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TNO-report

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Research on continuous and instantaneous
heavy gas clouds

MT-TNO wind tunnel experiments

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SUMMARY

This report describes the contribution of MT-TNO to the joint CEC project 'Research on continuous and instantaneous heavy gas clouds'.

The aim of this CEC project is to provide enhanced numerical and/or physical methods to predict the behaviour of heavy gases released in the atmosphere. The dispersion of heavy gases over flat terrain in terms of time-averaged concentration is quite well understood. This project was focussed on the effect of obstacles on the dispersion and on concentration fluctuations:

- In practical situations obstacles in the form of buildings and other installations will be present. These obstacles may significantly influence the dispersion process, but little quantitative guidance can presently be given on the magnitude of the effect on the spatial and temporal distributions of the concentration field.
- Until now, models used for predicting atmospheric concentrations of contaminants have been those which produce time or ensemble-averaged values. However, some contaminants are so toxic that harmful effects may occur at short exposure times. For these contaminants, models that provide only expected values of averaged concentrations are inadequate.

Predicting the fluctuating concentration field is also important in considerations of the explosive and flammable properties of clouds, because whether complete burn-up follows ignition or not, depends on local and time-dependent conditions.

The project aimed at the creation of an experimental database and the development of adequate models.

At MT-TNO wind tunnel experiments, including the effect of obstacles and the determination of concentration fluctuations have been performed. The obtained wind tunnel results are part of the experimental database. The wind tunnel is also used as a physical model by remodelling a field test.

Intercomparison tests have been performed among the three wind tunnel groups. These experiments made clear that the ground roughness has a strong influence on the downwind concentration. The differences in

ground roughness explain the found differences between the wind tunnel groups.

Velocity measurements were made inside and outside a heavy gas cloud (continuous release), using a Laser Doppler technique. These experiments showed that the influence of the density of the cloud on profiles of velocity and turbulence intensity can only be found in that part of the gas cloud for which the mean gas concentration is higher than about 15%. Remodelling of a full scale test showed that the recovery of the (gas-air) flow after a sudden change in obstacle geometry is a process of long duration.

The remodelling experiments also indicated that the changes in measured concentrations due to a change in the orientation of $\pm 15^\circ$ of a fence acting as obstacle, are often smaller than the inherent variability in the concentration measurements.

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1. INTRODUCTION

In the framework of the CEC Action Programme on Major Technological Hazards, the joint project entitled 'Research on continuous and instantaneous heavy gas clouds' has been carried out by the following organisations:

- MT-TNO (The Netherlands)
- Risø National Laboratory (Denmark)
- Solvay SA Laboratory (Belgium)
- University of Hamburg, Meteorological Institute (Germany)
- UK Atomic Energy Authority, Safety and Reliability Directorate (United Kingdom)
- Health and Safety Executive, Safety Engineering Laboratory (United Kingdom)
- Warren Spring Laboratory, Dept. of Trade and Industry (United Kingdom)
- Brunel University (United Kingdom)
- Technischer Überwachungs-Verein Norddeutschland e.V. (Germany).

Heavy gas dispersion is a common element in the prediction of the consequences of many types of major accidents in the chemical and petrochemical industries. The dispersion of heavy gases over flat terrain in terms of time- or ensemble-averaged concentrations is quite well understood. As a result mathematical modelling is well developed for instantaneous and continuous plumes over flat ground. For practical risk analysis, involving repeated calculations for large numbers of release conditions, such models have to be fairly simple.

Past investigations have also considered the effect of natural topography and artificial structures on heavy gas dispersion. Experimental results are available from wind tunnel modelling and from the Thorney Island field trials.

Relevant information is also available from other fields of environmental research such as gravity currents down slopes and density-stratified flows past obstacles. So far little use has been made of this knowledge to improve mathematical models of heavy gas dispersion.

Wind tunnels have been used extensively to study heavy gas dispersion.

They have proven to be reliable methods, although a thorough intercomparison of different wind tunnels has not been reported before the start of this project.

Within hazard analysis, there is a need for systematic investigation of the effect of obstacles and source conditions on heavy gas dispersion.

Currently practical risk assessment is based on flat-ground models delivering predictions of time- or ensemble-averaged concentrations. The aim of this joint project is to extend these methods in two directions.

1. In practical situations obstacles in the form of buildings, installations and natural topography will be present. These obstacles may significantly influence the dispersion process, but little guidance can presently be given to the extent of the effect on the concentrations field. In this project methods have been developed to incorporate obstacle effects in heavy gas dispersion models.
2. Some contaminants are so toxic that harmful effects may be achieved by exposure times which are much shorter than the larger time scales of the evolving gas clouds. For these contaminants, models which provide only expected values of averaged concentrations are inadequate. Predicting the fluctuating concentrations field is also important in considerations of the explosive and flammable properties of clouds. In this project the variability of concentrations in instantaneous and continuous heavy gas clouds has been studied.

In the framework of the total project, TNO carried out model experiments in a wind tunnel on continuous and instantaneous releases of heavy gases:

- Two experiments, an instantaneous and continuous release test, have been carried out, of which the results have been used to intercompare with the results of identical experiments, carried out in the wind tunnels of Warren Spring Laboratory and the University of Hamburg (chapter 4).
- The continuous release experiments used in the intercomparison, has been repeated for other values of the wind speed (chapter 4).
- Continuous release experiments with different values of the roughness height have been carried out in order to study the influence of ground roughness on the downwind concentration (chapter 5).

- The profiles of velocity and turbulence intensity at several locations inside the cloud of a continuous release have been measured, using a Laser Doppler technique, and compared with the undisturbed profiles (chapter 6).
- A full scale experiment, carried out in the framework of the joint project, has been remodelled in the wind tunnel. Experiments, based on this 'remodelling test', including the effect of a changed orientation of the obstacle have been carried out (chapter 7).

The measuring equipment has been described in chapter 2 and 3. In chapter 8 the conclusions are summarized.

2. WIND TUNNEL

In figure 1 a schematic drawing of the PIA (Pollution Industrial Aerodynamics) wind tunnel is given. This wind tunnel has been used in the experiments.

The test section of the PIA wind tunnel has a cross section of $2.65 * 1.2 \text{ m}^2$, and a length in normal circumstances of 6.8 m. The wind speed in the test section can be set between about 0.2 m/s and 20 m/s. The boundary layer simulation method used in the wind tunnel is the method developed by Counihan, and is described in detail by Builtjes and Vermeulen [3].

The atmospheric boundary layer in the experiments was simulated by:

1. Using a smooth floor, resulting in a roughness length scale z_0 of about 0.005 mm. In figure 2 the profiles of the mean velocity and the along wind turbulence are drawn for a reference velocity close to that used in the experiments *).
2. Using a smooth carpet, resulting in a roughness length scale z_0 of about 0.05 mm. In figure 3 the profiles of the mean velocity and the along wind turbulence are drawn for a reference velocity close to that used in the experiments *).
3. Using a rough carpet, resulting in a roughness length scale z_0 of about 0.5 mm. In figure 4 the profiles of the mean velocity and the along wind turbulence are drawn *).

For a detailed description of the velocity profiles and the turbulence intensities at different surface roughnesses the reader is referred to Builtjes and Vermeulen [3].

Figure 5 shows that the logarithmic velocity profile, based on a roughness length scale $z_0 = 0.05 \text{ mm}$, fits well with the exponential velocity profile with exponent $n = 0.16$ (which has been used in the wind tunnel of the University of Hamburg) in the region from 0.01 to 0.1 m height, which is the major region in which the mixing process takes place.

*) The velocity U_B , mentioned in figures 2, 3 and 4, is the 'control velocity', measured in the inlet section of the wind tunnel.

3. ASPIRATED HOT WIRE PROBE

Concentration measurements in the wind tunnel have been performed using an aspirated hot wire probe.

The principle of the aspirated hot wire probe is based on the fact that the heat transfer from a thin heated cylinder in a gas depends on the flow speed and the physical properties of the gas. In an aspirated probe, the flow rate is kept constant, so that a variation of the physical properties of the gas, due to a concentration change, will lead to a change in heat transfer. The problem, however, is that it is difficult to obtain a flow rate, which is constant in time with a high precision, because the flow rate in reality always depends in some way on the pressure drop in the probe system, which in turn depends on the physical properties of the gas mixture too. In the MT-TNO probe this problem is solved by applying a sonic nozzle. The flow rate is then independent of the pressure drop over the nozzle. The hot wire should be positioned just before the sonic nozzle, because the suction velocity depends on the sonic speed, which on its turn depends on the composition of the gas mixture. In the MT-TNO probe the hot wire is positioned 1.5 mm before the sonic nozzle.

A schematic drawing of the MT-TNO probe, used in the intercomparison tests, is given in figure 6a. The intake diameter is 2.0 mm. and the suction velocity is about 0.5 m/s (for air), which results in a suction rate of 5.6 l/h. When using SF₆ the suction velocity amounts 0.2 m/s, resulting in a suction rate of 2.2 l/h. The frequency response of this probe appeared to be about 70 Hz. when using SF₆ (-3dB point).

This probe sometimes showed a zero baseline drift, of which the cause was not clear. Therefore, the MT-TNO probe has been modified. This modified probe is drawn in figure 6b. This probe differs from the previous probe in both the geometry and the type of hot wire. Moreover, the hot wire is placed parallel to the flow (in the previous probe the hot wire was placed perpendicular to the flow). Due to the new type of hot wire and the changed orientation of the wire the modified probe appears to have a smaller zero baseline drift. The modified probe has an intake diameter of 2.2 mm and the suction velocity is about 1.2 m/s

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(for air), resulting in a suction rate of 16 l/h. For SF₆ the suction velocity amounts 0.5 m/s, resulting in a suction rate of 6.4 l/h.

The frequency response amounts about 70 Hz. for SF₆. In addition this probe has the advantage that it is easier to calibrate and to repair.

4. INTERCOMPARISON TESTS

During the project wind tunnel experiments on heavy gas dispersion, investigating both mean and fluctuating concentrations, have been carried out at three institutes, viz. Warren Spring Laboratory (UK), University of Hamburg (FRG) and MT-TNO (NL). It should be guaranteed that the experimental equipment used by the three institutes will measure the same mean and fluctuating concentrations under identical circumstances. In this way different experiments performed in one of the three wind tunnels can be considered as to belong to one coherent experimental data base. Consequently, a comparison has been made between the equipment used including the test facilities.

Two experiments, a instantaneous release test and a continuous release test, have been carried out. A detailed description of these tests is given in a separate report [1].

The concept for both tests, as well as the similarity requirements, have been worked out by the University of Hamburg [4], [5].

The sampling rate in both tests was 60 Hz. The atmospheric boundary layer was modelled as described in chapter 2, using a smooth carpet ($z_0 = 0.05$ mm).

4.1 Instantaneous release experiment

The instantaneous release experiment is a remodelling of Thorney Island Trial No. 17.

The full scale release conditions are:

Released gas volume	:	V_0	= 1700 m ³
Initial density excess	:	$(\rho_0 - \rho_a)/\rho_a$	= 3.2
Characteristic length	:	L_{ci}	= 11.9 m
Characteristic velocity	:	U_{ci}	= 19.4 m/s
Characteristic time	:	T_{ci}	= 0.6 s
Ambient wind	:	U_r	= 0.26 U_{ci} (at 0.84 L_{ci} height)

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In which the characteristic length scale L_{ci} , characteristic time scale T_{ci} and characteristic velocity scale U_{ci} for an instantaneous release are defined as [4], [5]:

$$L_{ci} = V_o^{1/3} \quad [m]$$

$$T_{ci} = \left(\frac{L_{ci}}{g'} \right)^{1/2} \quad [s]$$

$$U_{ci} = (L_{ci} \cdot g')^{1/2} \quad [m/s]$$

with the effective gravity g' as:

$$g' = g \cdot \frac{\rho_o - \rho_a}{\rho_a} \quad [m/s^2]$$

and ρ_o = initial density of the gas cloud $[kg/m^3]$

ρ_a = density of the surrounding air $[kg/m^3]$

g = acceleration of gravity ($\sim 9.81 \text{ m/s}^2$)

The model release conditions are:

Released gas volume	:	V_o	= $1.4 \cdot 10^{-3} \text{ m}^3$ (model scale 1:107)
Initial density excess	:	$(\rho_o - \rho_a)/\rho_a$	= 4.12 (using SF6)
Characteristic length	:	L_{ci}	= 0.112 m
Characteristic velocity	:	U_{ci}	= 2.126 m/s
Characteristic time	:	T_{ci}	= 0.053 s
Wind speed	:	U_r	= $0.26 U_{ci}$ (at $0.84 L_{ci}$ height)
Ground roughness	:	z_o	= 0.05 mm

The release device consist of a cylindrical tube of 0.13 m. diameter and a height of 0.105 m. (figure 7). This tube is retractable in the floor of the wind tunnel. The top of the tube is closed with a lid which is removed just before each experiment by simply pulling a string.

Seven sampling stations have been used, with the following coordinates (figure 8):

sampling station [no.]	x-coordinate [L _{ci}]	y-coordinate [L _{ci}]	z-coordinate [L _{ci}]
1	1.87	1.68	0.034
2	3.12	2.79	0.034
3	4.37	3.92	0.034
4	5.61	5.04	0.034
5	5.91	-0.33	0.034
6	8.88	-0.48	0.034
7	11.84	-0.64	0.034

coordinates: x - downstream | origin in the middle of
 y - lateral | the gas source, at the wind
 z - height | tunnel floor

An example of the experimental results is given in figure 9 (sampling station 5 and 6).

In figure 10a and 10b the measured maximum concentrations are given as function of the dimensionless distance to the source R/L_{ci} . The pictures clearly show the decrease of maximum concentration with increasing distance from the source, due to the dispersion of the gas.

Comparison of the UH and TNO results, carried out by Hall [6], showed a significant difference ¹⁾. Continuous release experiments, carried out by Hall [6], showed a large influence of the ground roughness on the downwind concentration. Further experiments, carried out by MT-TNO (described in chapter 5), confirmed this effect.

4.2 Continuous release experiment

At the moment of defining the conditions for the continuous release experiments, no results were available from the TÜV propane tests

¹⁾ A detailed description of the intercomparison results of UH, WSL and MT-TNO will be given in the final report of WSL.

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(continuous releases, field experiments carried out in the framework of the joint project), so a remodelling of a full scale release was not possible. The concept for the model conditions, based on a previous TÜV-field test, have been defined by UH [4].

The model release conditions are:

Gas release rate	:	$\dot{V}_O$	= $1.744 * 10^{-4} \text{ m}^3/\text{s}$ (628 l/h)
Initial density excess	:	$(\rho_O - \rho_a)/\rho_a$	= 4.12 (using SF6)
Characteristic length	:	L_{CC}	= 0.015 m
Characteristic velocity	:	U_{CC}	= 0.783 m/s
Characteristic time	:	T_{CC}	= 0.019 s
Wind speed	:	U_R	= 1.0 U_{CC} (at 1.0 L_{CC} height)
Ground roughness	:	z_O	= 0.05 mm

in which the characteristic length scale L_{CC} , characteristic time scale T_{CC} and characteristic velocity scale U_{CC} for a continuous release are defined as [4], [5]:

$$L_{CC} = (\dot{V}_O^2 / g')^{1/5} \quad [\text{m}]$$

$$T_{CC} = (\dot{V}_O / g'^3)^{1/5} \quad [\text{s}]$$

$$U_{CC} = (\dot{V}_O \cdot g'^2)^{1/5} \quad [\text{m/s}]$$

with g' the effective gravity (defined in 4.1).

The release source is circular, 0.107 m diameter and flat with the wind tunnel floor. The source is covered with a gauze of 50% porosity. The outflow velocity of the gas amounts $v_{out} = 0.04 \text{ m/s}$ ($= 0.05 U_{CC}$). Eight sampling stations have been used, with the following coordinates (figure 11):

sampling station [no.]	x-coordinate [L _c]	y-coordinate [L _c]	z-coordinate [L _c]
1	42.7	0.0	0.0
2	85.5	0.0	0.0
3	128.2	0.0	0.0
4	171.0	0.0	0.0
5	213.7	0.0	0.0
6	256.4	0.0	0.0
7	299.5	0.0	0.0
8	342.3	0.0	0.0

coordinates: x - downstream	origin in the middle of the gas source, at the wind tunnel floor
y - lateral	
z - height	

An example of the experimental results is given in figure 12 (sampling station 1). At most locations repeated measurements have been carried out.

In figure 13 the measured mean, minimum and maximum concentrations for several repeated measurements are given as function of the dimensionless distance downwind from the source, X/L_{cc} . The picture shows clearly the decrease of gas concentration with increasing distance to the source. The concentrations at sample station 5 are relatively low; moreover, the minimum value of measured concentration is below zero (-0.5%). This may be due to zero drift of the 'old' MT-TNO probe, mentioned in chapter 3, of which the reason is not clear. The same effect may have occurred at sample station 7 and 8. In figure 14 the standard deviation is given as function of the dimensionless downward distance, which shows a decrease of the standard deviation with increasing distance.

As in the case of the instantaneous release experiment, significant differences were found between the results of UH and TNO [6]. Hall showed a large influence of the ground roughness z_0 on the downwind concentration [6] which was confirmed by TNO experiments (see chapter 5).

Besides the above experiments, two additional continuous release tests have been carried out, which do not belong to the intercomparison. Both tests however are interesting with relation to gas dispersion and can be used in the data base for testing mathematical models. The experimental set-up in both tests is equal to the continuous release experiment described above, except the wind speed: in the first additional test the wind speed is $0.5 U_{cc}$ at $1.0 L_{cc}$ height; in the second test the wind speed is $2.0 U_{cc}$ at $1.0 L_{cc}$ height. The summarized results are given in figure 15 (mean concentration) and 16 (standard deviation). From figure 15 it can be seen that the wind speed has a large effect on the downwind gas concentration: as expected a higher wind speed leads to a lower gas concentration at a fixed downwind spot. However, the influence of the wind speed on the standard deviation (figure 16) is less clear.

5. INFLUENCE OF GROUND ROUGHNESS

The results of the intercomparison tests of UH and TNO have been compared by Hall [6]; this comparison showed significant difference between the results of UH and TNO. Experiments by Hall [6], carried out in the framework of the intercomparison, showed a large influence of the ground roughness on the downwind concentration. In order to study this effect in more detail, TNO carried out measurements at different values of the ground roughness height for a continuous release experiment (similar to that described in chapter 4.2).

Two values of release rate have been used in these tests:

A	Gas release rate	:	$\dot{V}_O$	=	$1.744 * 10^{-4} \text{ m}^3/\text{s}$ (628 l/h)
	Initial density excess	:	$(\rho_O - \rho_a)/\rho_a$	=	4.12 (using SF6)
	Characteristic length	:	L_{cc}	=	0.015 m
	Characteristic velocity	:	U_{cc}	=	0.783 m/s
	Characteristic time	:	T_{cc}	=	0.019 s
	Wind speed	:	U_r	=	$1.0 U_{cc}$ (at $1.0 L_{cc}$ height)
B	Gas release rate	:	$\dot{V}_O$	=	$3.528 * 10^{-5} \text{ m}^3/\text{s}$ (127 l/h)
	Initial density excess	:	$(\rho_O - \rho_a)/\rho_a$	=	4.12 (using SF6)
	Characteristic length	:	L_{cc}	=	0.008 m
	Characteristic velocity	:	U_{cc}	=	0.565 m/s
	Characteristic time	:	T_{cc}	=	0.014 s
	Wind speed	:	U_r	=	$1.0 U_{cc}$ (at $1.0 L_{cc}$ height)

The definitions of the characteristic length scale L_{cc} , time scale T_{cc} and velocity scale U_{cc} are given in chapter 4.2.

For both release rates, three experiments with different values of roughness length scale z_O have been carried out:

1. $z_O = 0.005 \text{ mm}$, by using a smooth floor
2. $z_O = 0.05 \text{ mm}$, by using a smooth carpet
3. $z_O = 0.5 \text{ mm}$, by using a rough carpet

The matching profiles of mean velocity and along wind turbulence are drawn in figures 2, 3 and 4 (see also chapter 2).

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The release source is the same as used in the intercomparison continuous experiment. The outflow velocity of the gas amounts

$V_{\text{out}} = 0.04 \text{ m/s}$ ($= 0.050 U_{\text{cc}}$) for a release rate of 628 l/h and

$V_{\text{out}} = 0.008 \text{ m/s}$ ($= 0.014 U_{\text{cc}}$) for a release rate of 127 l/h.

For case A, a release rate of 628 l/h, seven sampling stations have been used (figure 17):

Sampling station [no.]	x-coordinate [L_{cc}]	y-coordinate [L_{cc}]	z-coordinate [L_{cc}]
1	42.3	0.0	0.0
2	84.6	0.0	0.0
3	126.9	0.0	0.0
4	169.2	0.0	0.0
5	211.6	0.0	0.0
6	296.2	0.0	0.0
7	338.5	0.0	0.0

For case B, a release rate of 127 l/h, four sampling stations have been used (figure 17):

Sampling station [no.]	x-coordinate [L_{cc}]	y-coordinate [L_{cc}]	z-coordinate [L_{cc}]
1	81.0	0.0	0.0
2	162.0	0.0	0.0
3	243.0	0.0	0.0
4	324.0	0.0	0.0

The sampling rate is 60 Hz, using the new, modified probe.

The experimental results are given in detail in ref. [2].

In figures 18 to 21 the measured mean concentrations and standard deviations are given as function of the dimensionless distance downwind from the source, X/L_{cc} . In figure 18 and 19 the results are given for a release rate of 628 l/h, in figure 20 and 21 for a release rate of 127 l/h.

The pictures clearly show the large influence of ground roughness on the downwind concentration: an increase of the roughness length scale results in lower downwind concentrations.

In figure 22 the mean concentration is given as function of the ground roughness length scale. The downwind concentration seems to be linearly dependent of z_0 although too few data are available to confirm this.

From these results it can be concluded that the original differences found between the results of UH and TNO are a result of the different ground roughness used in these experiments.

6. VELOCITY MEASUREMENTS

In the framework of the joint project numerical models have been developed. For the validation of these models, a data base has been created which contains concentration measurements (full scale and wind tunnel) and velocity and turbulence measurements within and outside the cloud.

The velocity and turbulence measurements in the wind tunnel has been carried out by MT-TNO, using a Fiber Optics Laser Doppler Anometer (FOLDA system, 15 mW Helium - Neon (632 nm) Laser), for a continuous release test.

The model release conditions are equal to the intercomparison continuous release experiment, which has the advantage that the concentrations downwind from the source are known at several positions. These model release conditions are given in chapter 4.2.

Velocities and turbulence intensities have been measured at 6 positions downwind from the source (figure 23):

Position [no.]	x-coordinate [L _{cc}]	y-coordinate [L _{cc}]	concentration [%]
1	14.0	0.0	~ 15.0
2	28.5	0.0	~ 7.5
3	42.7	0.0	5.9
4	85.3	0.0	2.3
5	128.0	0.0	1.4
6	170.7	0.0	1.0

In this table the gasconcentration at ground level is also given, for which the results of the continuous release experiment are used, carried out in the 'ground roughness tests' (chapter 5). For the determination of the concentration at positions 3 to 6 an interpolation method has been used; the resulting 'concentration line' has been extrapolated to positions 1 and 2.

At each position the velocity and turbulence intensity has been measured at several heights:

- from 1 mm to 26 mm in steps of 1 mm;
- from 26 mm to 50 mm in steps of 2 mm;
- from 50 mm tot 100 mm in steps of 5 mm.

At each position the velocity and turbulence intensity profile has been measured with and without the gas source, in order to find the difference in the profile with and without gas release, or in other words: the difference of the velocity profile inside the cloud and the undisturbed velocity, and the difference in turbulence intensity.

The results of the measurements are given in:

Figure 24 : profiles of turbulence and velocity, without source;

Figure 25 : profiles of turbulence and velocity with source;

Figure 26 : profiles of 'turbulence difference' and 'velocity difference', calculated as velocity (turbulence) without source minus velocity (turbulence) with source.

Figure 24 shows that the profiles of turbulence and velocity of the 'undisturbed' (without source) flow at the different positions match rather well. Deviations are mainly due to the fact that, when the wind tunnel is stopped (for example at the end of the day), it is very difficult to create exactly the same wind tunnel speed when the wind tunnel has been started up again.

Figure 25 shows that the deviations between velocity and turbulence intensity profiles inside the cloud are larger. This means that there is an influence of the presence of the gas cloud.

The velocity difference profiles however does not show a systematic difference, which means that there is no consistent influence of the gas cloud. Although it is not quite clear from the figures, it seems that at the first position ($x = 14.0 L_{CC}$, ~15% gasconcentration) the velocities inside the cloud are slightly lower than outside (without) the cloud. For the turbulence difference this is less clear, although the turbulence intensity at the first position ($x = 14 L_{CC}$) inside the cloud, near to the ground, is lower than outside the cloud.

The turbulence difference at position 6 ($x = 170.0 L_{CC}$) at 70 mm heights is probably an erroneous result, due to a measurement error, which resulted in a relative high turbulence intensity in the cloud at that particular spot (see figure 25).

From these results it can be concluded that for continuous releases there is no significant difference in velocity and turbulence profiles at positions for which the (mean) gas concentration is lower than about 15%.

7. REMODELLING OF FULL-SCALE EXPERIMENTS

In the framework of the joint project full-scale experiments have been carried out by TÜV Norddeutschland and Risø National Laboratory at the Lathen test site.

The test which has been remodelled (trial EEC57) consisted of a cyclone-release of propane (which can be considered as a continuous release, without momentum).

Downwind from the source, a straight fence of 2.0 m height and 51.24 m width had been erected, which was removed suddenly during the release. The wind tunnel concept of this test has been elaborated by the University of Hamburg.

In figure 27 the source, the (catalytic type) concentration detectors and the fence are drawn for the field test, in which the distances are expressed in characteristic length scales. The closed symbols indicate the positions at which wind tunnel measurements have been carried out.

The full scale release conditions are:

Gas release rate	: $\dot{V}_o$	= 0.881 m ³ /s (3.17 * 10 ⁶ l/h)
Initial density excess	: $(\rho_o - \rho_a)/\rho_a$	= 0.64 (using propane)
Characteristic length	: L_{cc}	= 0.659 m
Characteristic velocity	: U_{cc}	= 2.032 m/s
Characteristic time	: T_{cc}	= 0.324 s
Wind speed	: U_r	= 1.1 U_{cc} at 9.1 L_{cc} height

The model release conditions are (model scale 1:78):

Gas release rate	: $\dot{V}_o$	= 0.417 * 10 ⁻⁴ m ³ /s (150 l/h)
Initial density excess	: $(\rho_o - \rho_a)/\rho_a$	= 4.12 (using SF6)
Characteristic length	: L_{cc}	= 0.008 m
Characteristic velocity	: U_{cc}	= 0.586 m/s
Characteristic time	: T_{cc}	= 0.014 s
Wind speed	: U_r	= 1.0 U_{cc} (at 1.0 L_{cc} height)

In setting the wind tunnel mean velocity a mistake has been made. Correct transformation of the full-scale data leads to a wind tunnel wind speed of $1.1 U_{cc}$ at $9.1 L_{cc}$ height. Using a logarithmic velocity profile, this results in a wind speed of $0.8 U_{cc}$ at $1.0 L_{cc}$ height. In the wind tunnel experiments a wind speed of $1.0 U_{cc}$ at $1.0 L_{cc}$ height has been used. This means that the wind tunnel experiments have been carried out with a wind speed which was about 25% too high, compared to the full-scale situation. Although the wind tunnel results are consequently not fully comparable with the full-scale results, a qualitative comparison can be made. Moreover, the results can be used for testing the numerical models.

The sampling rate is 60 Hz. The release device is equal to that used in the intercomparison continuous test, which means that outflow velocity of the gas amounts $v_{out} = 0.009 \text{ m/s}$ ($= 0.016 U_{cc}$).

Three experiments have been carried out:

1. without the fence;
2. with the fence;
3. the fence removed after about 30 sec. ($= 2150 T_{cc}$).

The results of these experiments are given in figure 28 to 34. The results clearly show the increase in gas concentration in front of the fence, when the fence is present (figures 28 to 31). Behind the fence, the gas concentration decreases which is to be expected.

Remarkable is the slow decrease of concentration after the sudden increase due to the removal of the fence, at some measuring stations (26, 32, 35 and 36). The reason for this is not quite clear. It may indicate that the adaption of the flow to new circumstances (flow without a fence instead of with fence) may take a lot of time.

This effect is not visible in the full-scale experiments, due to the relative short duration ($2500 T_{cc}$) of the full-scale experiment.

As these experiments should be considered as one of an ensemble, deviations occur sometimes between the mean concentration in experiment 2 (with fence) and the mean concentration (up to the removal of the fence) in experiment 3.

It should be noted that as all experiments have been performed with one probe only, the experiment is repeated everytime that the probe is placed in a new position. As can be seen from the results, the inherent variability of the results is considerably. Although it has been tried to repeat the experiments under exactly the same conditions, the results show nevertheless this large variability. So in this respect it is a clear disadvantage that the experiments have been performed with only one probe.

It should also be noted that - although not directly visible from the figures - also this new, modified probe still incidentally suffers from a small zero baseline drift.

Besides this 'remodelling test' two tests have been carried out in which the fence is rotated.

In the first test, the fence is rotated over $+15^\circ$ (see figure 35, in which also the measuring stations are drawn).

The model release conditions are equal to that in the 'remodelling' test.

The results of this test are given in figure 36 to 39.

The result of measuring station 35 (figure 38) seems somewhat strange, due to the strong increase in gas concentration after the removal of the fence. This effect is however also present in the second test (see below).

In the results of this measuring station, the decrease in gas concentration (after the sudden increase, due to the removal of the fence) is again visible, which strengthens the idea that the adaption of the flow, after the removal of the fence, is a process of long duration.

In the second test, the fence is rotated over -15° (see figure 40, in which also the measuring stations are drawn). For this test, the model release conditions are also equal to that in the 'remodelling test'.

The results are given in figure 41 to 44.

Also this test shows for measuring station 35 a strong increase in gas concentration, which is not expected from the results for the same station for the situation 'without fence'. A similar effect is visible for measuring station 36. Both station (35 and 36) show the slow

decrease of gas concentration after sudden increase as a result of the removal of the fence. It should be noted again that all experiments have been performed with one probe, using repeated tests.

It is concluded from the wind tunnel results that full-scale experiments, in which a sudden change of the geometry takes place (such as the removal of obstacles), should not be finished before the flow has adapted itself to the changed circumstances. The process which is responsible for the long duration of this adaption is not fully clear. It is therefore advised to study this in more detail.

The inherent variability of the results also leads to the fact that no consistent differences can be found between the concentration measurements for the situation with the fence in 0° , $+15^\circ$ and -15° position.

8. OVERVIEWS OF THE AVAILABLE EXPERIMENTAL DATABASE

All the experiments described in the preceding chapters are part of the experimental data base of the joint project. Here an overview is given of all these experiments which are also available on floppy discs.

All the experiments are performed with SF₆. The sampling rate in the concentration measurements is 60 Hz.

Concentration measurements

release type	release rate	length scale	velocity scale	time scale	ground roughness	wind speed	lay-out in fig. nr
	V_0	L_c	U_c	T_c	Z_0	U_r	
	[l/h]	[m]	[m/s]	[s]	[mm]	[m/s]	
instantaneous	1.4 [l]	0.112	2.126	0.053	0.05	0.26 U_{cc} at 0.85 L_{cc}	8
continuous	628	0.015	0.783	0.019	0.05	1.0 U_{cc} at 1.0 L_{cc}	11
continuous	628	0.015	0.783	0.019	0.005	1.0 U_{cc} at 1.0 L_{cc}	17
"	628	0.015	0.783	0.019	0.05	"	17
"	628	0.015	0.783	0.019	0.5	"	17
"	127	0.008	0.565	0.014	0.005	"	17
"	127	0.008	0.565	0.014	0.05	"	17
"	127	0.008	0.565	0.014	0.5	"	17
continous with fence	150	0.008	0.586	0.014	0.005	1.0 U_{cc} at 1.0 L_{cc}	27
	150	0.008	0.586	0.014	0.005	"	35
	150	0.008	0.586	0.014	0.005	"	40

Velocity measurements

release type	release rate	length scale	velocity scale	time scale	ground roughness	wind speed	lay-out in fig. nr
	V_0	L_c	U_c	T_c	Z_0	U_r	
	[l/h]	[m]	[m/s]	[s]	[mm]	[m/s]	
continuous	628	0.015	0.783	0.019	0.05	1.0 U_{cc} at 1.0 L_{cc}	23

9. CONCLUSIONS

- Wind tunnel experiments have been performed on the effect of obstacles on the dispersion of a heavy gas cloud, including the investigation of concentration fluctuations. These results form part of an experimental data-base available for testing of mathematical models.
- Results of intercomparison tests between the three wind tunnel groups showed a large influence of ground roughness: experiments showed a significant decrease of gas concentration when the ground roughness increased. Taking this effect into account, the experiments by the three groups showed the same results.
- For continuous releases it appears from FOLDA (Laser Doppler) measurements that the velocity and turbulence intensity profiles differ from the undisturbed profiles only in that part of the gas cloud for which the mean gas concentration is higher than about 15%. At higher concentrations, the wind speed and turbulence intensity are reduced relative to the situation without the presence of a cloud.
- The remodelling test of a full-scale trial showed that the adaption of the gas cloud flow to new circumstances, after a sudden change in obstacle geometry, is a process of long duration, although it is not fully clear which process is responsible for this.
Full-scale experiments should therefore not be finished before complete adaption of the flow.
- The inherent variability of the concentration measurements is of such an extent that differences in concentrations due to a change in fence position of $+15^\circ$ and -15° cannot be detected consistently.

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10. REFERENCES

- [1] Oort, H. van, Builtjes, P.J.H.
Instantaneous and continuous release tests for
intercomparison of experimental equipment
MT-TNO, ref.no. 90-346, October 1990.
- [2] Oort, H. van, Builtjes, P.J.H.
Influence of ground roughness on downwind
concentrations during continuous releases
MT-TNO, ref.no. 90-409, November 1990.
- [3] Builtjes, P.J.H., Vermeulen, P.E.J.
Atmospheric boundary layer simulation in the PIA and MIA
wind tunnels of TNO-Apeldoorn.
MT-TNO, ref.no. 80-0290, January, 1980.
- [4] Schatzmann, M.
Intercomparison of wind tunnels
First progress report of project BA (topic 1.2)
'Research on continuous and instantaneous heavy gas clouds'
November 1, 1987 - June 1, 1988
(MT-TNO, ref.no. 88-09097/8724-18768).
- [5] Schatzmann, M.
Report on the meeting of the CEC-project BA:
'Research on continuous and instantaneous heavy gas
clouds' contribution of University of Hamburg
University of Hamburg, February 22, 23, 1988
(edited by P.J.H. Builtjes, MT-TNO).
- [6] Hall, D.J., Marsland, G.A., Emmot, M.A.
CEC-MTH wind tunnel intercomparison of heavy gas dispersion
Warren Spring Laboratory
Ref.no. CR 3256 (PA), April 1990.

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11. AUTHENTICATION

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- Date upon which, or period in which, the research took place:

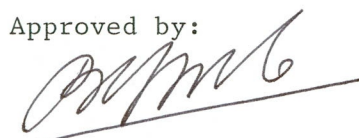
January 1991

- Signature:

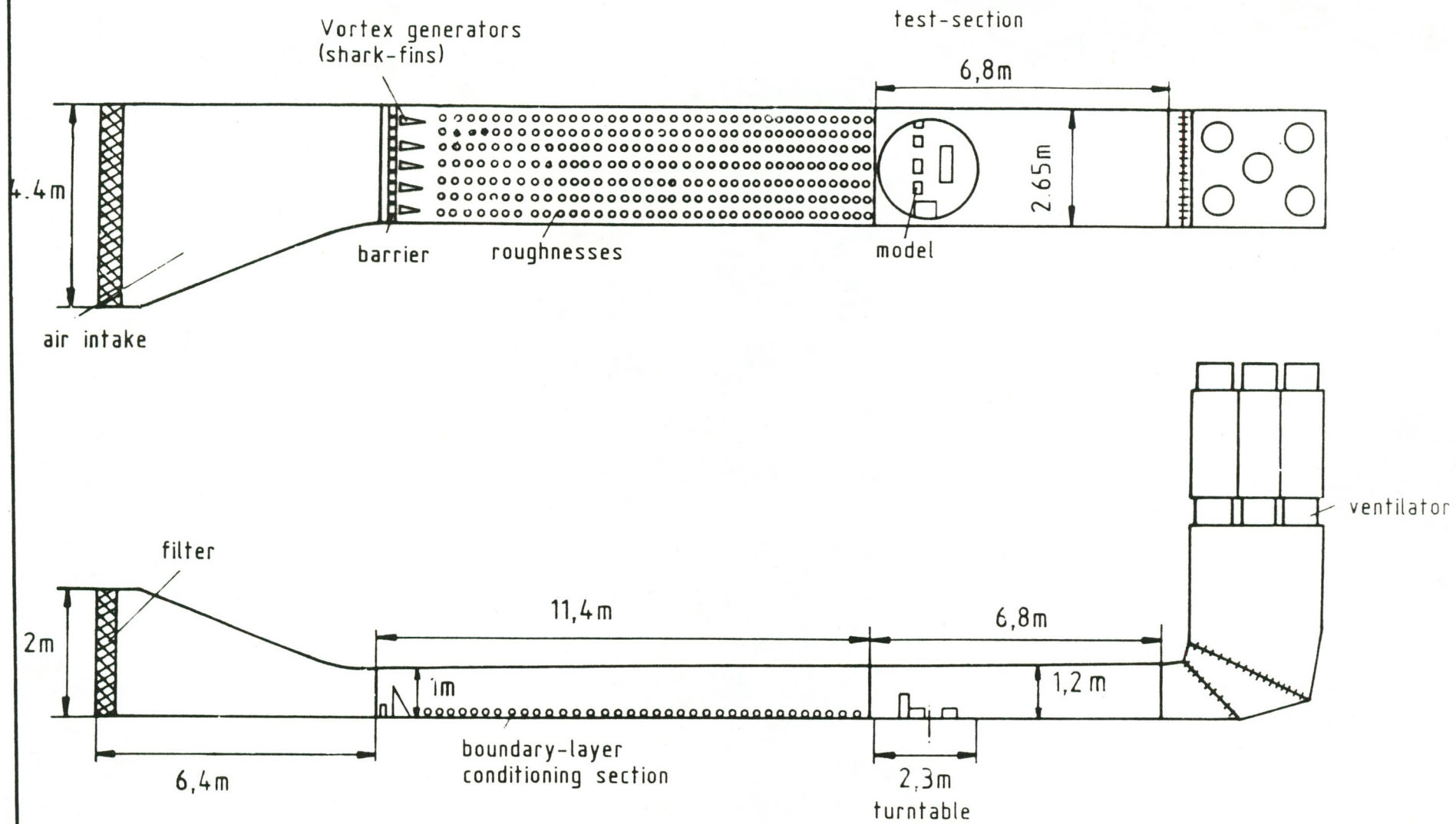


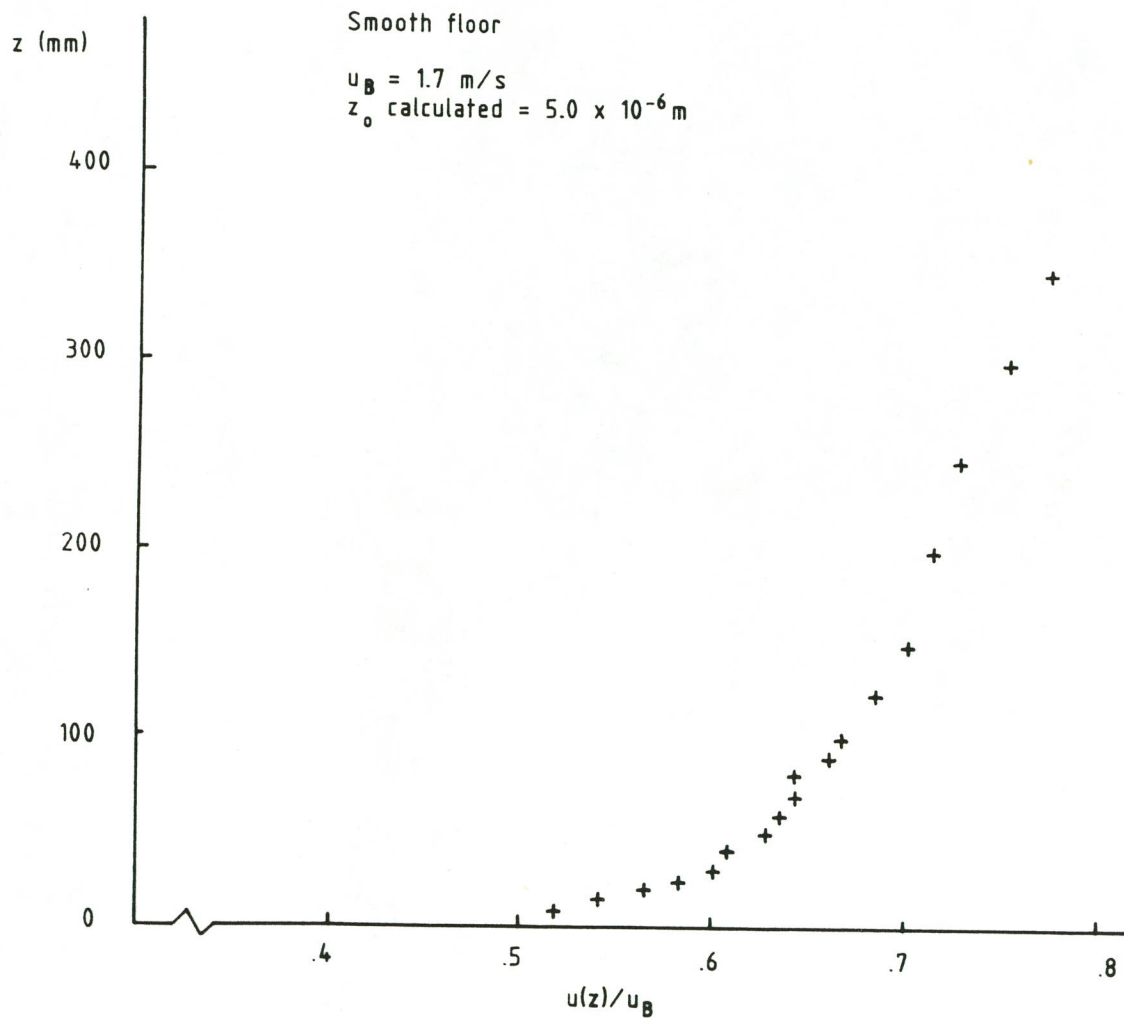
P.J.H. Builtjes
research coordinator

Approved by:



