in the ideal fumigation conditions experienced in the trial. In more windy conditions a greater saving would be expected because in normal fumigation practice more top-up gas would need to be applied because of the risk of leakage. There is a need for a margin of safety in the amount of gas applied because the mill is not constantly monitored throughout the fumigation.

In normal practice most fumigant is added at the start of the fumigation, usually to the upper floors of the mill, with the option of topping up later as the concentration falls. A minimum methyl bromide CTP of 200 g h m^3, recommended to achieve complete control of pests, is the target aimed for in most fumigations, which are generally conducted in the summer season. In the present trials, the automated, sensor-controlled dosing has demonstrated the capacity to compensate for leakage in mill fumigations, improving efficacy and achieving moderate dosage reductions over conventional dosing methods which introduce most gas at the start of fumigation. The system is only suitable for use with a pressurised supply of methyl bromide. This can be provided by pressurising standard cylinders of methyl bromide with air or nitrogen or from a cylinder-based supply of 80% methyl bromide in 20% carbon dioxide.

CONCLUSION

Concentration-time products high enough to control all stages of pest species have to be obtained for successful treatment of flour mills. Conventional fumigation techniques achieve this by topping up a high initial dose of methyl bromide.

Use of the automated dosing system offers the prospect of reducing the amount of methyl bromide used. This was demonstrated at the site where two mills were treated, one with the help of the dosing system and the other without, under the ideal weather conditions observed. In more usual weather conditions a greater saving of gas would be expected.

ACKNOWLEDGEMENTS.

The authors are grateful to Igrox Limited for all their help.

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Table 1. Dosage rates and theoretical concentration-time products on the mill side at Mill A.

Floor	Volume treated (m^3)	Initial Dosage Rate (kg)	Top-Up Dosage Rate (kg)	Top-Up Dose from Dosing System (kg)	Total Dose (kg)	Theoretical Concentration-Time Product ($g\ h\ m^{-3}$)
5	538	29.5	15.0	3.29	23.4	1045
4	651			7.93	32.3	1191
3	651	16.5	5.0	0	21.5	793
2	651	16.5	5.0	6.58	28.1	1035
1 (ground)	651	16.5	5.0	6.58	28.1	1035
Total	3142	79.0	30	24.38	133.4	1019

Table 2. Dosage rates and theoretical concentration-time products on the bin side at Mill A.

Floor	Volume treated (m^3)	Initial Dosage Rate (kg)	Top-Up Dosage Rate (kg)	Top-Up Dose from Dosing System (kg)	Total Dose (kg)	Theoretical Concentration-Time Product ($g\ h\ m^{-3}$)
5	56.6	8.0	20.0	5.41	33.4	14167
4	368	30.0	0	1.35	8.8	577
3	368			0	7.5	489
2	368			1.35	8.8	577
1 (ground)	368			4.93	12.4	811
Total	1529	38.0	20.0	13.04	71.0	1115

Table 3. Performance of the dosing system at Mill A.

Floor	Number of times the dosing system operated.				Mass of methyl bromide dosed by dosing system (kg)	
	Mill Side		Bin Side			
	Initially	Set at 12 g m^{-3}	Initially	Set at 12 g m^{-3}	Mill Side	Bin Side
5	0	2	4	0	3.29	5.41
4	1	4	1	0	7.93	1.35
3	0	0	0	0	0	0
2	0	4	1	0	6.58	1.35
1 (ground)	0	4	0	3	6.58	4.93
Methyl bromide dosed by dosing system (kg)	1.35	23.03	8.11	4.93		

Table 4. Dosage Rates and Theoretical Concentration-Time Products at Mill B.

Floor	Volume treated (m^3)	Initial Dosage Rate (kg)	Top-Up Dose from Dosing System (kg)	Theoretical Concentration-Time Product ($g\ h\ m^{-3}$)
4	637	15.9	16.9	1236
3	425	10.0	6.9	954
2	425	10.0	10.0	1129
1 (ground)	550	13.6	16.9	1331
Total	2037	49.5	50.7	1181

Table 5. Performance of the dosing system at mill B.

Floor	Number of times the dosing system dosed.		Mass of methyl bromide dosed (kg)	
	Left	Right	Left	Right
Attic	13		9.97	
4	5	4	3.83	3.06
3	3	6	2.30	4.60
2	6	7	4.60	5.37
1 (ground)	9	13	6.90	9.97
Total dose of methyl bromide (kg)	50.6			

Table 6. Dosage Rates and Theoretical Concentration-Time Products at Mill C.

Floor	Volume treated (m^3)	Initial Dosage Rate (kg)	Top-Up Dose from Dosing System (kg)	Theoretical Concentration-Time Product ($g\ h\ m^{-3}$)
4	1200	52	7.06	704
3	1016		6.47	716
2	762	16	7.64	745
1 (ground)	1219	23	7.64	603
Total	4197	91	28.80	685

Table 7. Performance of the dosing system at mill C.

Floor	Number of times the dosing system dosed.		Mass of methyl bromide dosed (kg)	
	A	B	A	B
4	6	6	3.53	3.53
3	6	5	3.53	2.94
2	7	6	4.11	3.53
1 (ground)	7	6	4.11	3.53
Total dose of methyl bromide (kg)	28.8		28.8	

Table 8. Dosage Rates and Theoretical Concentration-Time Products at Mill D.

Floor	Volume treated (m^3)	Initial Dosage Rate (kg)	Theoretical Concentration-Time Product ($g\ h\ m^{-3}$)
3 and 4	708	23	780
2	425	14	791
1 (ground)	680	22	776
Total	1813	59	781

Table 9. Concentration-Time Products (CTPs) at Mill A.

Side	Floor	Sampling Position	Height (m)	CTP in 1996 ($g\ h\ m^{-3}$)	CTP in 1994 ($g\ h\ m^{-3}$)
Mill	5	A	3	297	235
Mill	5	B	0.5	349	302
Bin	5	C	2	357	-
Mill	4	A	3	369	321
Mill	4	B	0.5	338	330
Bin	4	C	3	394	345
Mill	3	A	3	374	308
Mill	3	B	0.5	372	305
Bin	3	C	3	263	379
Bin	3	D	0.5	424	376
Mill	2	A	3	389	358
Mill	2	B	0.5	376	367
Bin	2	C	3	411	440
Bin	2	D	0.5	409	437
Mill	1 (ground)	A	3	365	441
Mill	1 (ground)	B	0.5	547	533
Bin	1 (ground)	C	3	397	514
Bin	1 (ground)	D	0.5	614	781
Inside bin 3 m from the top				387	-
Average CTP ($g\ h\ m^{-3}$)				391	398
Standard deviation ($g\ h\ m^{-3}$)				78	126
Average CTP bin side ($g\ h\ m^{-3}$)				409	467
Standard deviation bin side ($g\ h\ m^{-3}$)				98	149

Table 10. Concentration-Time Products at Mill B.

Floor	Sampling Position	Height (m)	Associated Dosing Position	Concentration-Time Product (g h m^{-3})
4 (Attic)	1	6		241
4 (Attic)	2	4	A	222
4	3	3	B	284
4	4	0.5	C	280
3	5	0.5	D	289
3	6	3	E	262
2	5	0.5	D	278
2	6	3	E	275
2	7	3		274
1 (ground)	5	0.5	D	273
1 (ground)	6	3	E	188
1 (ground)	8	3		279
Average Concentration-time product (g h m^{-3})				262
Standard Deviation (g h m^{-3})				30.2

Table 11. Concentration-Time Products at Mill C.

Floor	Sampling Position	Height (m)	Associated Dosing Position	Concentration-Time Product (g h m^{-3})
4	A	3.5	A	298
4	B	0.5	B	293
3	A	3	A	291
3	B	0.5	B	293
2	A	2.5	A	281
2	B	0.5	B	285
1 (ground)	A	4	A	250
1 (ground)	B	0.5	B	278
1 (ground)	C	1		264
Average Concentration-time product (g h m^{-3})				281
Standard Deviation (g h m^{-3})				15.5

Table 12. Concentration-Time Products at Mill D.

Floor	Sampling Position	Height (m)	Concentration-Time Product (g h m^{-3})
4	D	3	306
3	E	1	309
2	D	3	301
1 (ground)	E	1	282
Average Concentration-time product (g h m^{-3})			300
Standard Deviation (g h m^{-3})			12.4

Table 13. Temperature and wind speed at Mills A, B, C and D.

	Temperature (°C)			Wind Speed (m s^{-1})		
	Mill A	Mill B	Mills C and D	Mill A	Mill B	Mills C and D
Average	15.1	26.0	22.9	2.29	1.14	1.3
Maximum	17.4	27.4	24.1	7.03	4.27	2.8
Minimum	13.5	22.0	19.3	0.09	0.00	0.04

Fig. 1 Microprocessor-controlled dosing system.

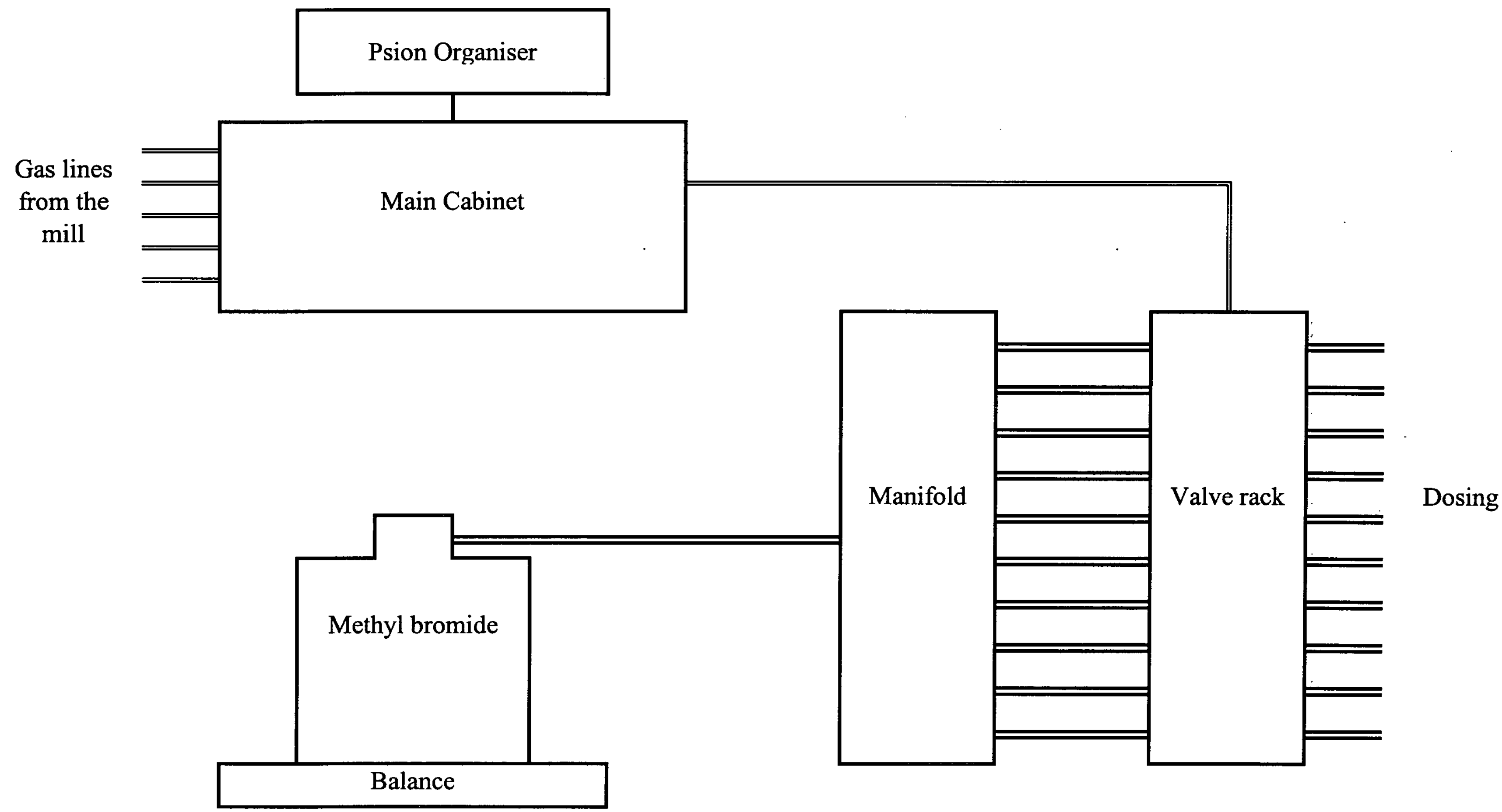

Fig 2. Sampling and automated dosing positions at mill A

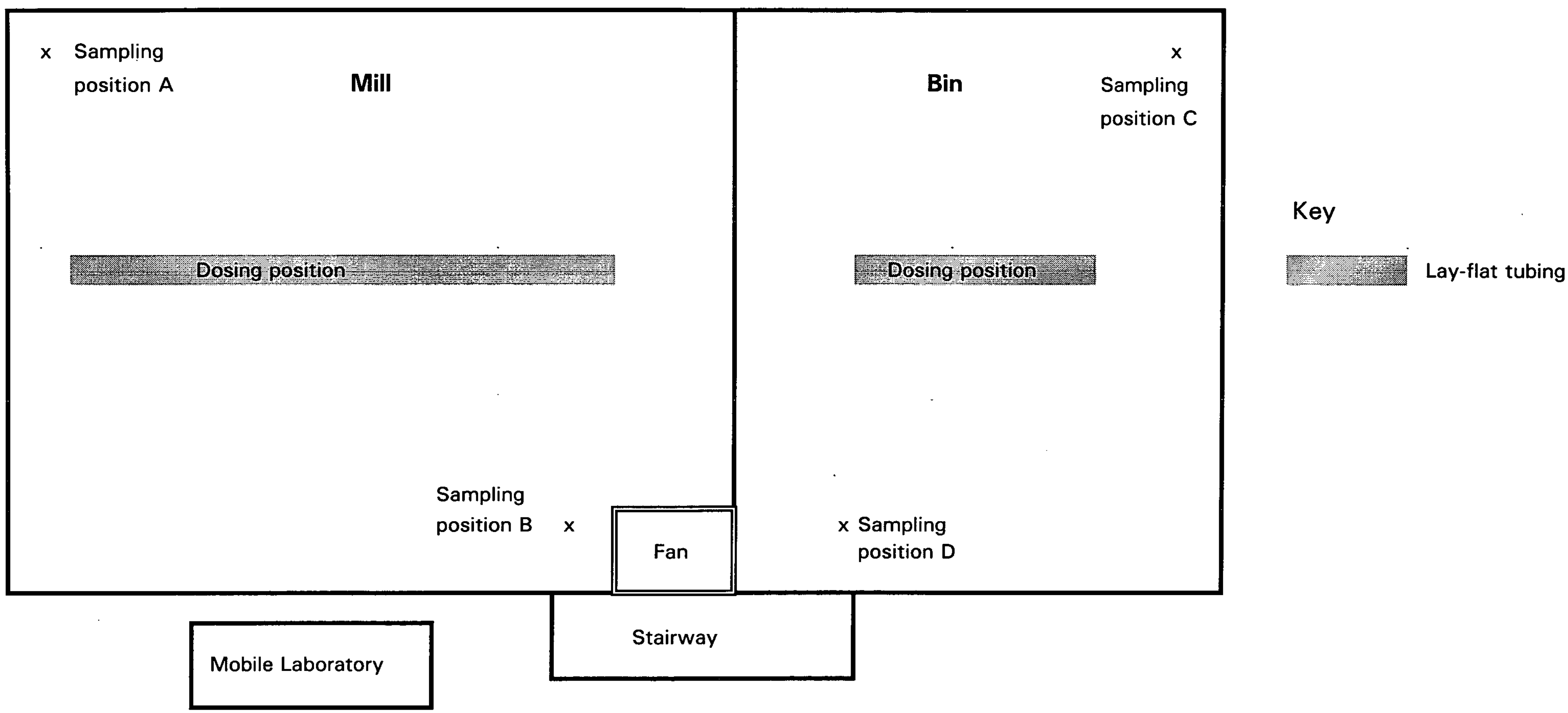

Fig 3. Sampling and automated dosing positions on the top floor at mill B

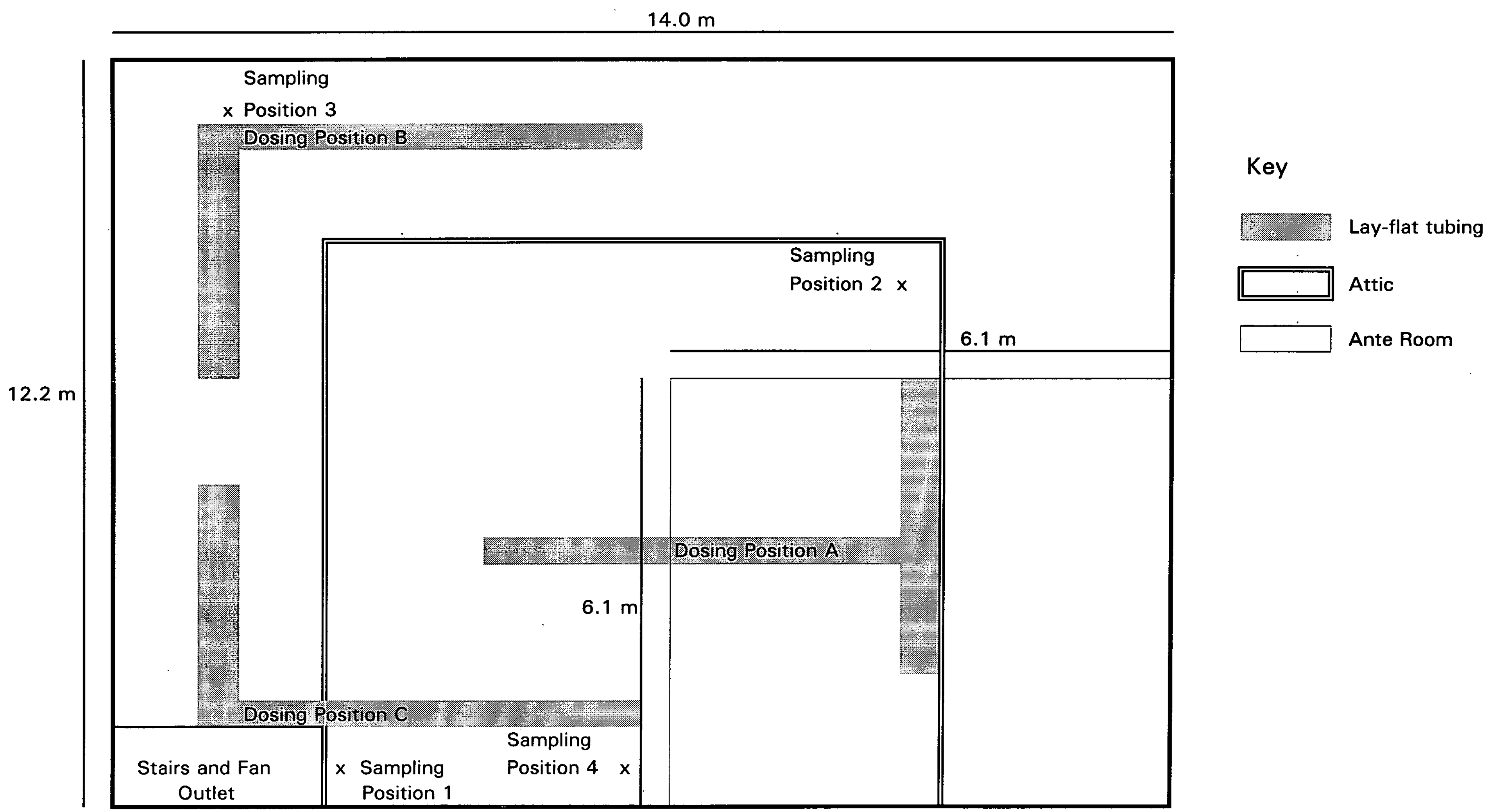

Fig 4. Sampling and automated dosing positions on floors 1, 2 and 3 at mill B.