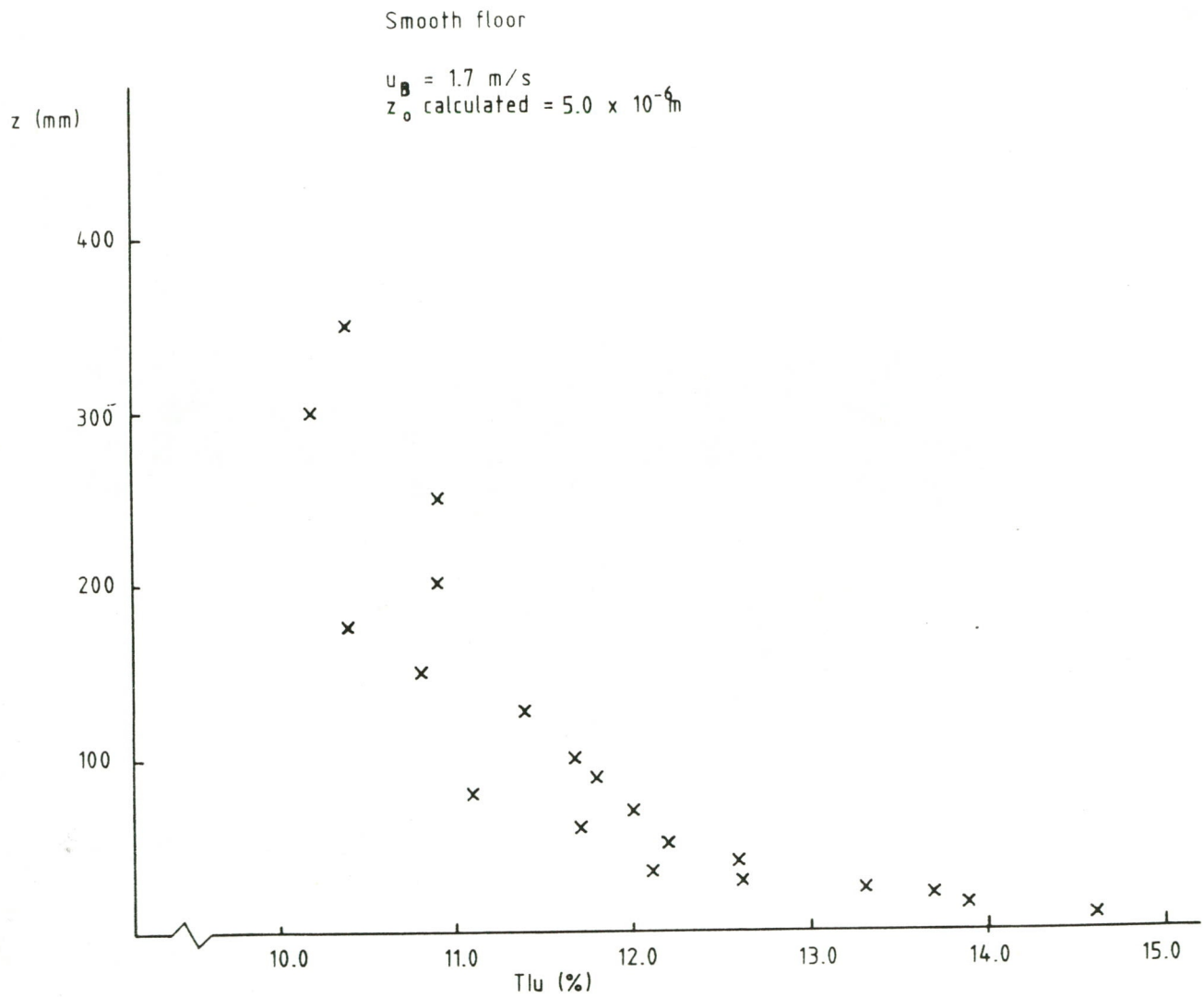
B. Stork
Head Department of
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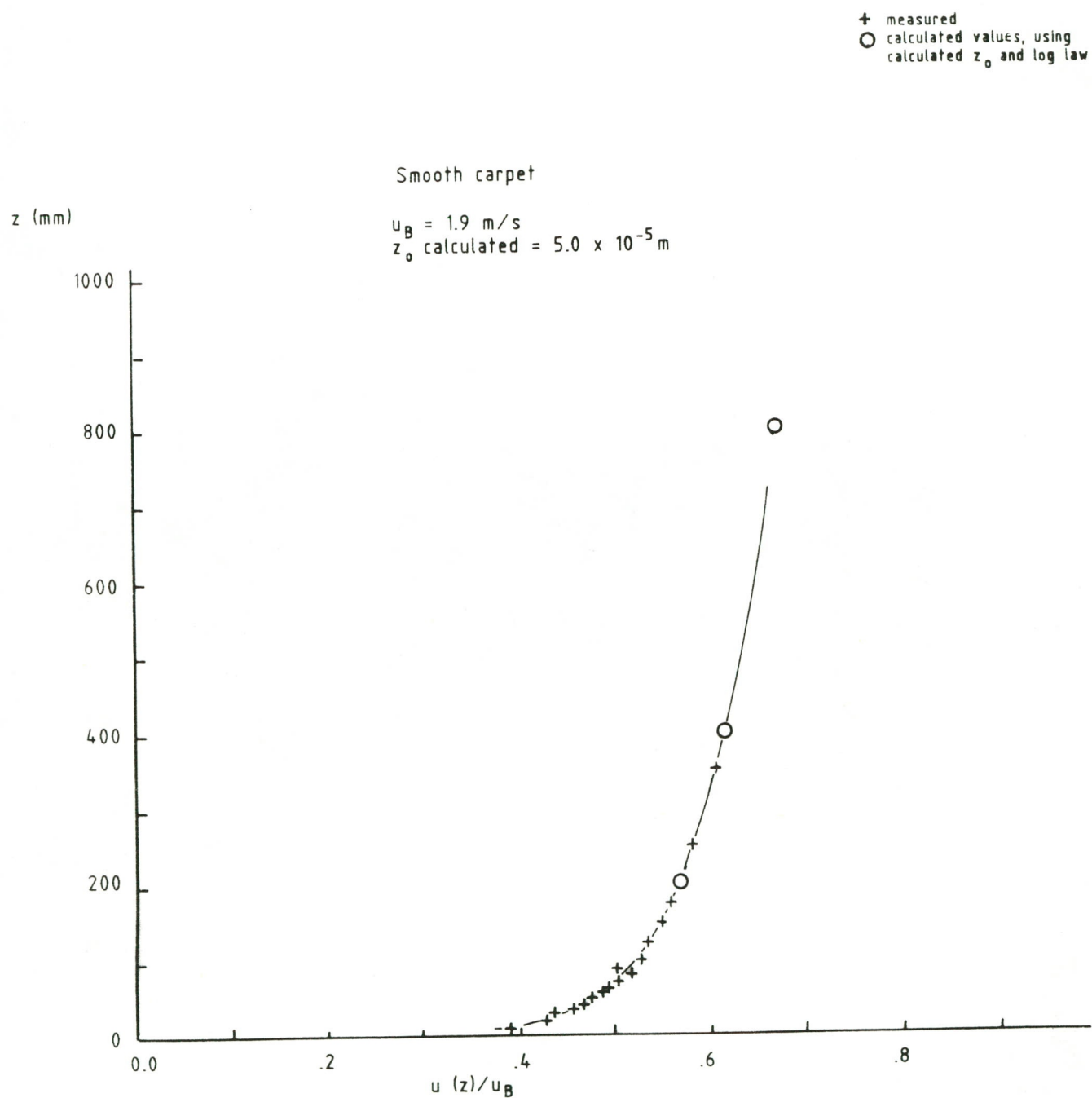
Mean velocity profile for smooth floor.

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Fig. 2a



Longitudinal turbulence intensity profile for smooth floor.

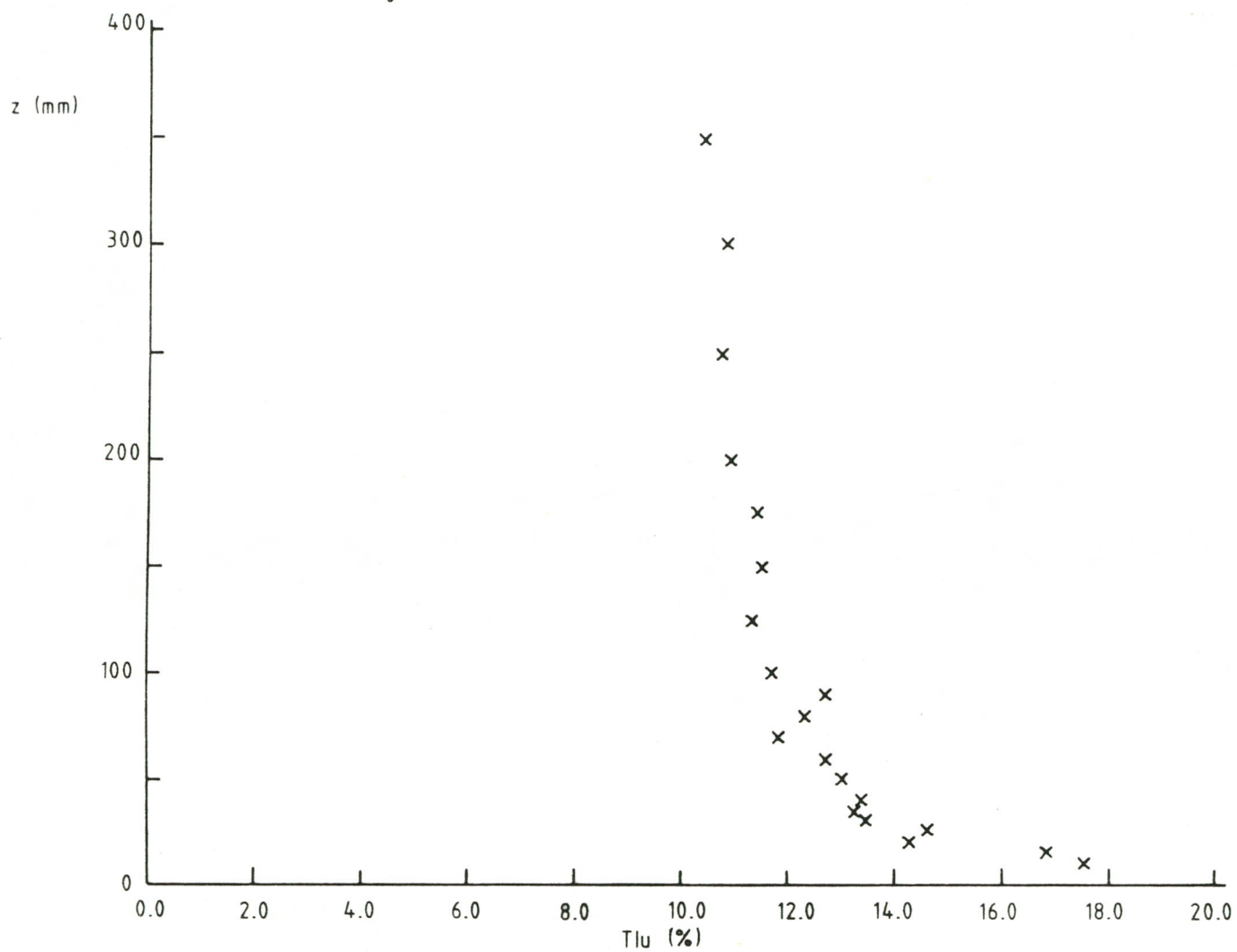
MT - TNO
91-026
Fig. 2b



Smooth carpet

$$u_B = 1.9 \text{ m/s}$$

$$z_0 \text{ calculated} = 5.0 \times 10^{-5} \text{ m}$$



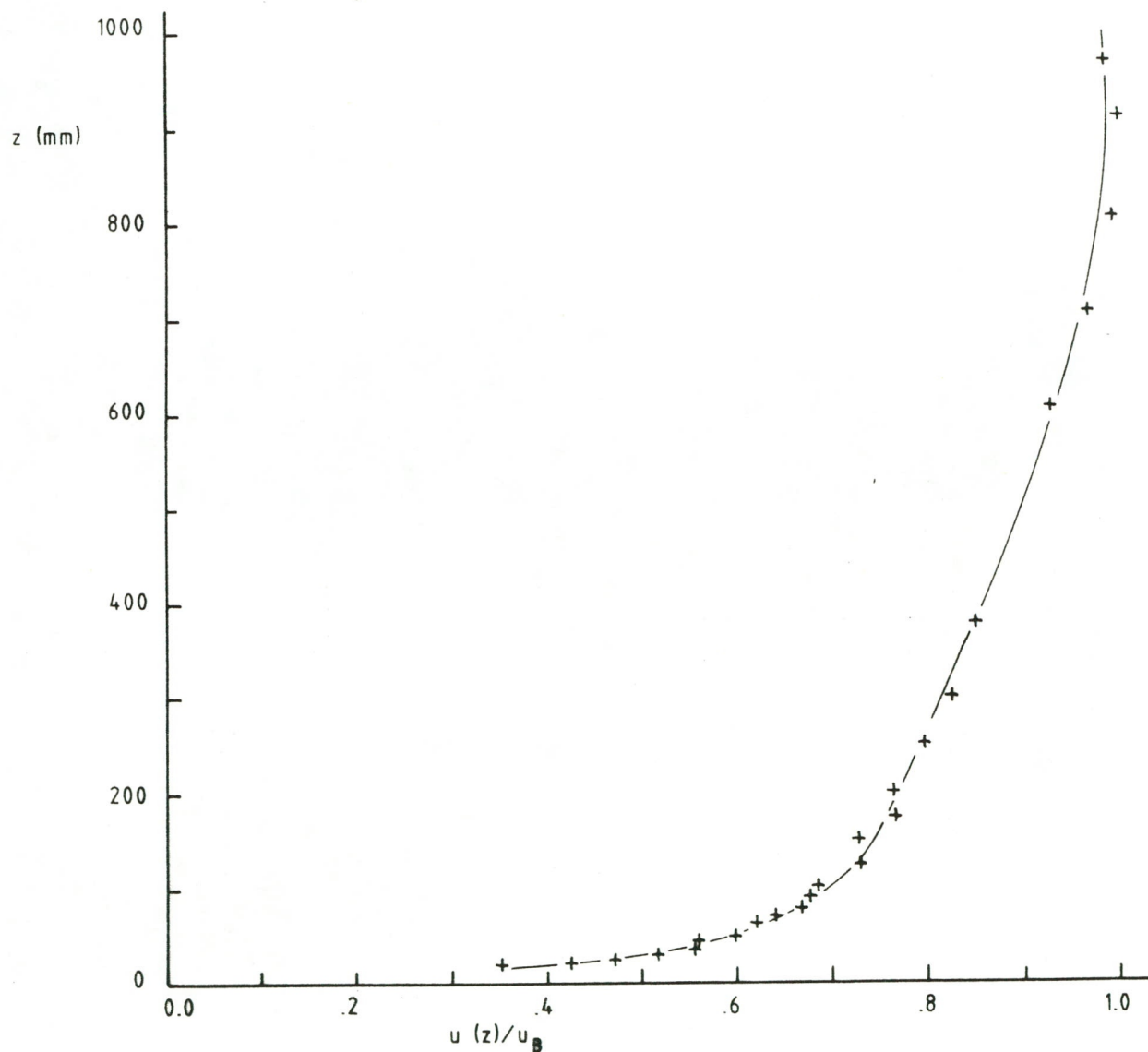
Longitudinal turbulence intensity profile for smooth carpet

MT - TNO
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Fig. 3b

Rough carpet

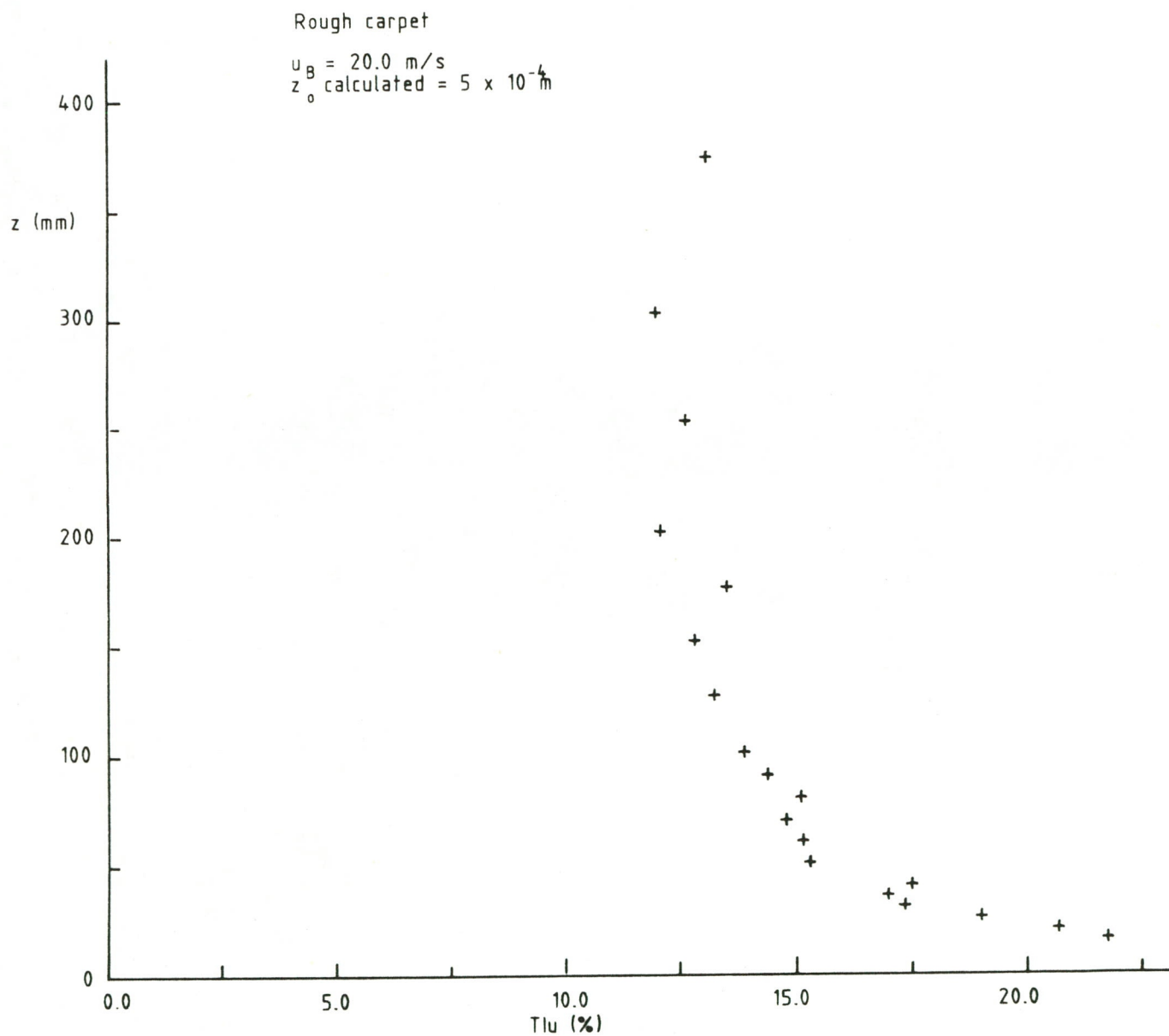
$u_B = 20.0 \text{ m/s}$

$z_0 \text{ calculated} = 5.0 \times 10^{-4} \text{ m}$



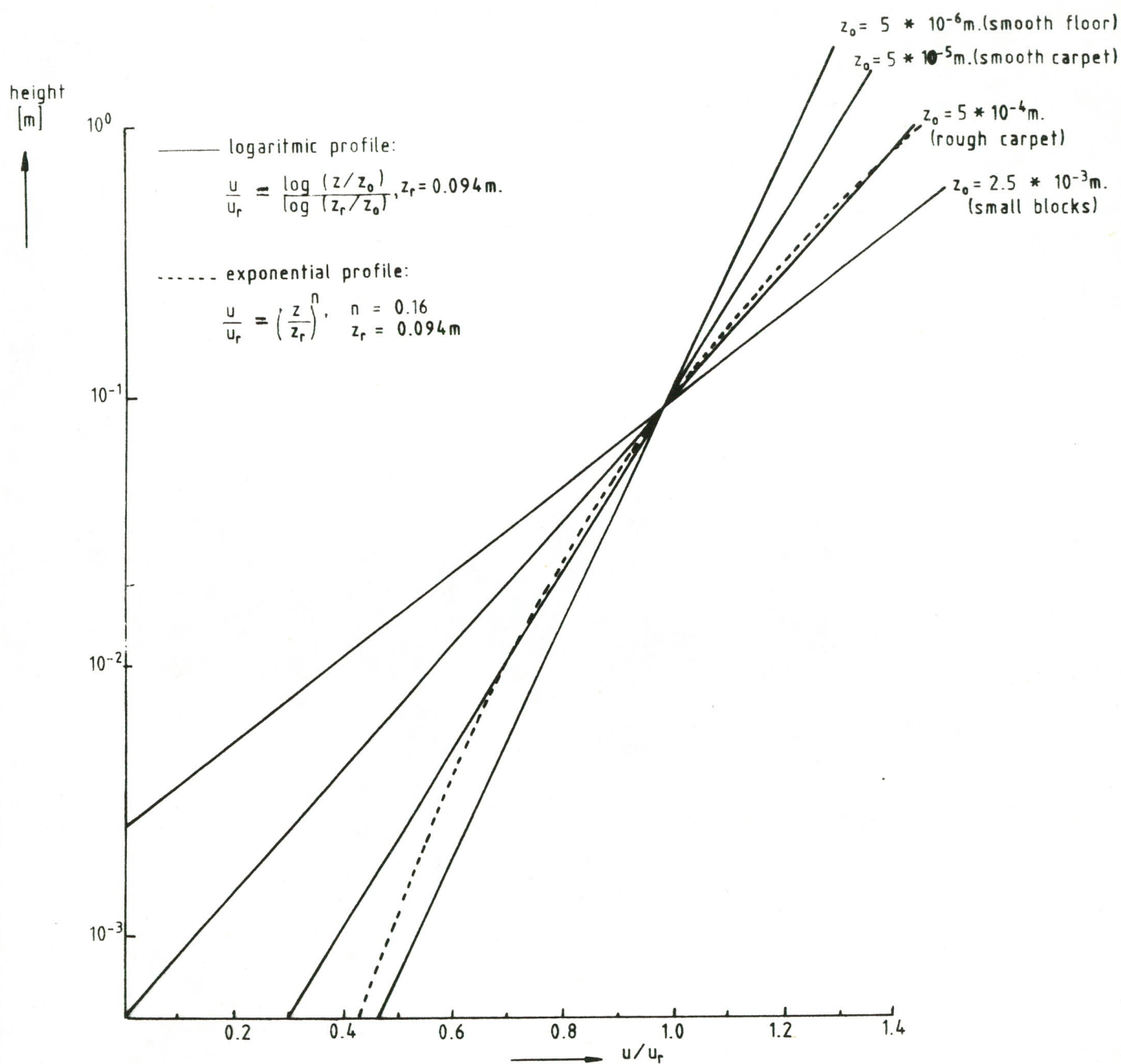
Mean velocity profile for rough carpet..

MT - TNO
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Fig. 4a

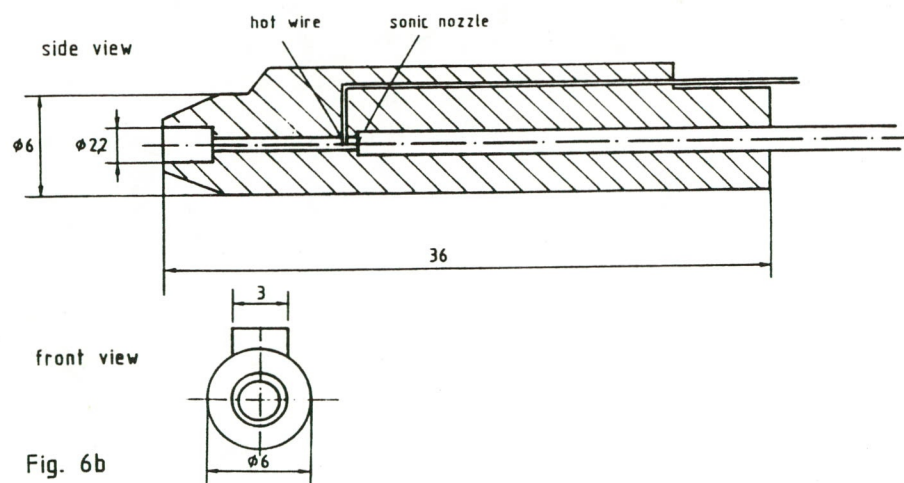
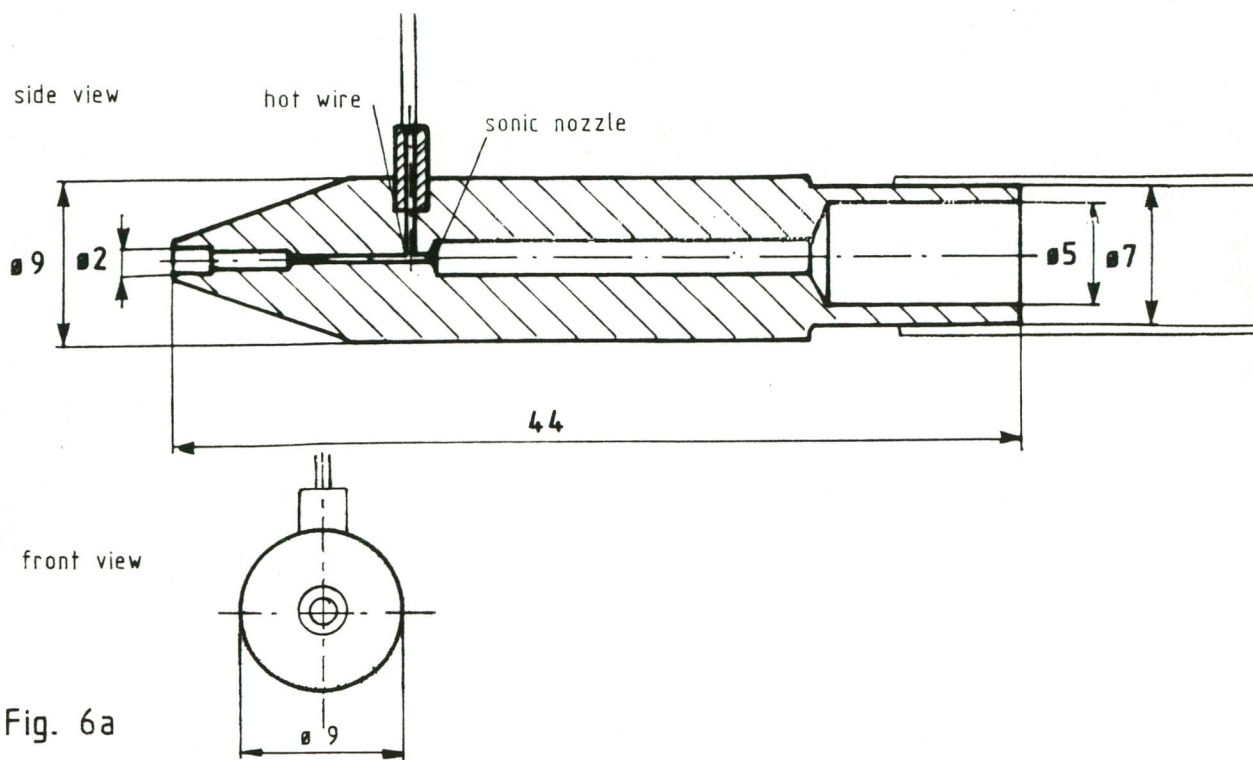


Longitudinal turbulence intensity profile for rough carpet.

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Fig. 4b



Comparison between logarithmic and exponential velocity profile.



(measures in mm)

6a) MT-TNO aspirated hot wire probe
6b) Modified MT-TNO aspirated hot wire probe.

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Fig. 6a + 6b

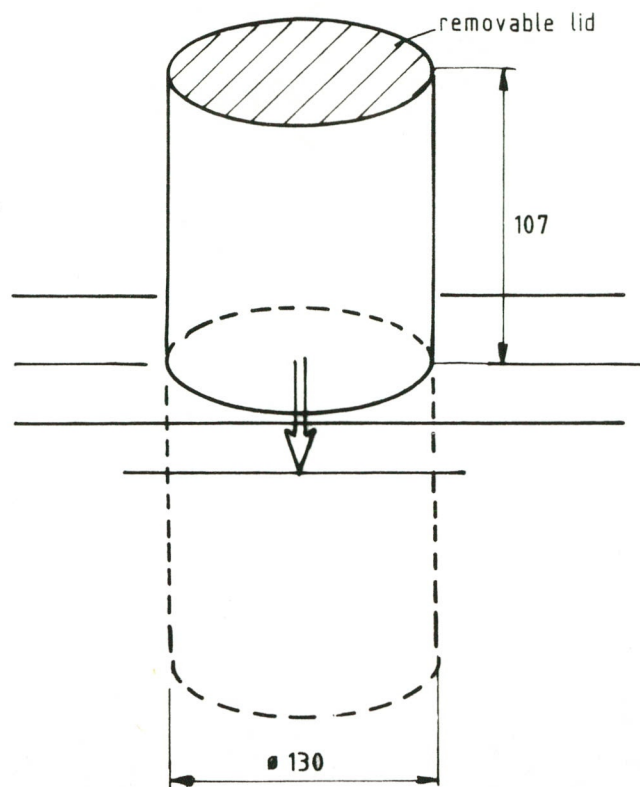


Fig. 7

(measures in mm)

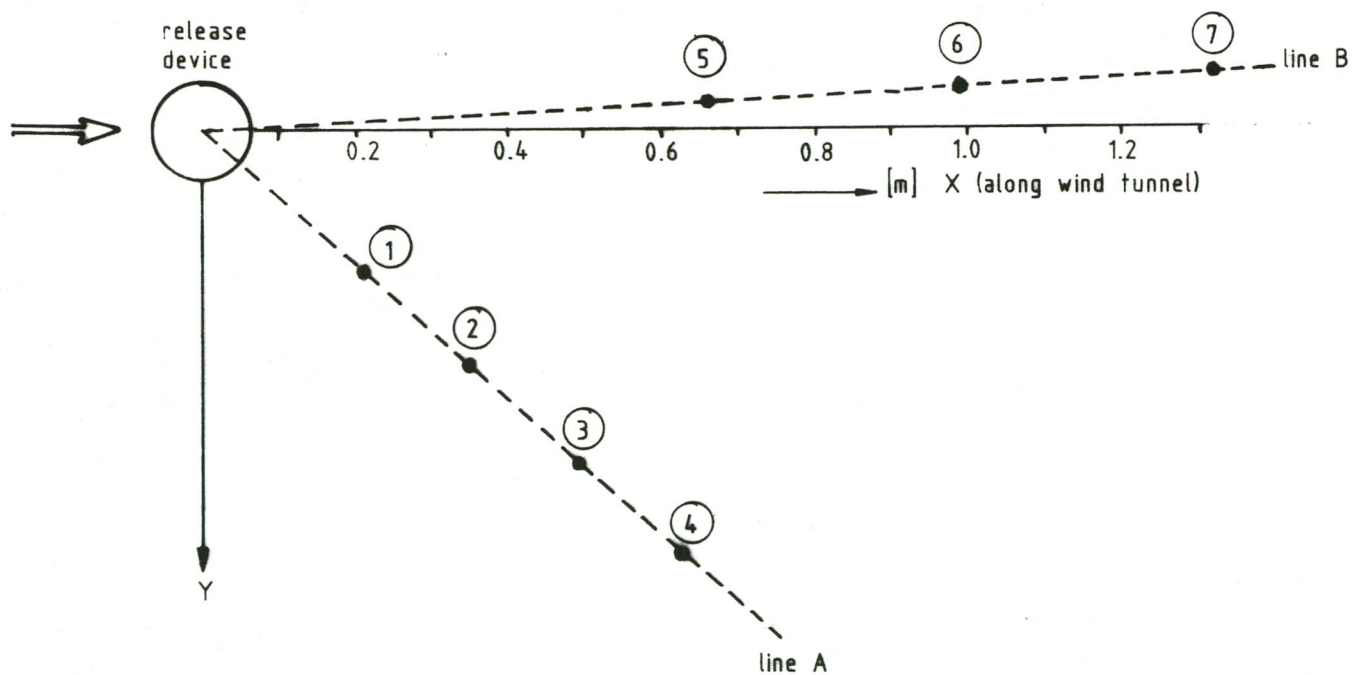
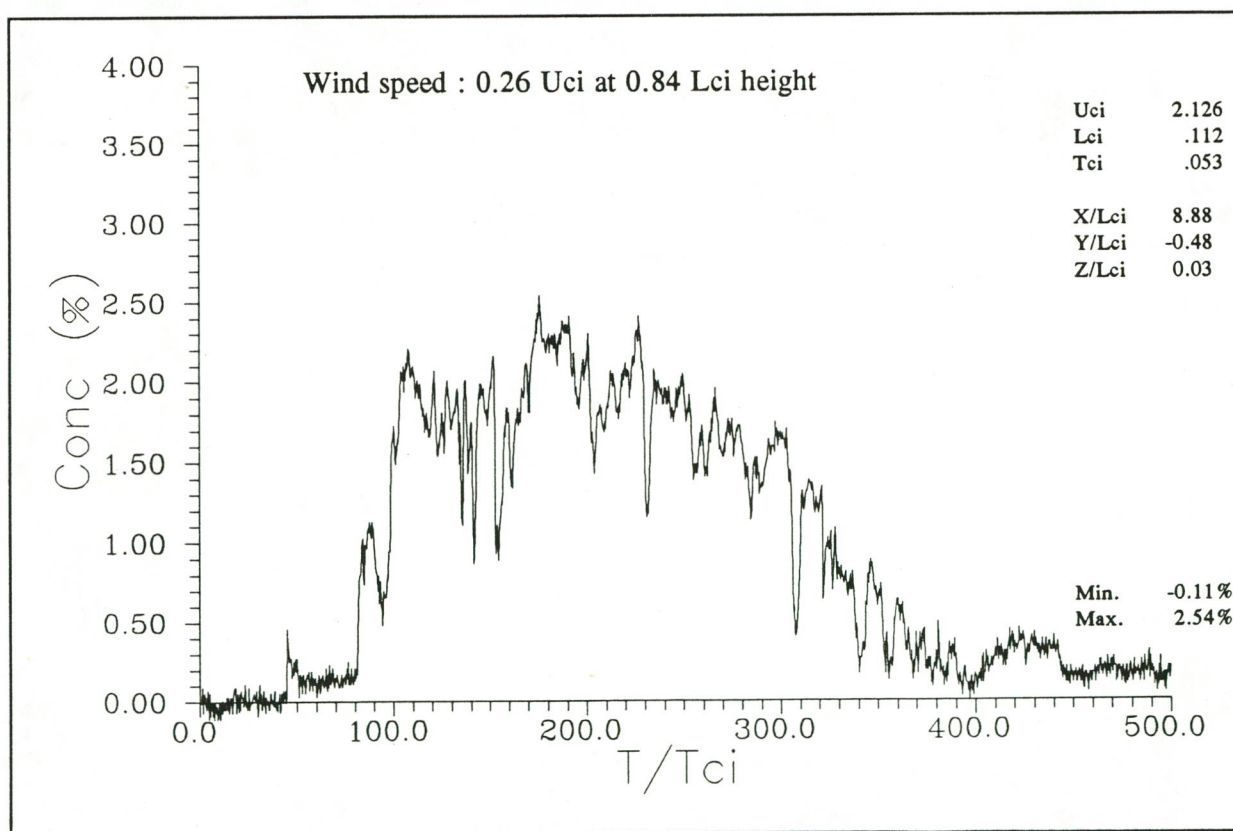
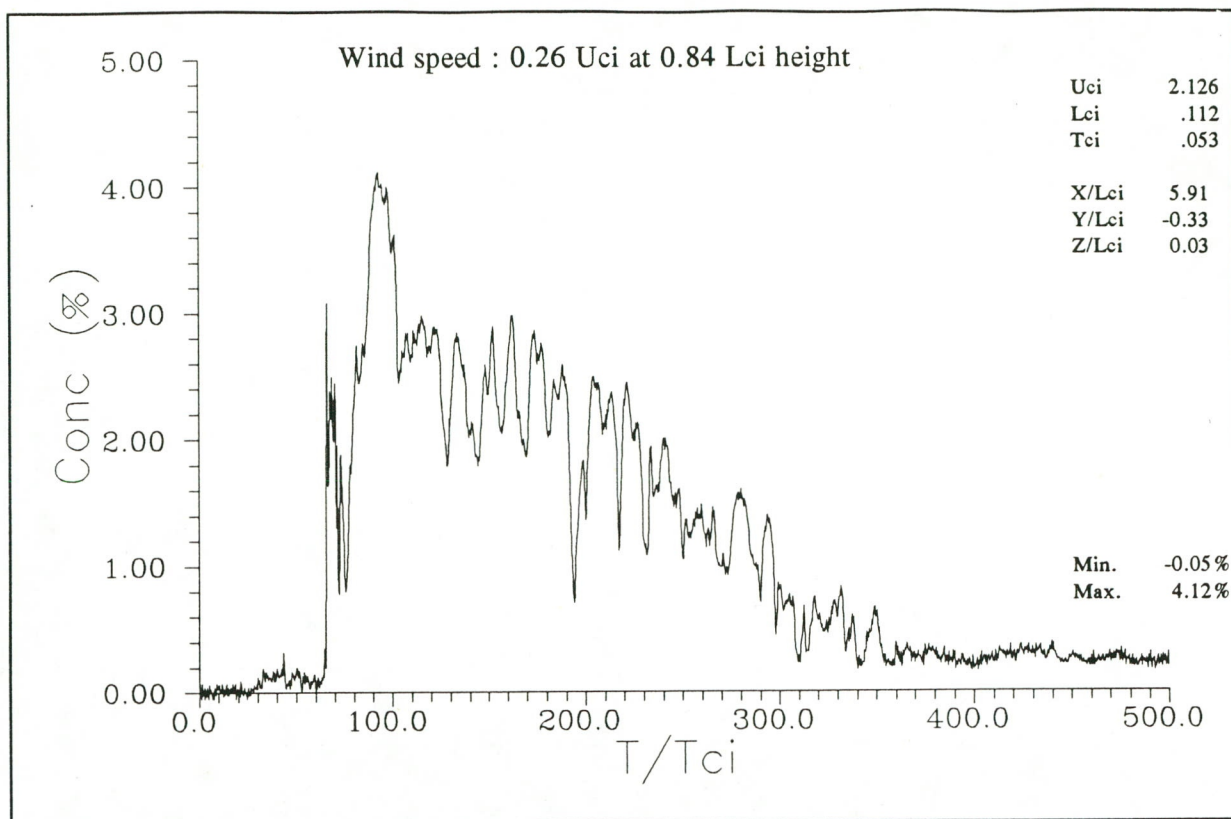


Fig. 8

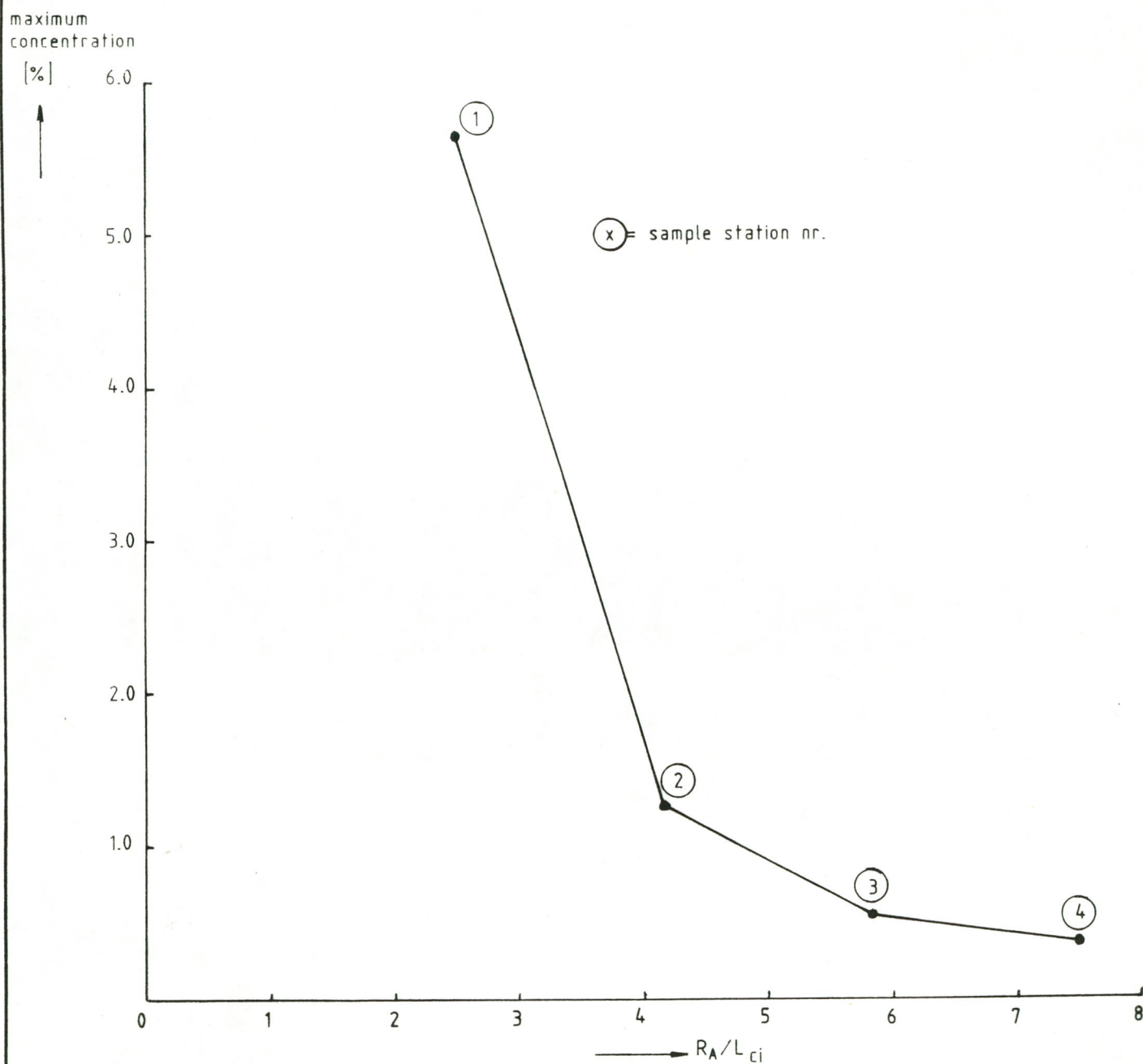
7) Release device in the instantaneous release experiment
8) Sampling station for the instantaneous release experiment.