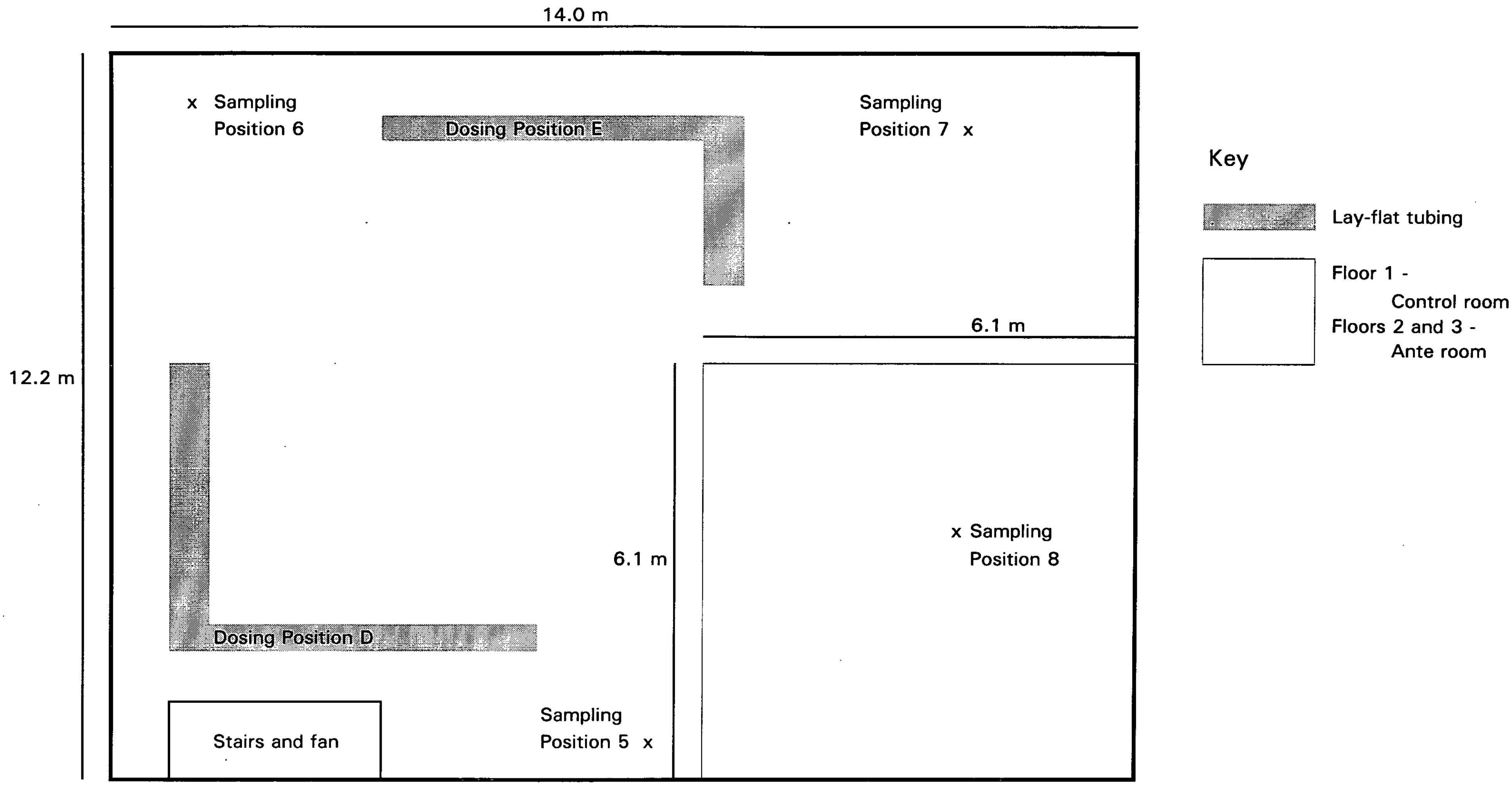

Fig 5. Sampling and automated dosing positions at Mills C and D

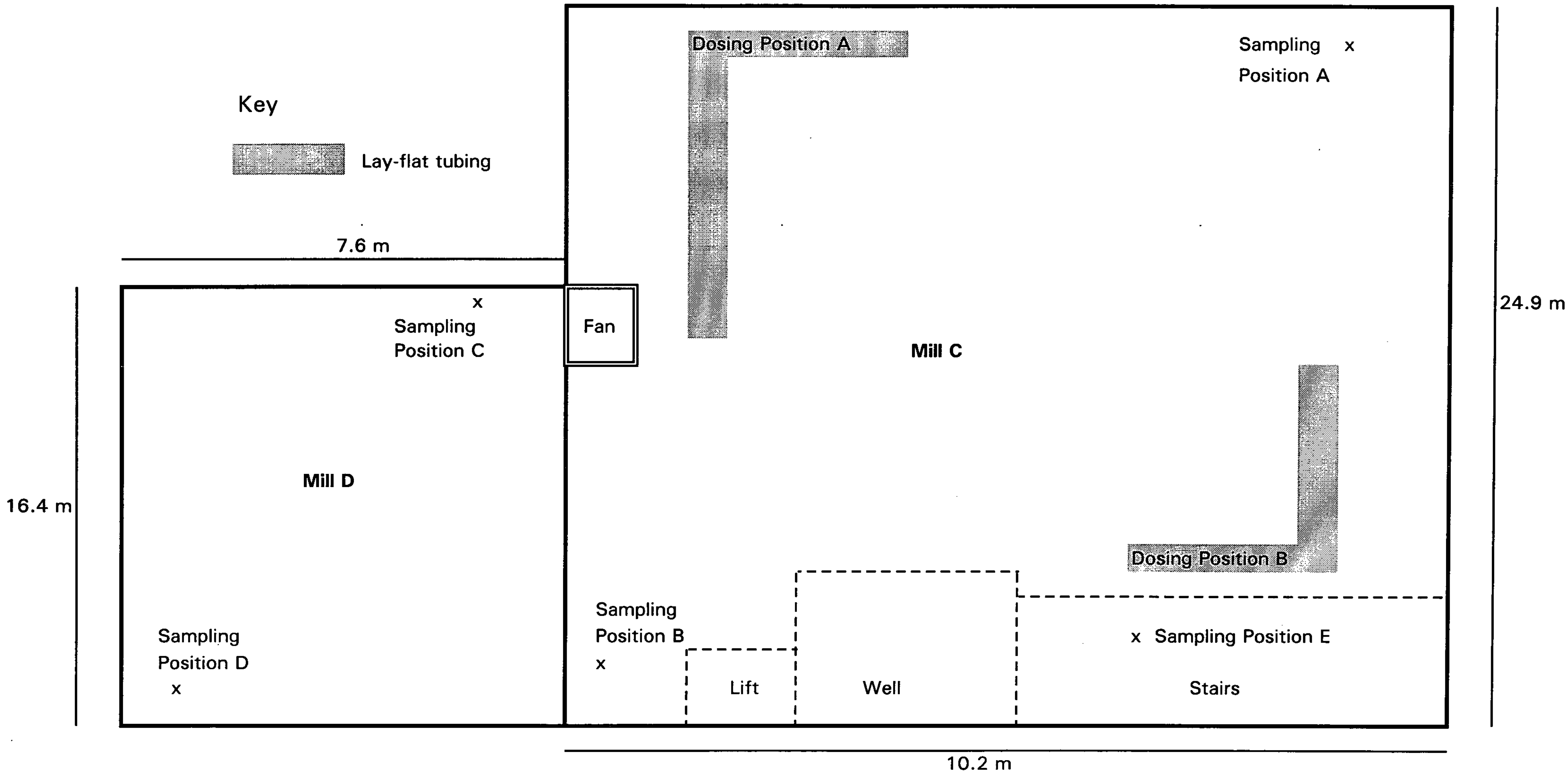

Fig 6. Concentration of methyl bromide against time on floor 5 of Mill A.

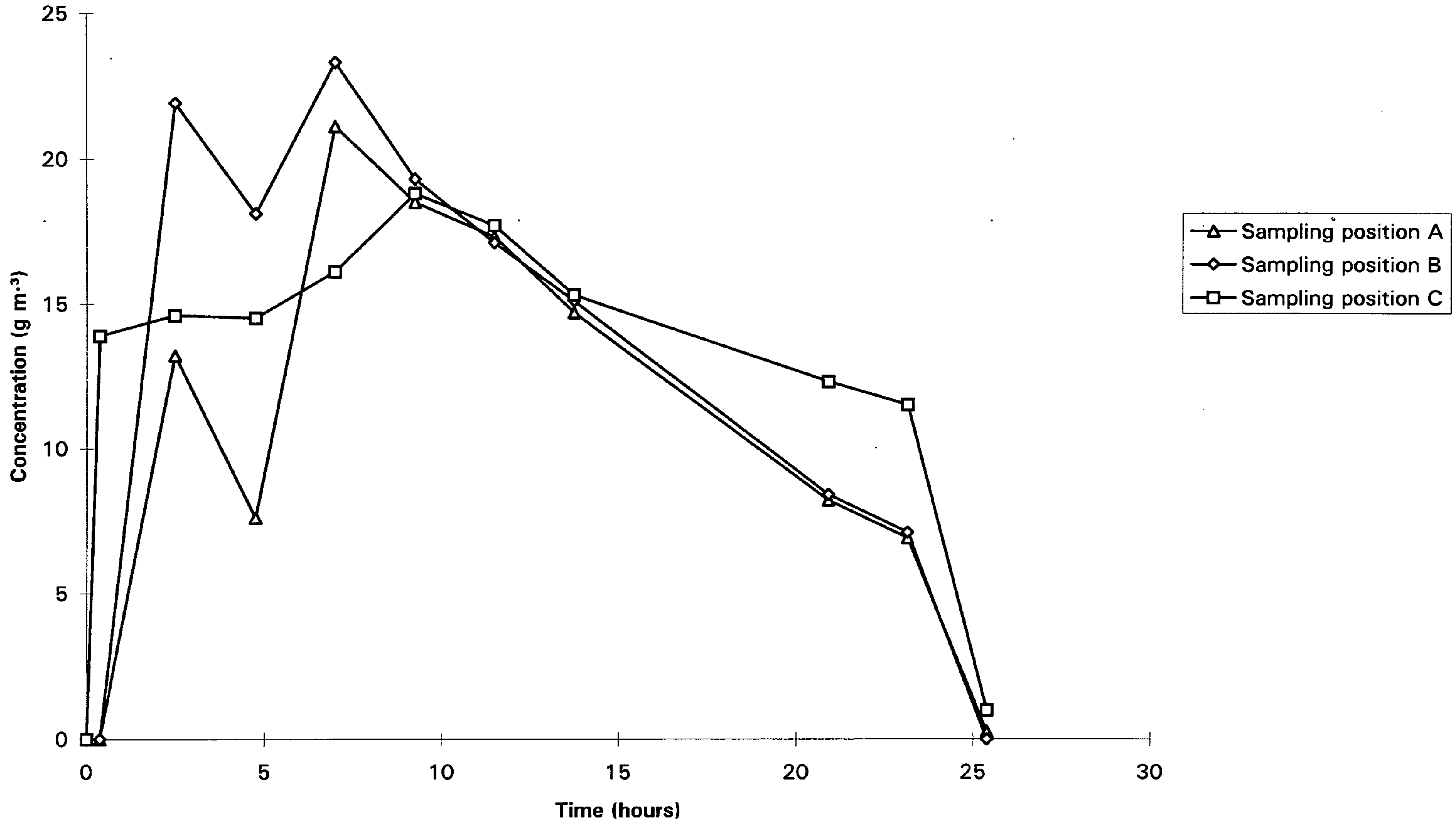

Fig 7. Concentration of methyl bromide against time on floor 4 of Mill A.

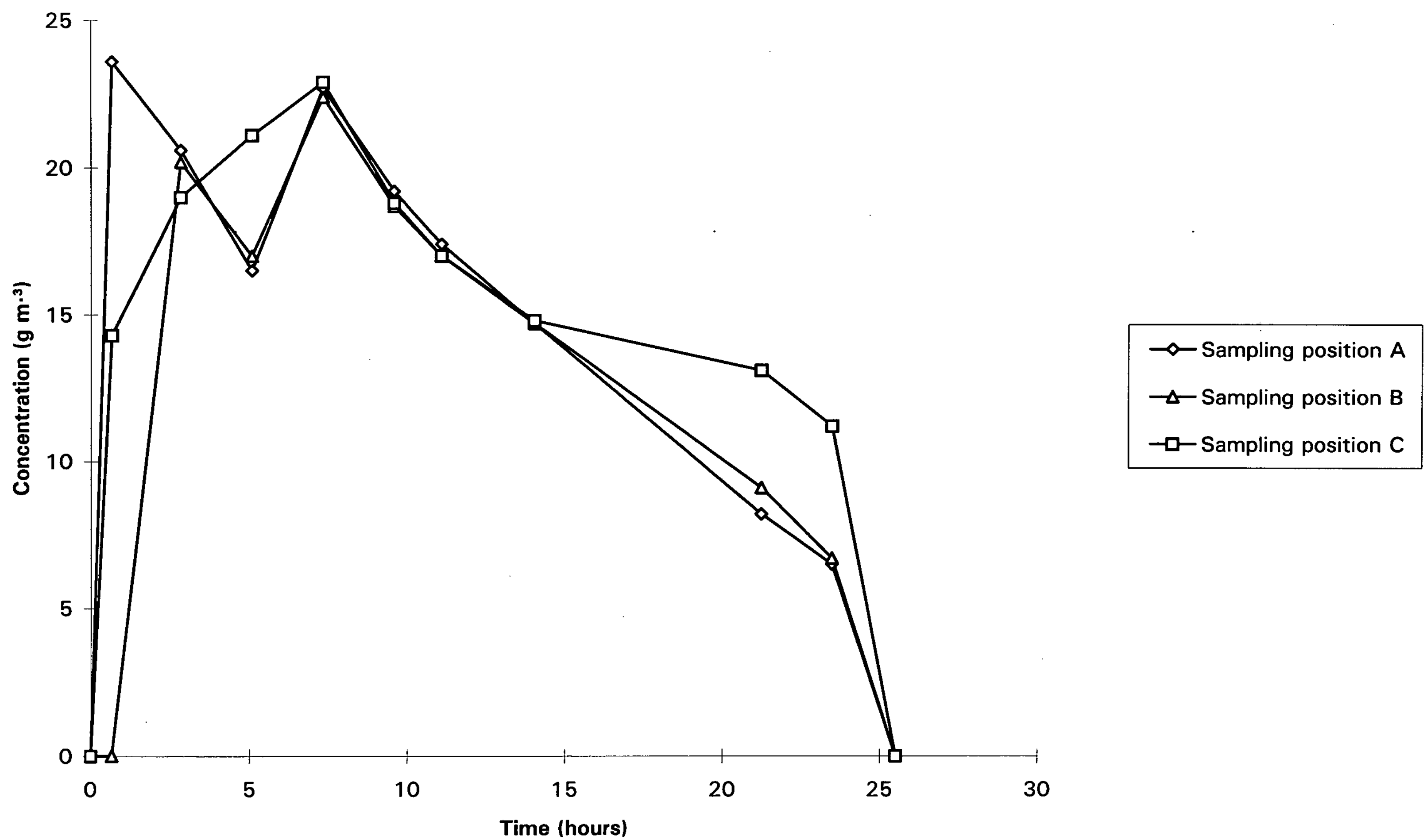

Fig 8. Concentration of methyl bromide against time on floor 3 of mill A.

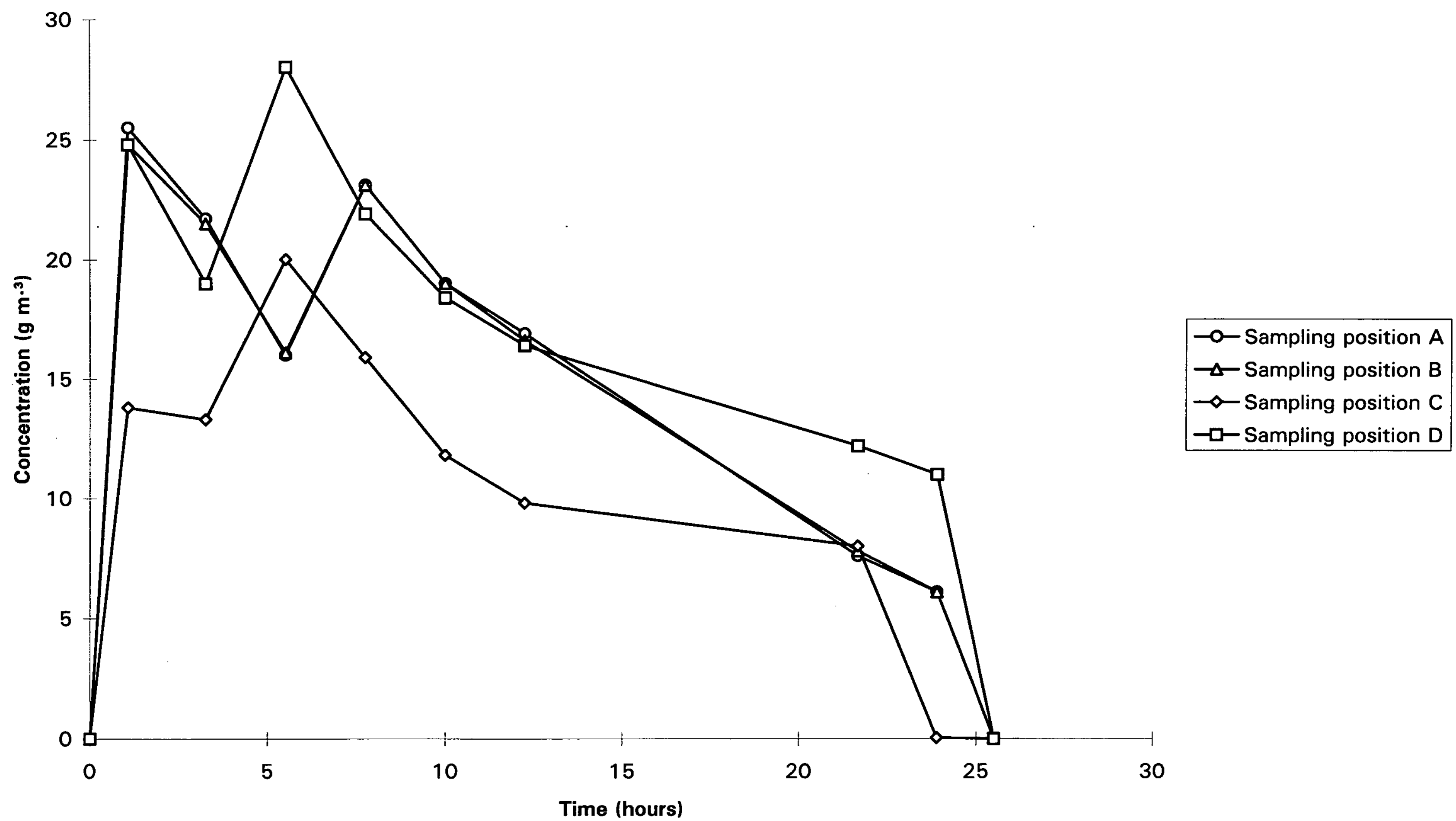

Fig 9. Concentration of methyl bromide against time on floor 2 of Mill A.

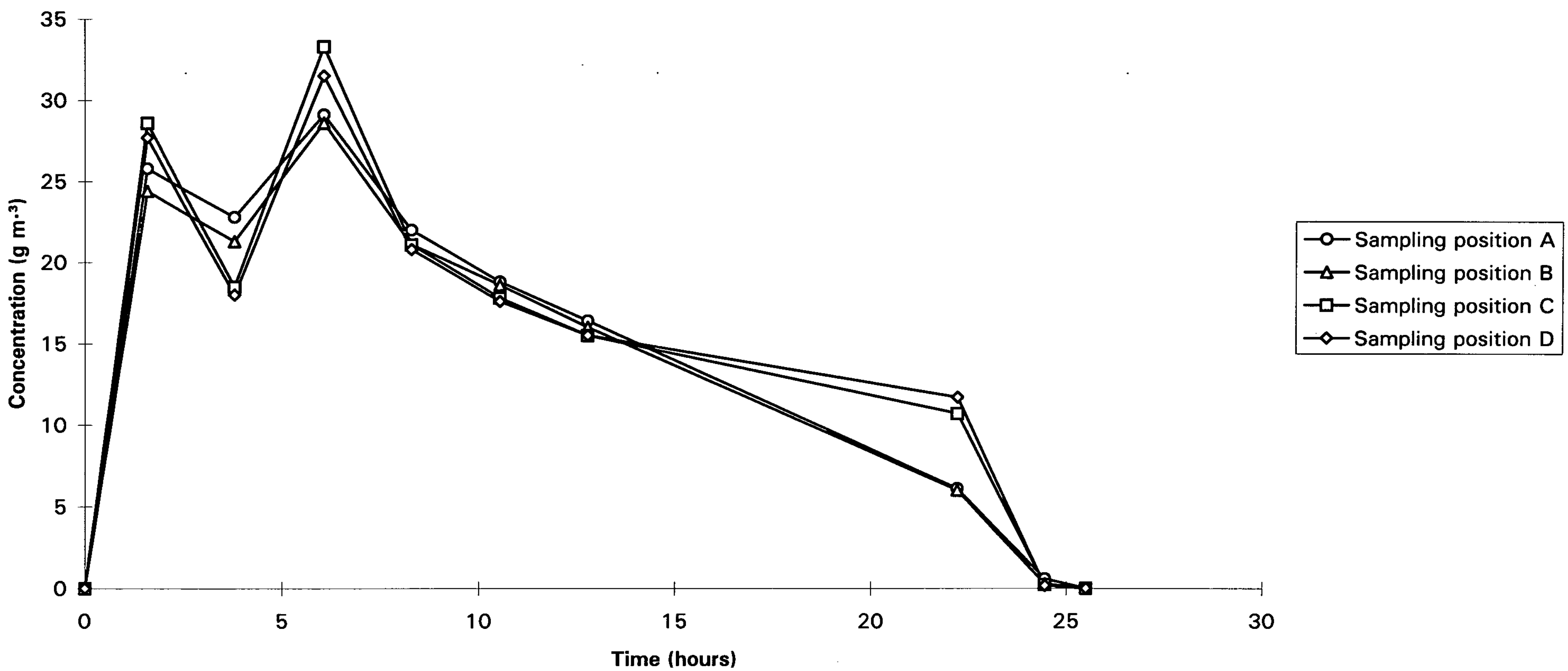

Fig 10. Concentration of methyl bromide against time on the floor 1 (ground floor) of Mill A.