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Fig. 7 + 8



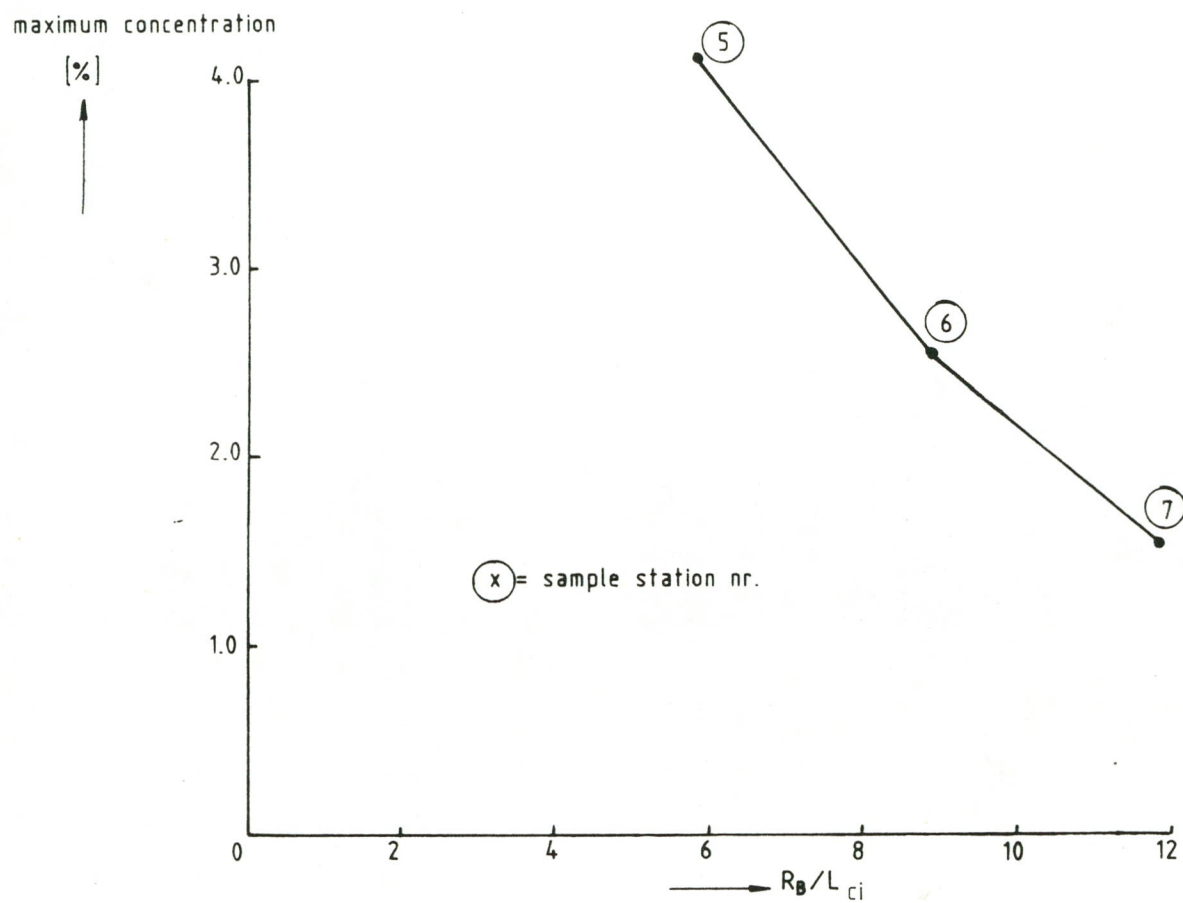
Example result of the instantaneous release.

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Fig. 9



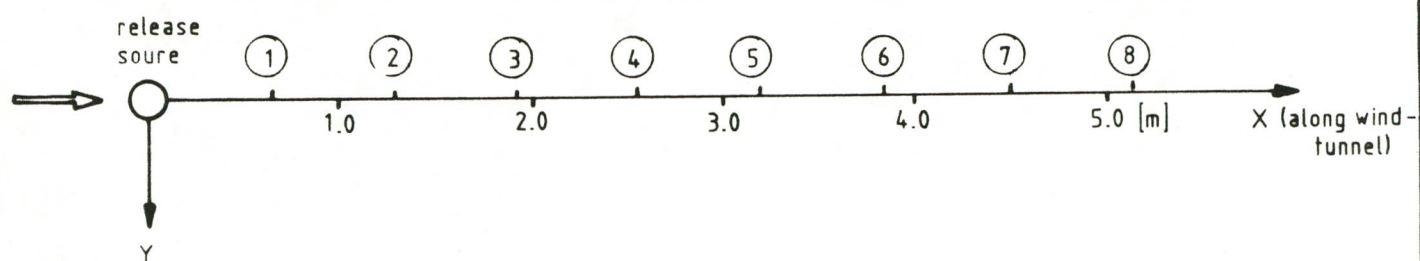
Maximum concentrations for the instantaneous release at
line A (see figure 8).

MT-TNO
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Fig. 10a



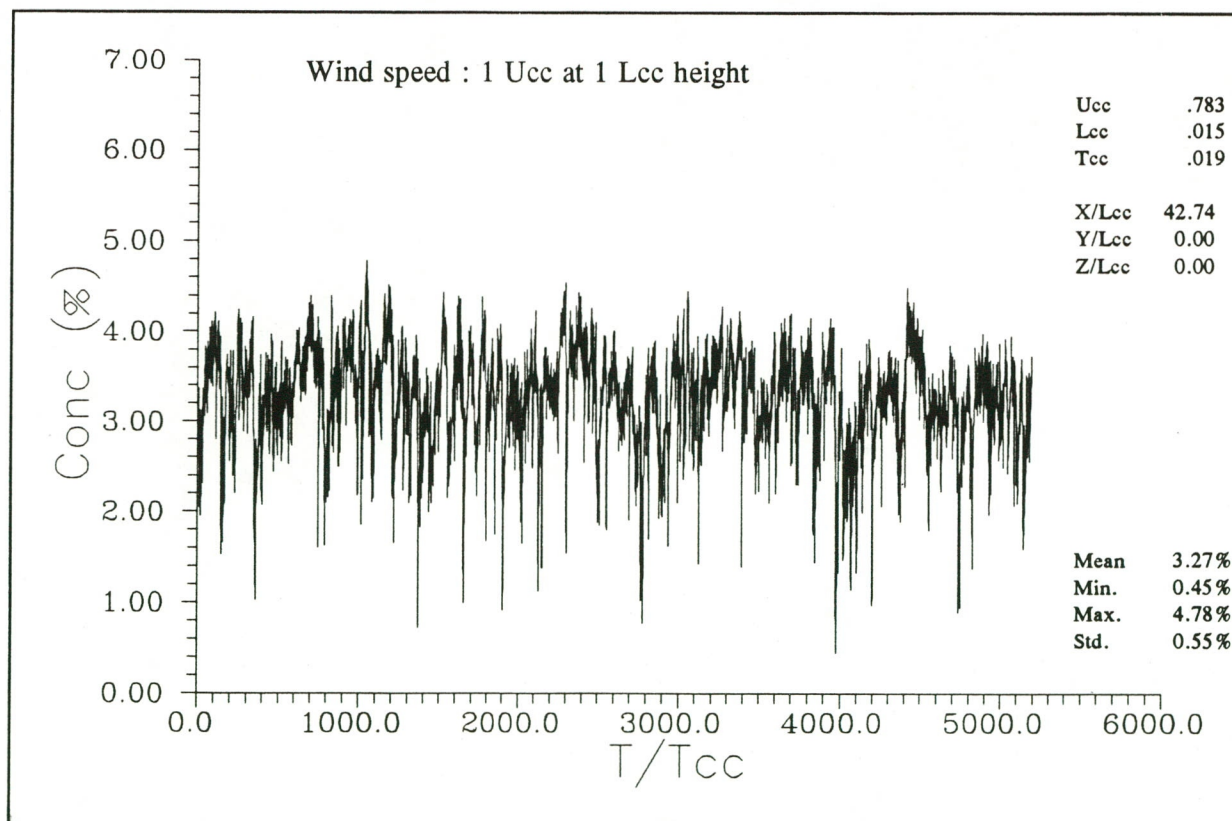
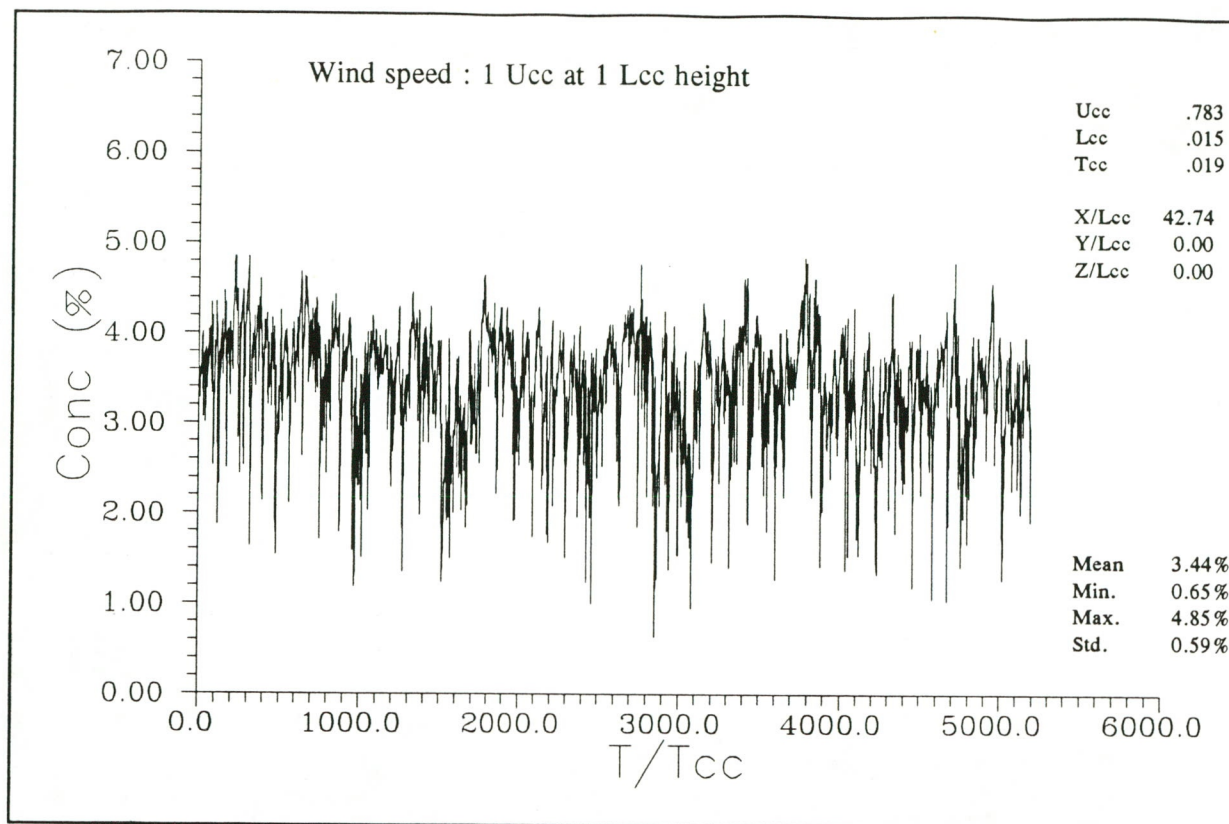
Maximum concentrations for the instantaneous release at line B, (see figure 8).

MT-TNO
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Fig. 10b



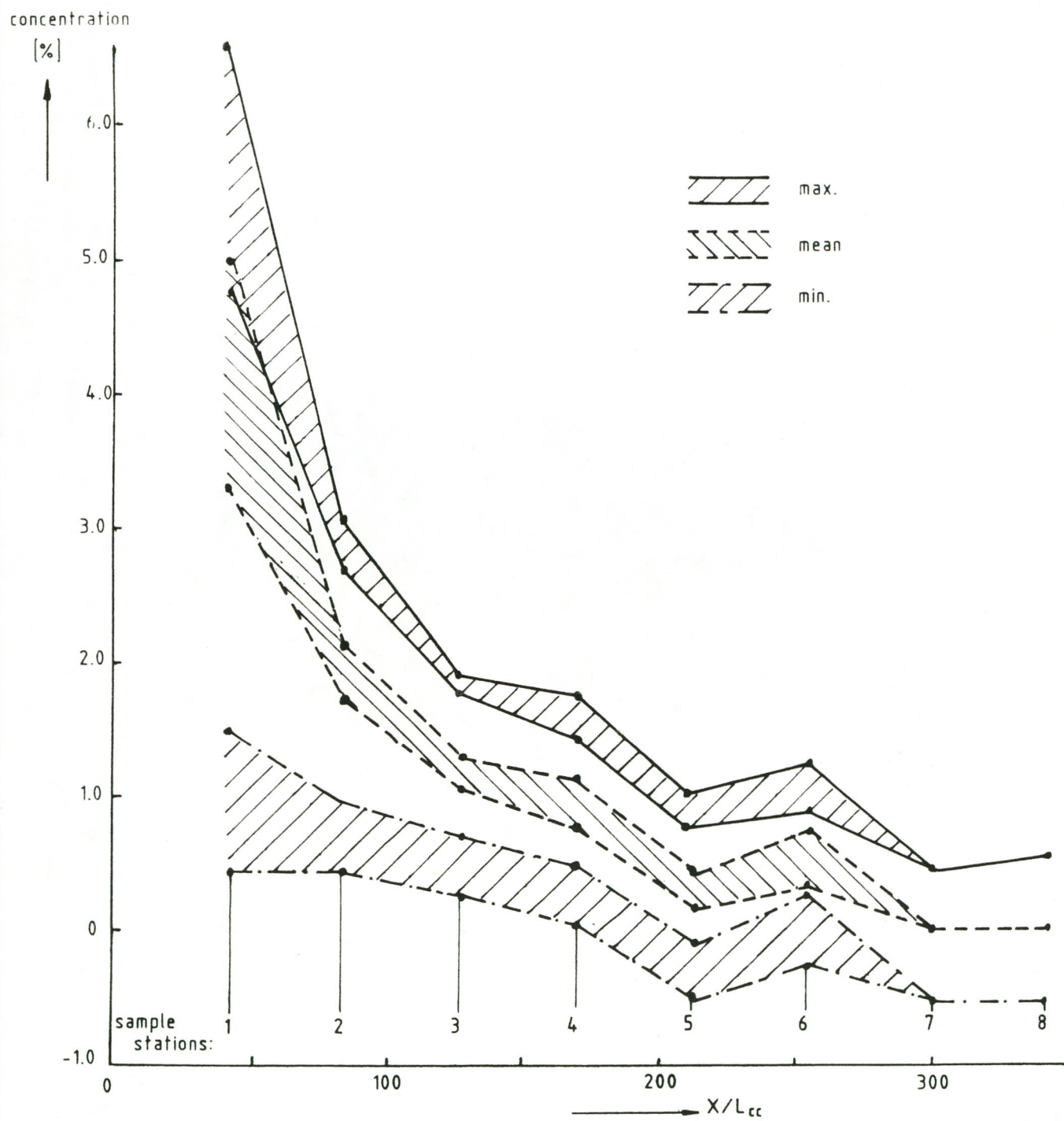
Sampling stations for the continuous test.

MT-TNO
91-026
Fig. 11



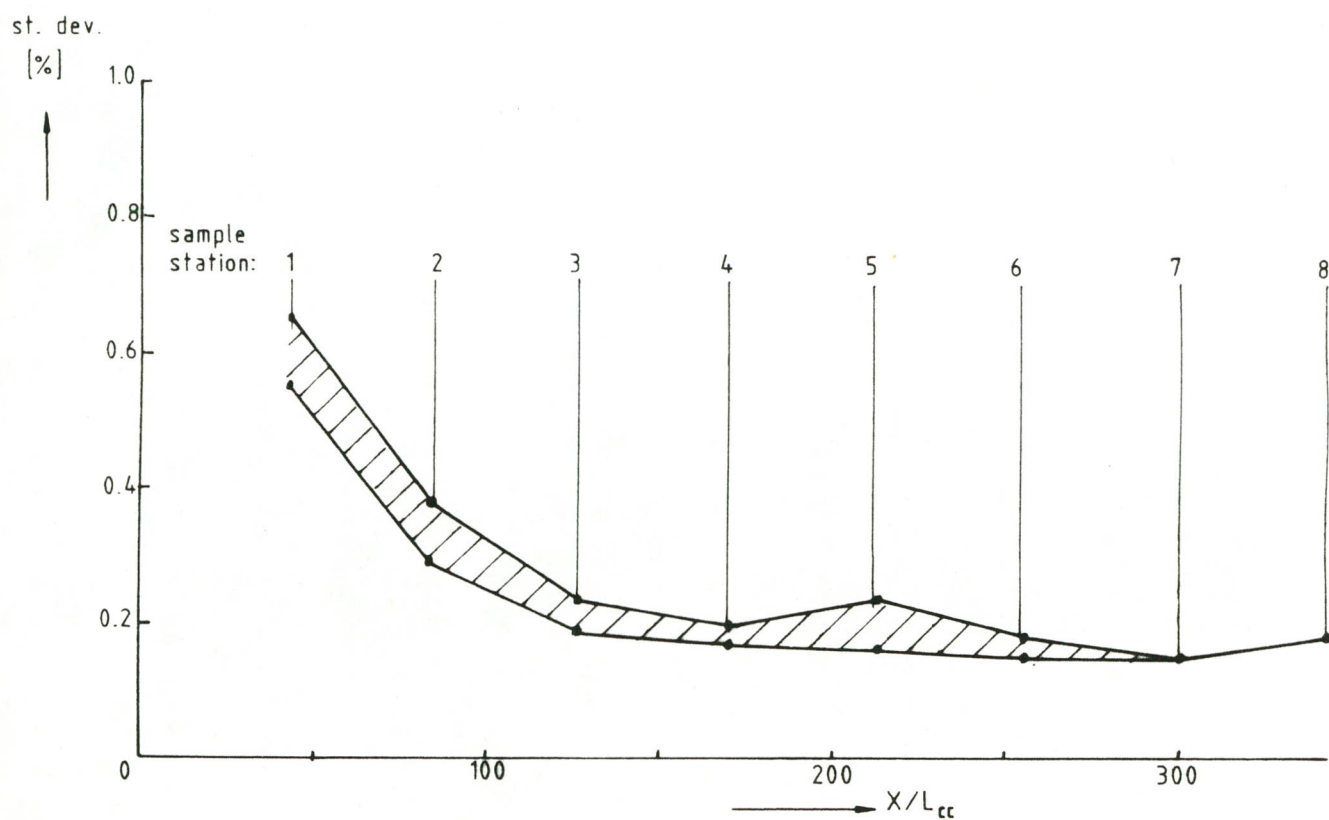
Example result of the continuous release.

MT - TNO
91 - 026
Fig. 12



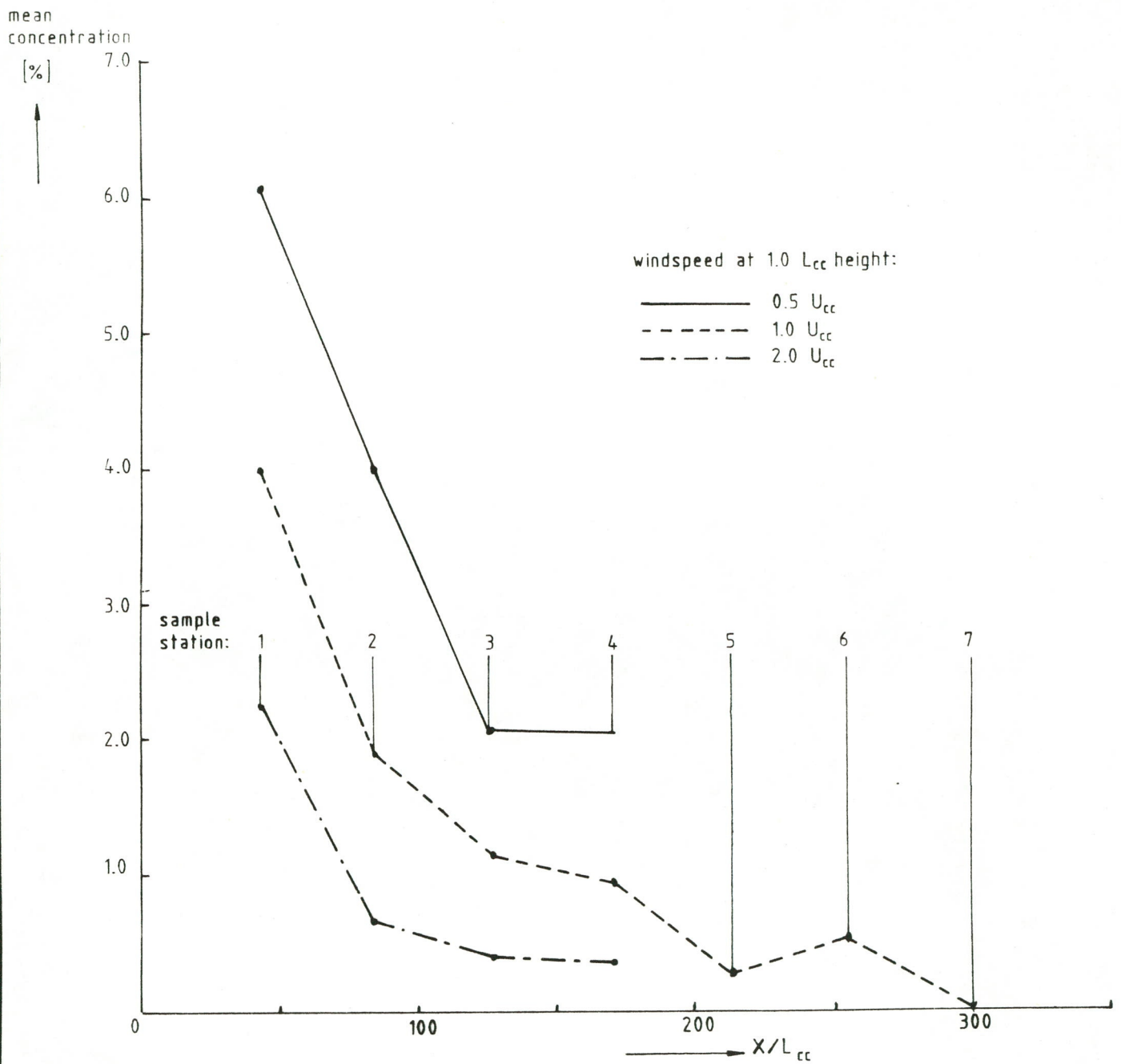
Mean, minimum and maximum concentrations for the continuous release test.

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Fig.13



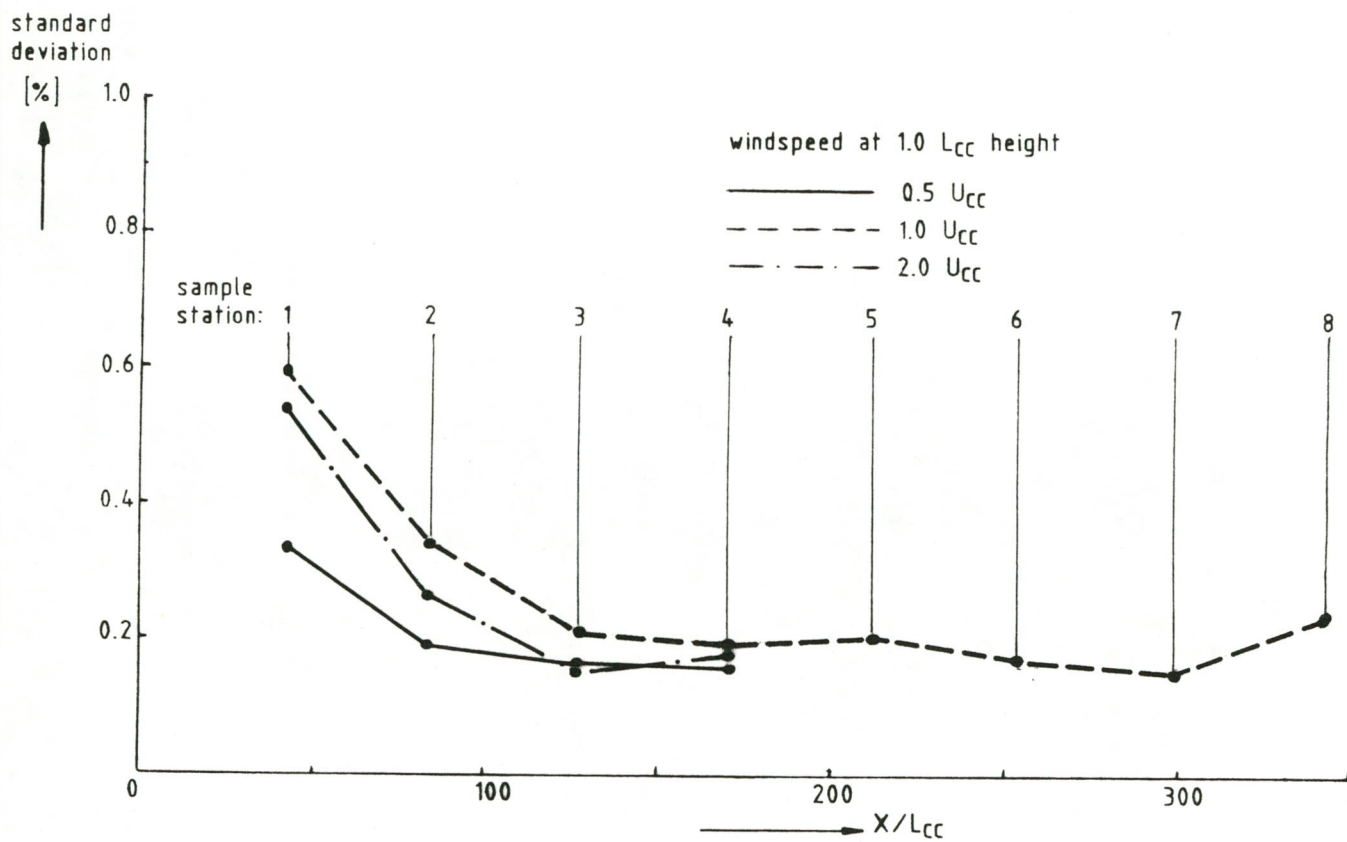
Standard deviation for the continuous release test.

MT-TNO
91-026
Fig. 14



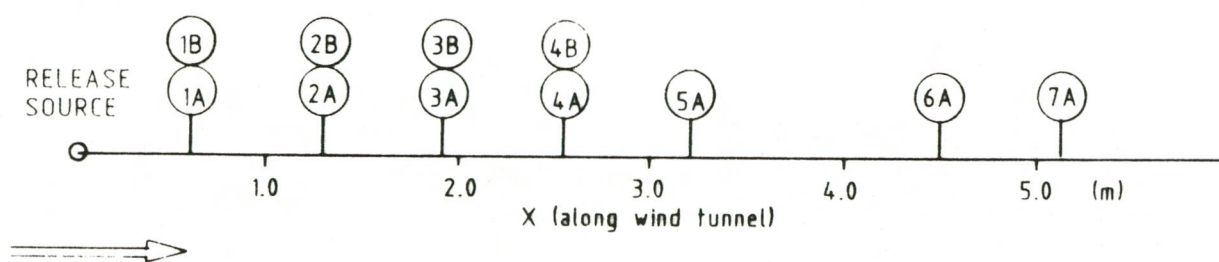
Mean concentration for the intercomparison continuous test and both additional test.

MT-TNO
91-026
Fig.15



Standard deviation for the intercomparison continuous test and both additional tests.

MT-TNO
91-026
Fig.16



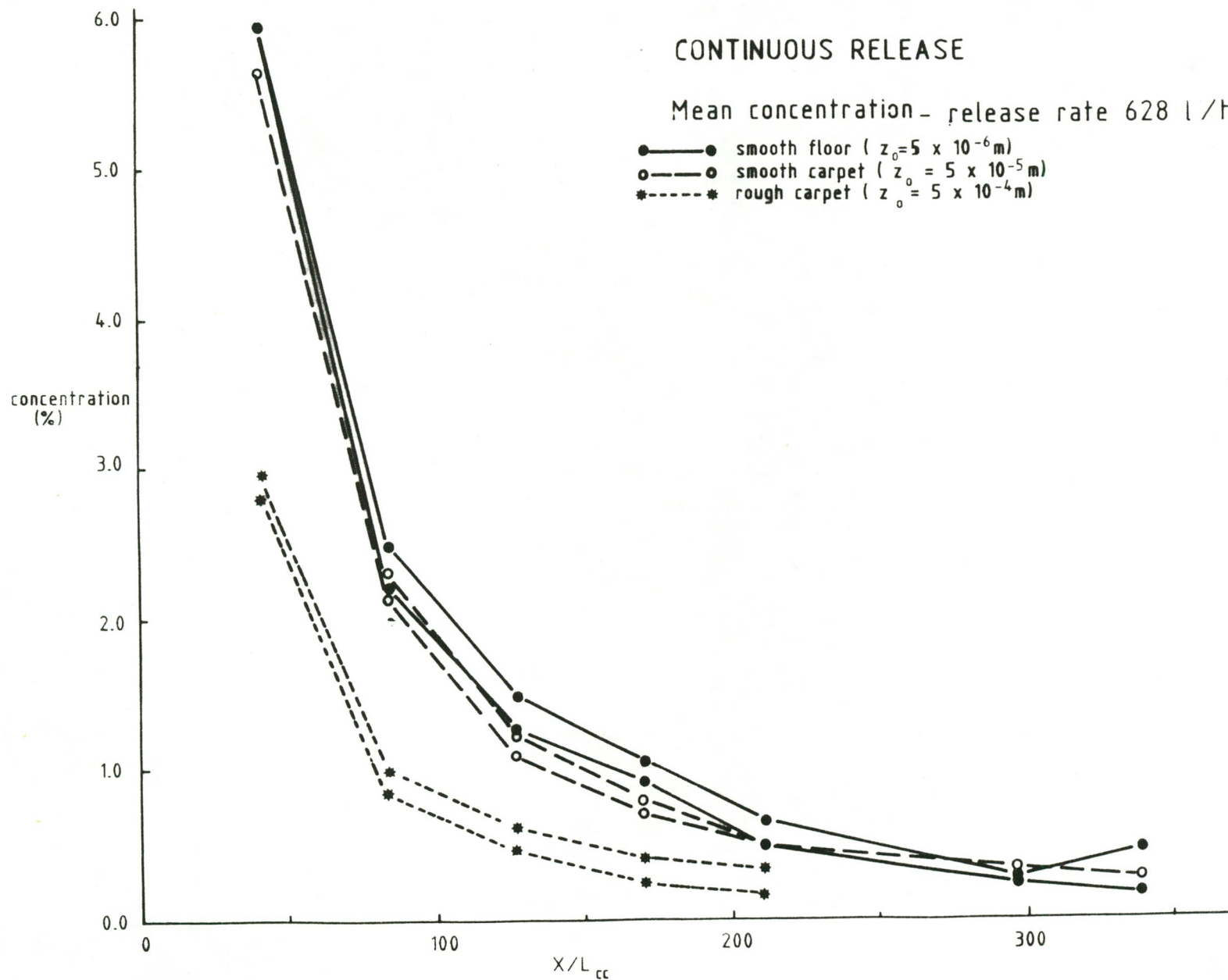
Sampling station for case A (628l/h) and case B (127l/h)

MT - TNO
91 - 026
Fig. 17

CONTINUOUS RELEASE

Mean concentration - release rate 628 l/h

- smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- *---* rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)



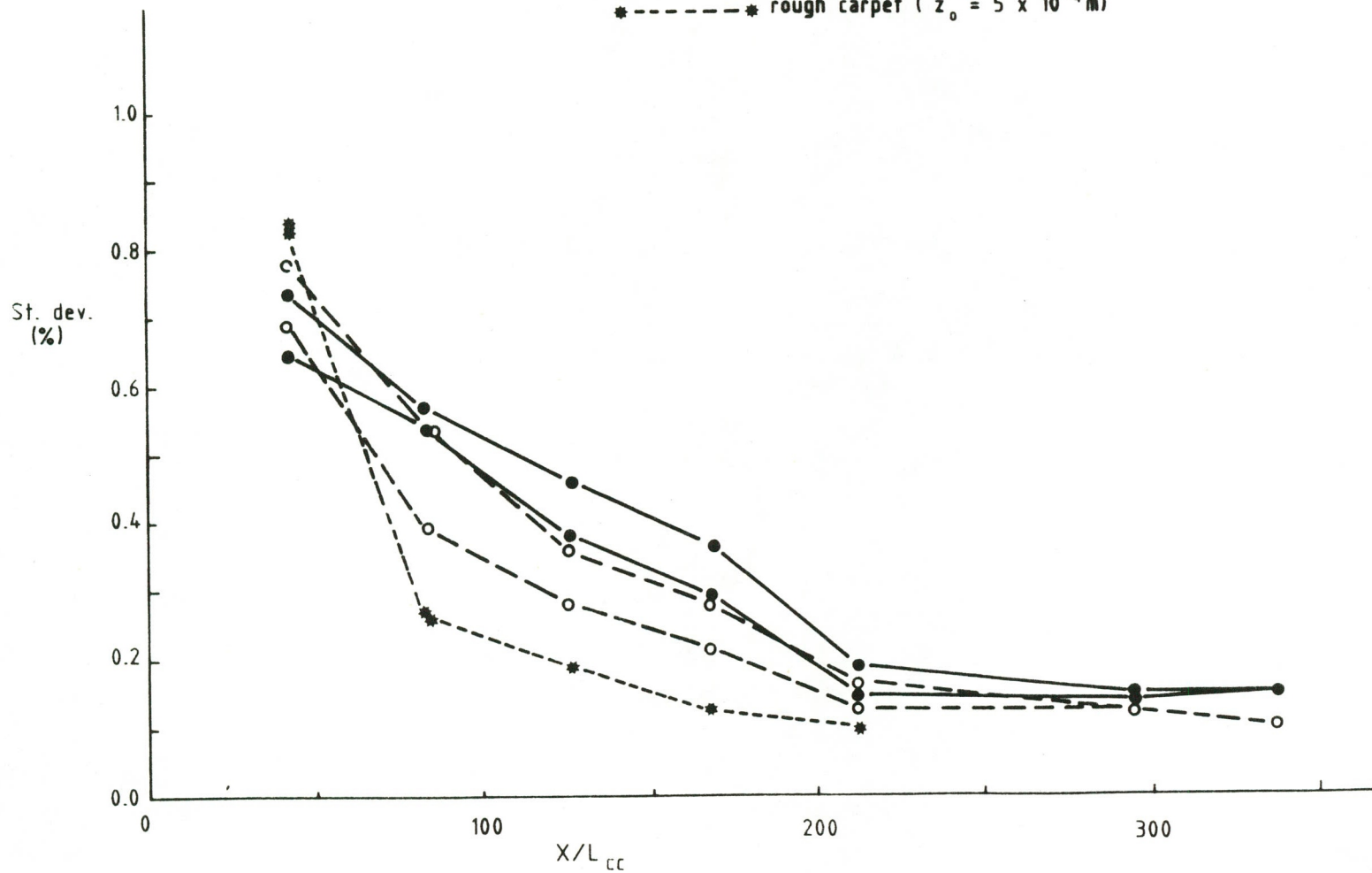
Mean concentrations for a release rate of 628 l/h

MT - TNO
91-026
Fig. 18

CONTINUOUS RELEASE

Standard deviation - release rate 628 l/h

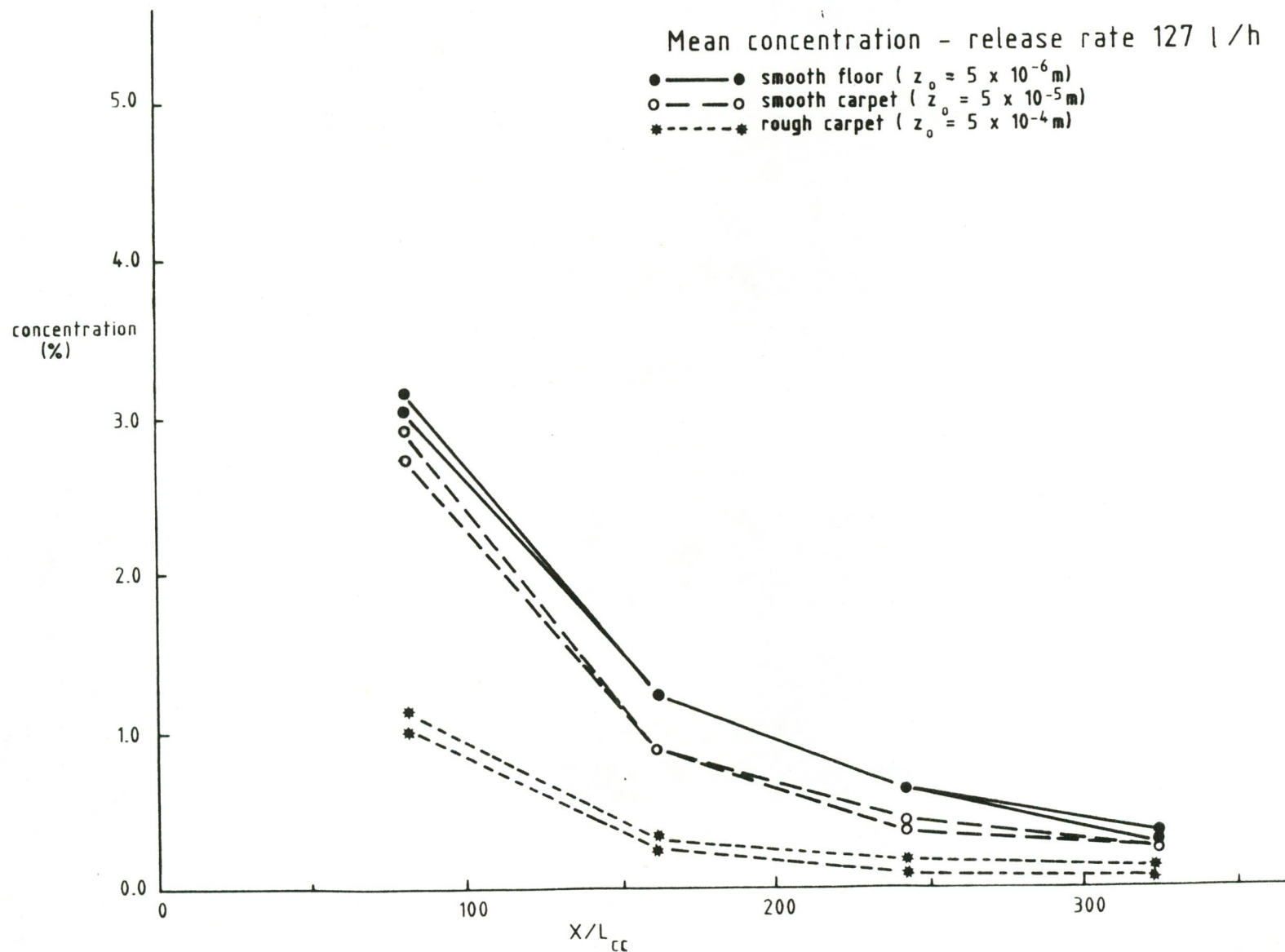
- — smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- — smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- * - - - rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)



CONTINUOUS RELEASE

Mean concentration - release rate 127 l/h

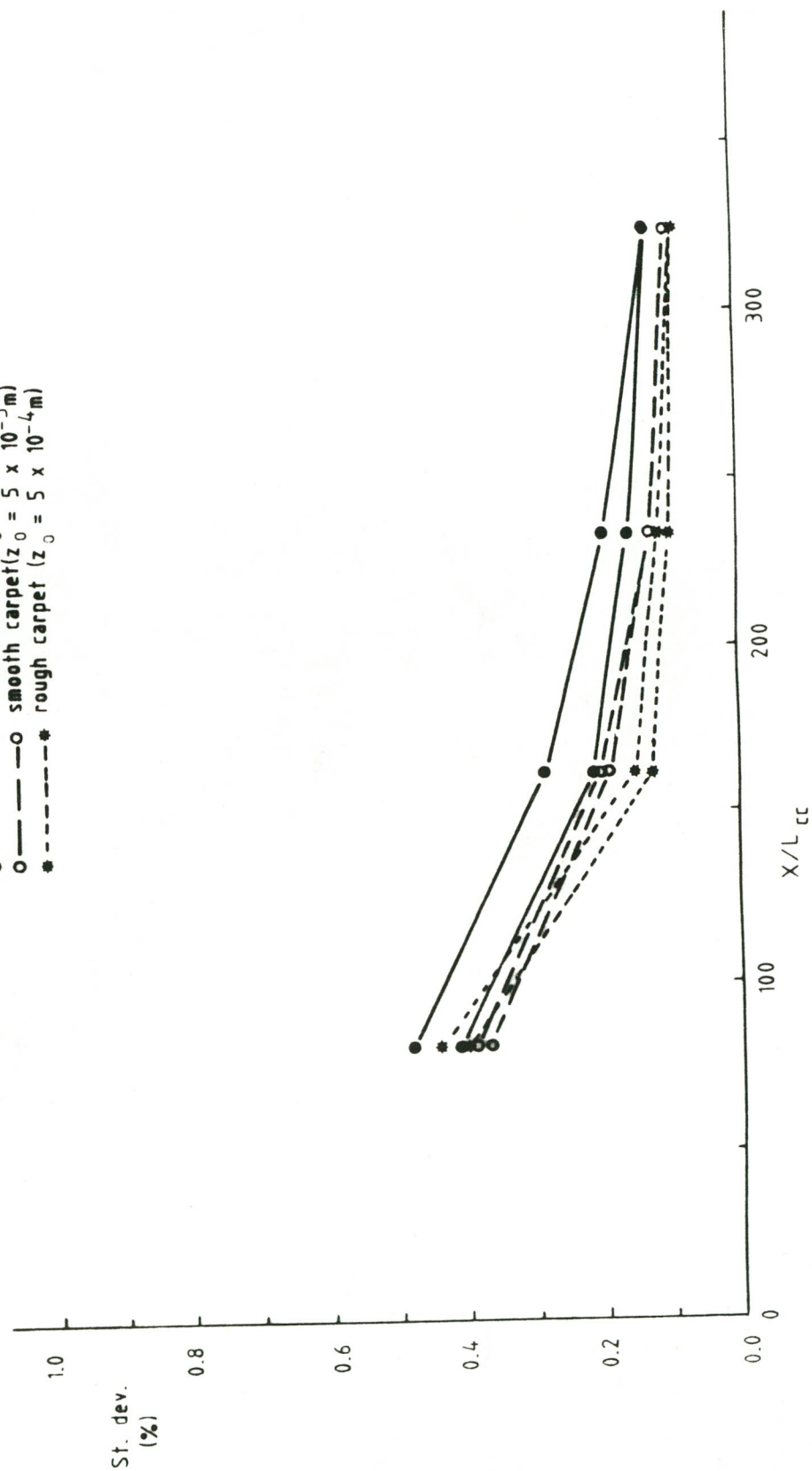
- —● smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- —○ smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- * - - * rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)



CONTINUOUS RELEASE

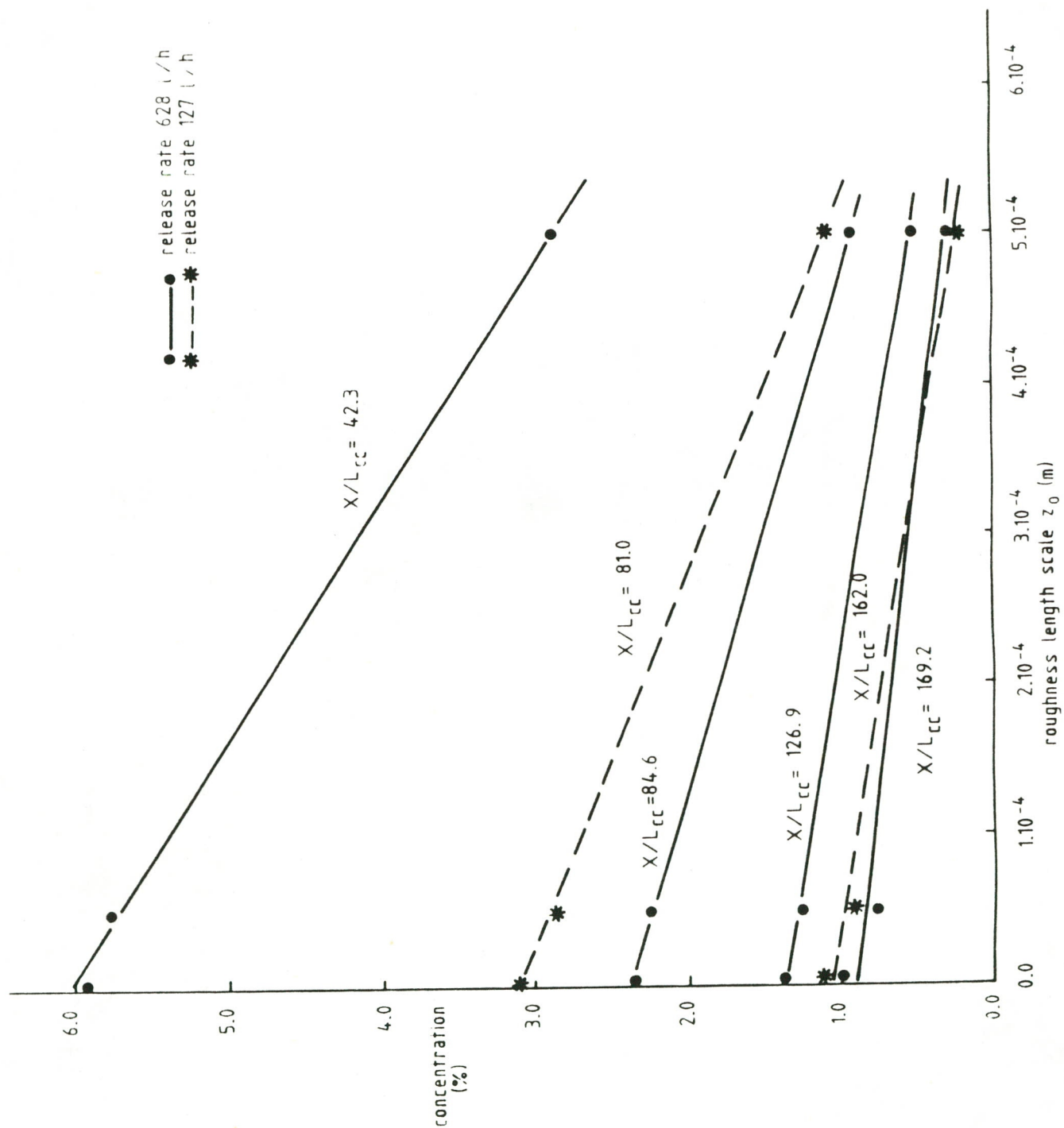
Standard deviation - release rate 127 l/h

- smooth floor ($z_0 = 5 \times 10^{-6}$ m)
- smooth carpet ($z_0 = 5 \times 10^{-5}$ m)
- * rough carpet ($z_0 = 5 \times 10^{-4}$ m)

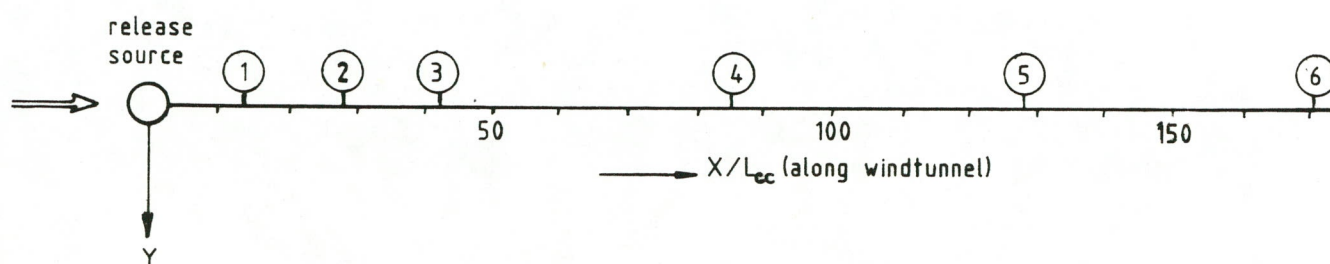


Standard deviation for a release rate of 127 l/h

MT - TNO
91-026
Fig. 21



Mean concentration as function of the roughness length scale.

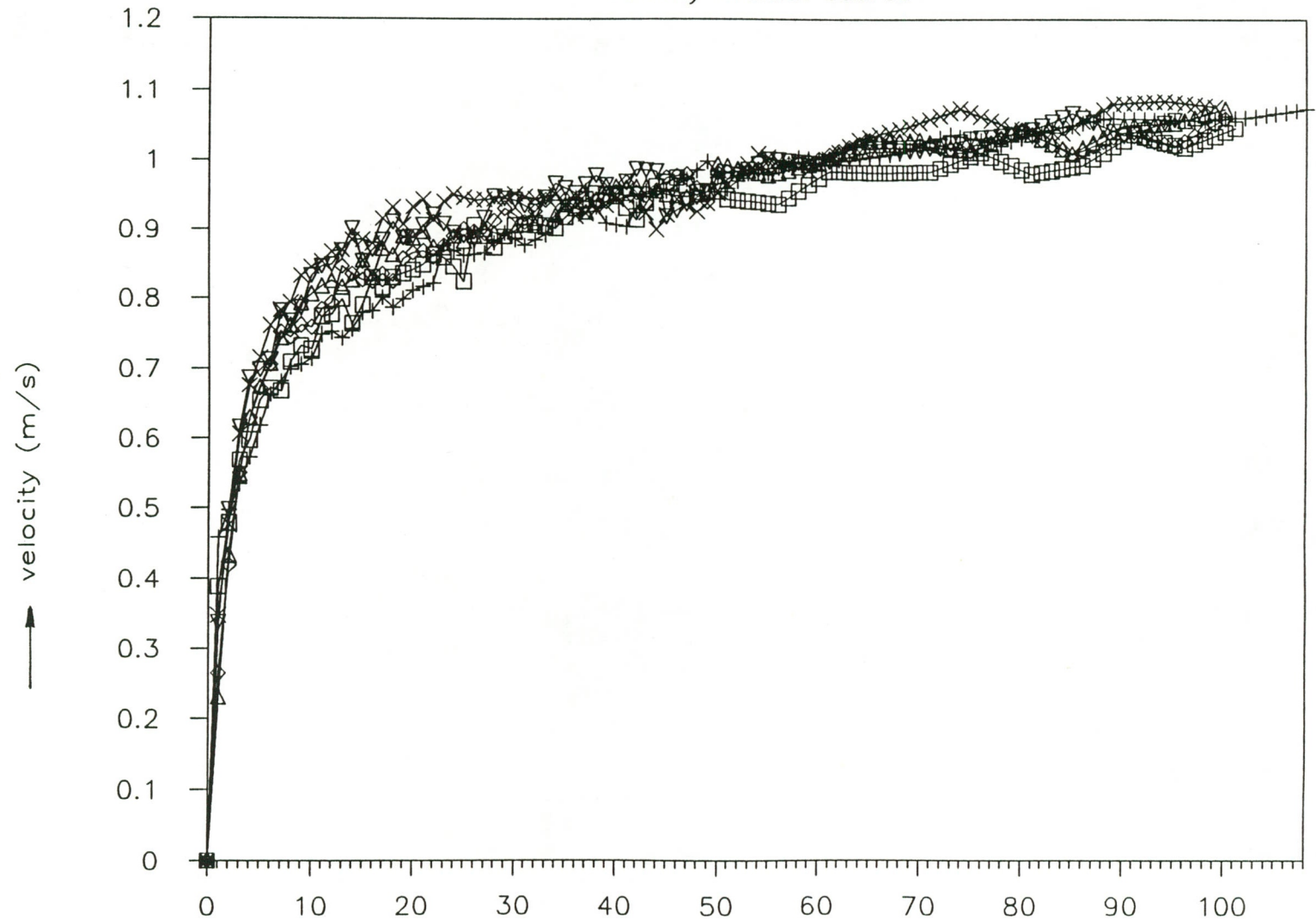


Positions for velocity profile measurements.

MT-TNO
91-026
Fig.23

HEAVY GAS – FOLDA measurements

velocity without source



□ = 14.0 Lcc
 Δ = 85.3 Lcc

+ = 28.5 Lcc
 × = 128.0 Lcc

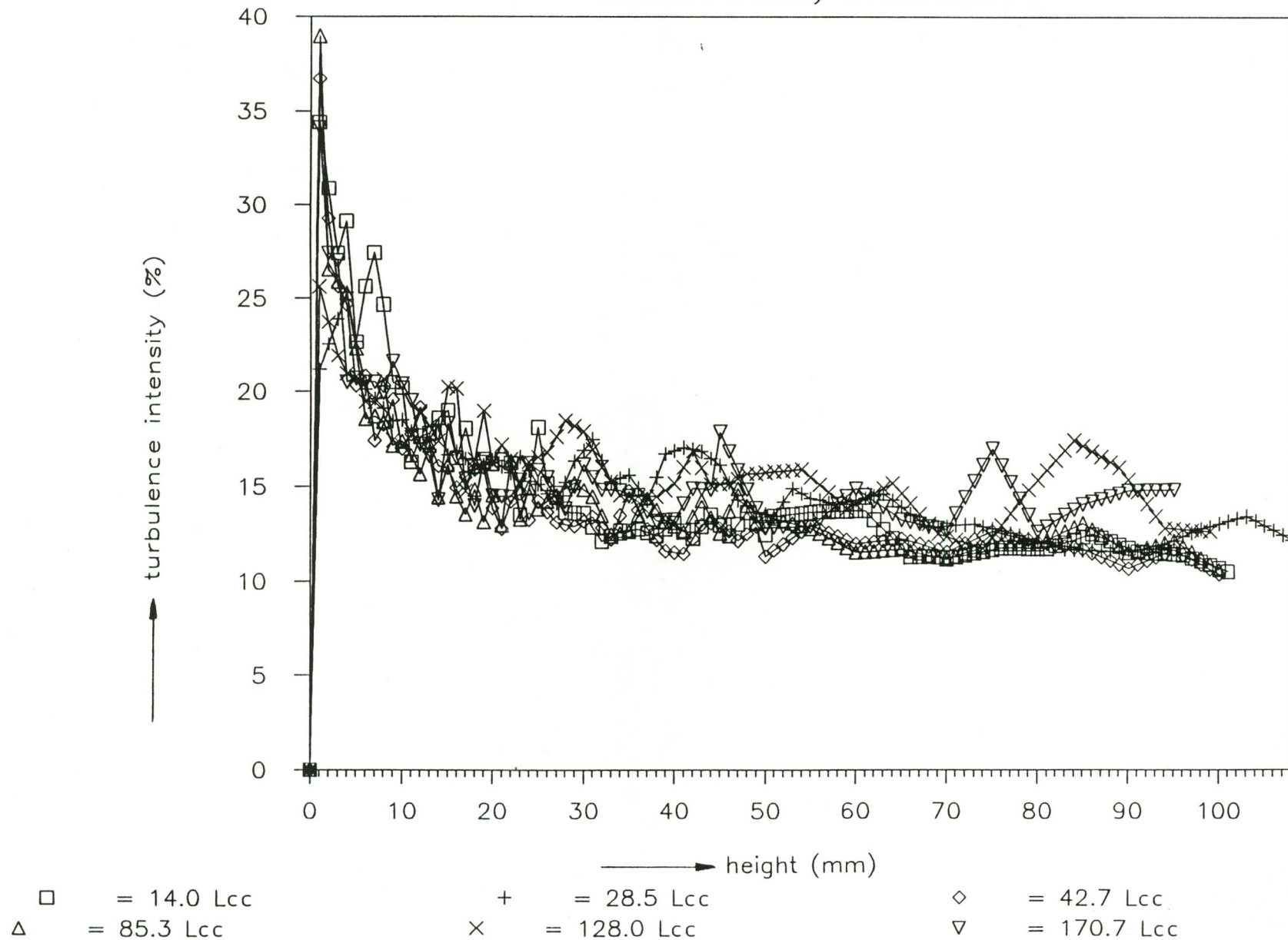
◇ = 42.7 Lcc
 ▽ = 170.7 Lcc

Velocity profiles (without source) at different positions

MT - TNO
 91 - 026
 Fig. 24a

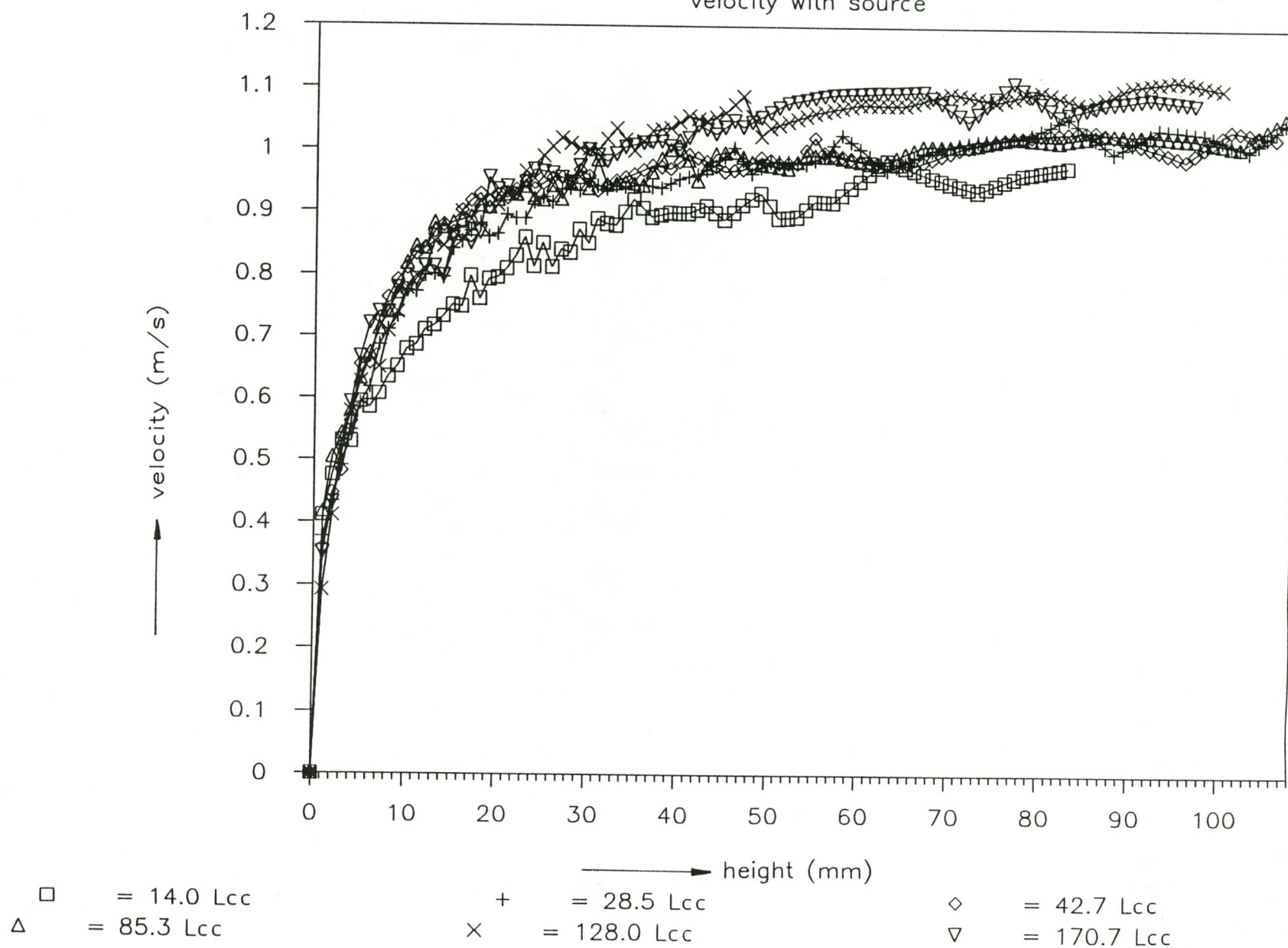
HEAVY GAS - FOLDA measurements

turbulence intensity without source



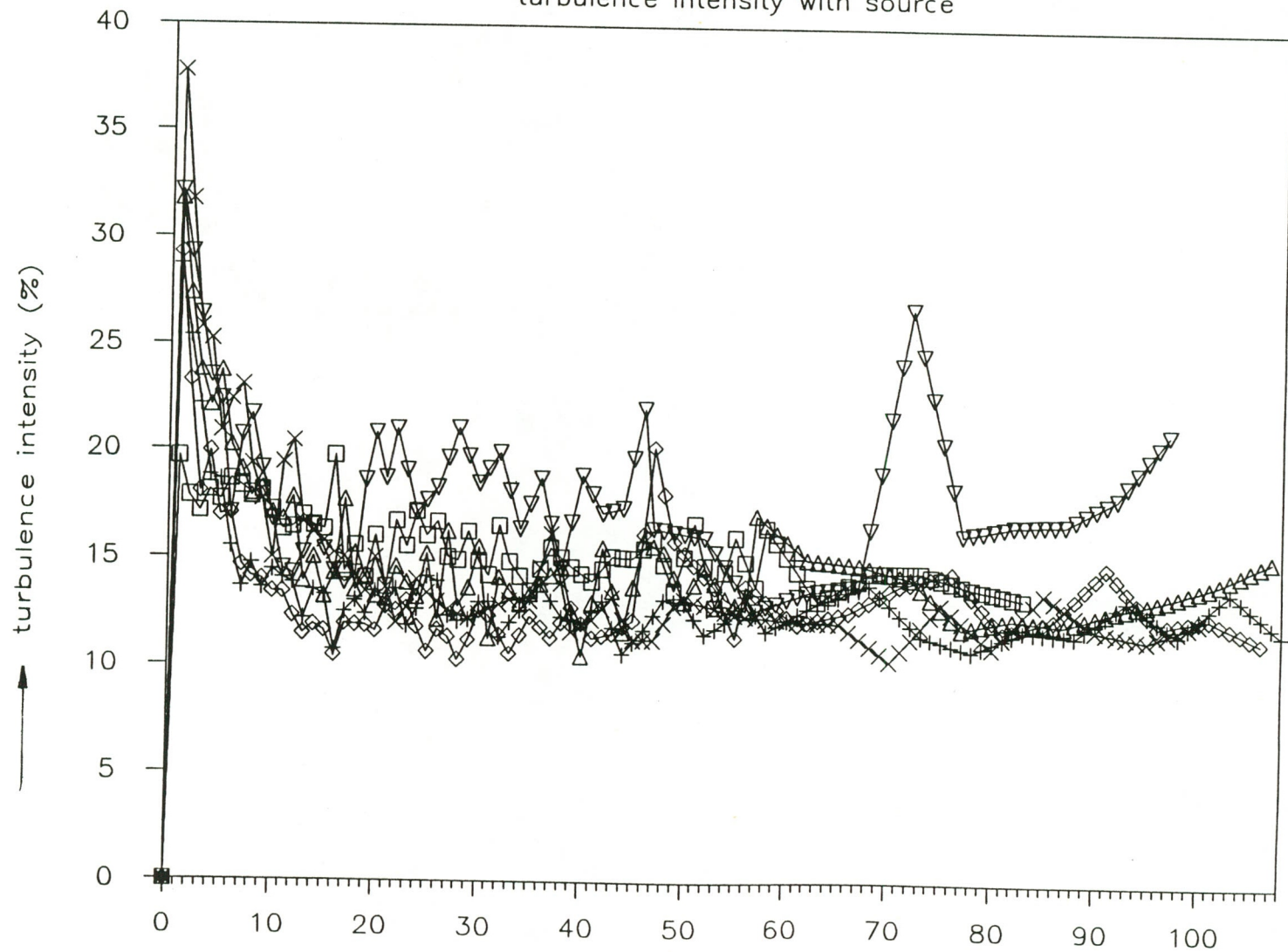
HEAVY GAS - FOLDA measurements

velocity with source



HEAVY GAS – FOLDA measurements

turbulence intensity with source



□ = 14.0 Lcc
 Δ = 85.3 Lcc

+ = 28.5 Lcc
 × = 128.0 Lcc

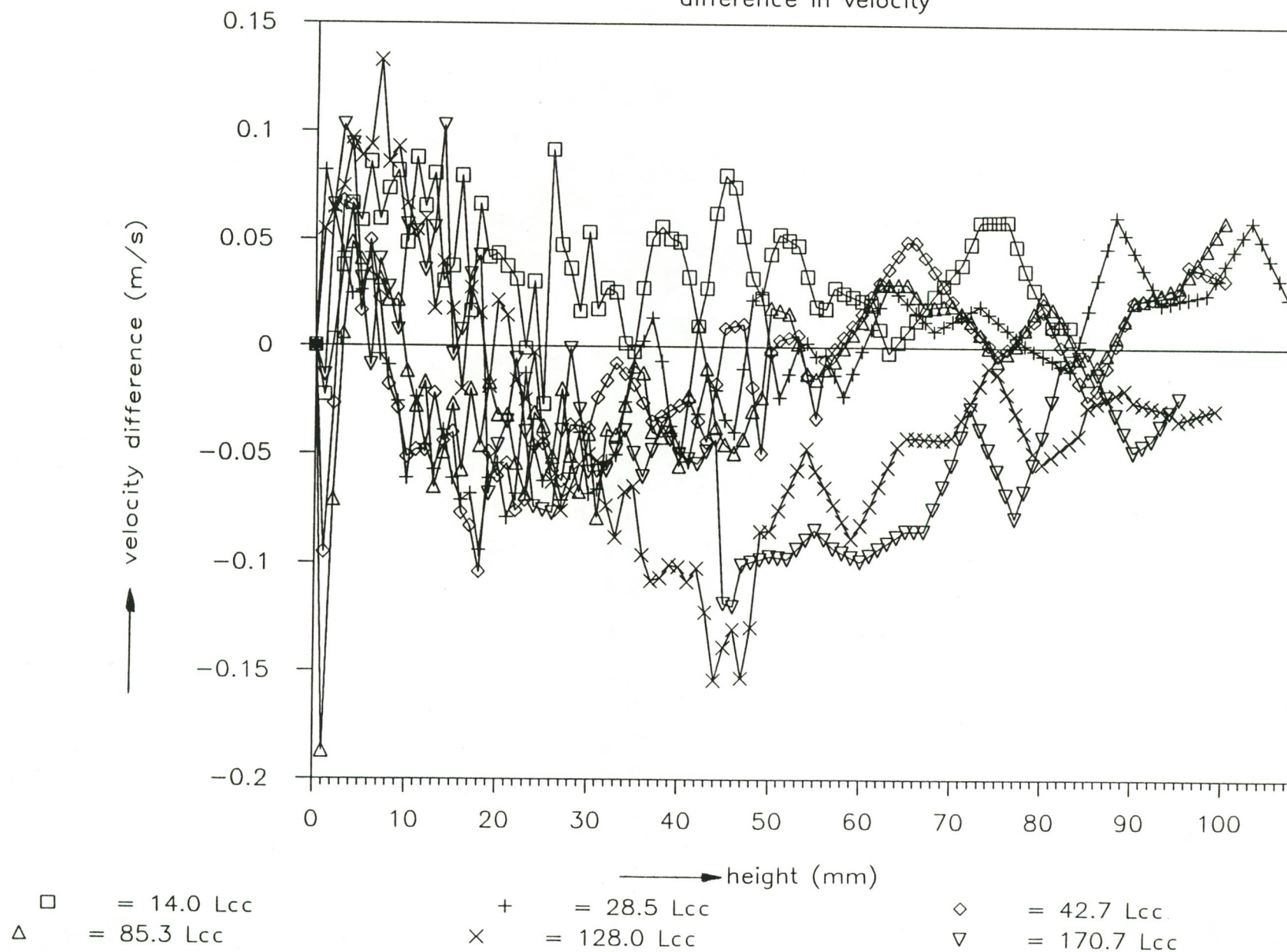
◇ = 42.7 Lcc
 ▽ = 170.7 Lcc

Profiles of turbulence intensity at positions downwind from the source.

MT - TNO
 91 - 026
 Fig. 25b

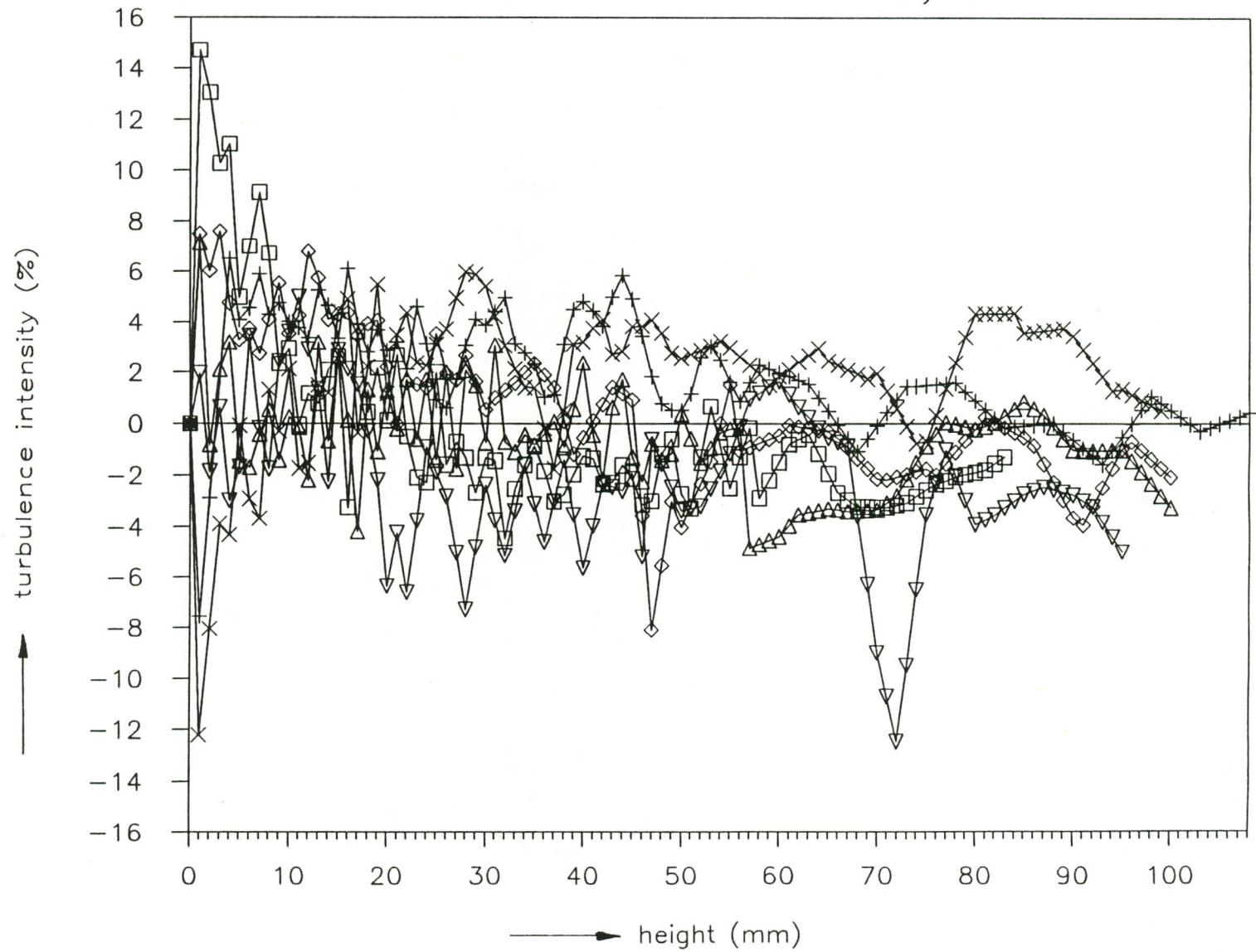
HEAVY GAS - FOLDA measurements

difference in velocity



HEAVY GAS — FOLDA measurements

difference in turbulence intensity



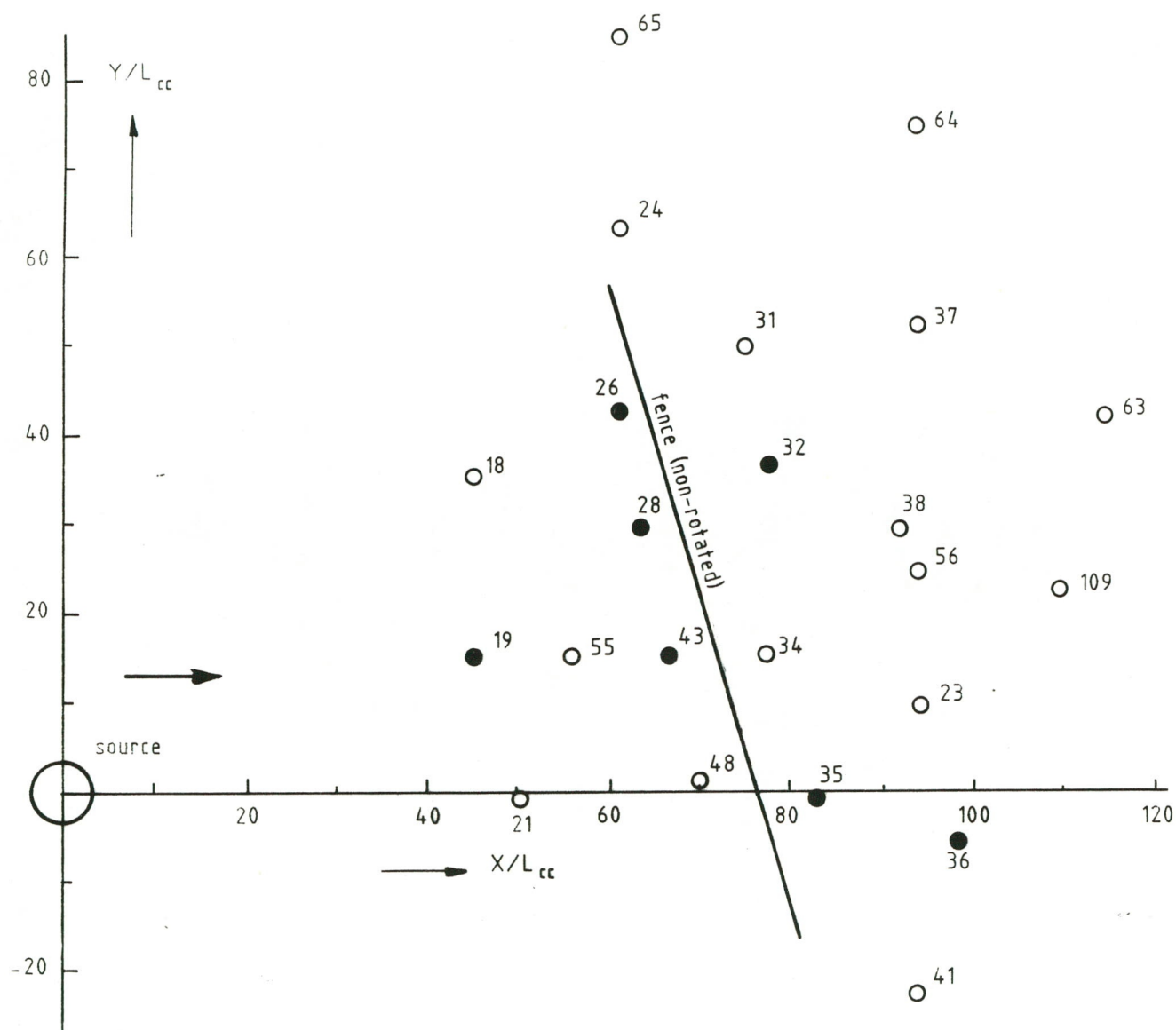
□ = 14.0 Lcc
 Δ = 85.3 Lcc

+ = 28.5 Lcc
 × = 128.0 Lcc

◇ = 42.7 Lcc
 ∇ = 170.7 Lcc

Profiles of turbulence intensity difference (without source-
 with source)

MT - TNO
 91 - 026
 Fig. 26b

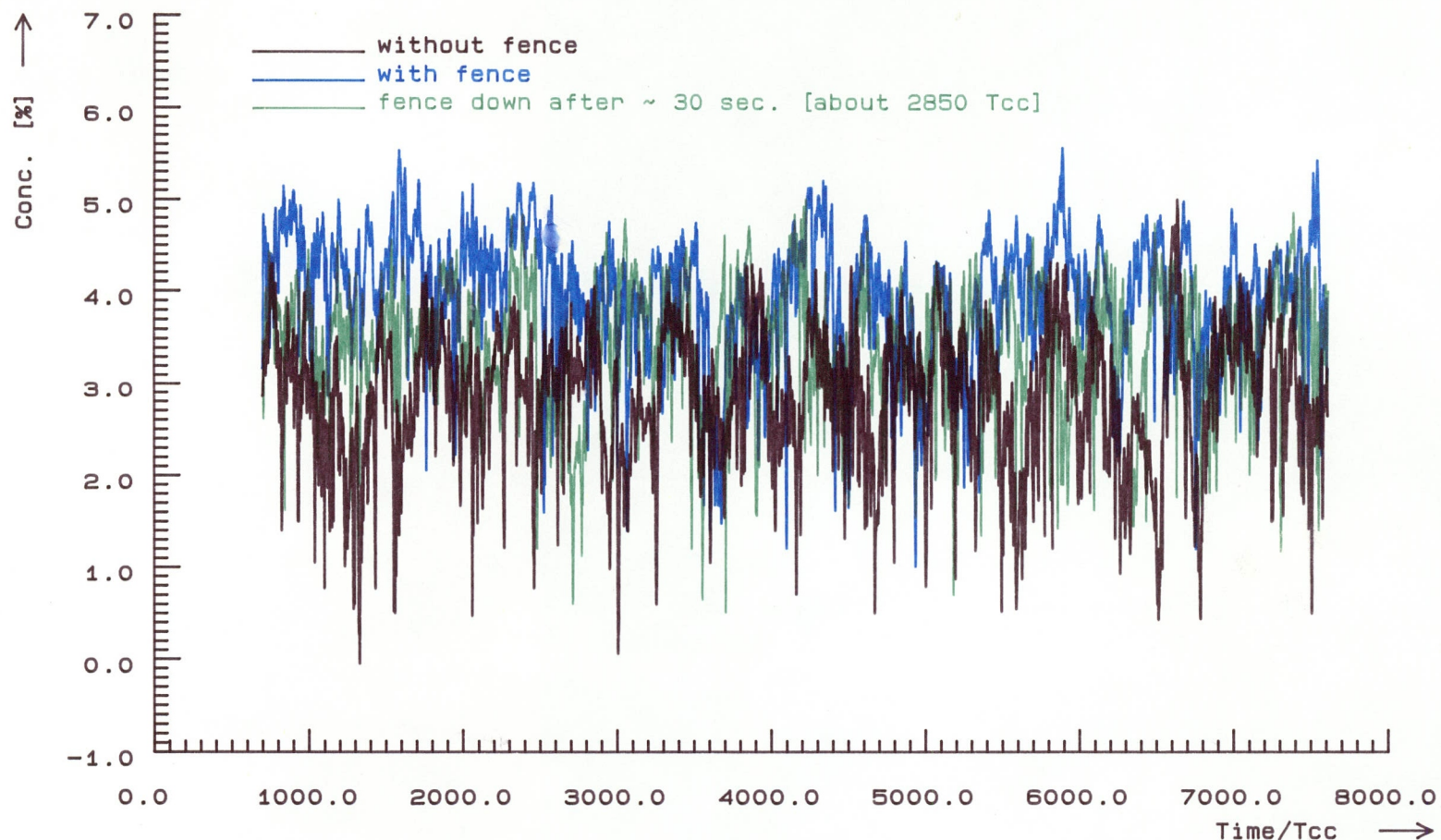


(closed symbols indicate the wind tunnel measuring stations)

Position of source, fence and probes for the full-scale test EEC 57.

MT TNO
91 - 026
Fig. 27

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 45.00
Y/Lcc= 15.28
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.85 %	3.96 %	3.52 %	3.43 %
Min.	-.05 %	1.01 %	1.32 %	.51 %
Max.	5.01 %	5.57 %	4.56 %	5.01 %
St. dev.	.73 %	.68 %	.47 %	.67 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS

Position:

X/Lcc= 61.10

Y/Lcc= 42.04

Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]

Lcc= .0084 [m]

Tcc= .0145 [s]

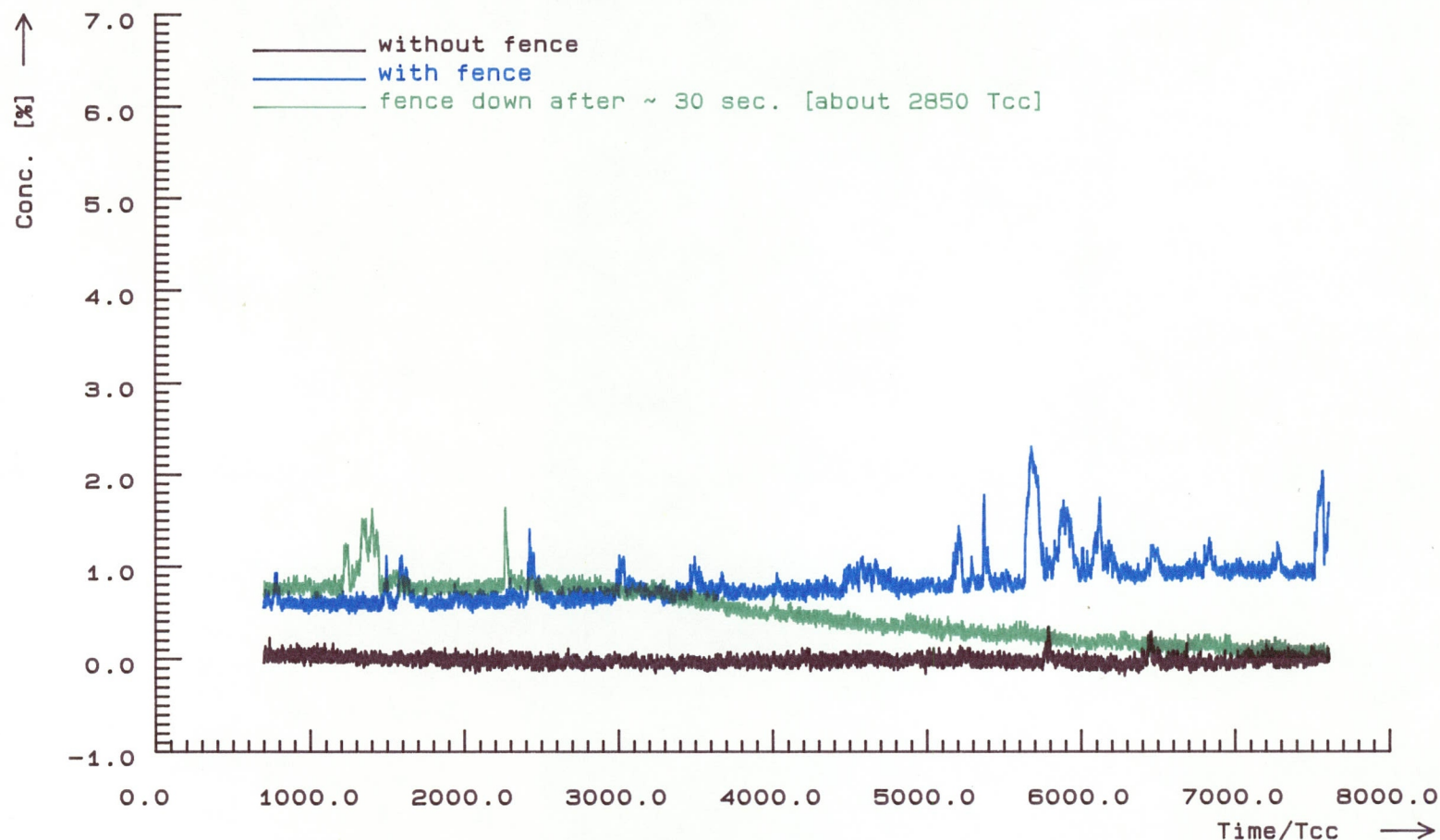
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0$ = 1.50E+02 [L/H]

Model gas= SF6

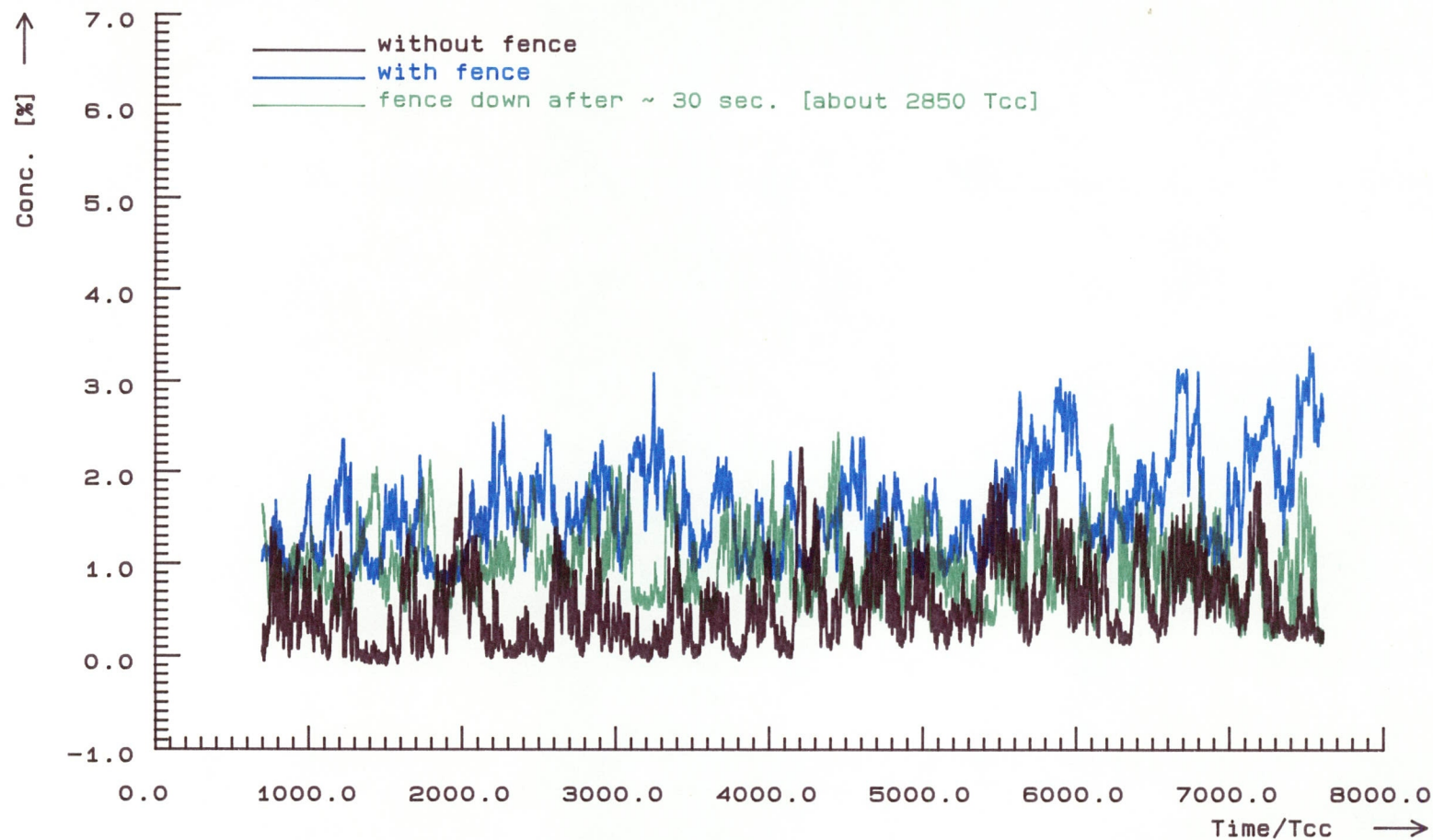
Wind speed:

1.0 Ucc at 1.0 Lcc height



	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	-.02 %	.83 %	.84 %	.29 %
Min.	-.18 %	.49 %	.66 %	0.00 %
Max.	.34 %	2.31 %	1.64 %	.75 %
St. dev.	.05 %	.25 %	.17 %	.17 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 63.23

Y/Lcc= 29.13

Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]

Lcc= .0084 [m]

Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]