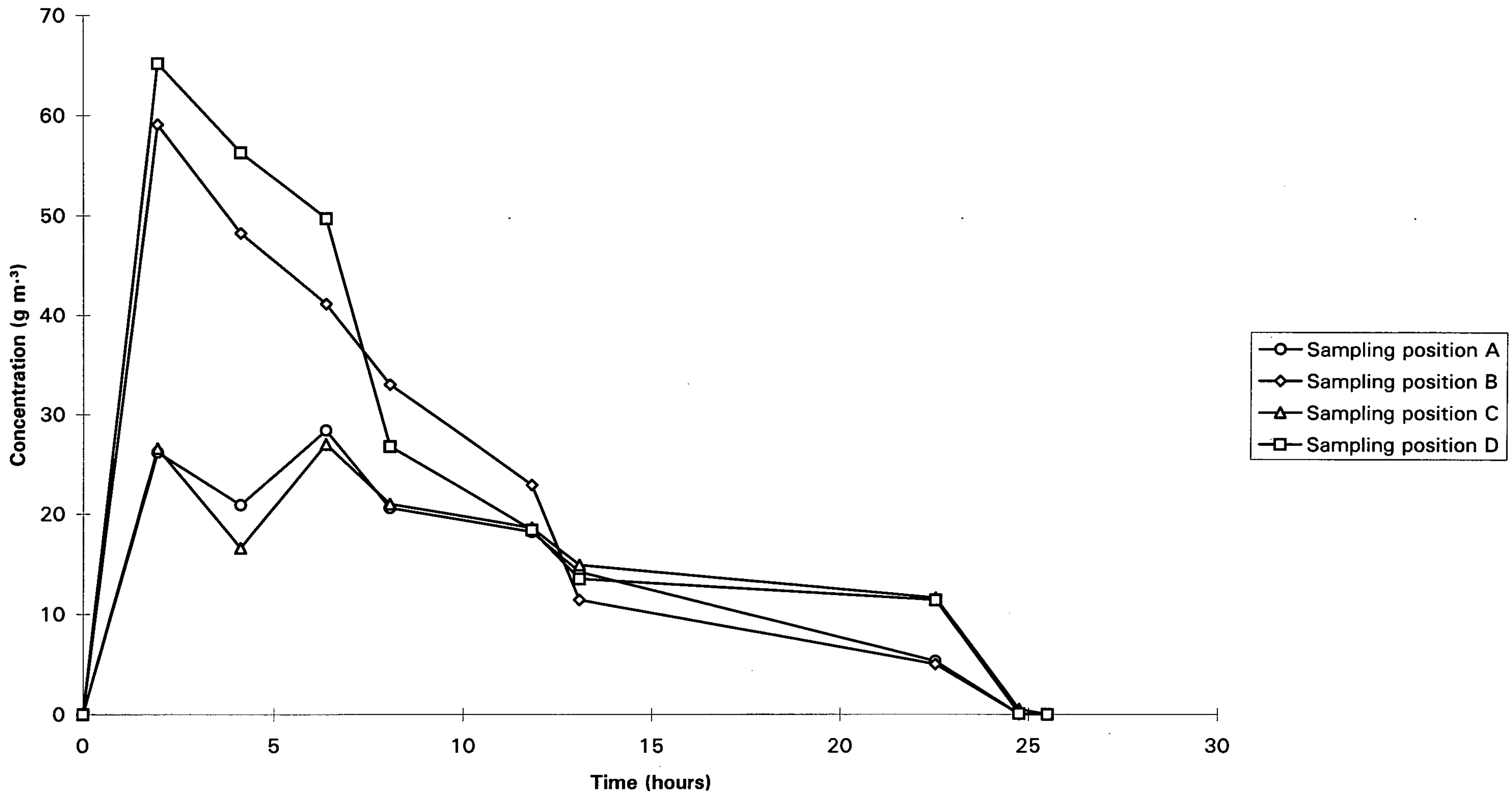

Fig 11. Concentration of methyl bromide against time on floor 4 of Mill B.

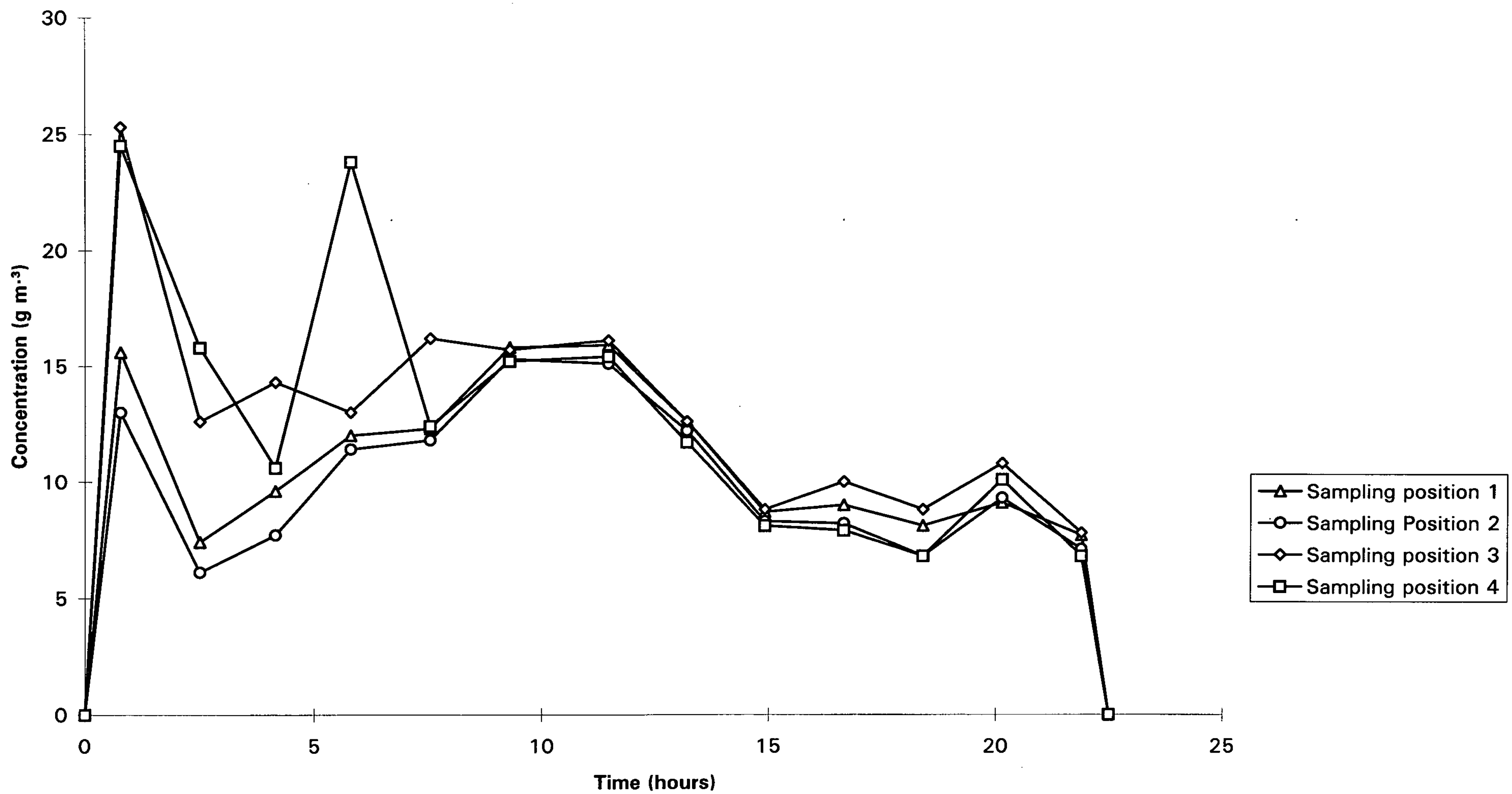

Fig 12. Concentration of methyl bromide against time on floor 3 of Mill B.

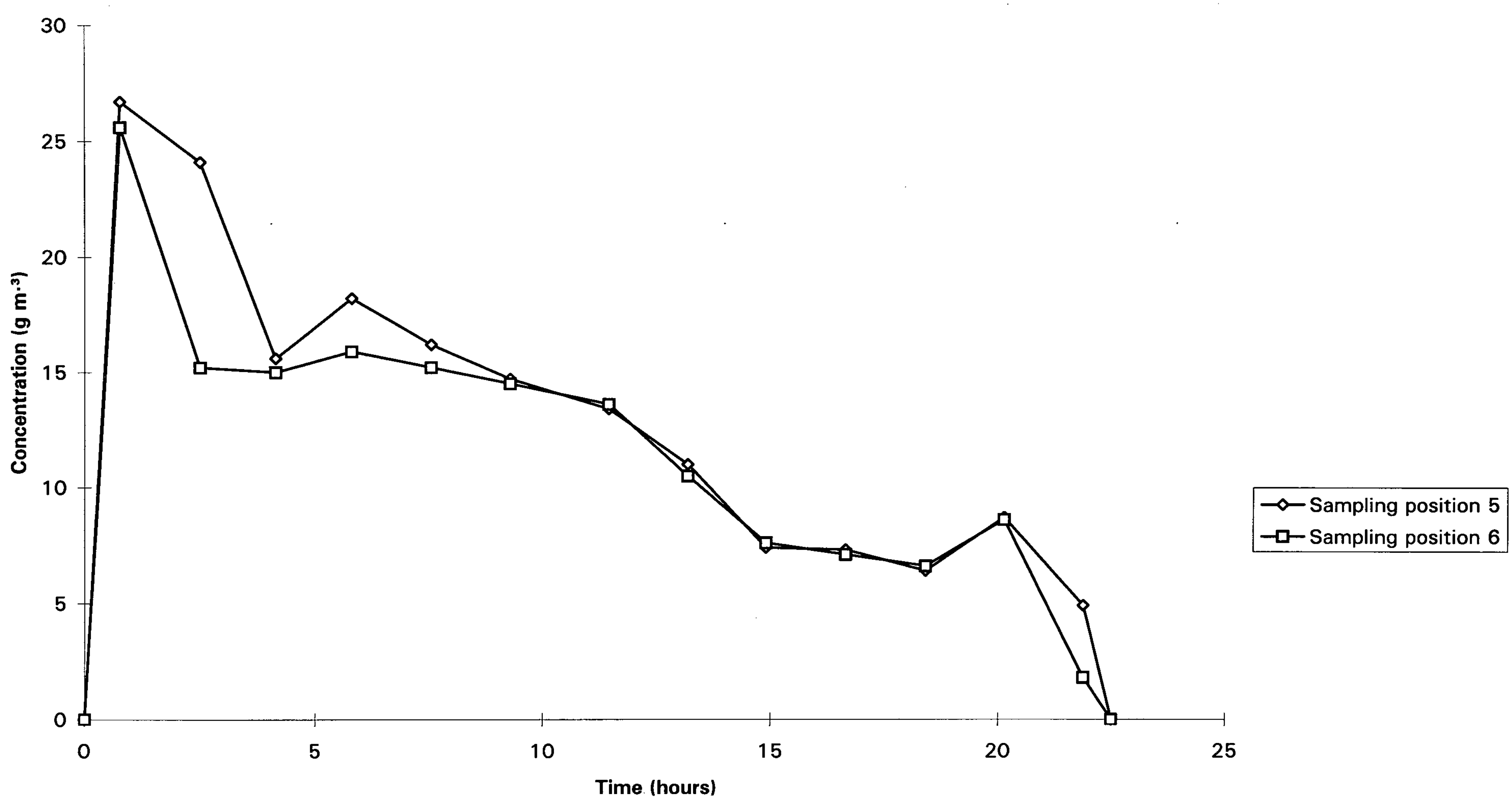

Fig 13. Concentration of methyl bromide against time on floor 2 of Mill B.