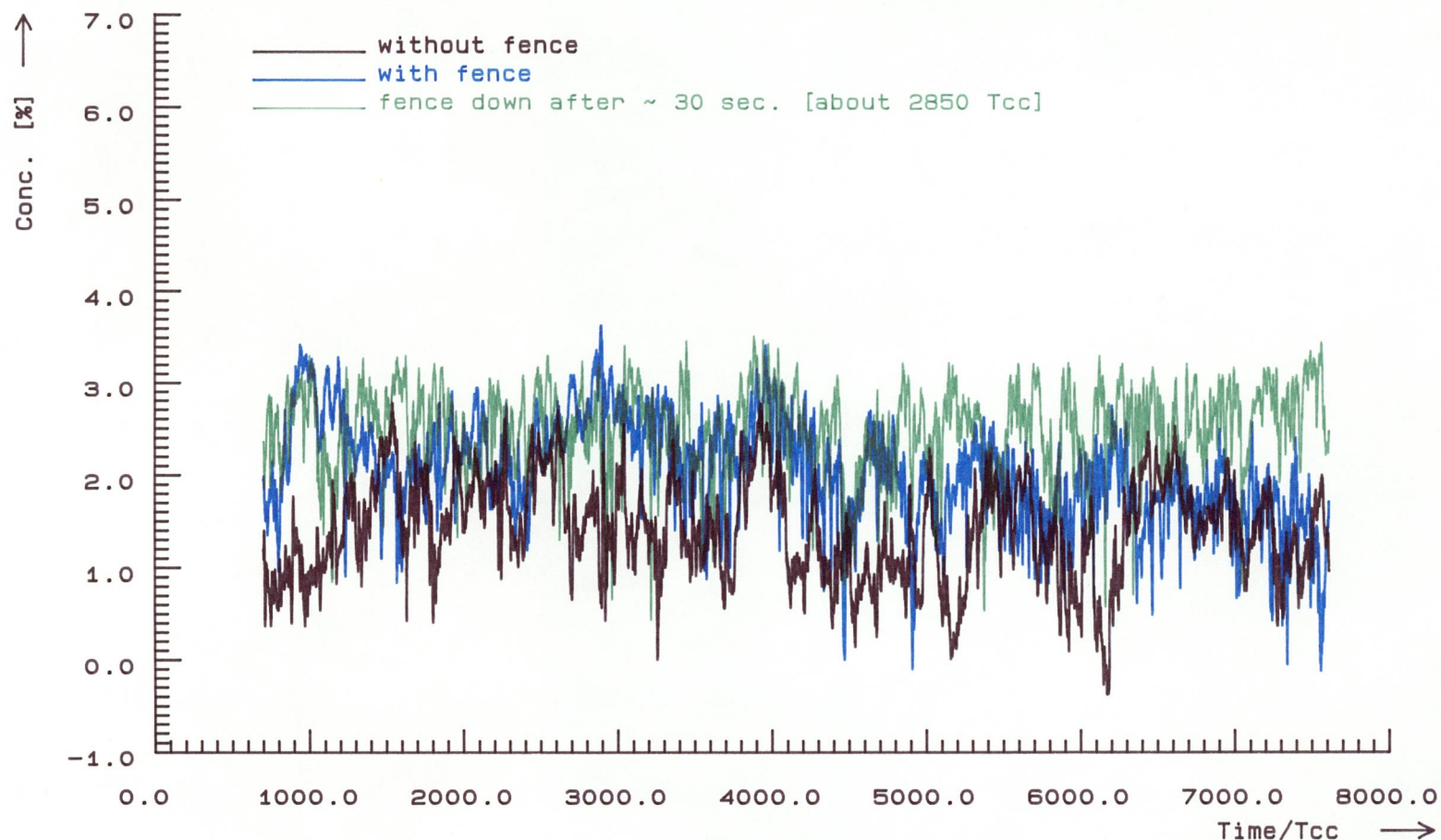
Model gas= SF6

Wind speed:

1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	.56 %	1.61 %	.98 %	1.01 %
Min.	-.10 %	.76 %	.43 %	.13 %
Max.	2.27 %	3.40 %	2.13 %	2.53 %
St. dev.	.43 %	.53 %	.33 %	.42 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 66.43
Y/Lcc= 15.28
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

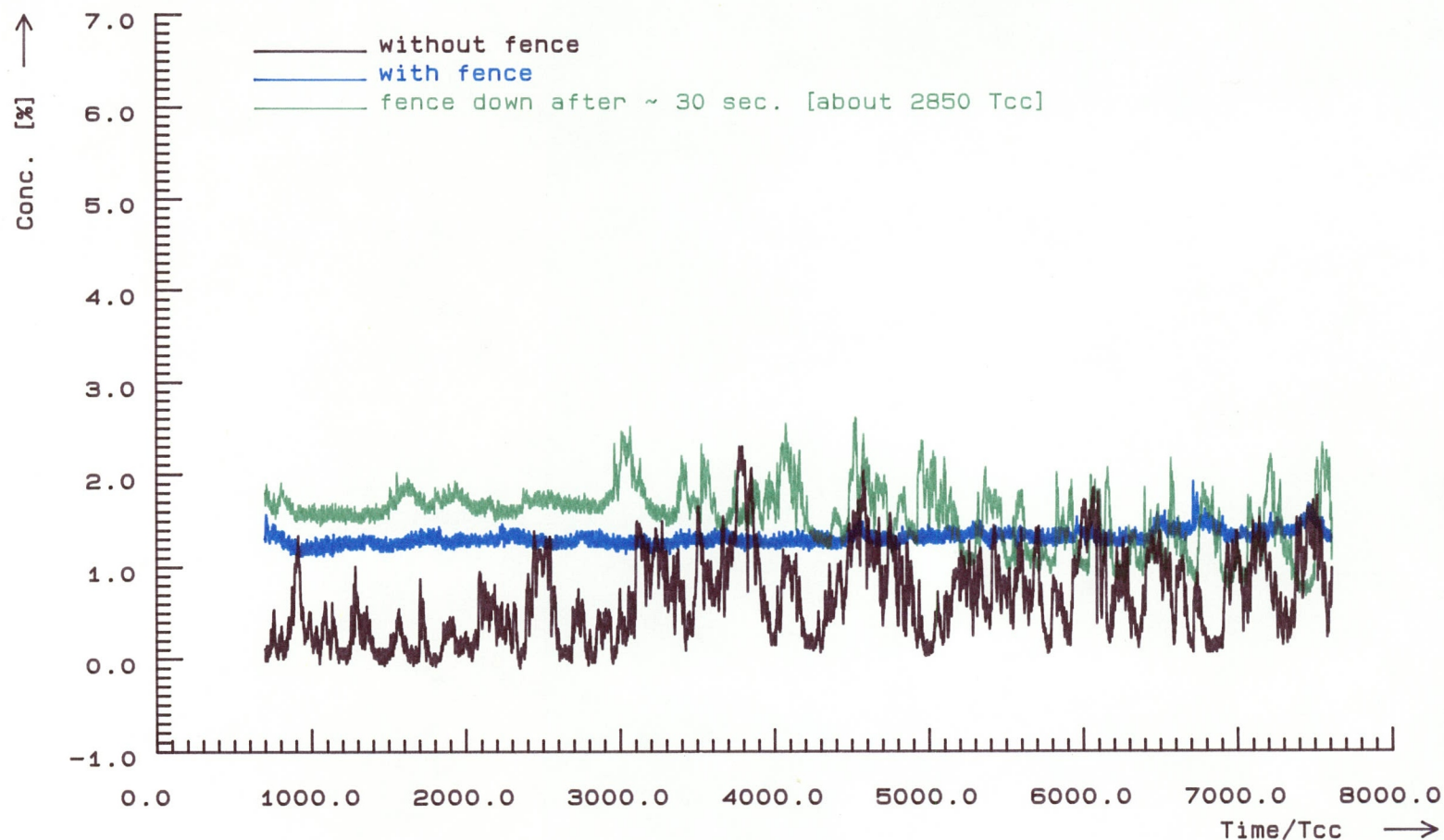
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	1.40 %	2.04 %	2.51 %	2.49 %
Min.	-.38 %	-.12 %	.85 %	.54 %
Max.	2.77 %	3.63 %	3.31 %	3.52 %
St. dev.	.53 %	.56 %	.41 %	.46 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 77.21
Y/Lcc= 36.71
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

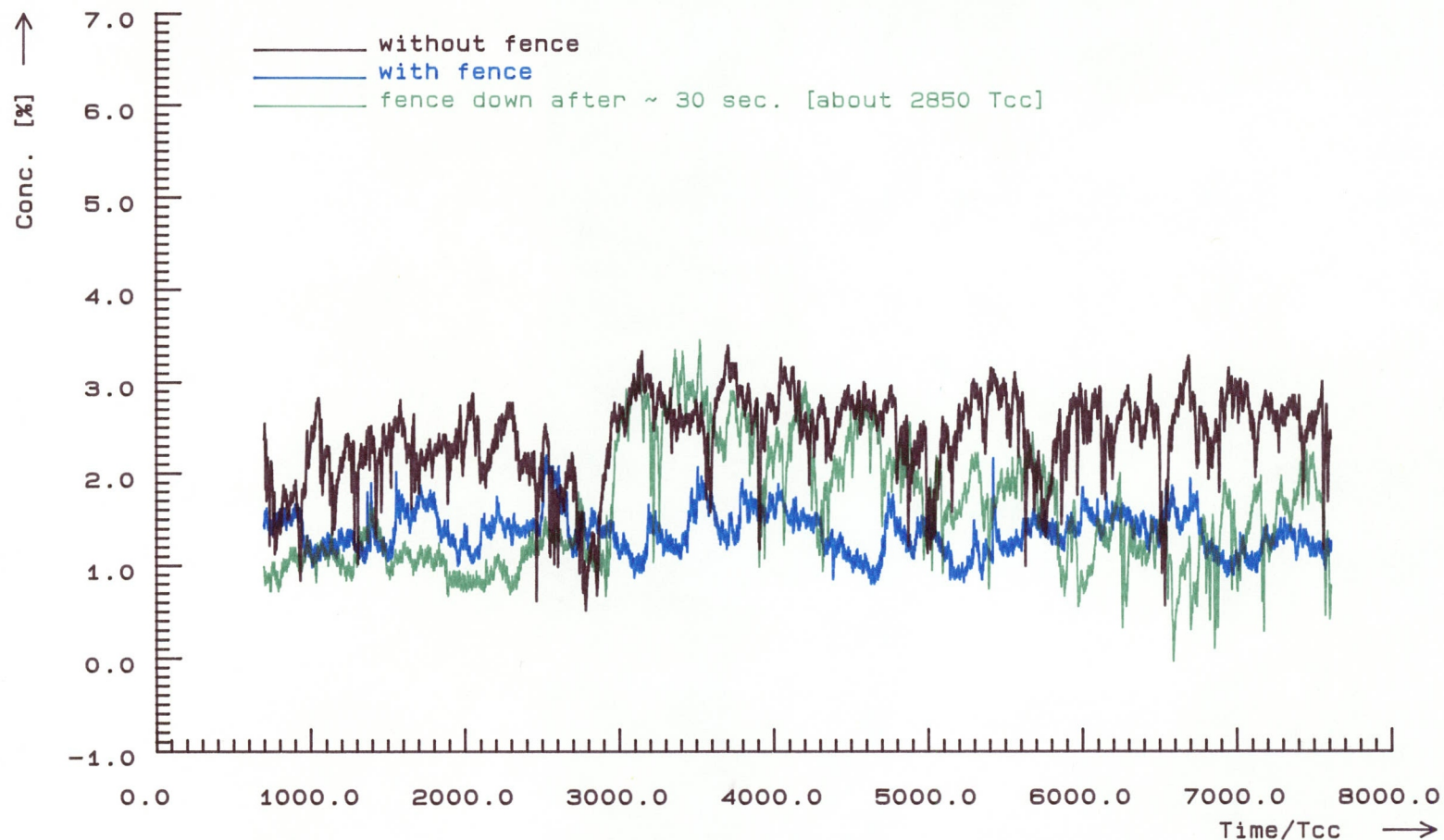
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	.65 %	1.31 %	1.66 %	1.47 %
Min.	-.10 %	1.12 %	1.45 %	.68 %
Max.	2.30 %	1.92 %	2.02 %	2.61 %
St. dev.	.46 %	.08 %	.10 %	.38 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 82.53

Y/Lcc= -.83

Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]

Lcc= .0084 [m]

Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]

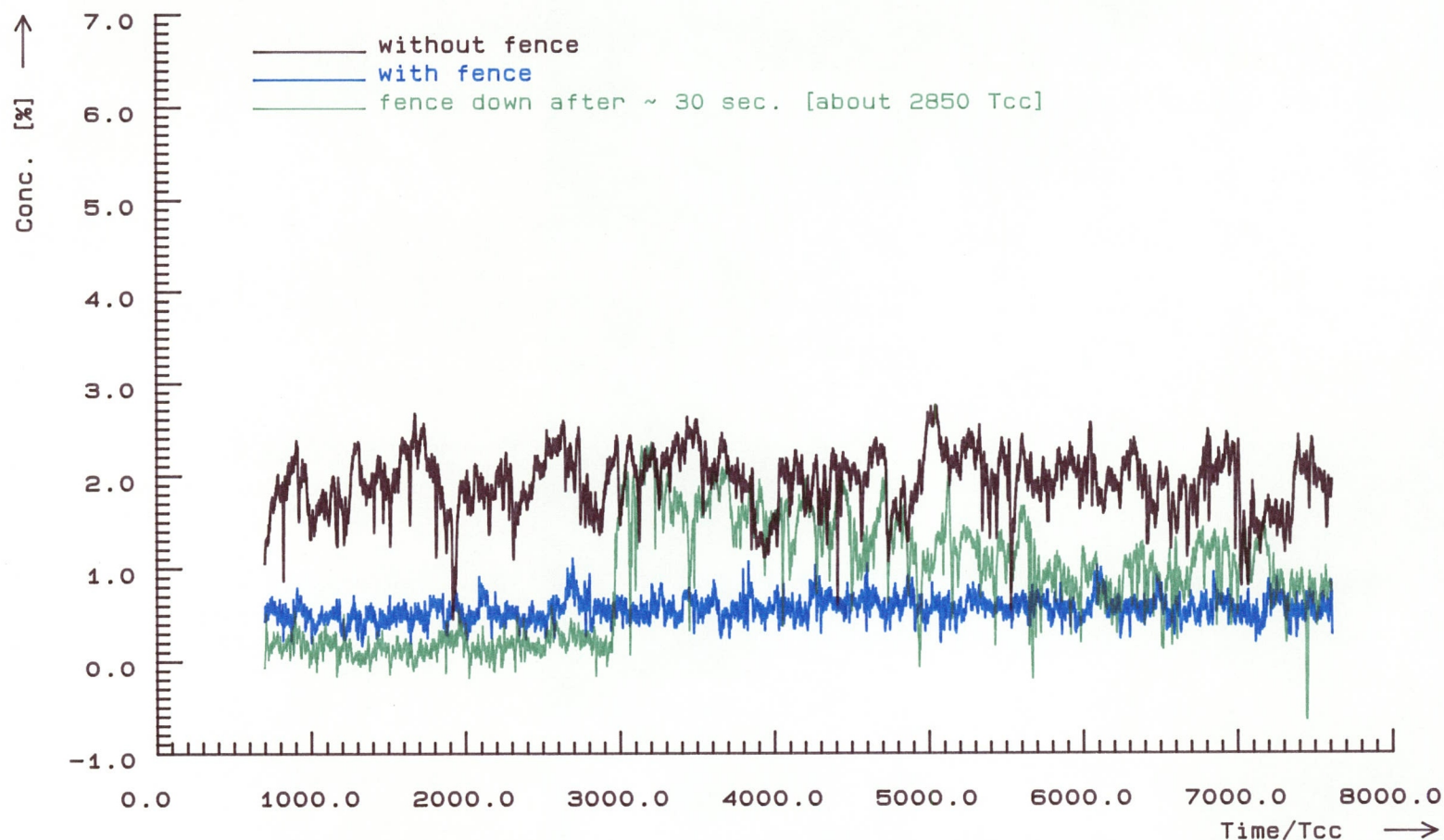
Model gas= SF6

Wind speed:

1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.40 %	1.36 %	1.03 %	1.79 %
Min.	.52 %	.80 %	.67 %	-.03 %
Max.	3.41 %	2.20 %	1.68 %	3.47 %
St. dev.	.46 %	.23 %	.17 %	.62 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 98.64

Y/Lcc= -6.28

Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]

Lcc= .0084 [m]

Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

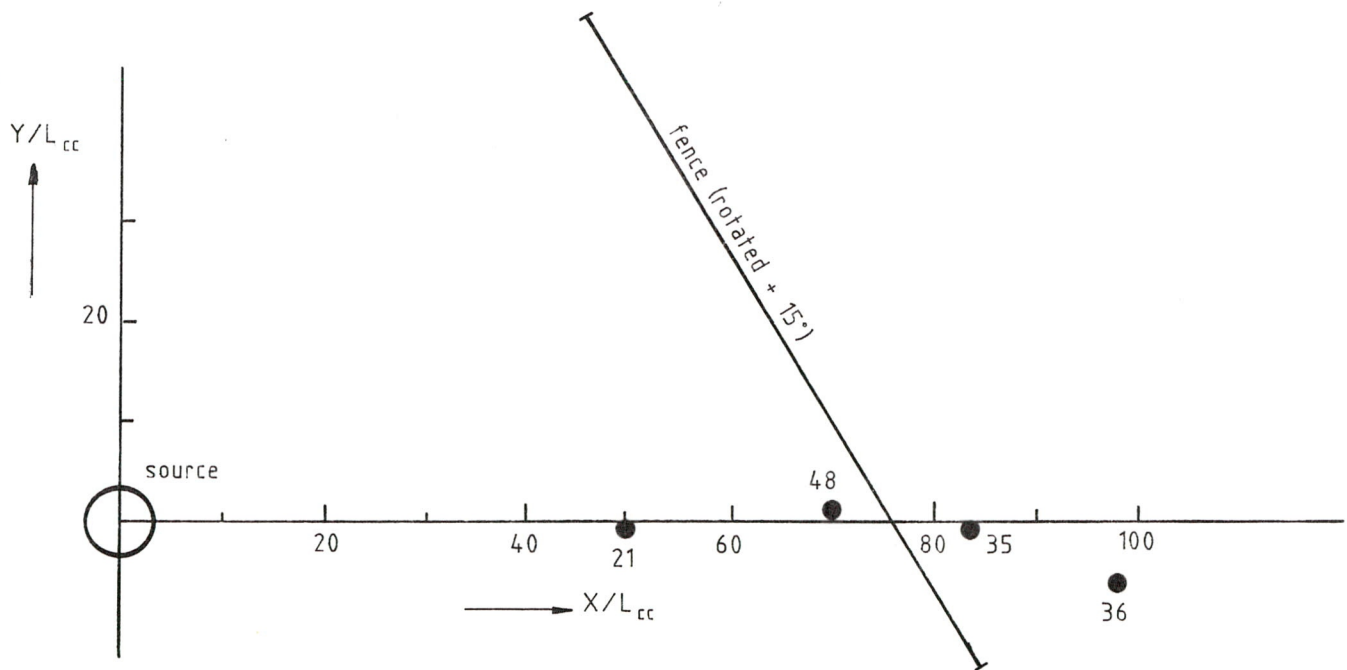
Source strength $\dot{V}_0 = 1.50E+02$ [L/H]

Model gas= SF6

Wind speed:

1.0 Ucc at 1.0 Lcc height

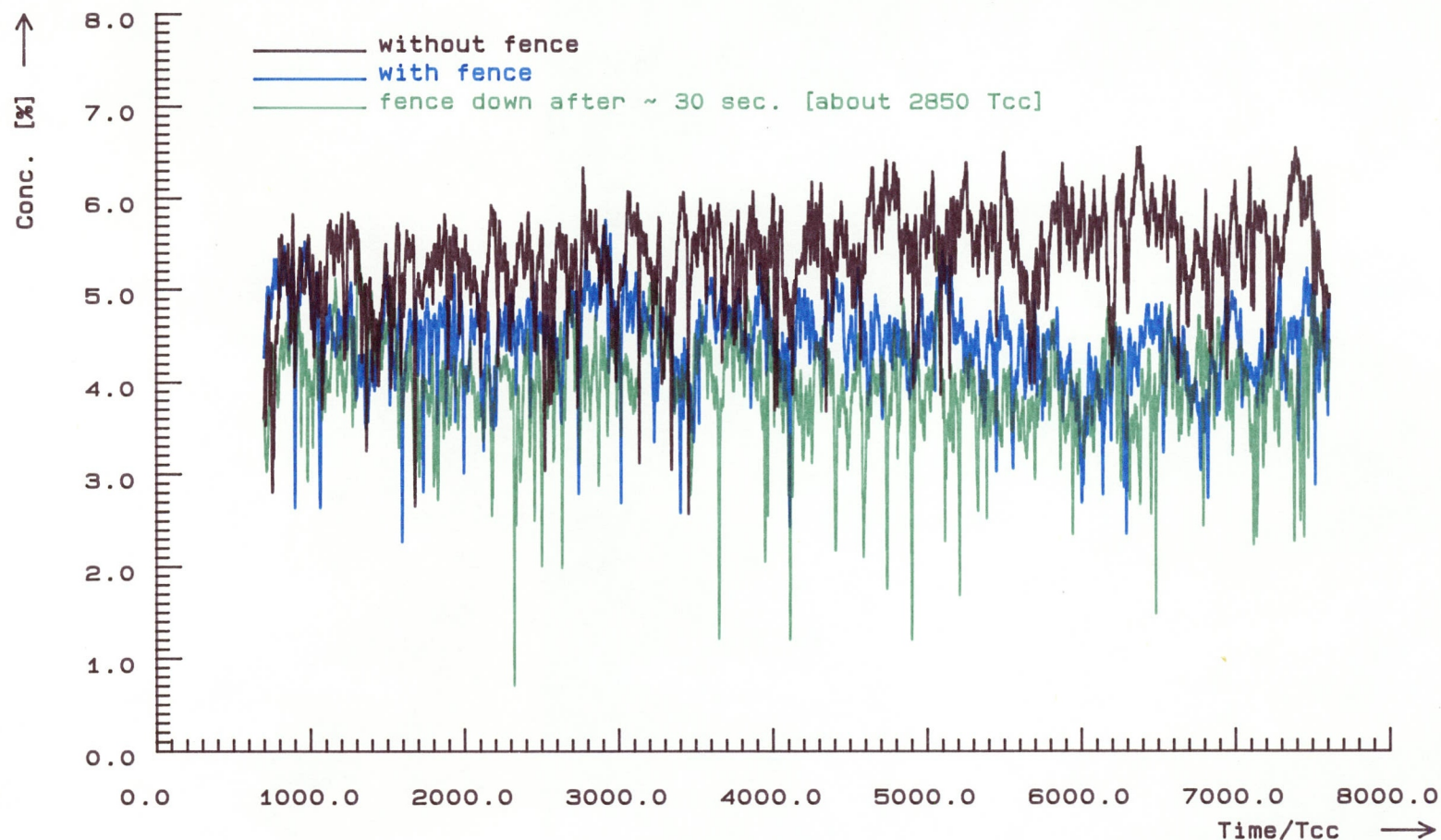
	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	1.93 %	.56 %	.15 %	1.18 %
Min.	.46 %	.17 %	-.18 %	-.64 %
Max.	2.76 %	1.11 %	.57 %	2.15 %
St. dev.	.33 %	.12 %	.11 %	.41 %



Position of probes for a fence rotation of + 15°

MT - TNO
91 - 026
Fig. 35

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 50.44
Y/Lcc= -.83
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

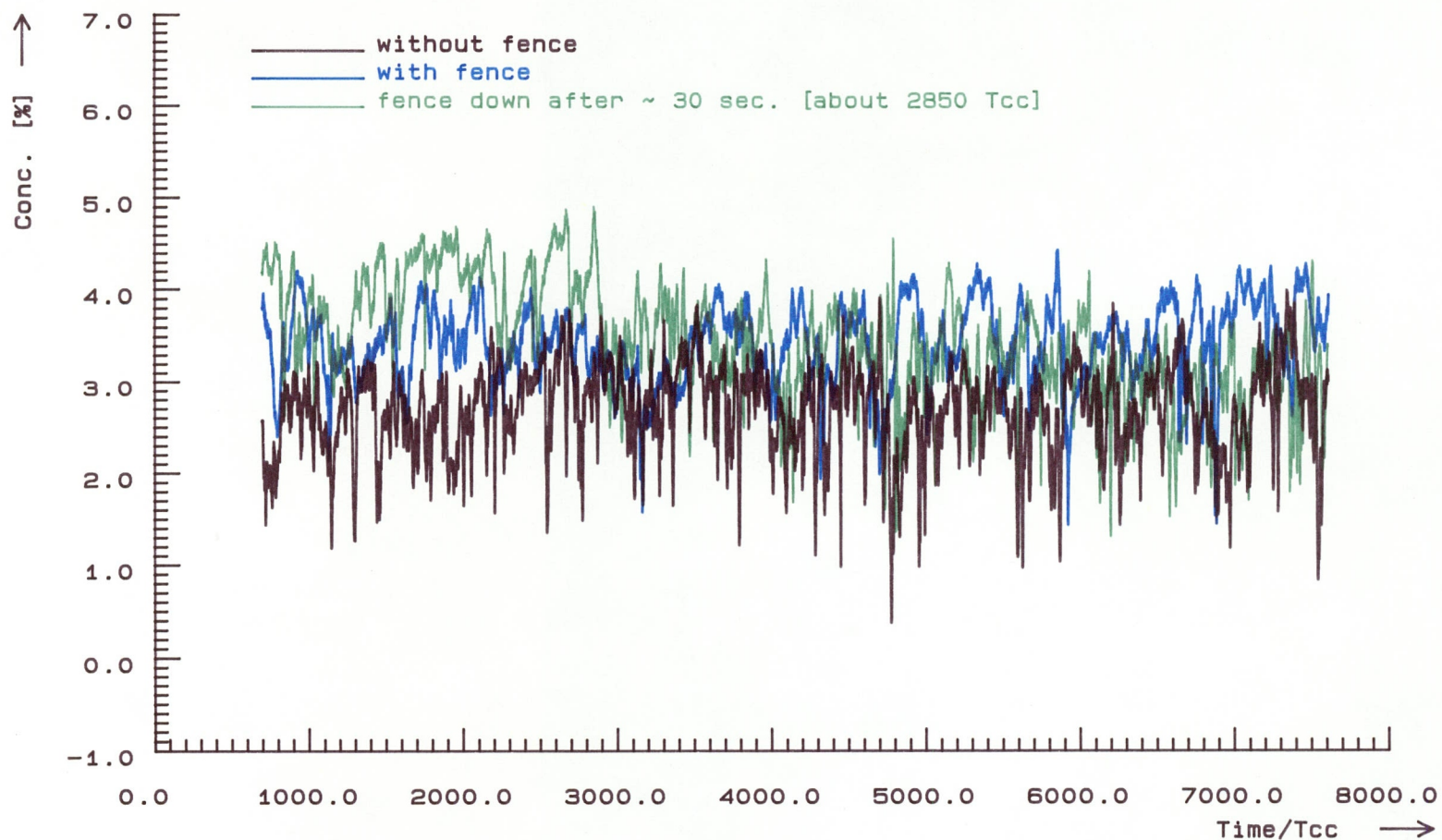
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	5.35 %	4.44 %	4.12 %	3.90 %
Min.	2.58 %	2.27 %	2.56 %	1.21 %
Max.	6.57 %	5.77 %	5.46 %	5.15 %
St. dev.	.52 %	.45 %	.45 %	.50 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 69.75

Y/Lcc= 1.30

Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]

Lcc= .0084 [m]

Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]

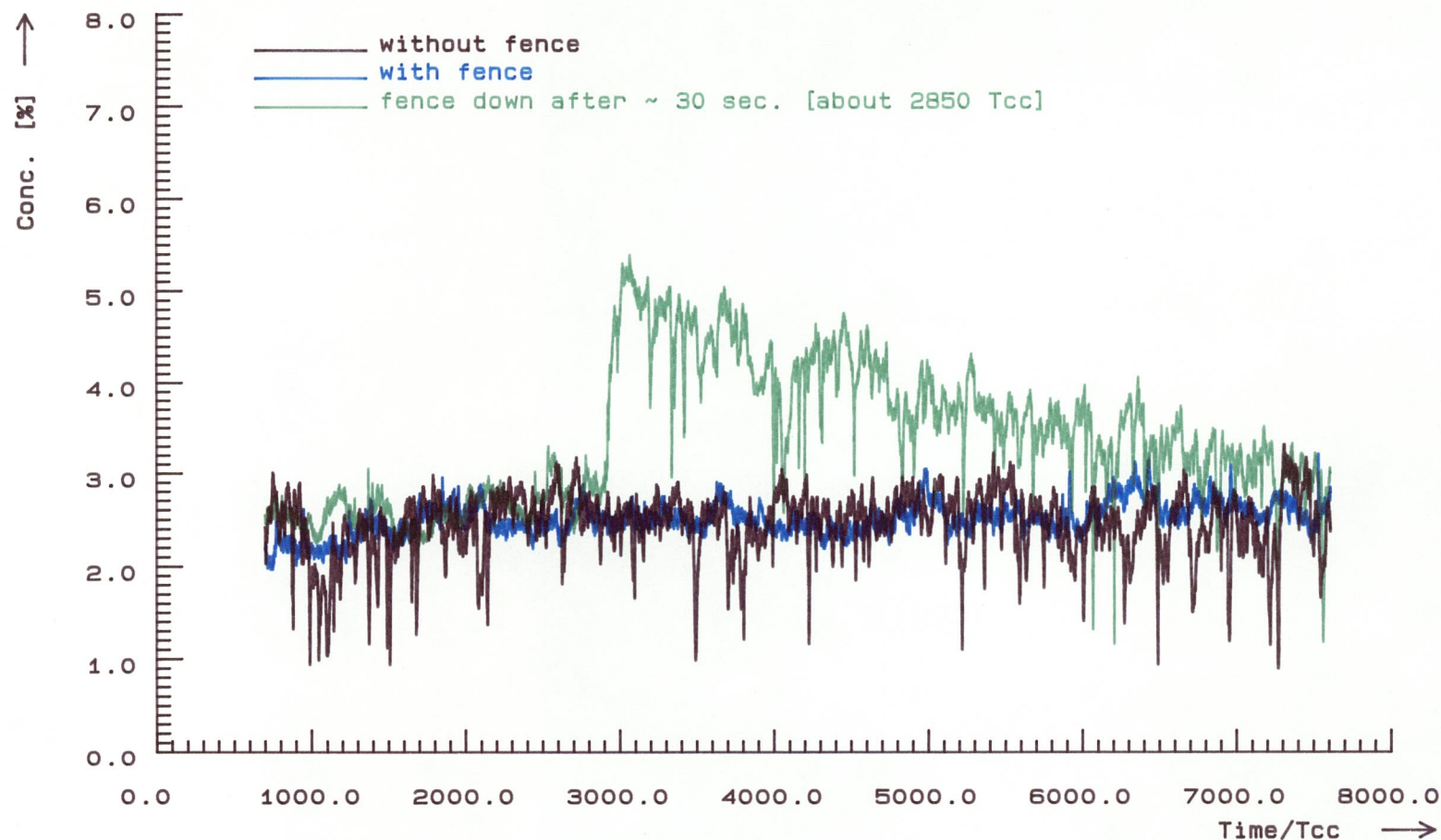
Model gas= SF6

Wind speed:

1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.68 %	3.41 %	3.98 %	3.17 %
Min.	.38 %	1.44 %	2.45 %	1.32 %
Max.	3.99 %	4.44 %	4.70 %	4.57 %
St. dev.	.49 %	.43 %	.44 %	.49 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 82.53
Y/Lcc= -.83
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

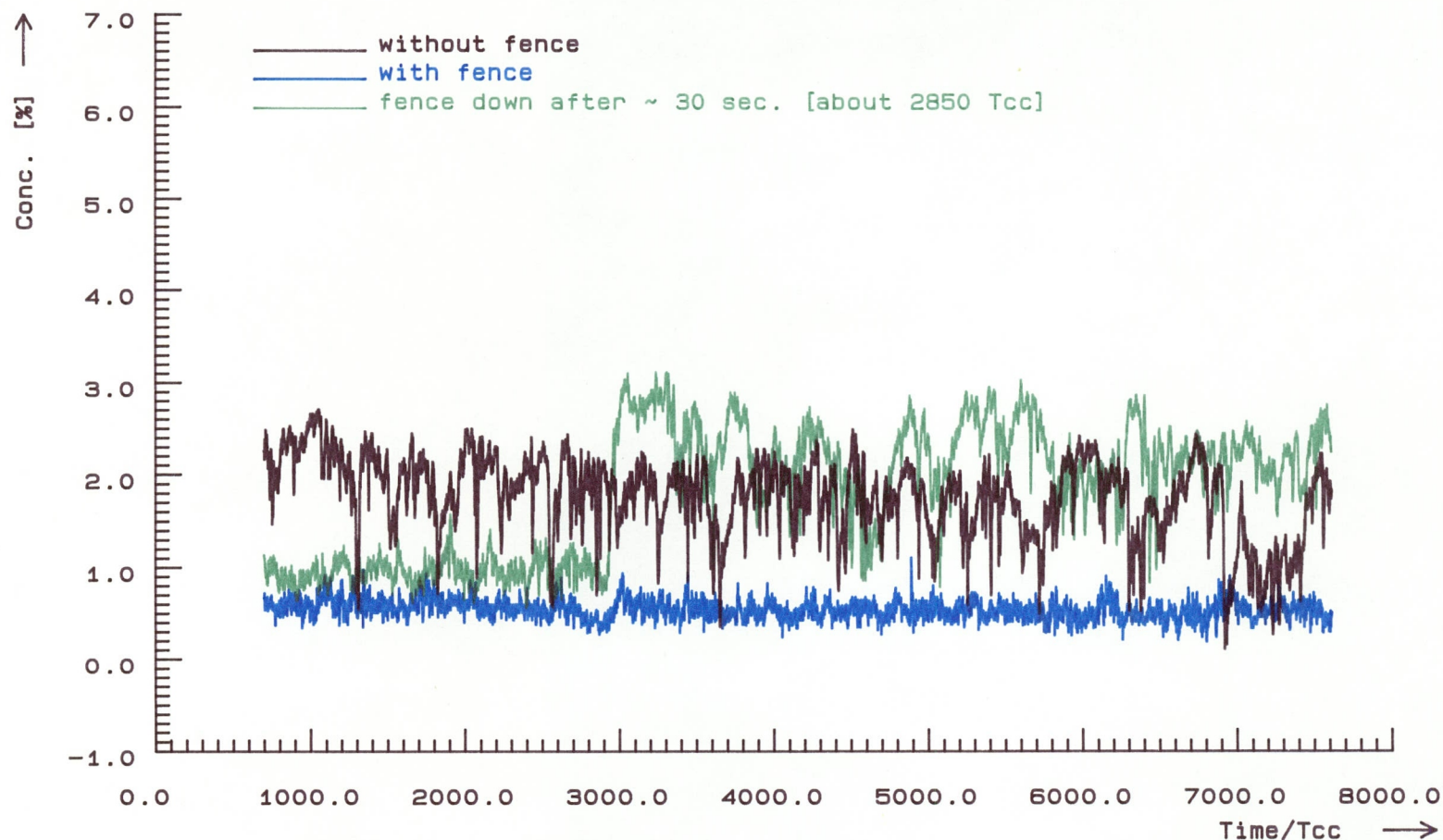
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.45 %	2.50 %	2.56 %	3.64 %
Min.	.90 %	1.97 %	2.18 %	1.16 %
Max.	3.32 %	3.22 %	3.06 %	5.05 %
St. dev.	.34 %	.17 %	.16 %	.59 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 98.64
Y/Lcc= -6.28
Z/Lcc= .12

Parameters:

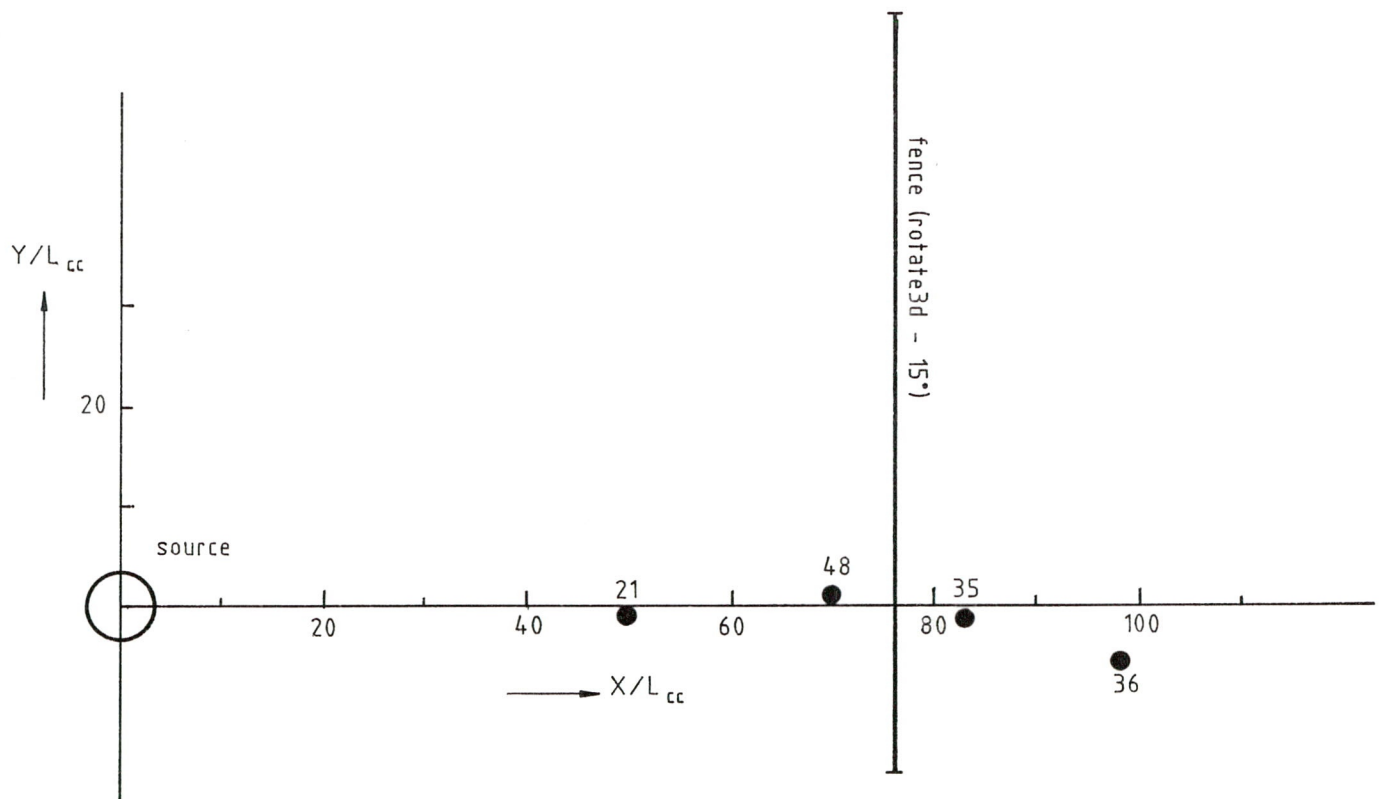
Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

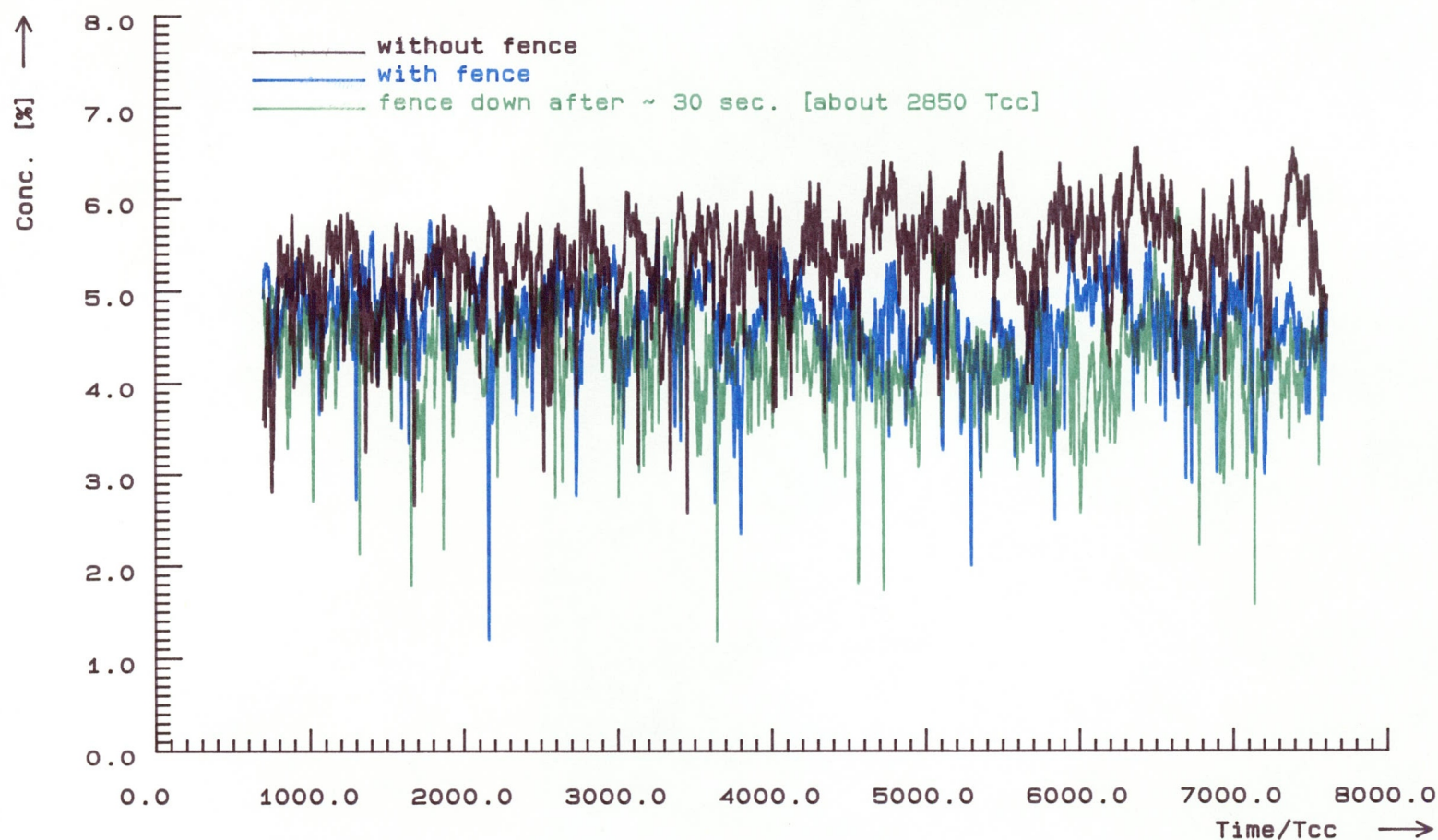
	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	1.76 %	.54 %	.95 %	2.18 %
Min.	.11 %	.19 %	.62 %	.79 %
Max.	2.71 %	1.11 %	1.58 %	3.04 %
St. dev.	.43 %	.10 %	.13 %	.38 %



Position of probes for a fence rotation of -15°

MT - TNO
91 - 026
Fig. 40

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 50.44
Y/Lcc= -.83
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

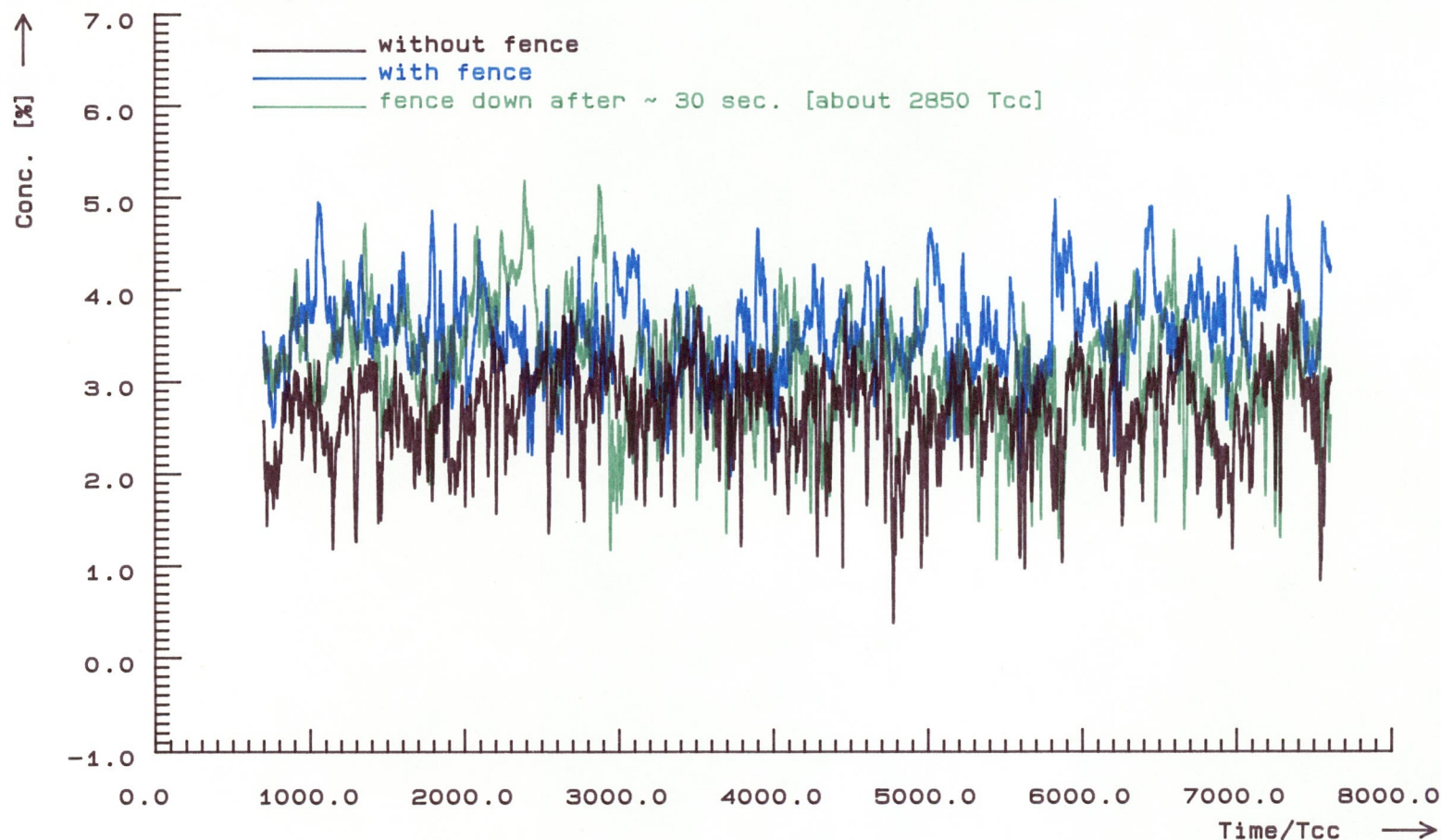
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	5.35 %	4.67 %	4.40 %	4.23 %
Min.	2.58 %	1.20 %	1.79 %	1.18 %
Max.	6.57 %	5.77 %	5.30 %	5.90 %
St. dev.	.52 %	.47 %	.46 %	.53 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 69.75
Y/Lcc= 1.30
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

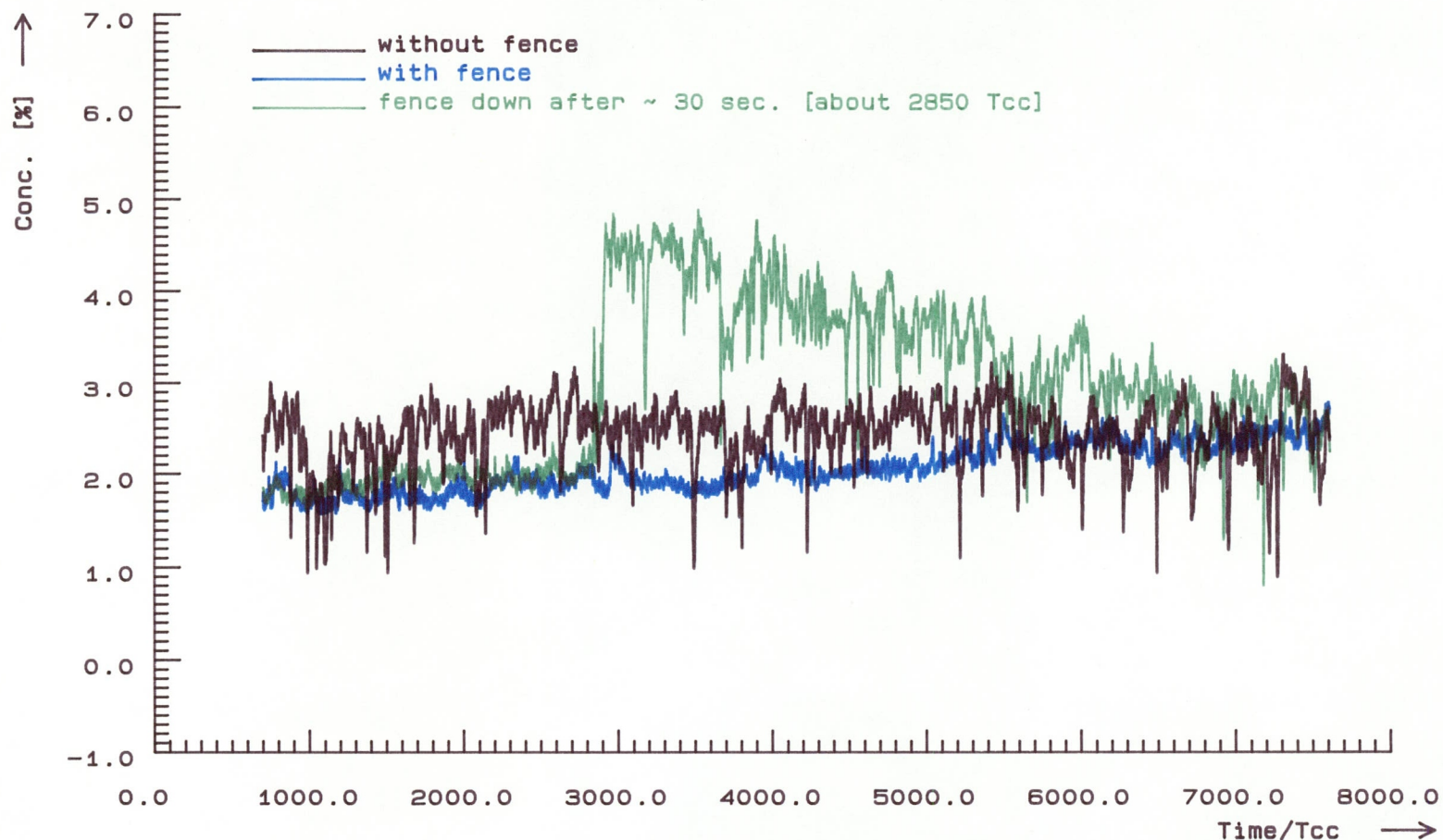
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0 = 1.50E+02$ [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.68 %	3.55 %	3.43 %	3.05 %
Min.	.38 %	1.98 %	1.89 %	1.07 %
Max.	3.99 %	5.02 %	4.72 %	4.65 %
St. dev.	.49 %	.48 %	.46 %	.52 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 82.53
Y/Lcc= -.83
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

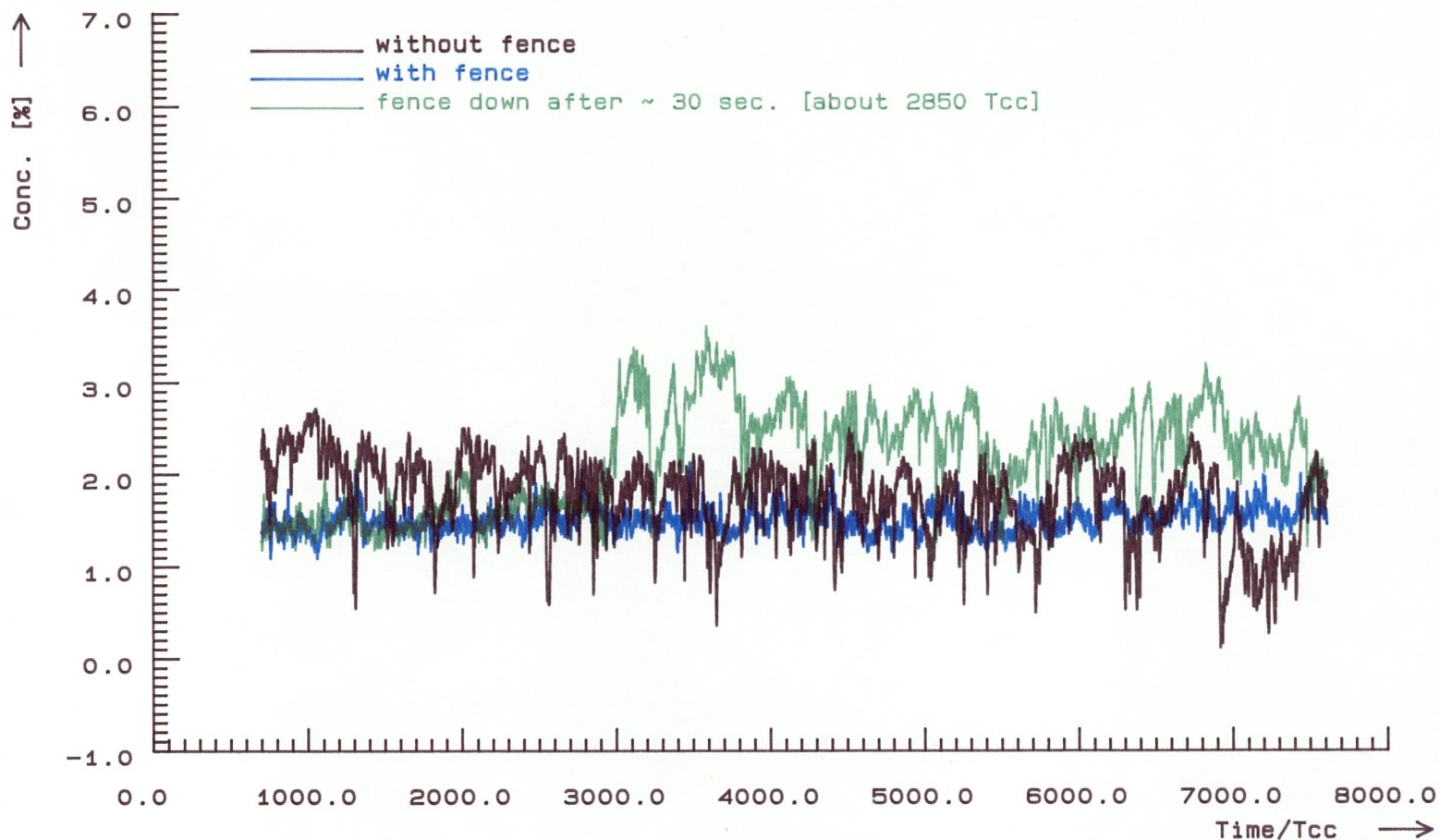
Sample freq.= 60.0 [Hz.]

Source strength $\dot{V}_0$ = 1.50E+02 [L/H]
Model gas= SF6

Wind speed:
1.0 Ucc at 1.0 Lcc height

	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	2.45 %	2.06 %	1.91 %	3.32 %
Min.	.90 %	1.57 %	1.61 %	.80 %
Max.	3.32 %	2.79 %	2.33 %	4.89 %
St. dev.	.34 %	.25 %	.11 %	.63 %

CONTINUOUS RELEASE / REMODELLING OF TUV-EXPERIMENTS



Position:

X/Lcc= 98.64
Y/Lcc= -6.28
Z/Lcc= .12

Parameters:

Ucc= .584 [m/s]
Lcc= .0084 [m]
Tcc= .0145 [s]

Sample freq.= 60.0 [Hz.]

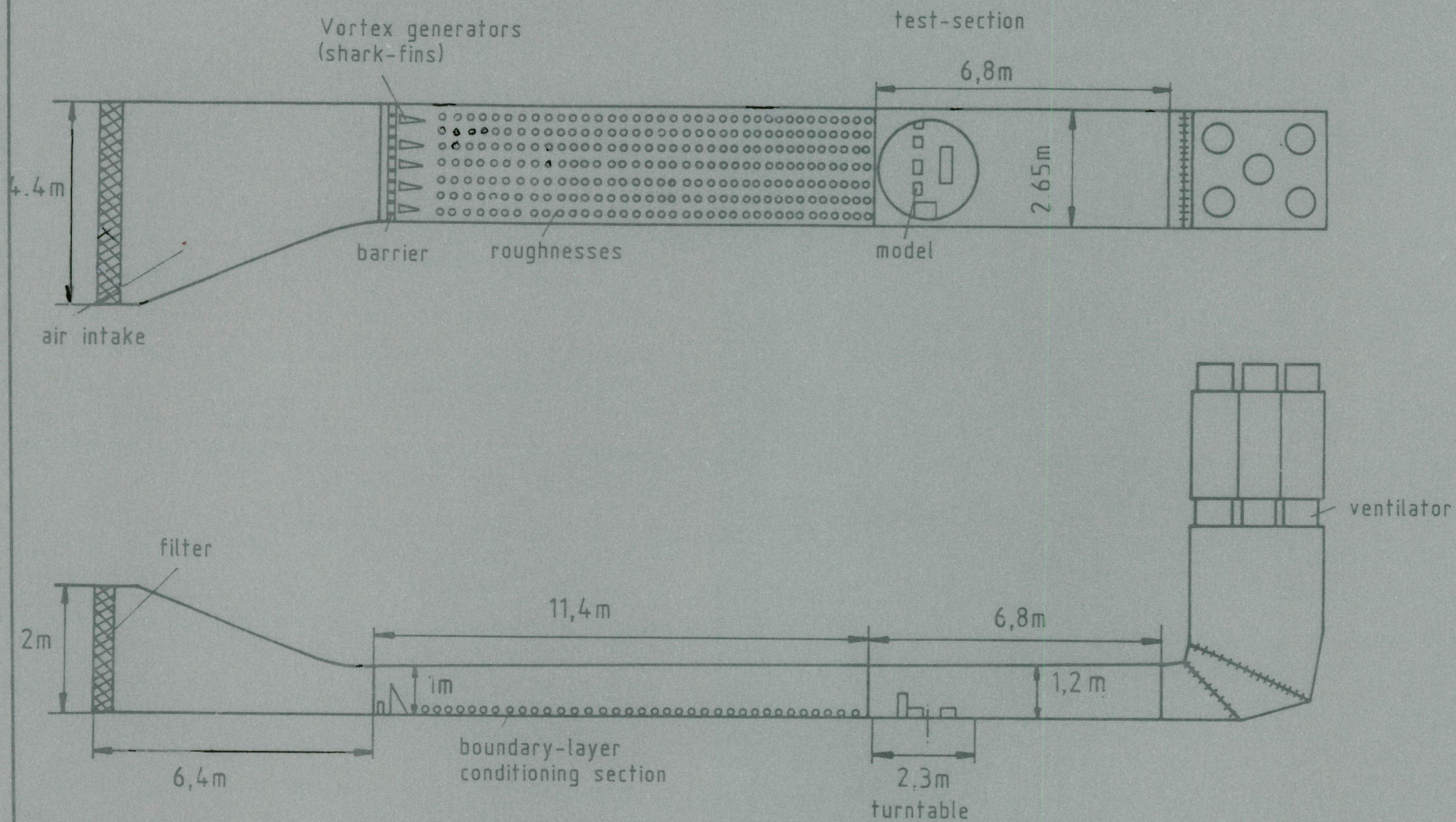
Source strength $\dot{V}_0$ = 1.50E+02 [L/H]
Model gas= SF6

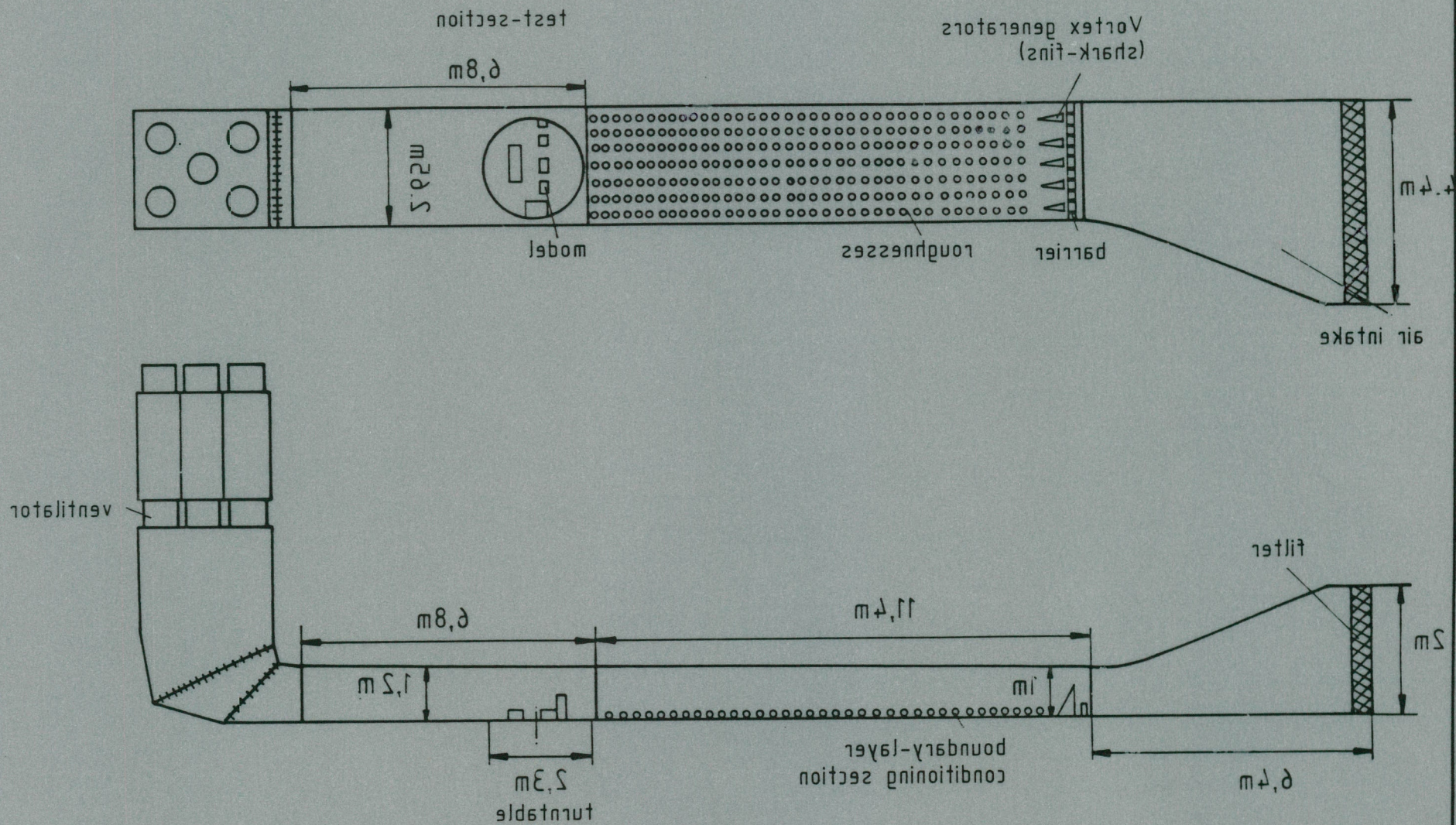
Wind speed:
1.0 Ucc at 1.0 Lcc height

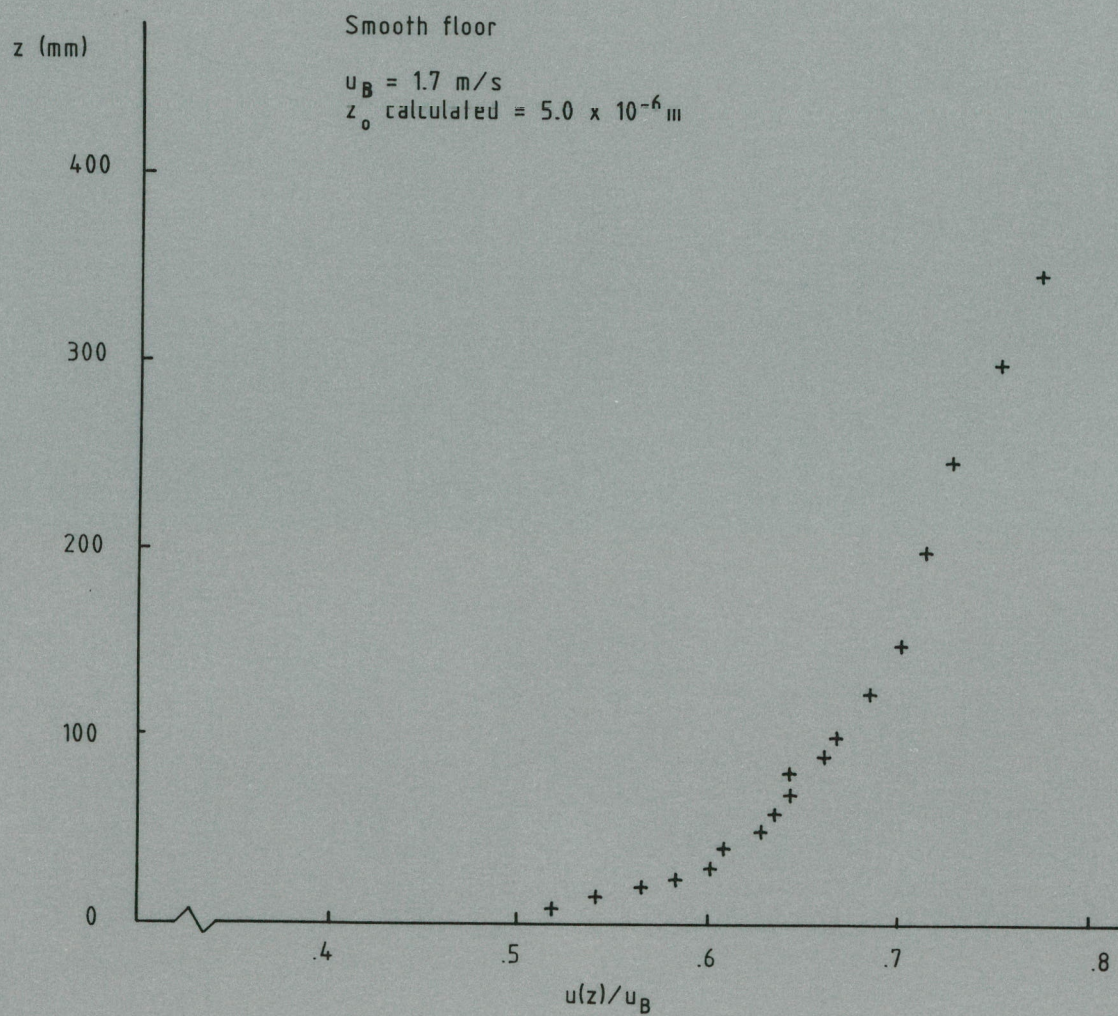
	without fence	with fence	fence down after ~ 30 sec.	
			before fence down	after fence down
Mean	1.76 %	1.51 %	1.53 %	2.46 %
Min.	.11 %	1.09 %	1.19 %	1.22 %
Max.	2.71 %	2.13 %	2.16 %	3.62 %
St. dev.	.43 %	.13 %	.16 %	.37 %

Originale
Figuren

The PIA windtunnel

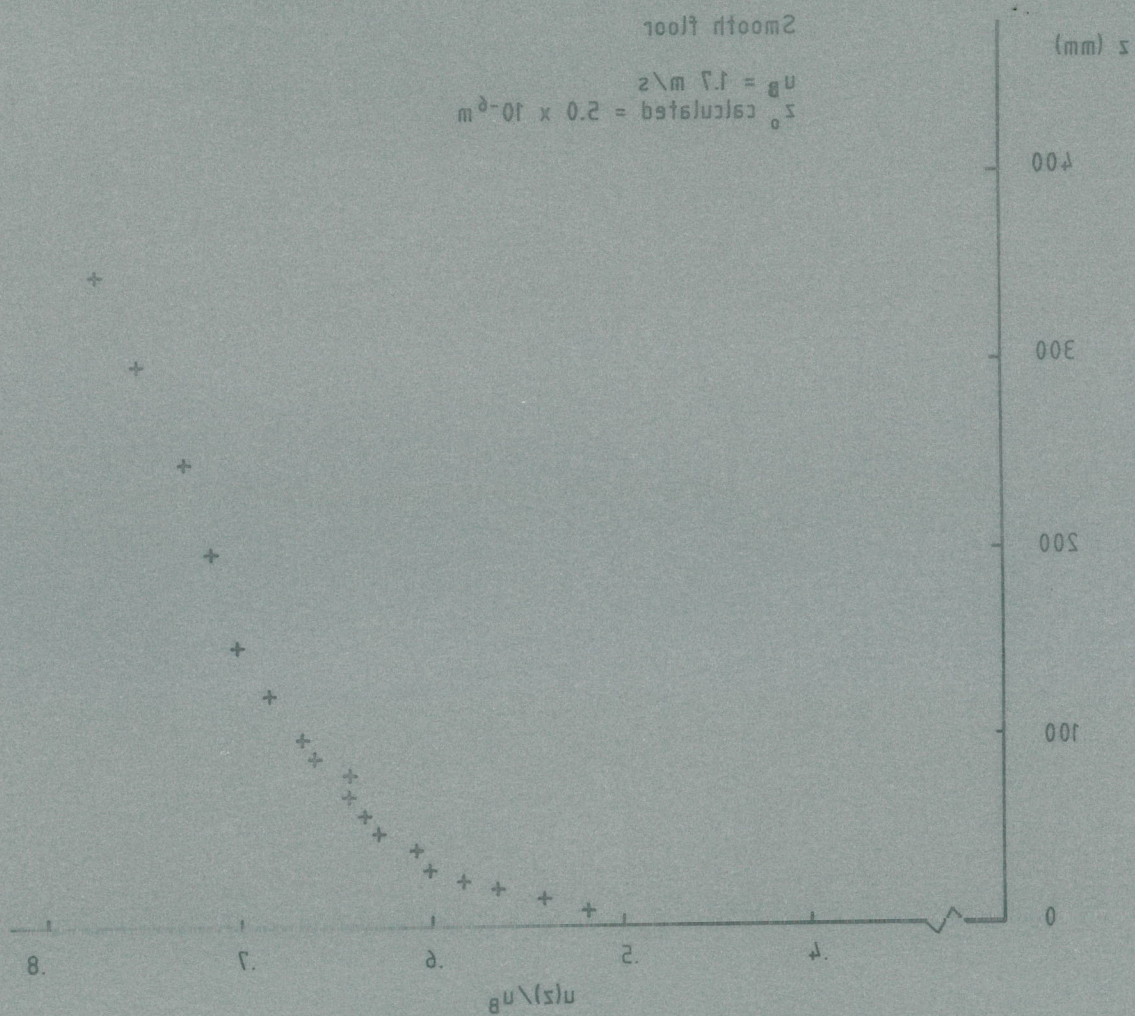




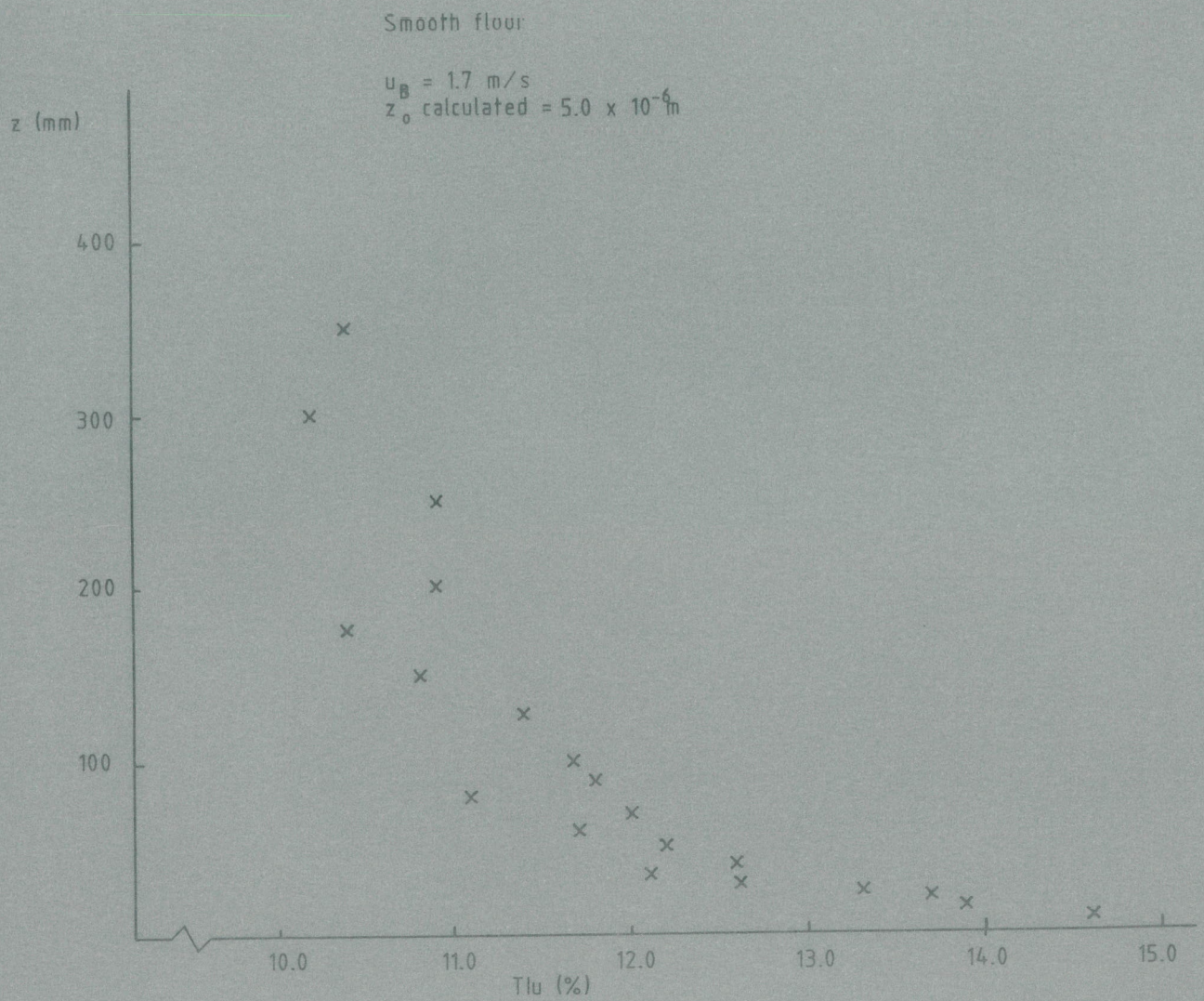


Mean velocity profile for smooth floor.

MT - TNO
91-026
Fig. 2a

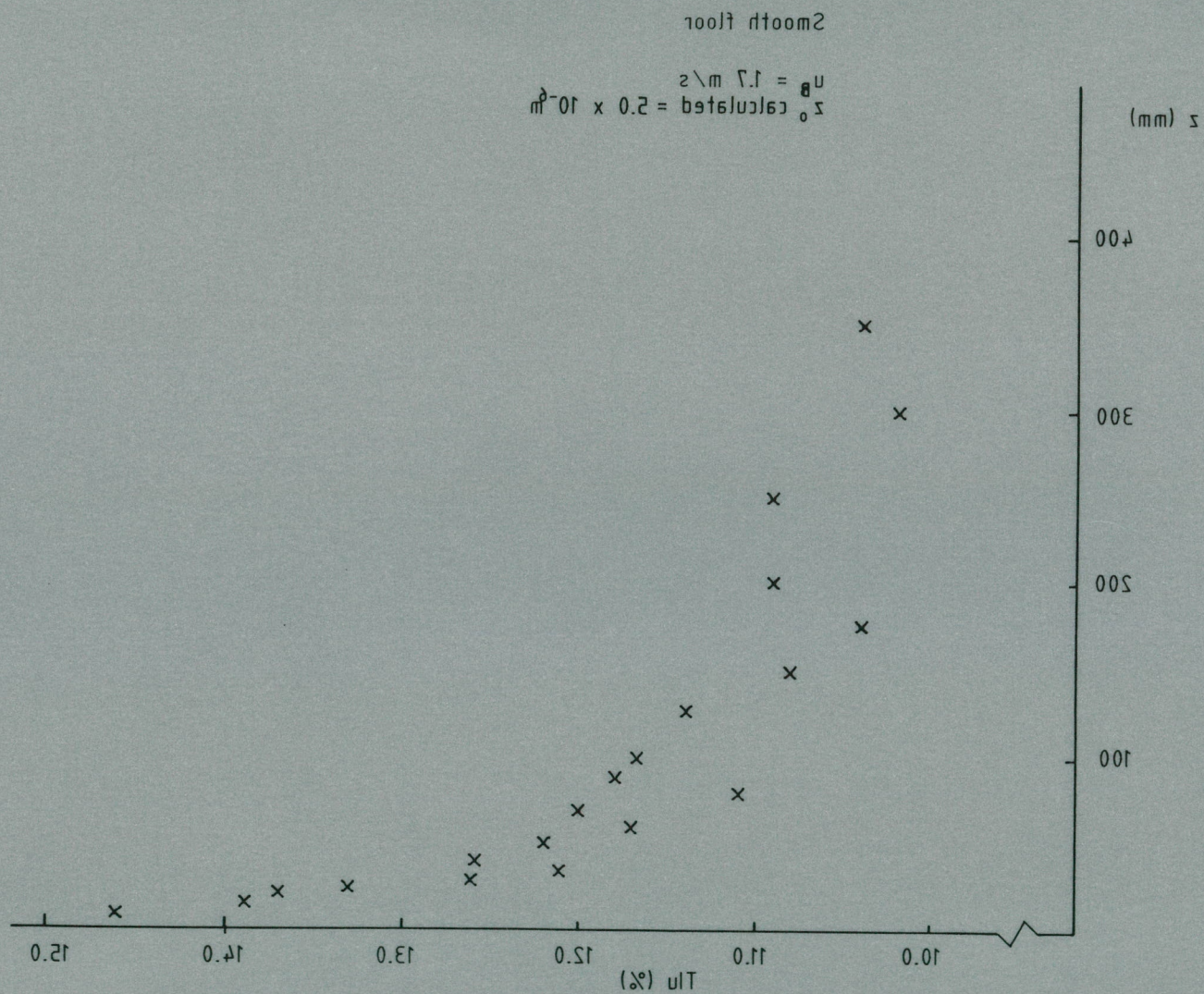


Mean velocity profile for smooth floor.



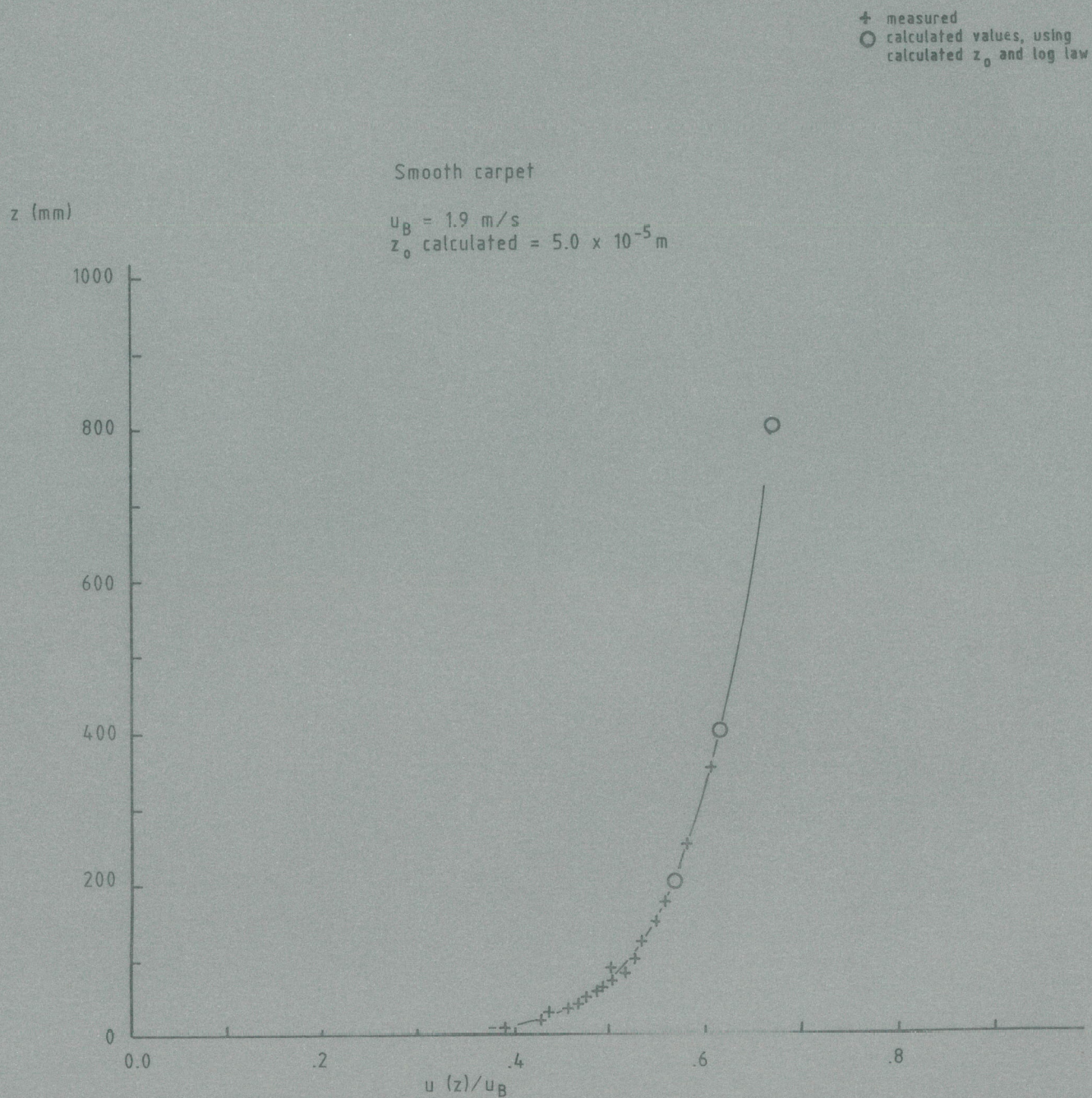
Longitudinal turbulence intensity profile for smooth floor.

MT - TNO
91-026
Fig. 2b



Longitudinal turbulence intensity profile for smooth floor.

MT - TM
 91-058
 Fig. 2b



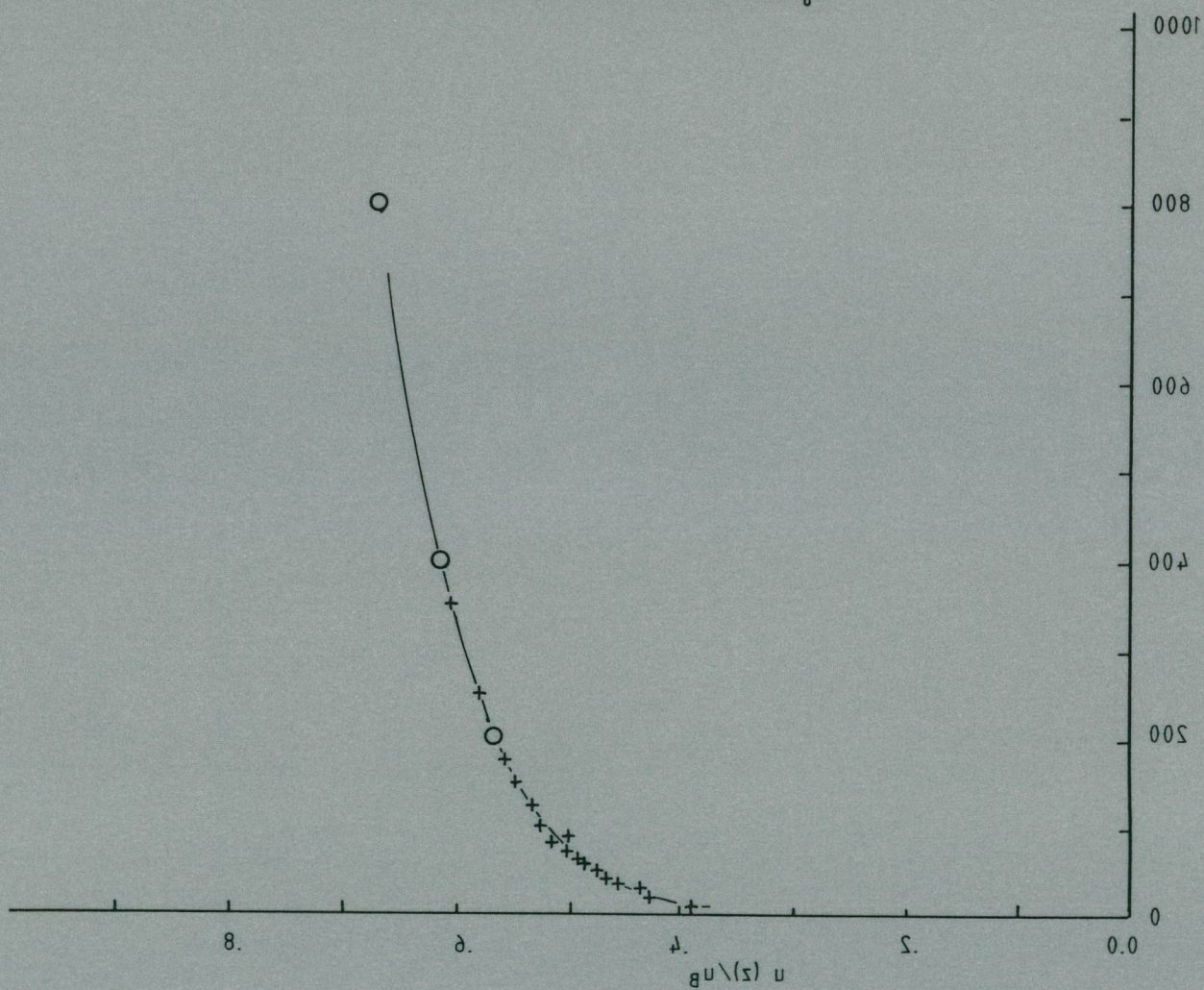
Mean velocity profile for smooth carpet.