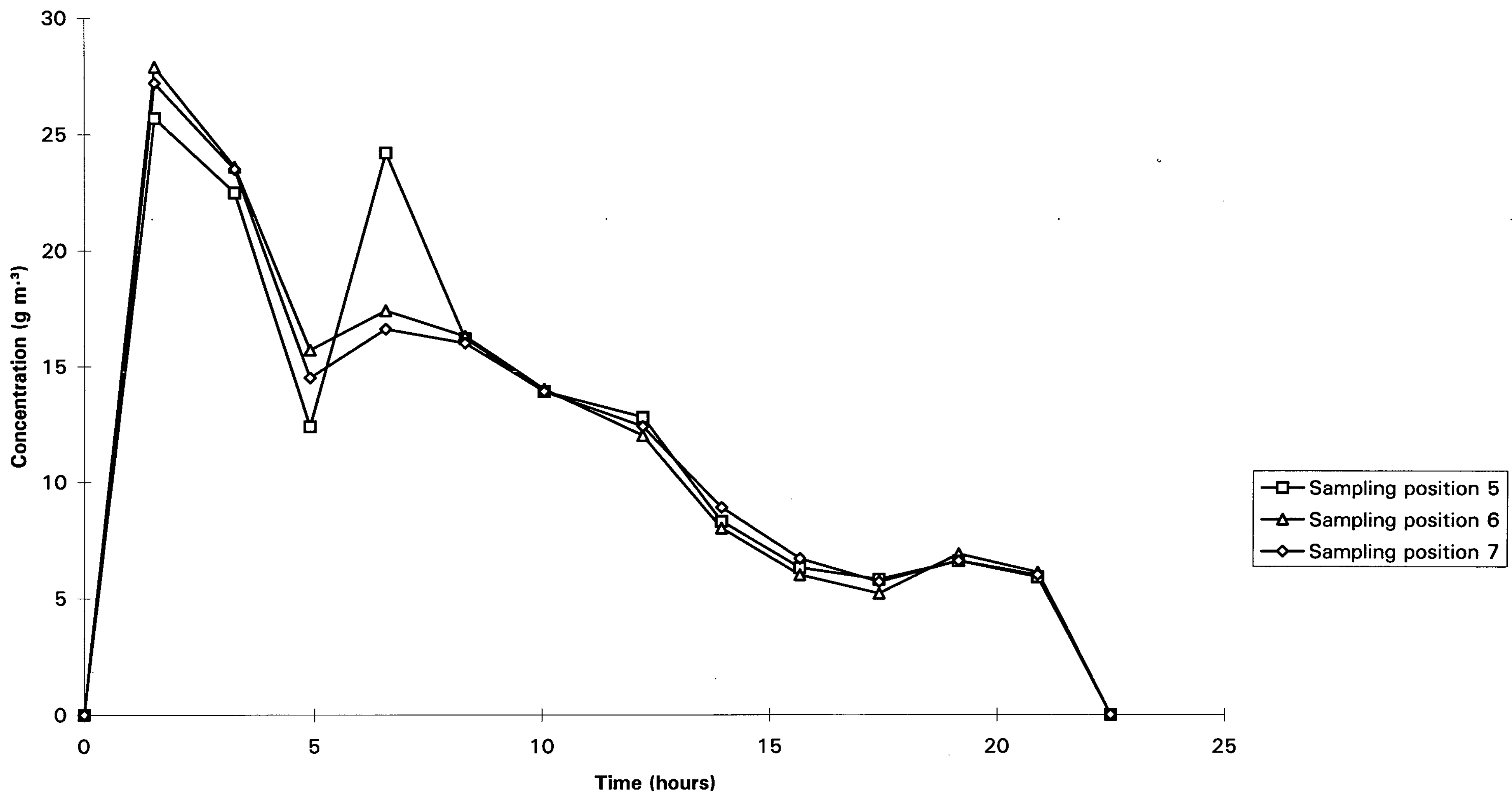

Fig 14. Concentration of methyl bromide against time on floor 1 (ground floor) of Mill B.

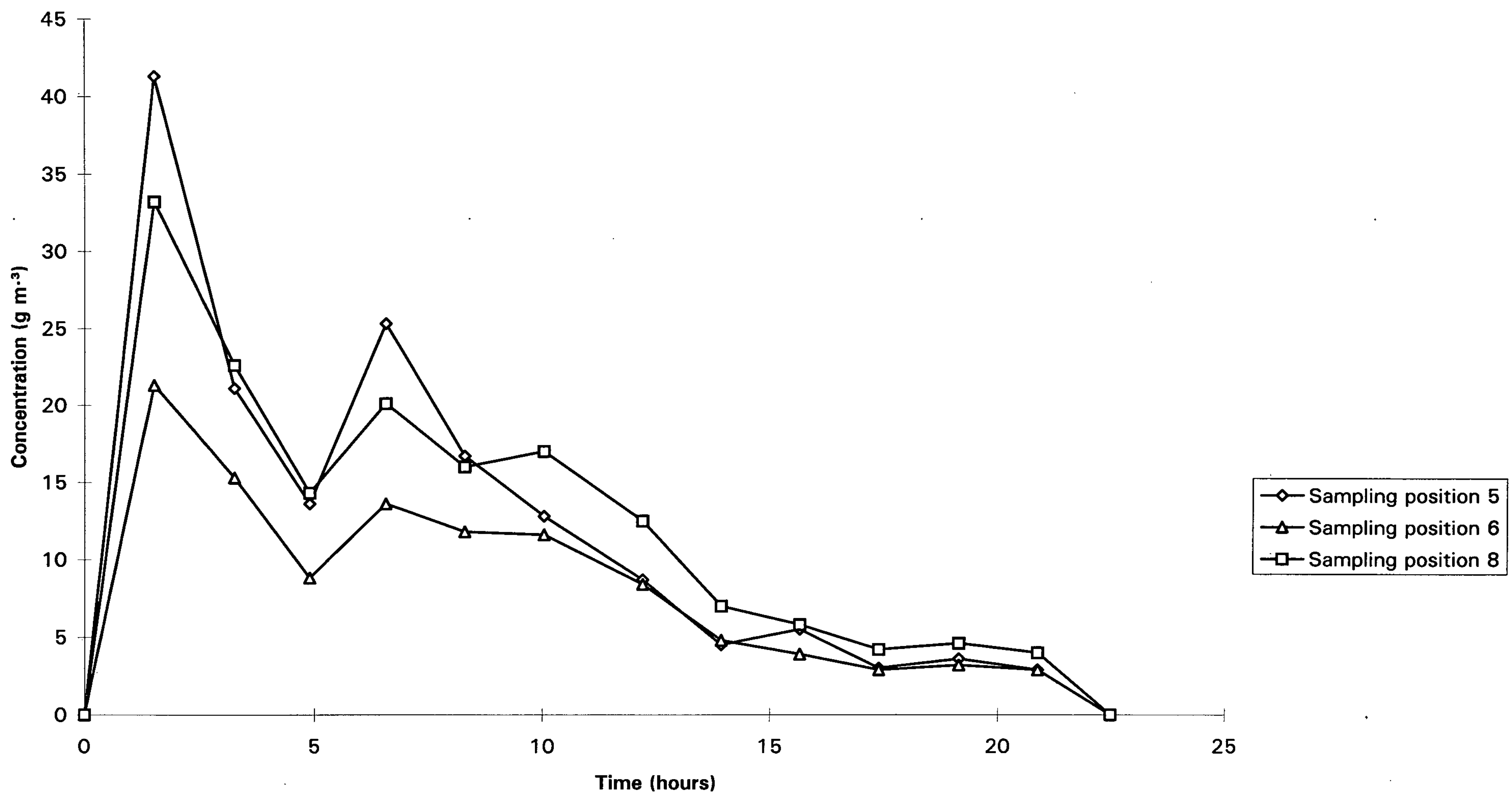

Fig 15. Concentration of methyl bromide against time on floor 4 of Mill C.