+ measured
 ○ calculated
 values of $u(z)$

smooth curve

$$u(z) = 0.17 z^{2.01} \times 10^{-2}$$

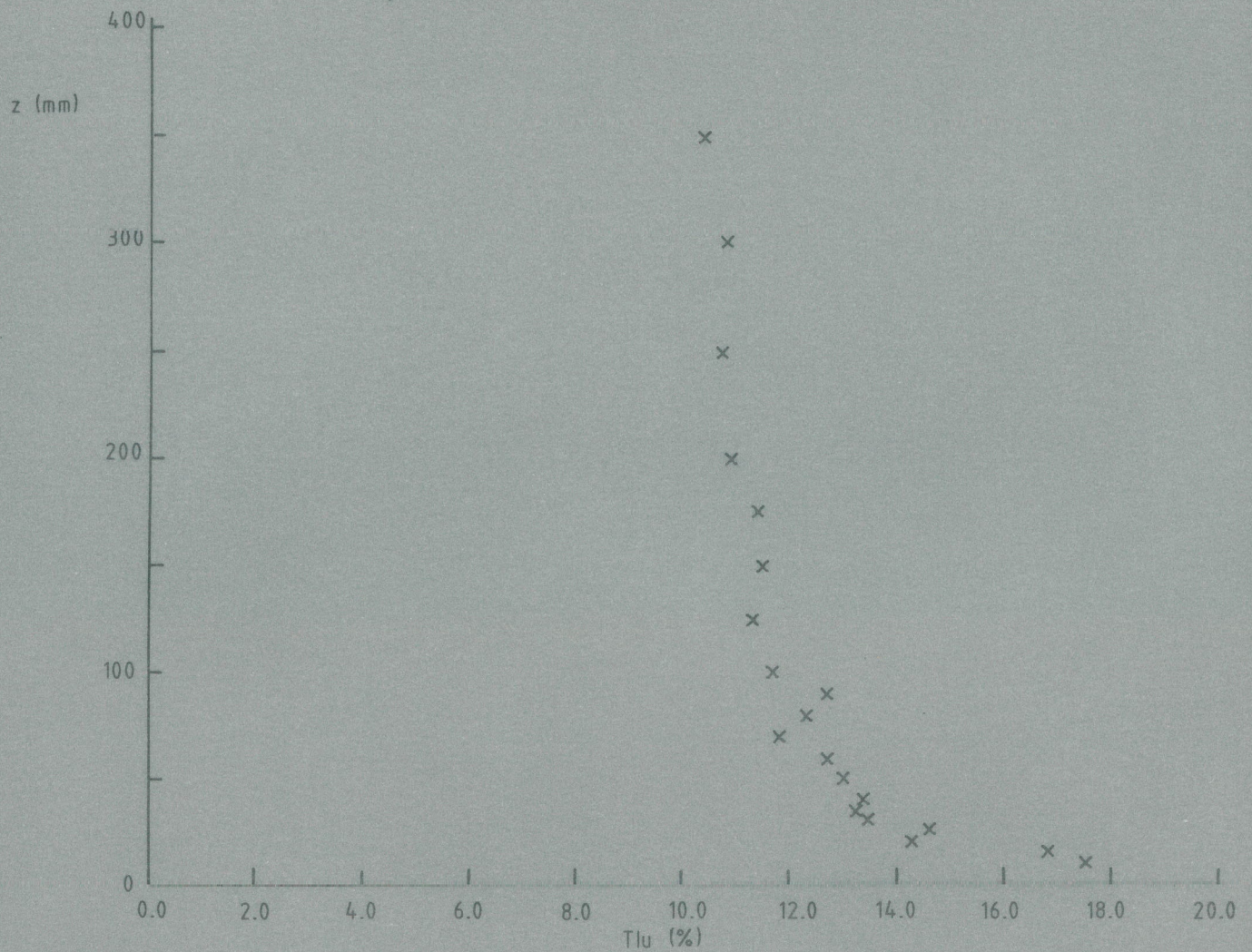
z (mm)



Smooth carpet

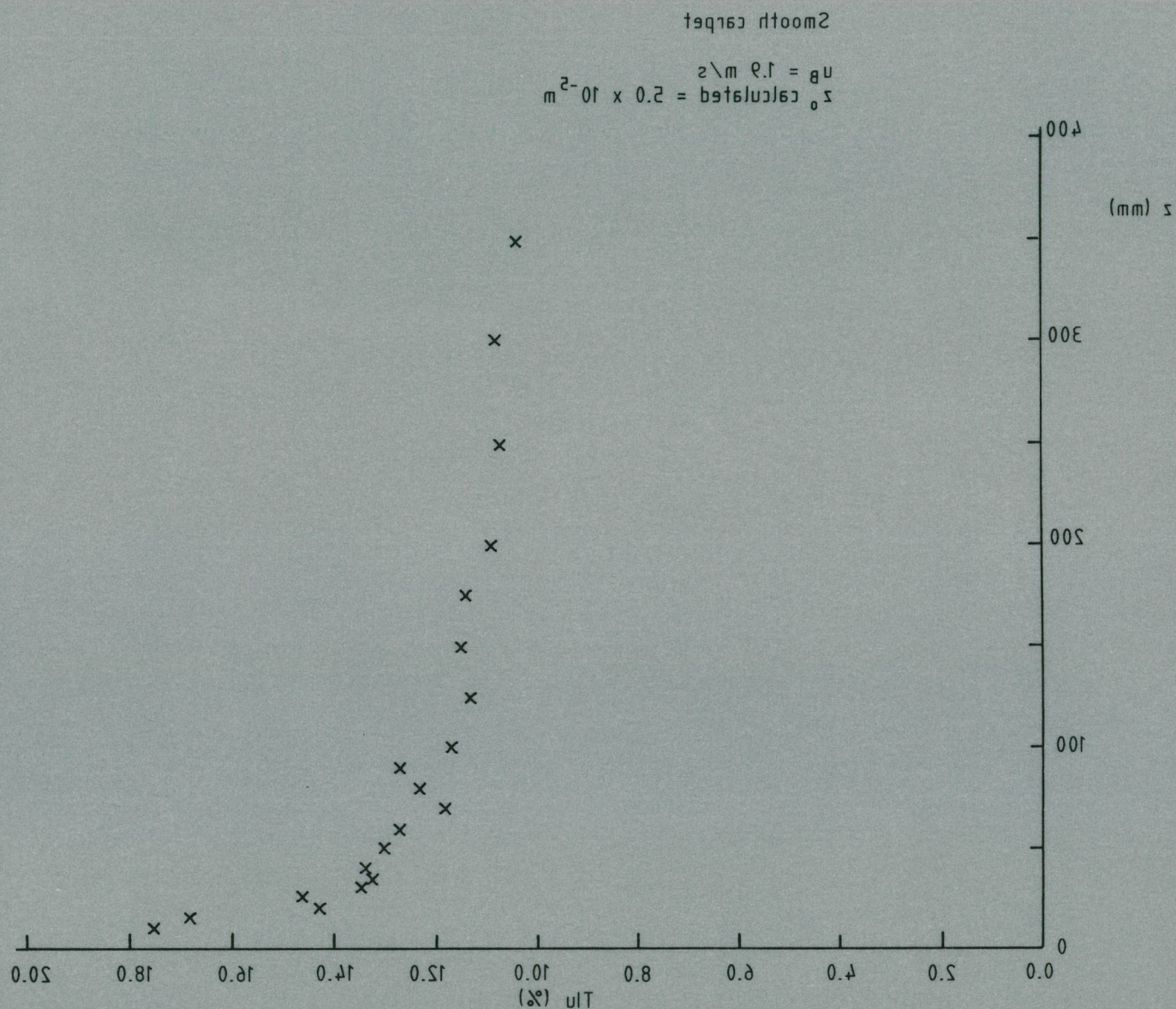
$u_B = 1.9 \text{ m/s}$

$z_0 \text{ calculated} = 5.0 \times 10^{-5} \text{ m}$



Longitudinal turbulence intensity profile for smooth carpet

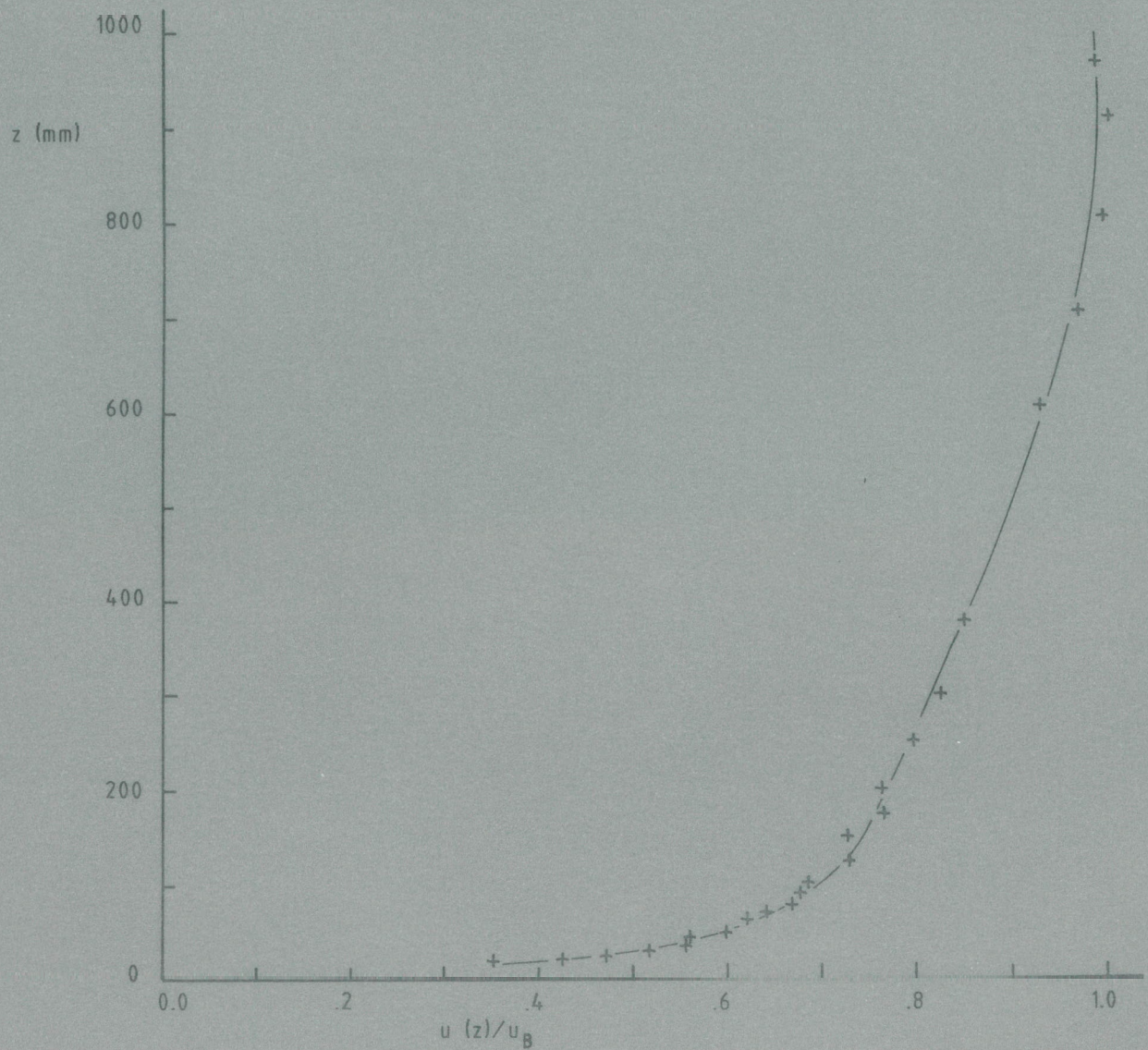
MT - TNO
91-026
Fig. 3b



Rough carpet

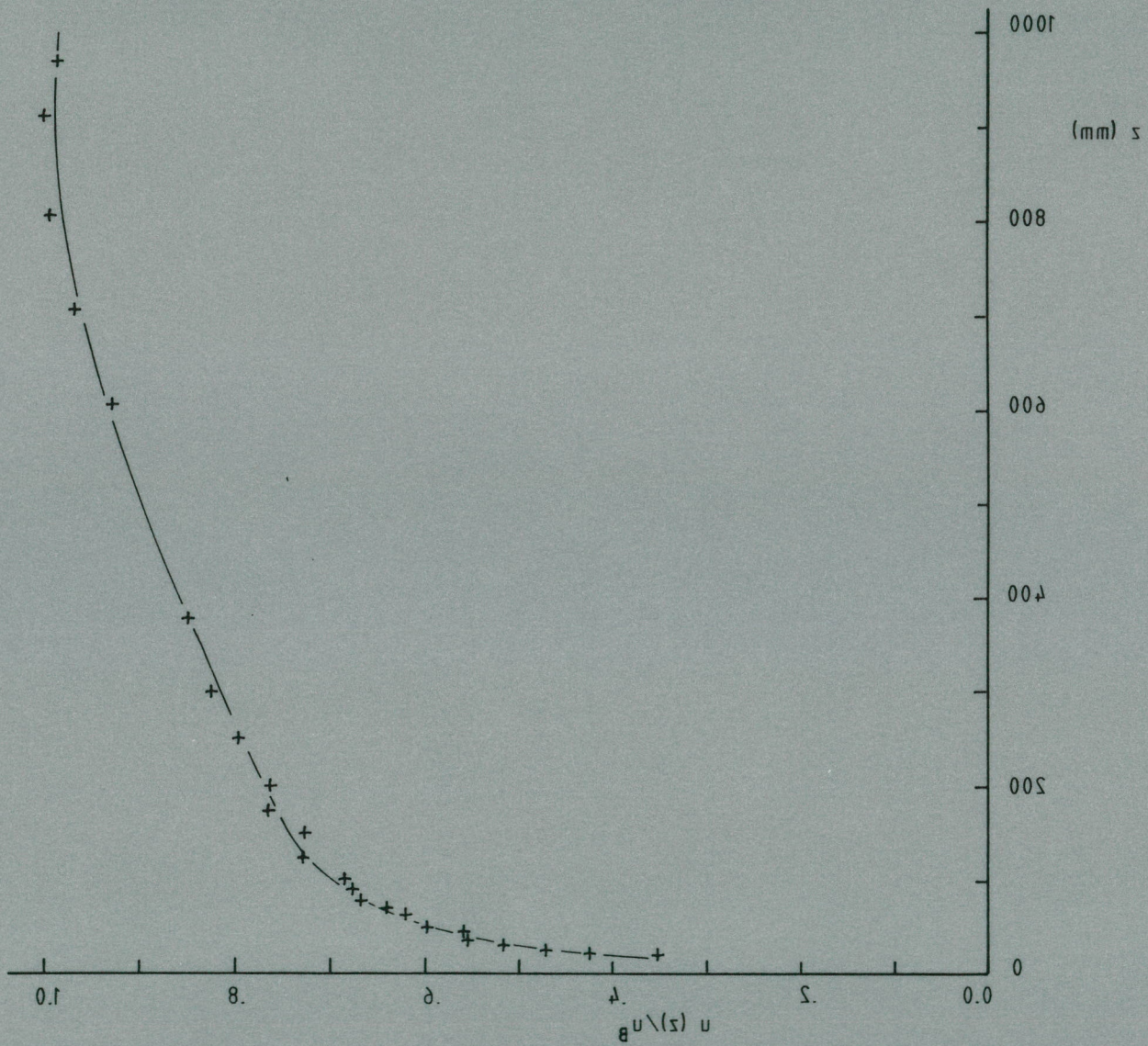
$u_B = 20.0 \text{ m/s}$

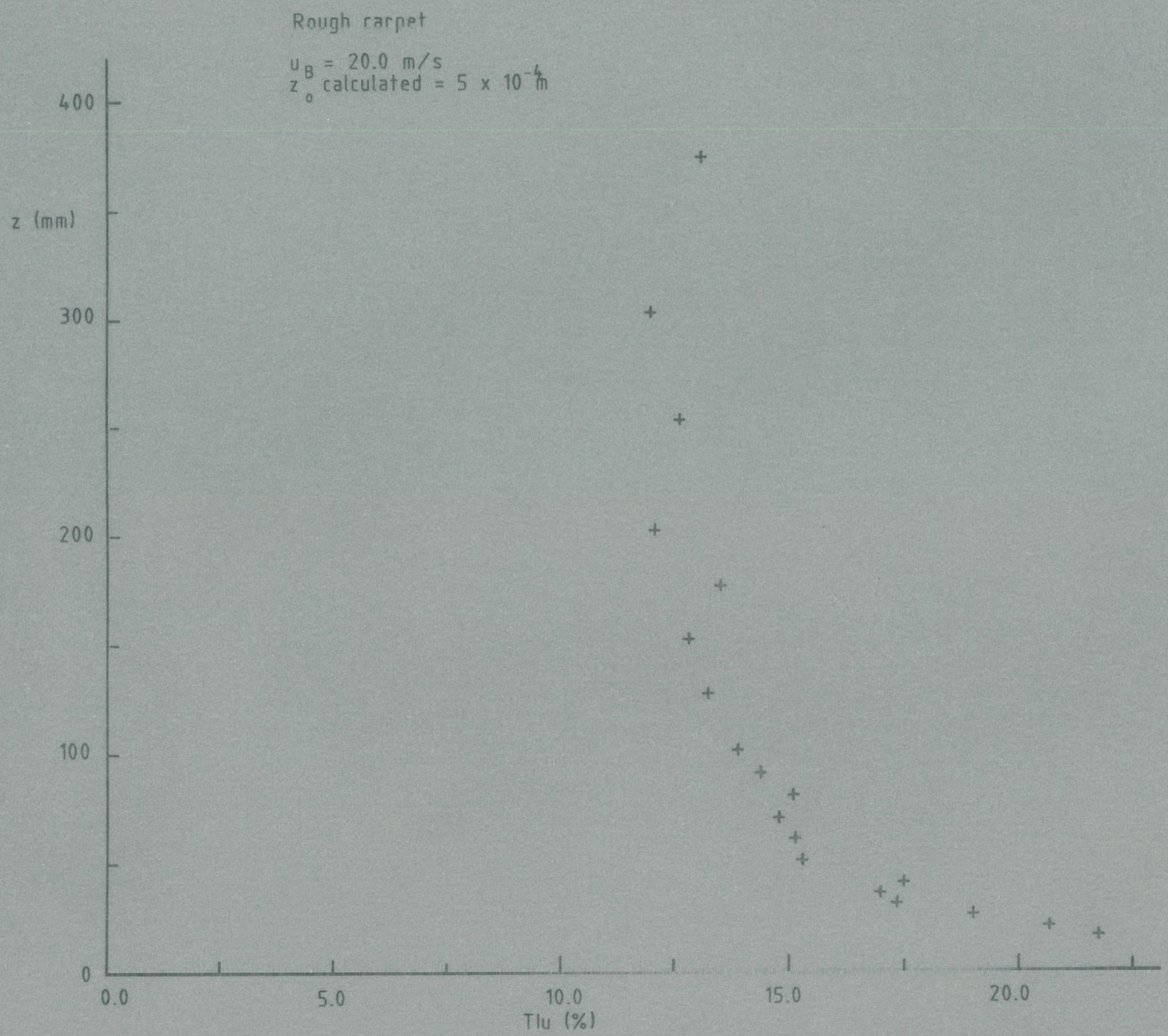
$z_o \text{ calculated} = 5.0 \times 10^{-4} \text{ m}$



Mean velocity profile for rough carpet..

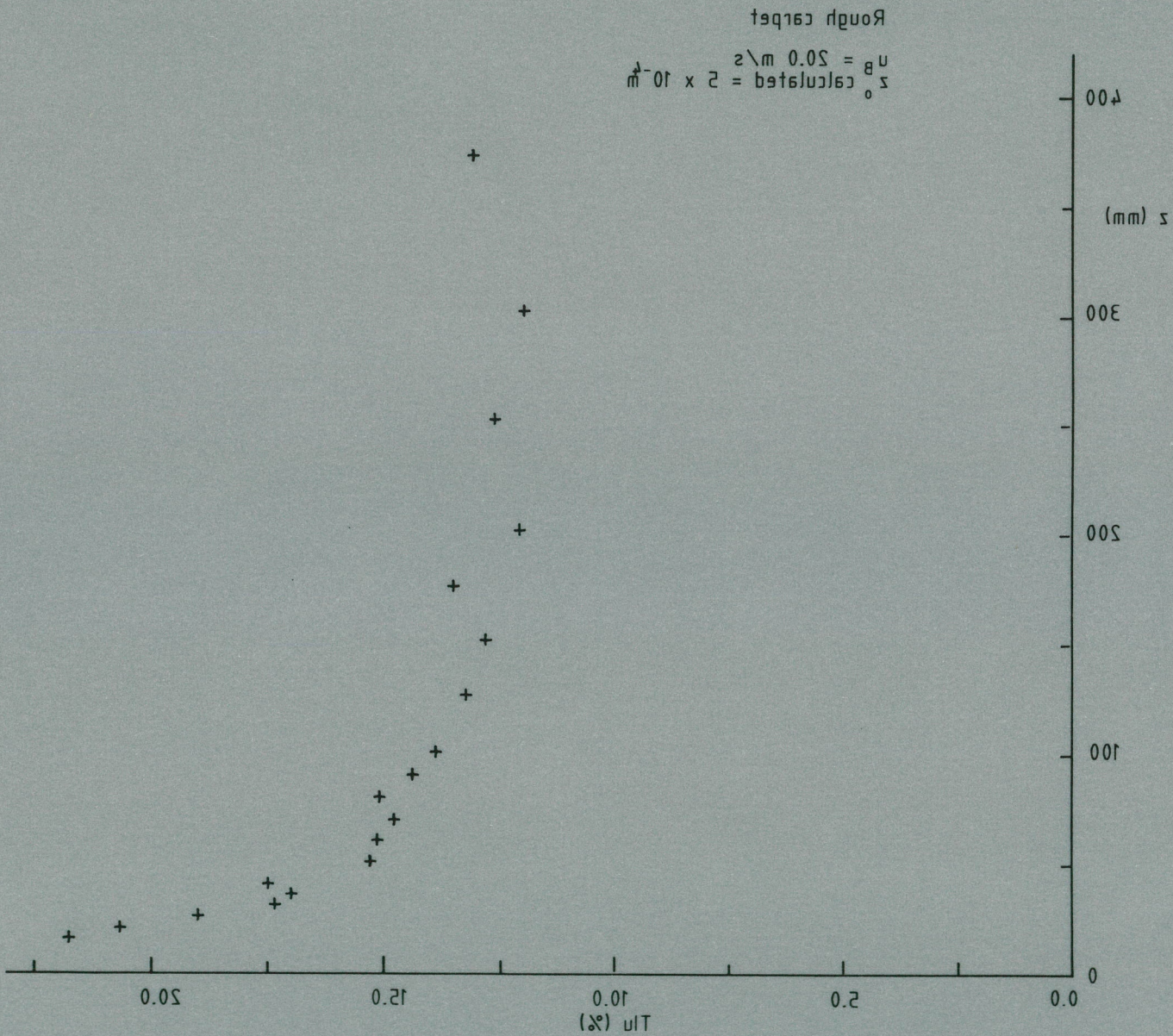
MT - TNO
91-026
Fig. 4a

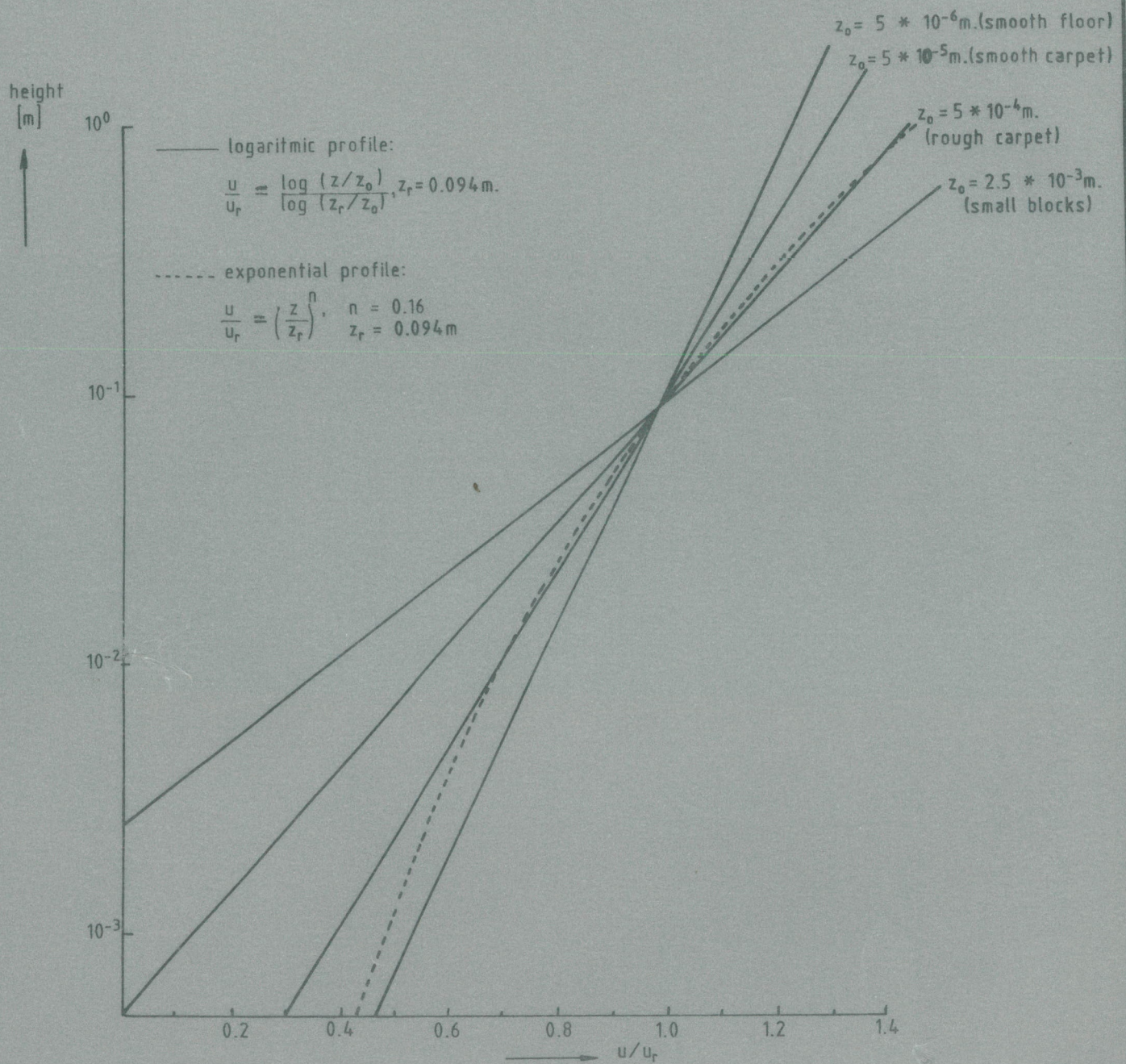




Longitudinal turbulence intensity profile for rough carpet.

MT - TNO
91-026
Fig.4b





Comparison between logarithmic and exponential velocity profile.

MT-TNO
 91-026
 Fig.5

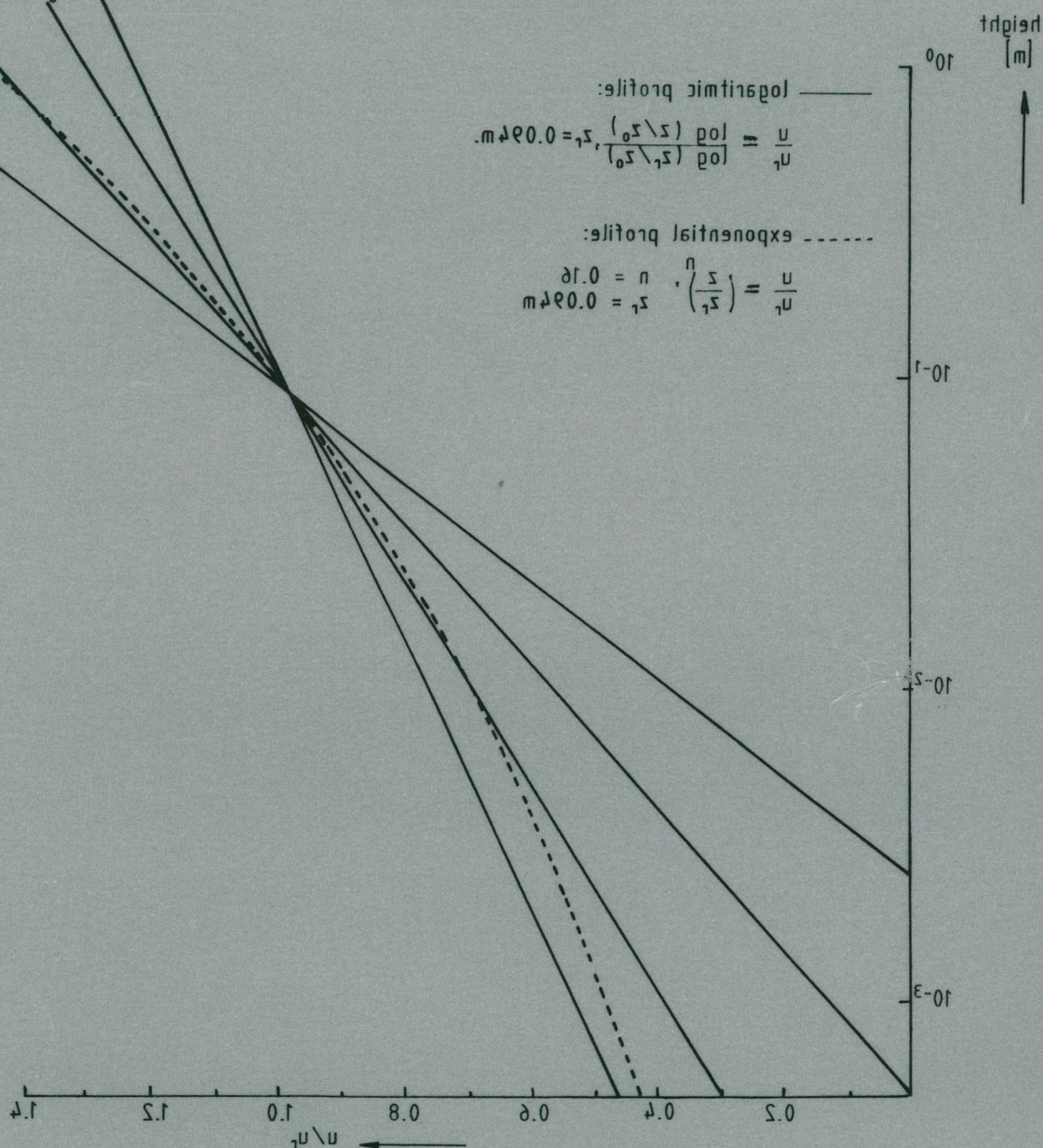
$z_0 = 2 \times 10^{-6} \text{ m}$ (smooth floor)
 $z_0 = 2 \times 10^{-2} \text{ m}$ (smooth carpet)

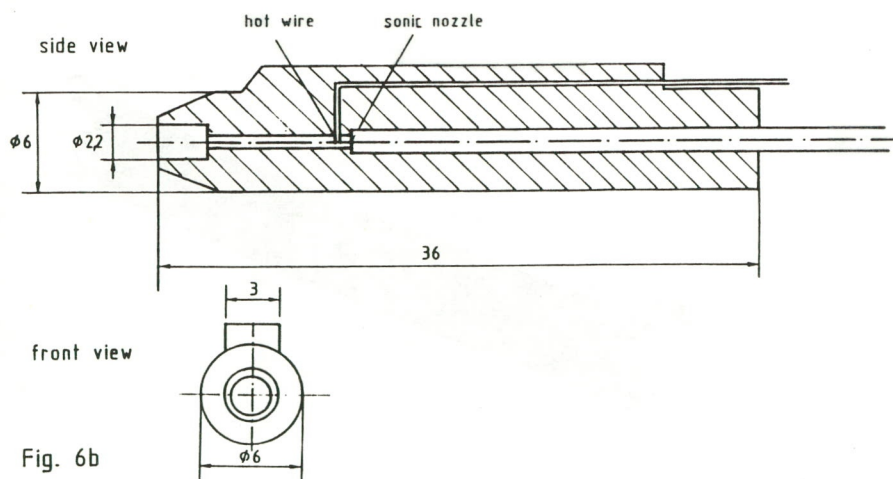
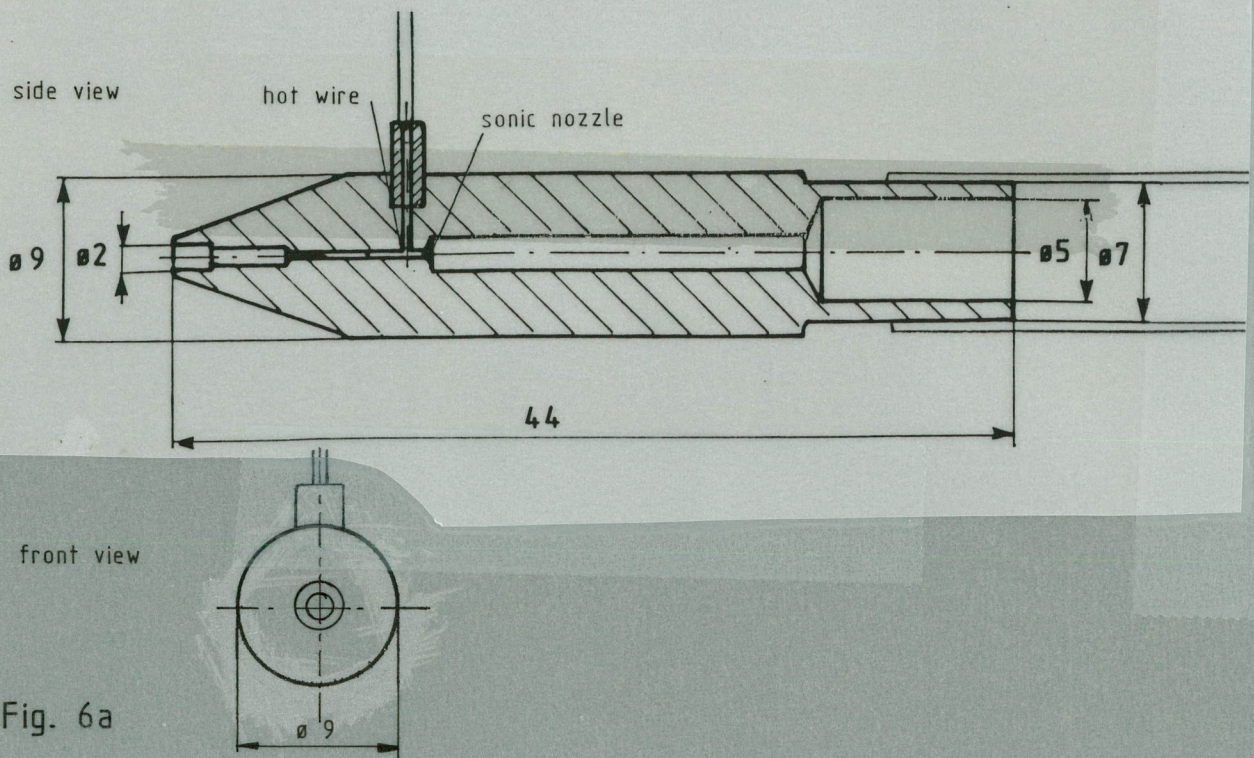
$z_0 = 2 \times 10^{-4} \text{ m}$ (rough carpet)

$z_0 = 2.2 \times 10^{-2} \text{ m}$ (small blocks)

logarithmic profile: $\frac{u}{u_*} = \frac{\log(z/z_0)}{\log(z_1/z_0)}$, $\frac{u}{u_*} = 0.094$

exponential profile: $\frac{u}{u_*} = \left(\frac{z}{z_1}\right)^n$, $n = 0.10$, $\frac{u}{u_*} = 0.094$

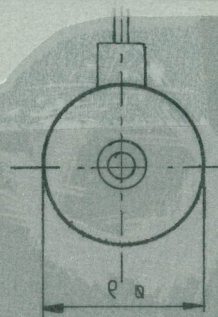
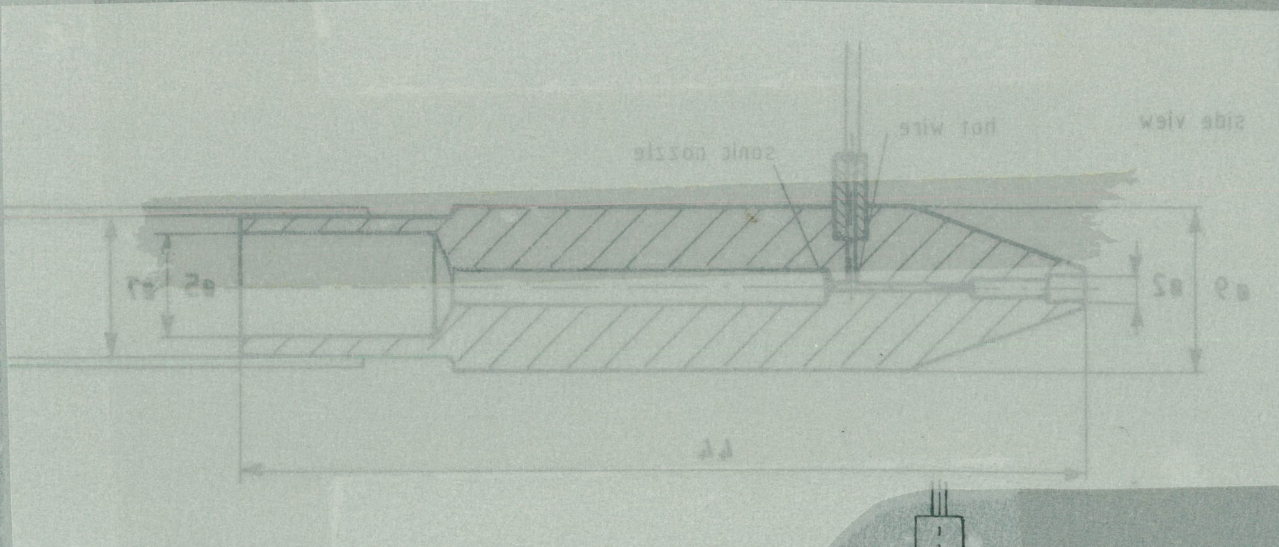




(measures in mm)

6a) MT-TNO aspirated hot wire probe
6b) Modified MT-TNO aspirated hot wire probe.

MT - TNO
91 - 026
Fig. 6a + 6b



front view

Fig. 6a



(mm ni 291259m)

ONT - TM
250 - 10
Fig. 6a + 6b

6a) MT-TNO aspirated hot wire probe
6b) Modified MT-TNO aspirated hot wire probe.

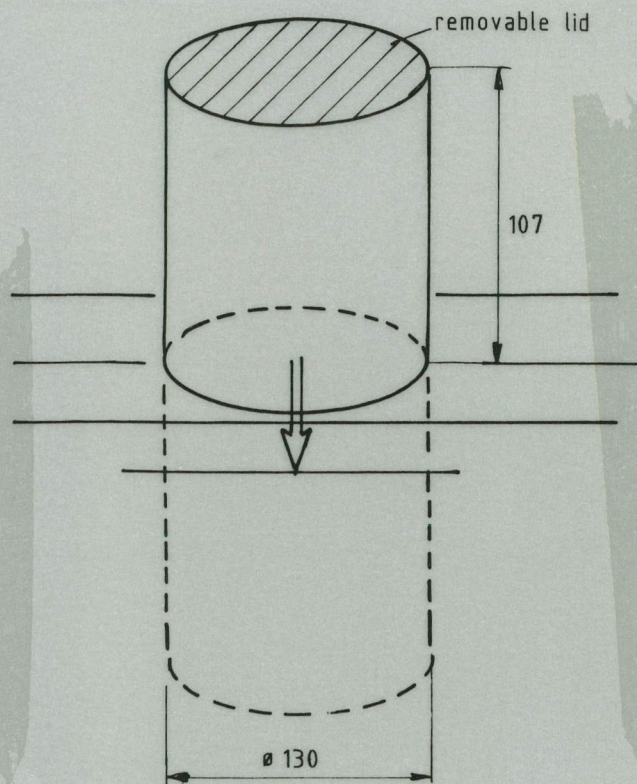


Fig. 7

(measures in mm)

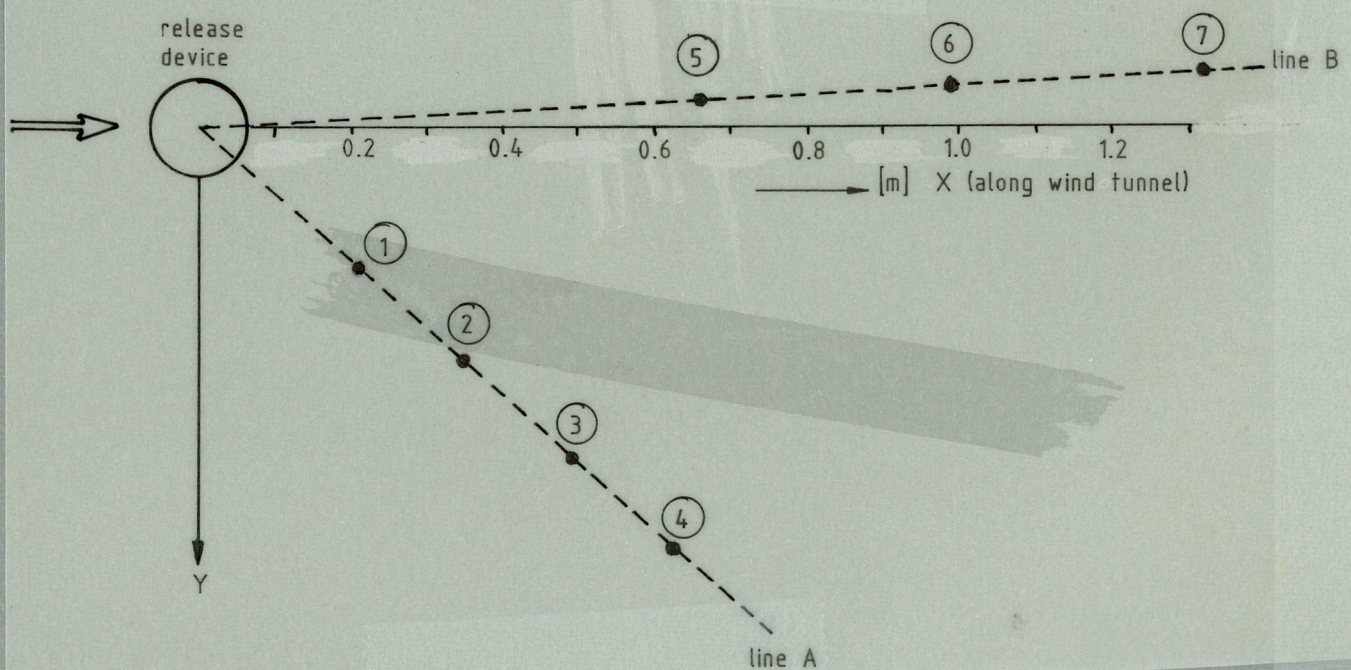


Fig. 8

7) Release device in the instantaneous release experiment
8) Sampling station for the instantaneous release experiment.