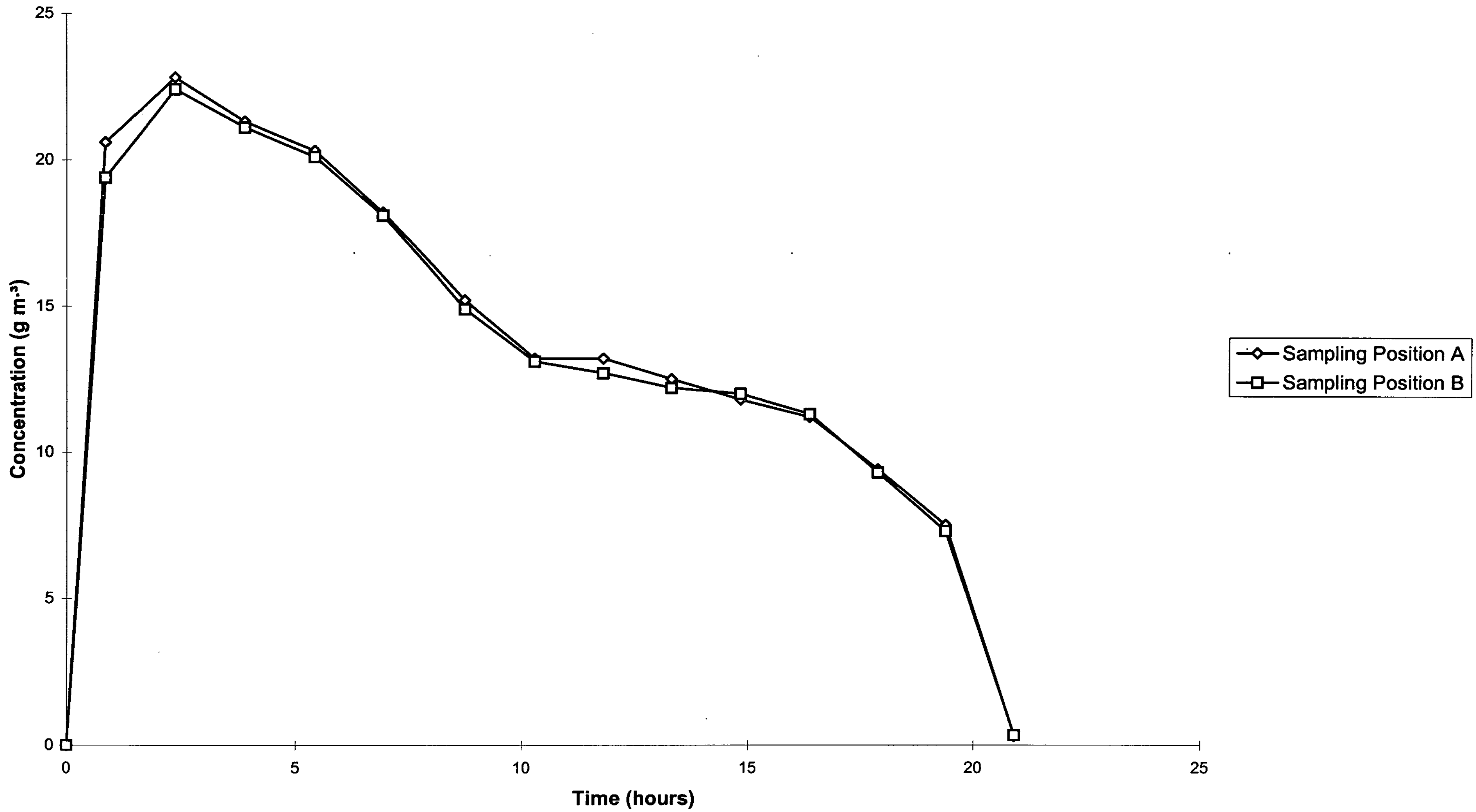

Fig 16. Concentration of methyl bromide against time on floor 3 of Mill C.

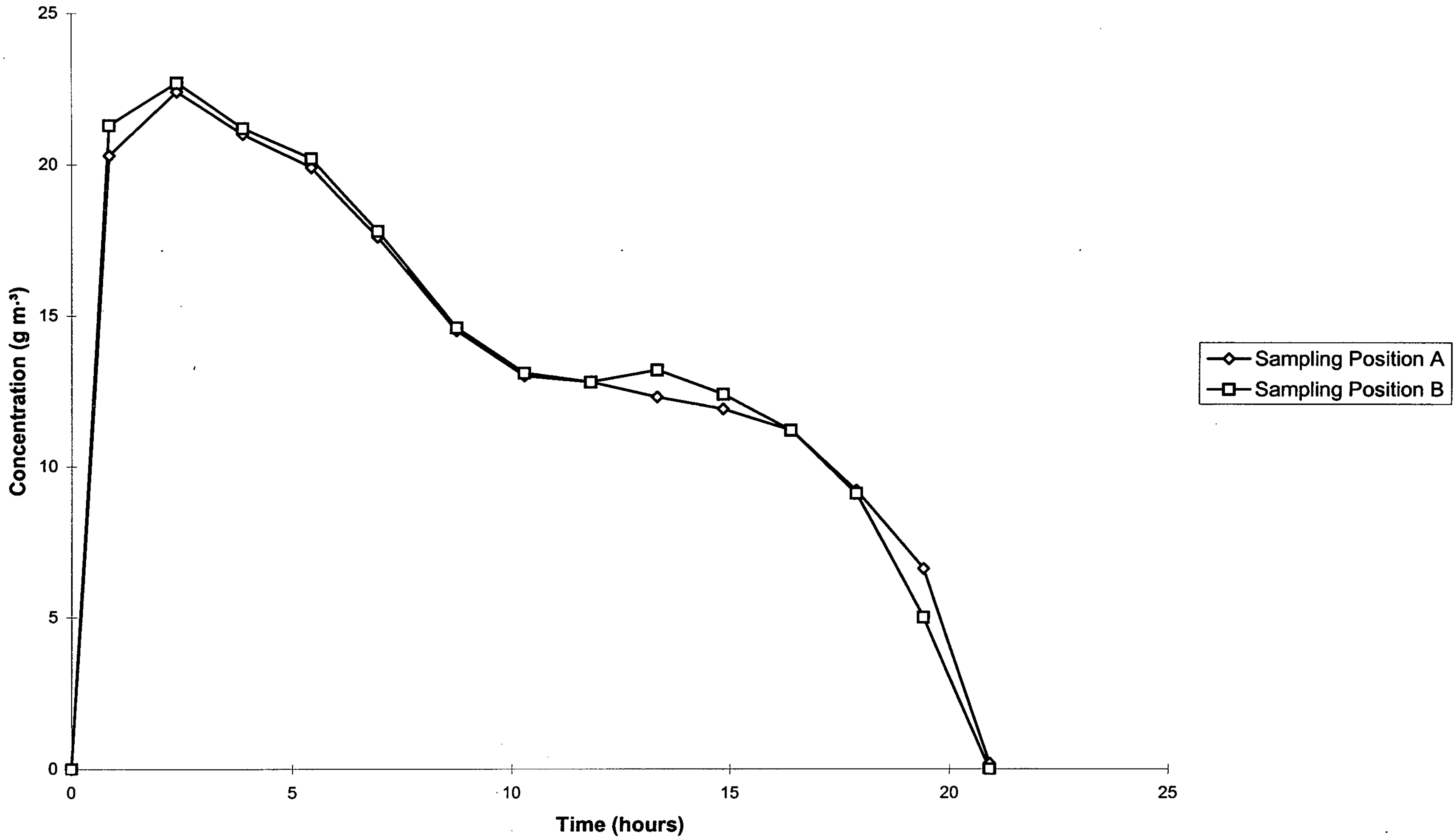

Fig 17. Concentration of methyl bromide against time on floor 2 of Mill C.

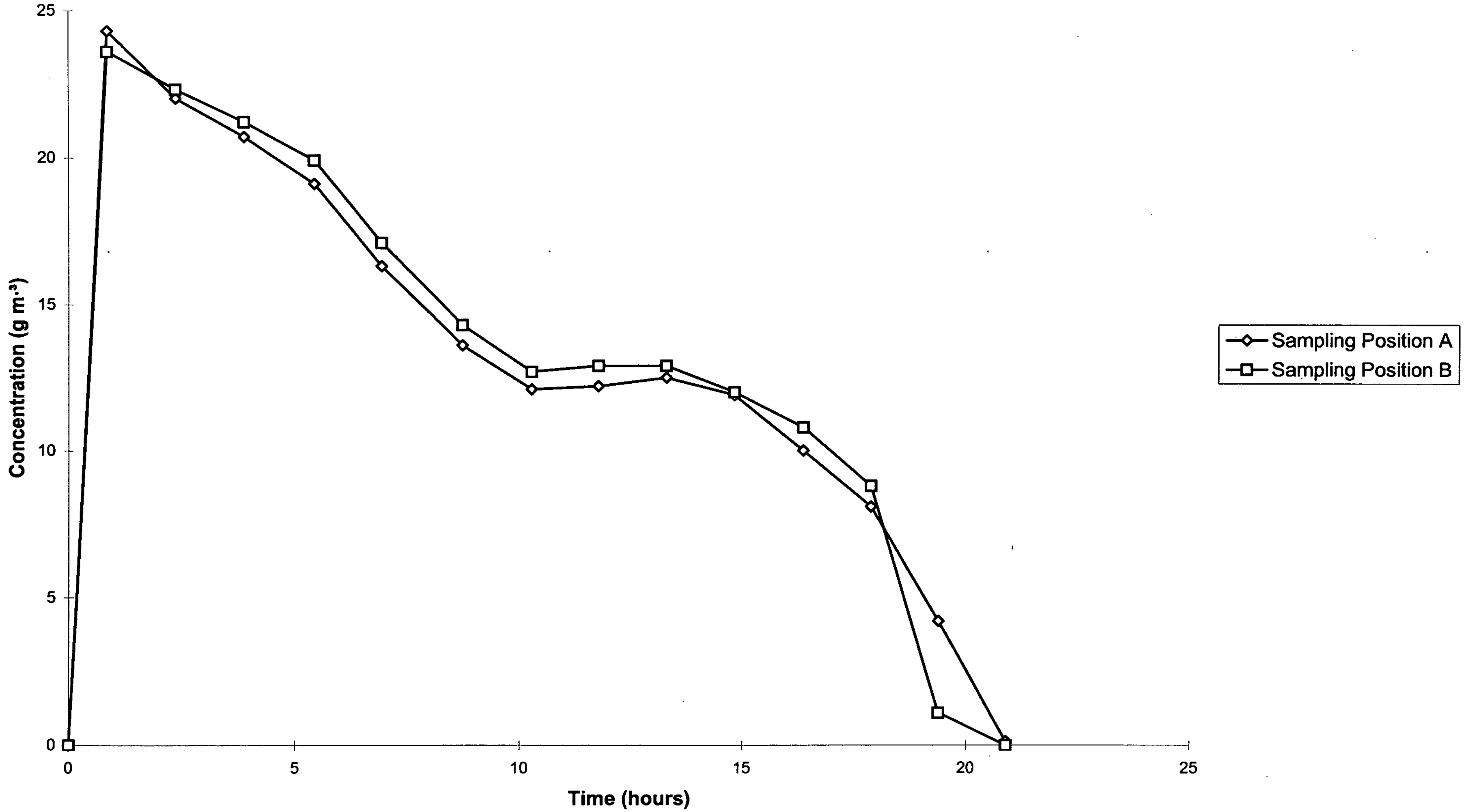

Fig 18. Concentration against time on floor 1 (ground floor) of Mill C.

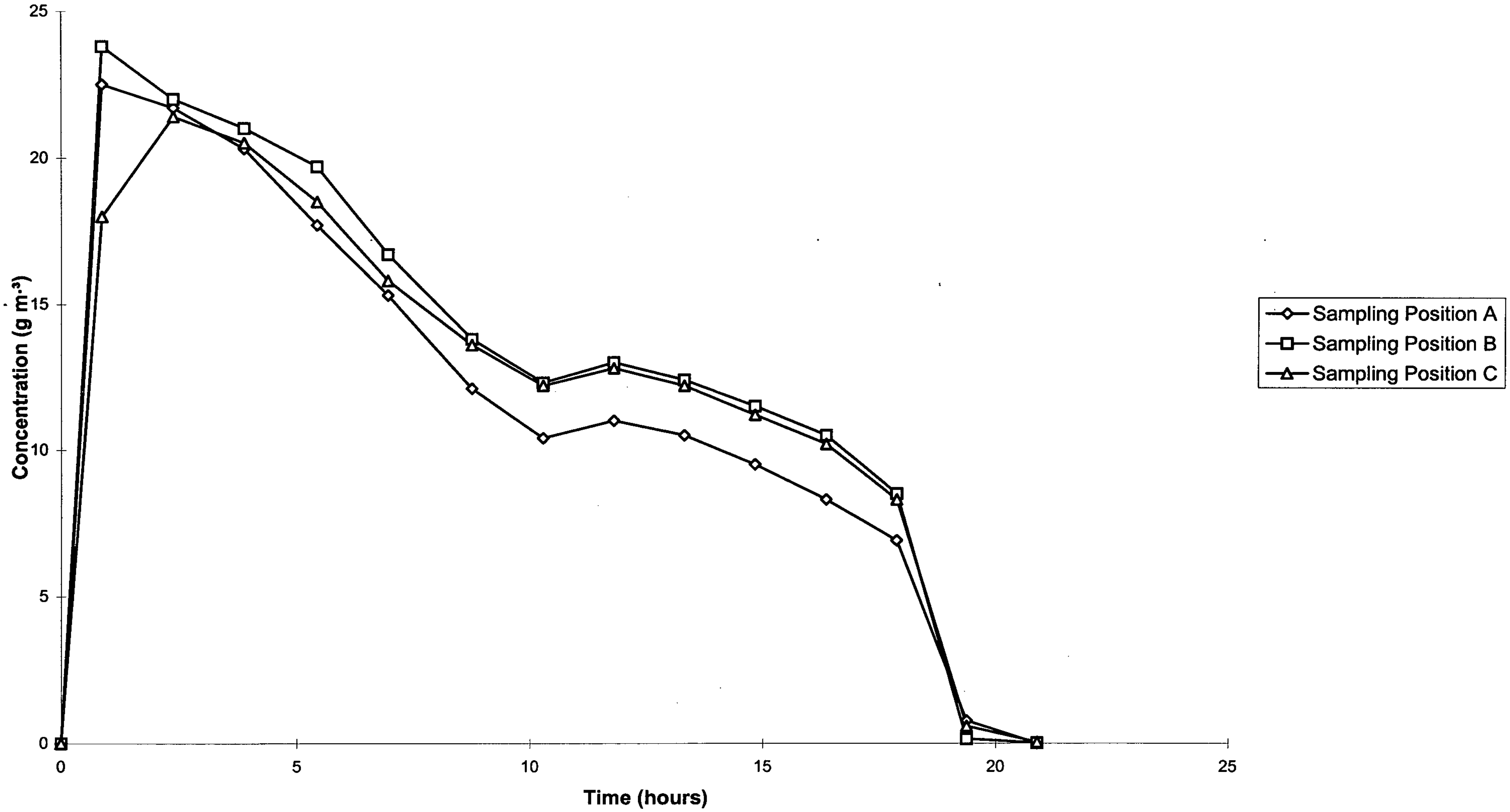

Fig 19. Concentration of methyl bromide against time in Mill D

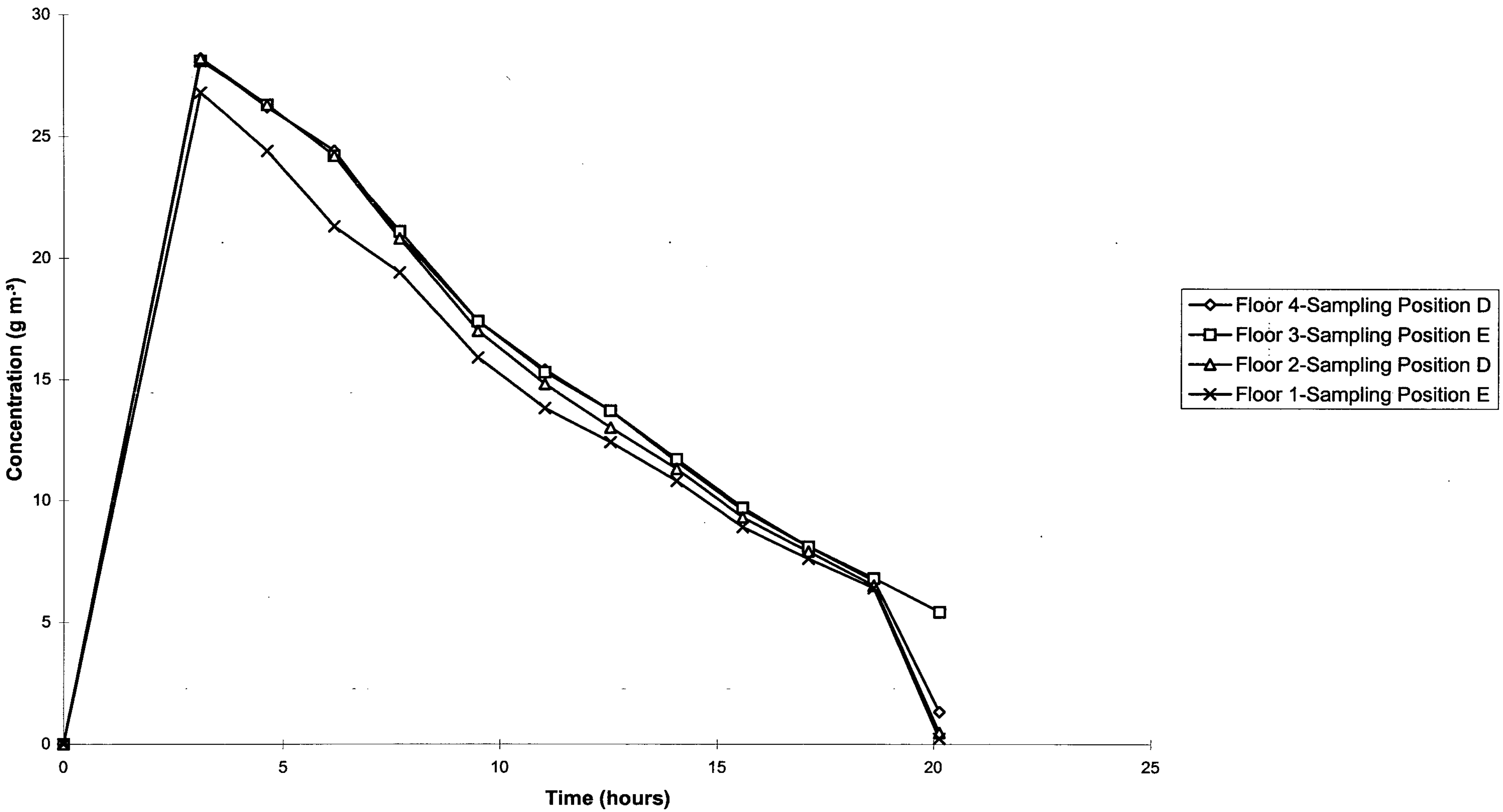

Fig 20. Wind speed at the three sites

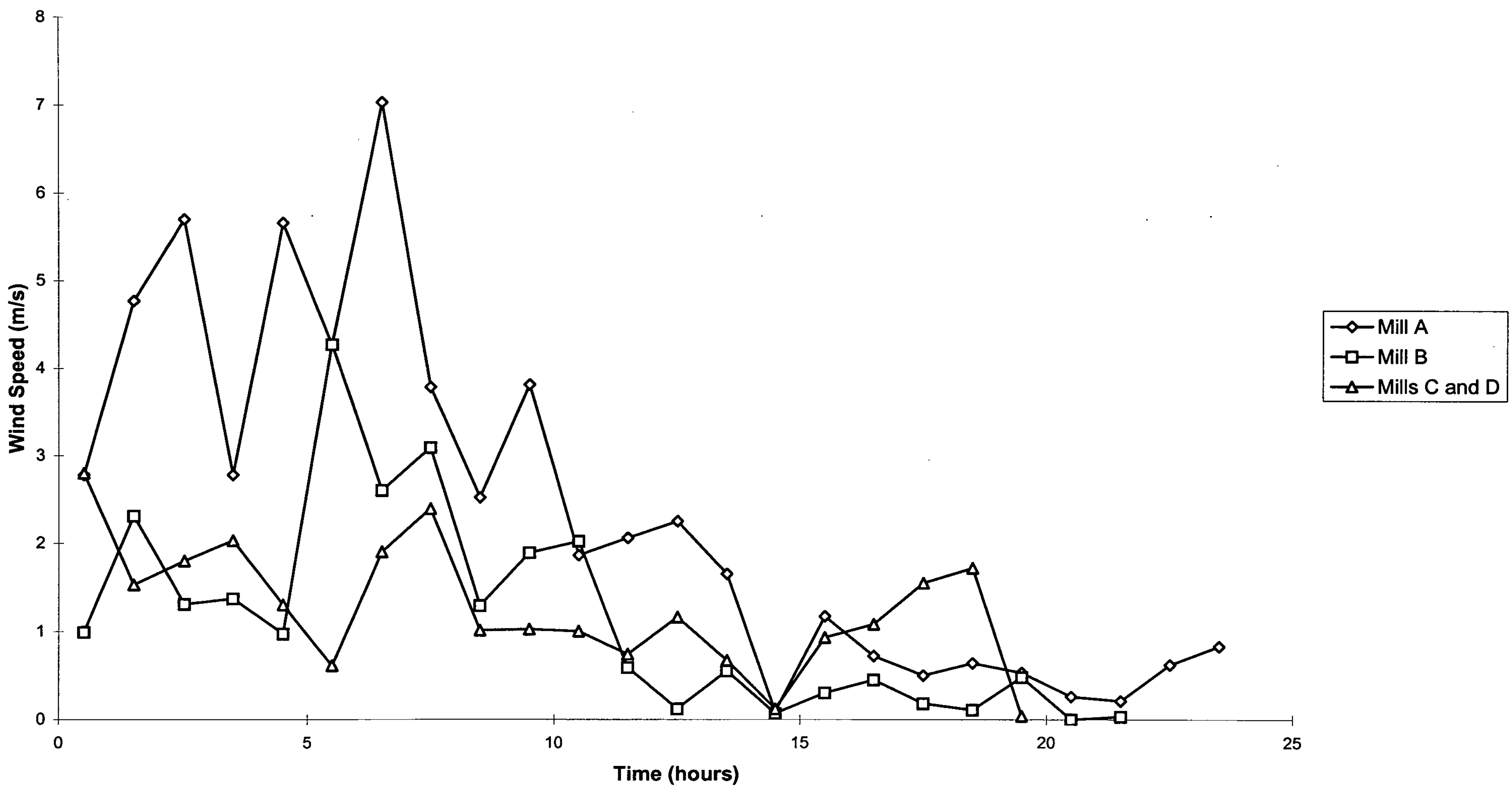

Fig 21. Average and theoretical Concentration-Time Products.