MT - TNO
91 - 026
Fig. 7 + 8

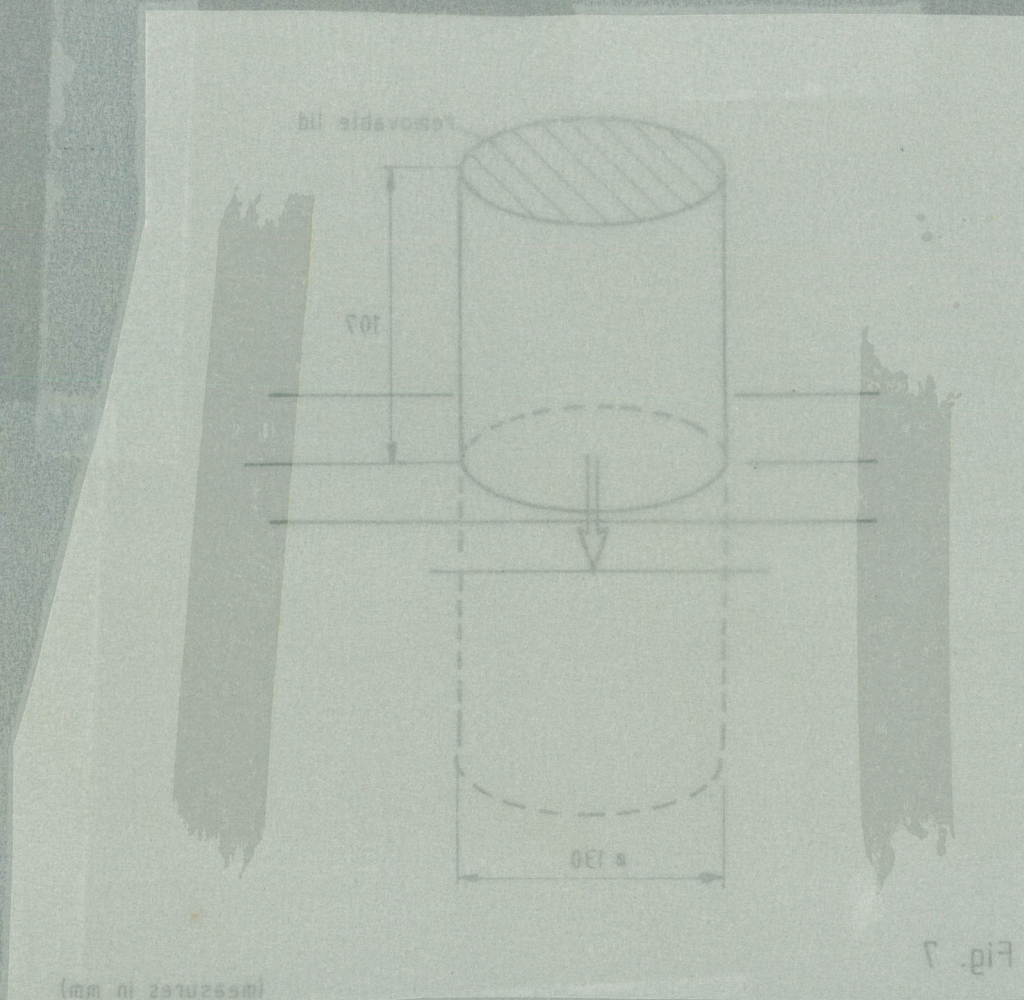


Fig. 7

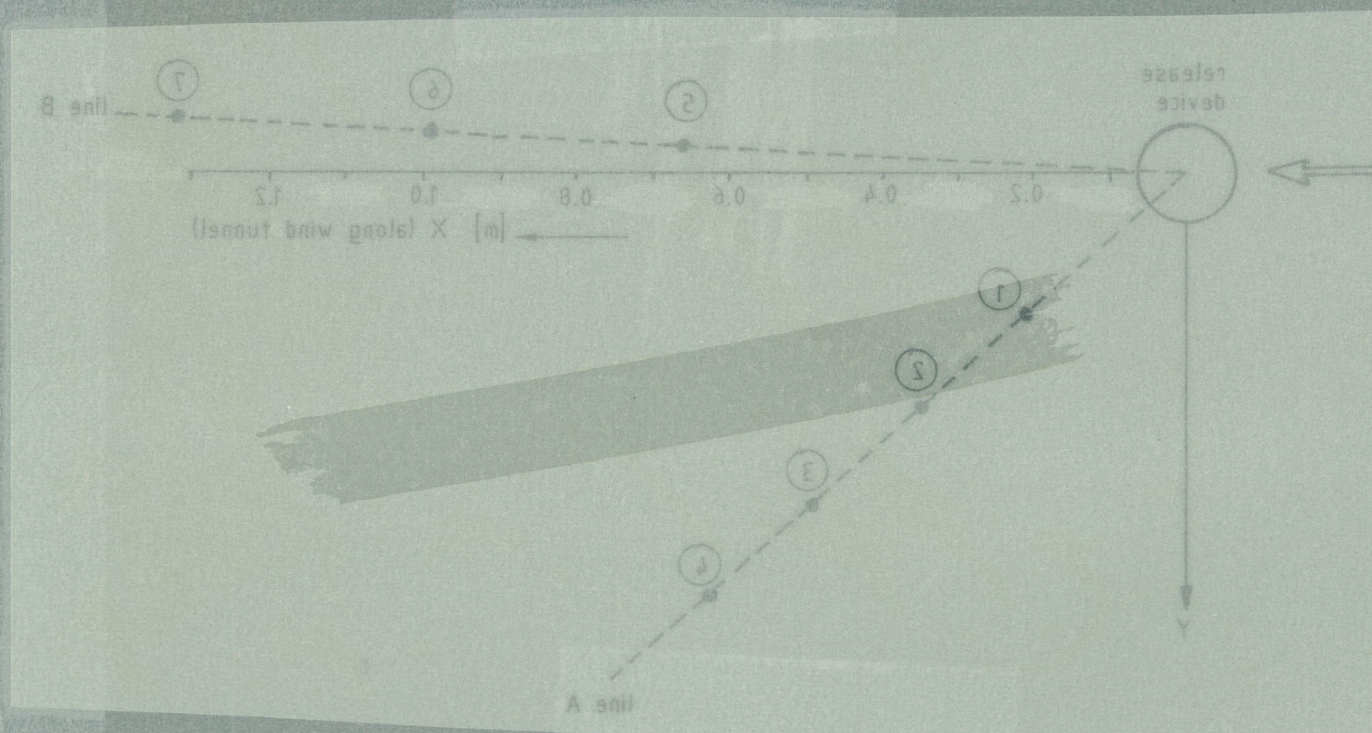
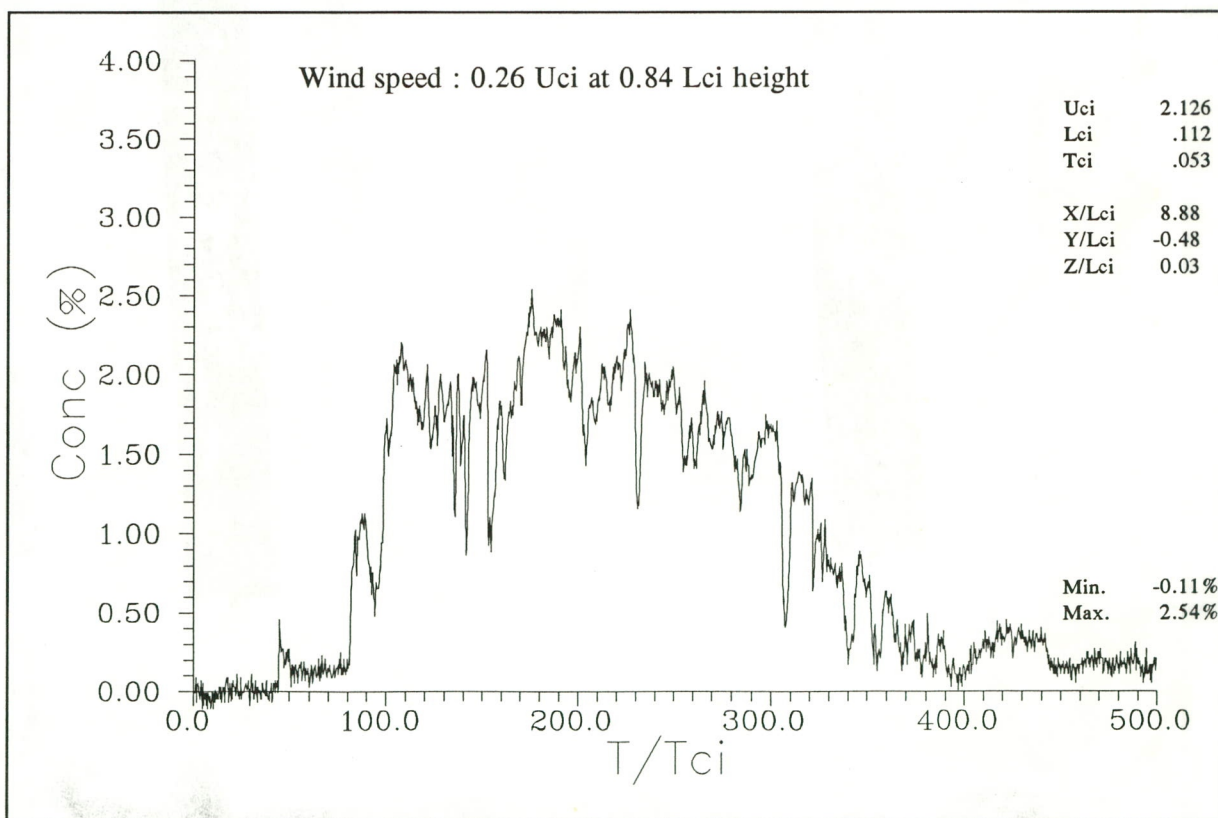
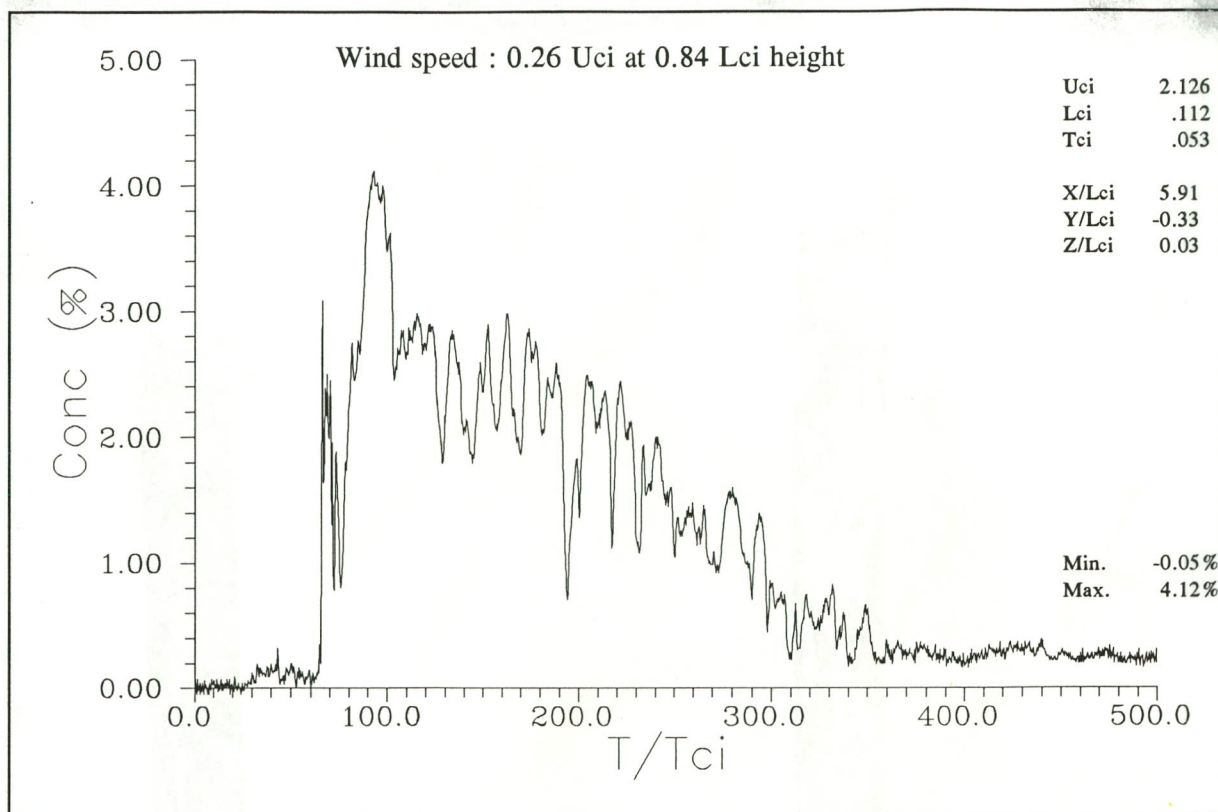


Fig. 8

7) Release device in the instantaneous release experiment.
8) Sampling station for the instantaneous release experiment.

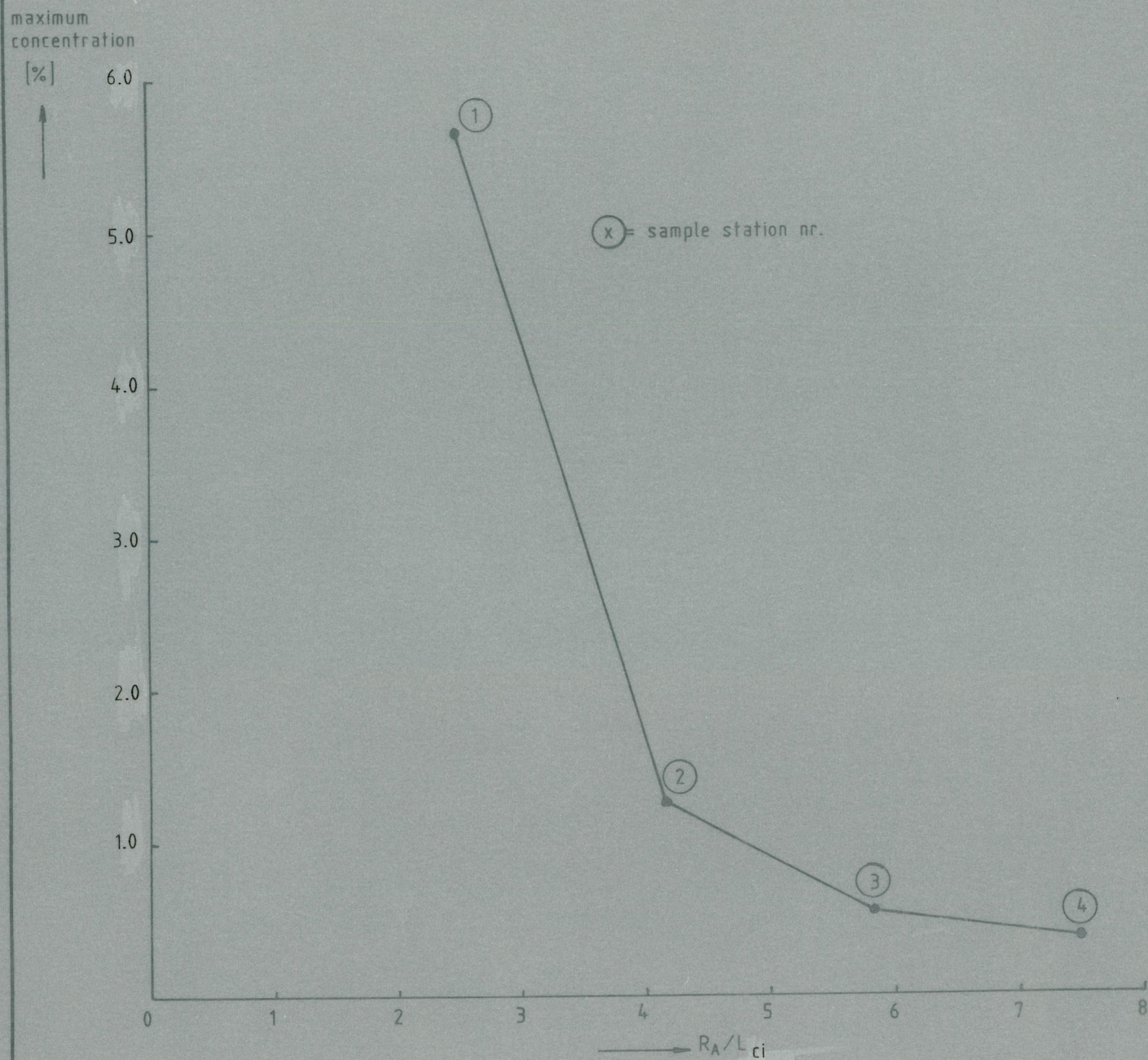


Example result of the instantaneous release.

MT - TNO
91 - 026
Fig. 9

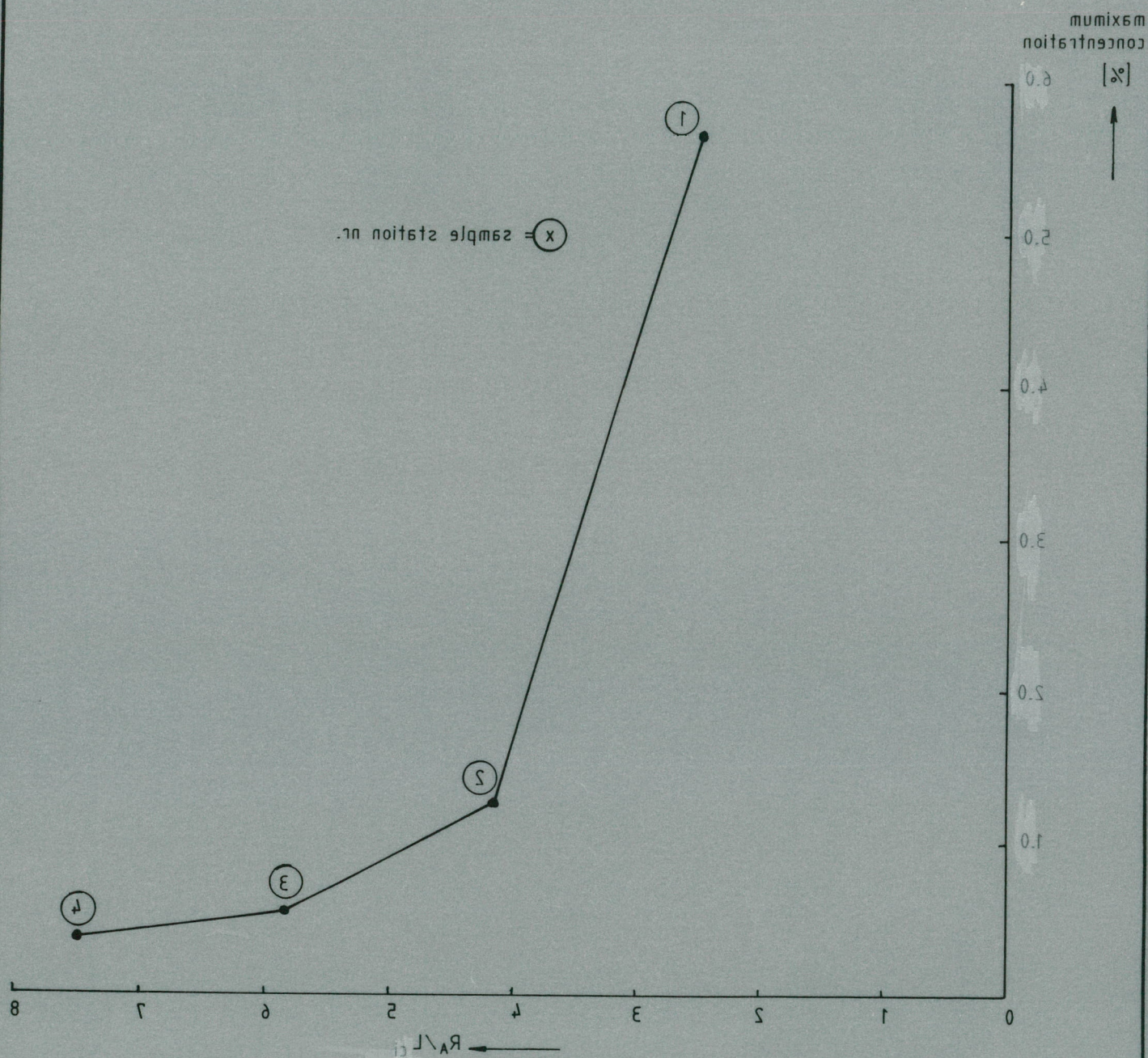
Example result of the instantaneous release.

Fig. 9
91 - 026
TM - TNO



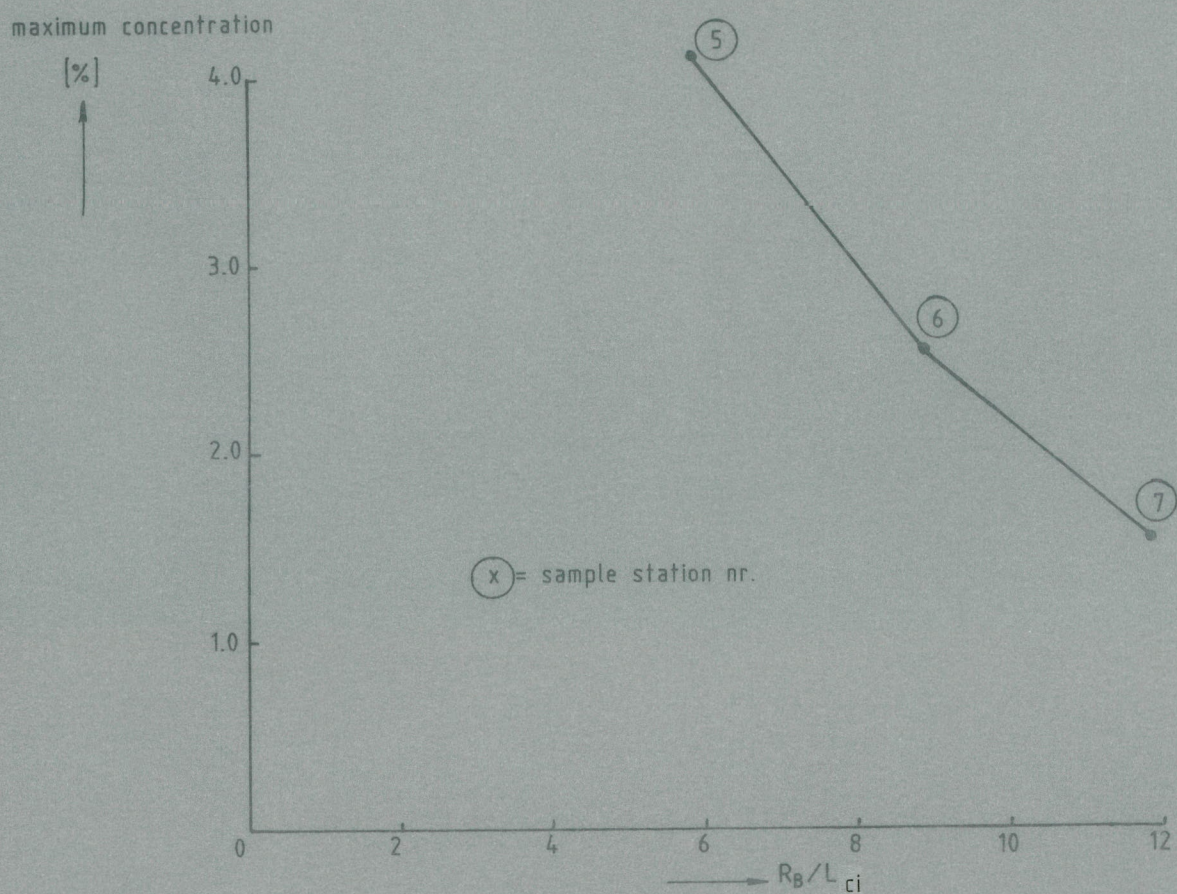
Maximum concentrations for the instantaneous release at line A (see figure 8).

MT-TNO
91-026
Fig. 10a



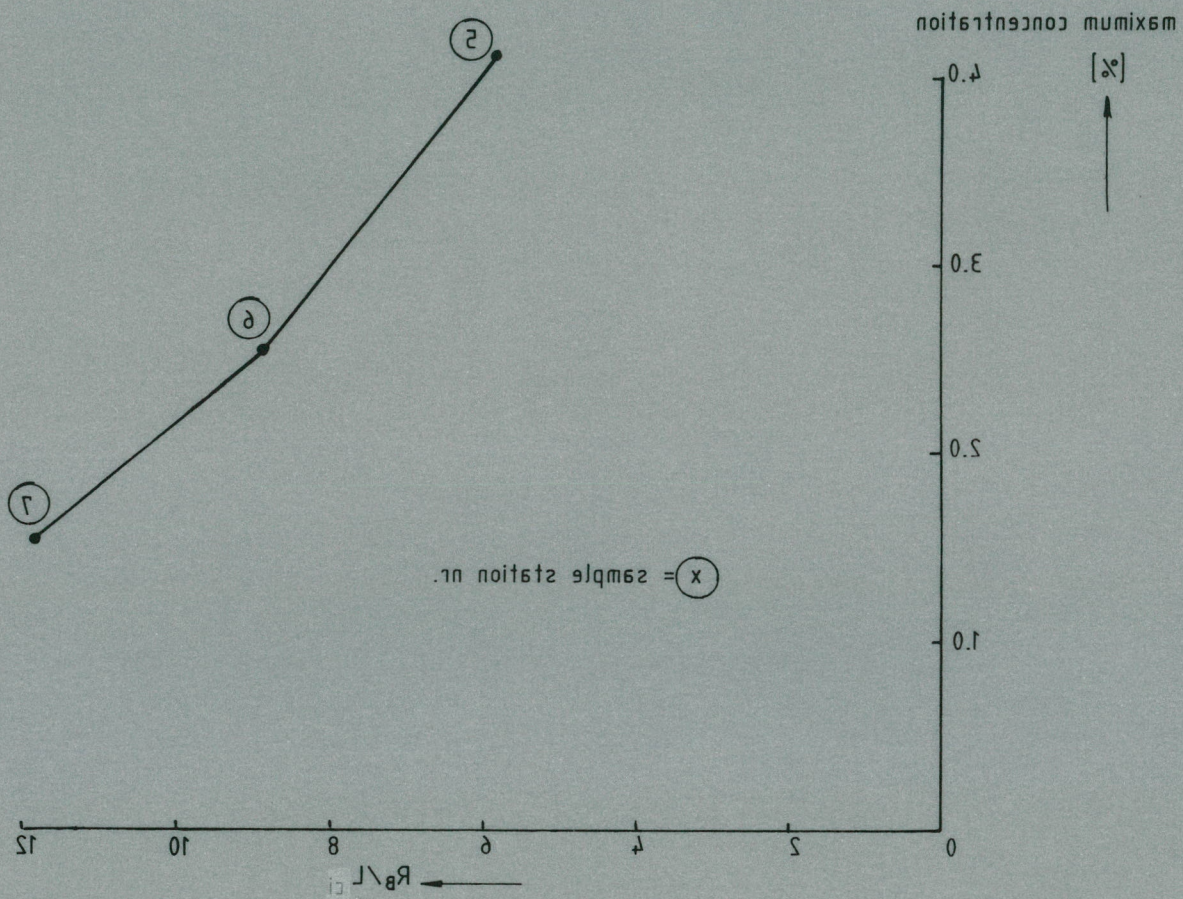
Maximum concentrations for the instantaneous release at
line A (see figure 8).

MT-TMO
91-056
Fig. 105

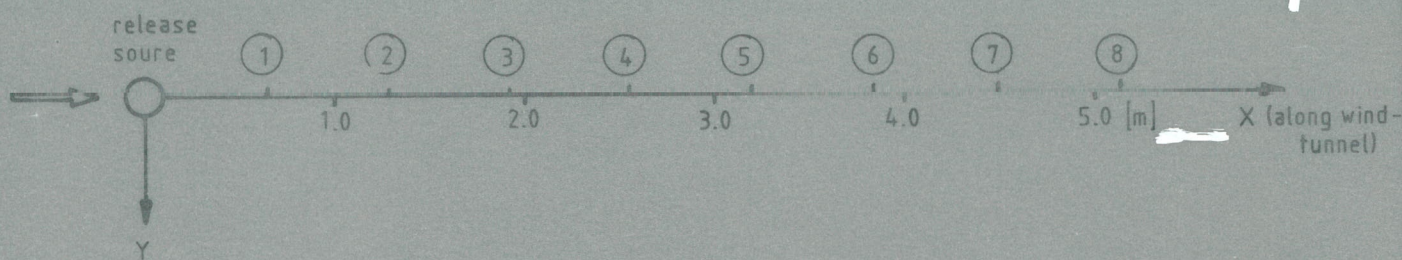


Maximum concentrations for the instantaneous release at line B, (see figure 8).

MT-TNO
91-026
Fig. 10b

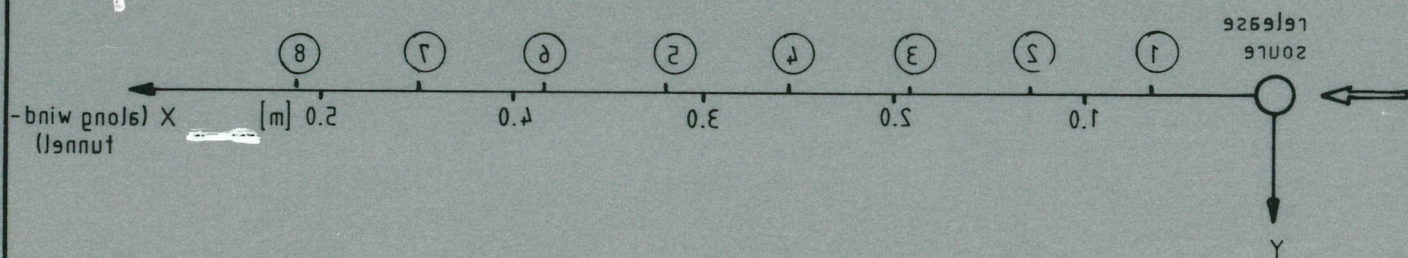


Maximum concentrations for the instantaneous release at
line B, (see figure 8).



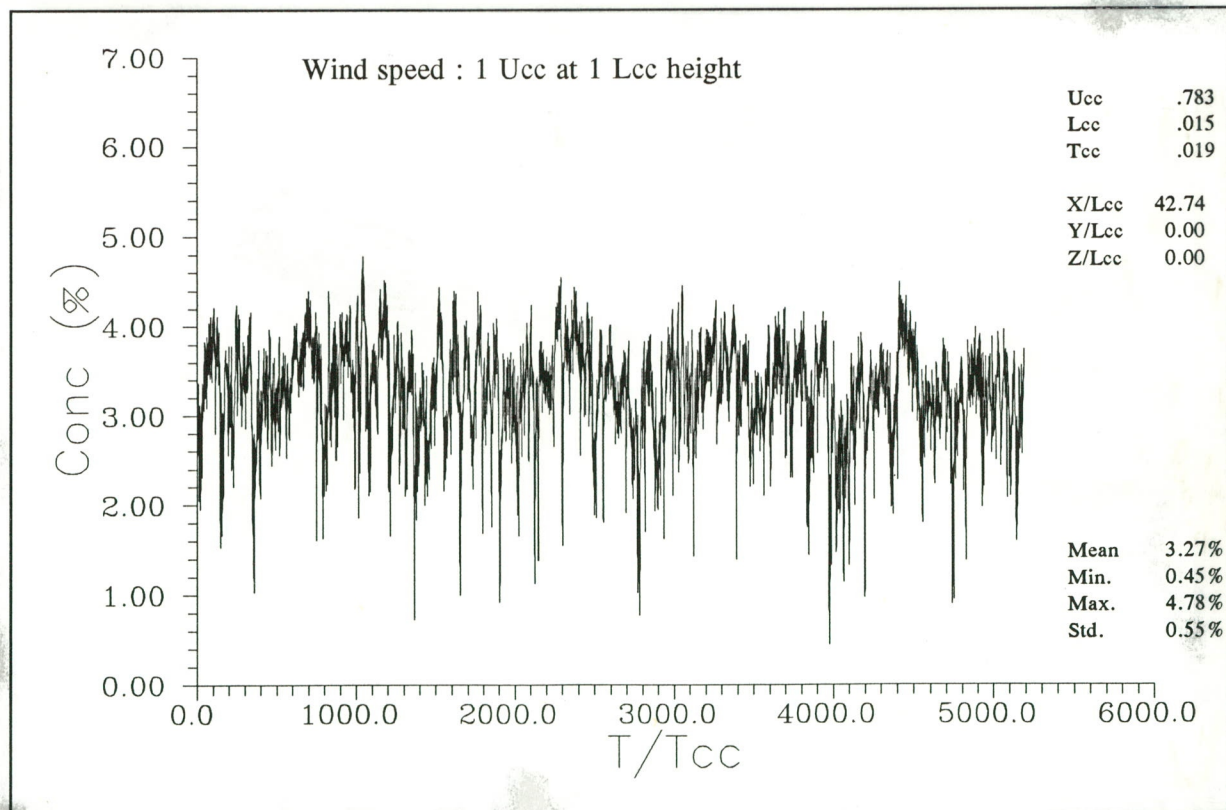
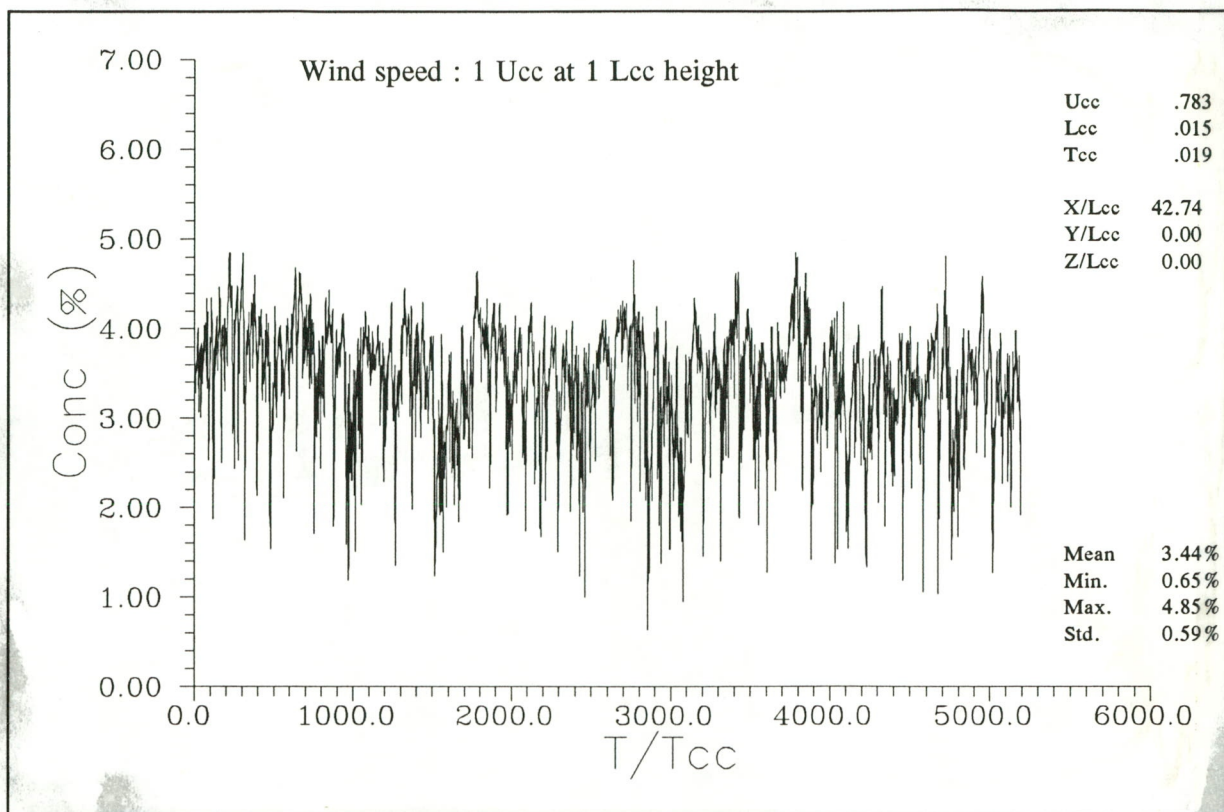
Sampling stations for the continuous test.

MT-TNO
91-026
Fig. 11



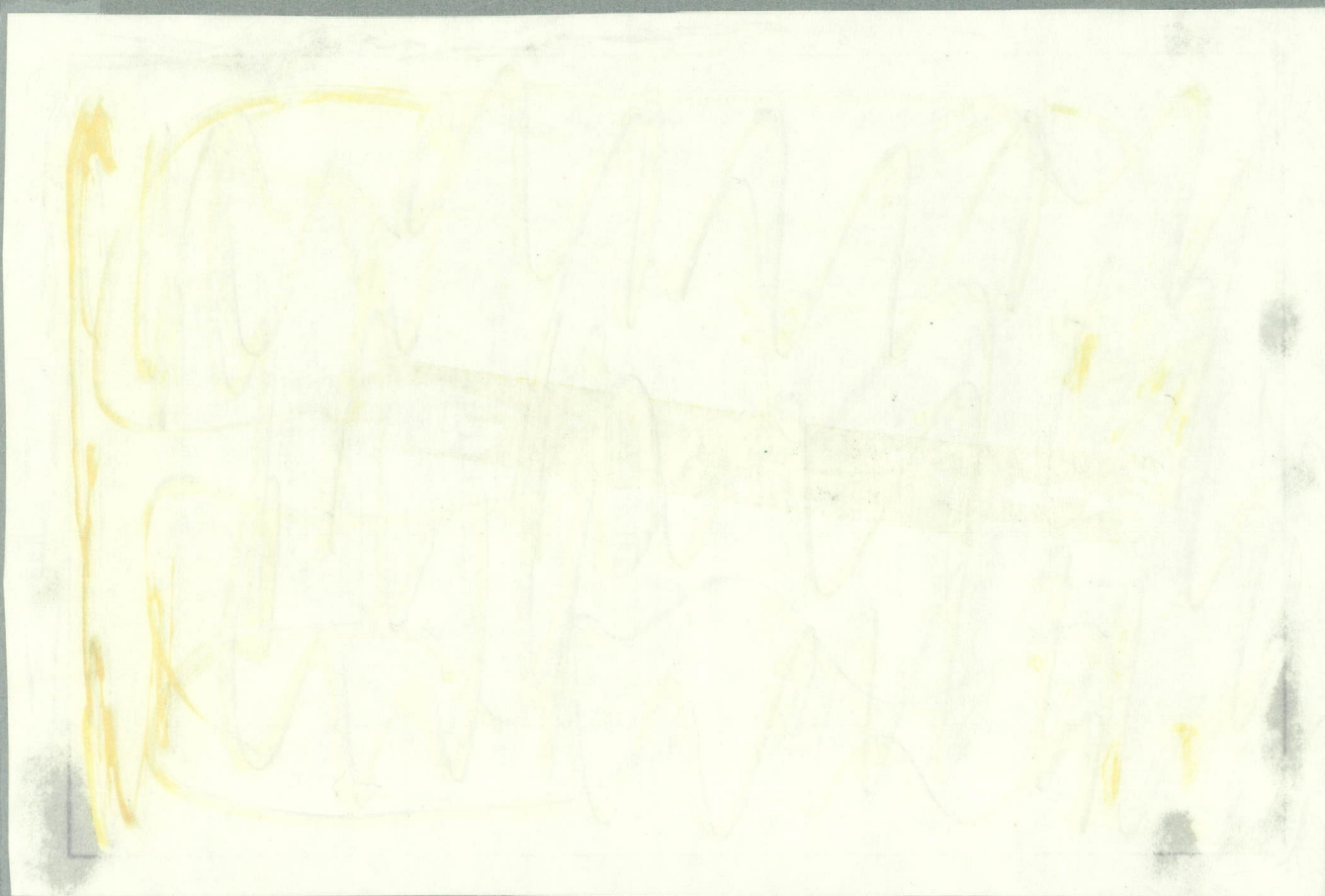
MT-TM
91-056
Fig. 11

Sampling stations for the continuous test.



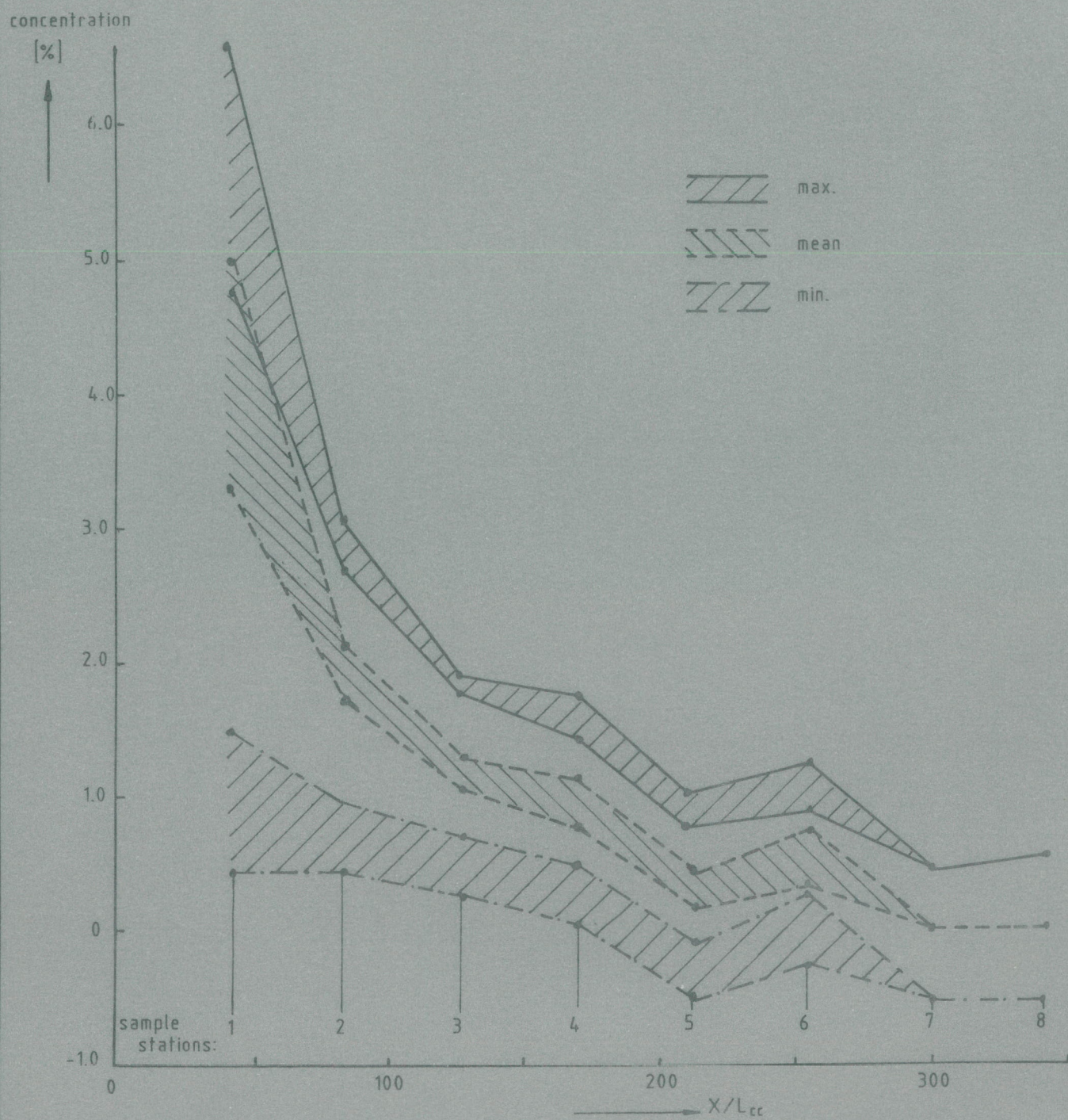
Example result of the continuous release.

MT - TNO
91 - 026
Fig. 12



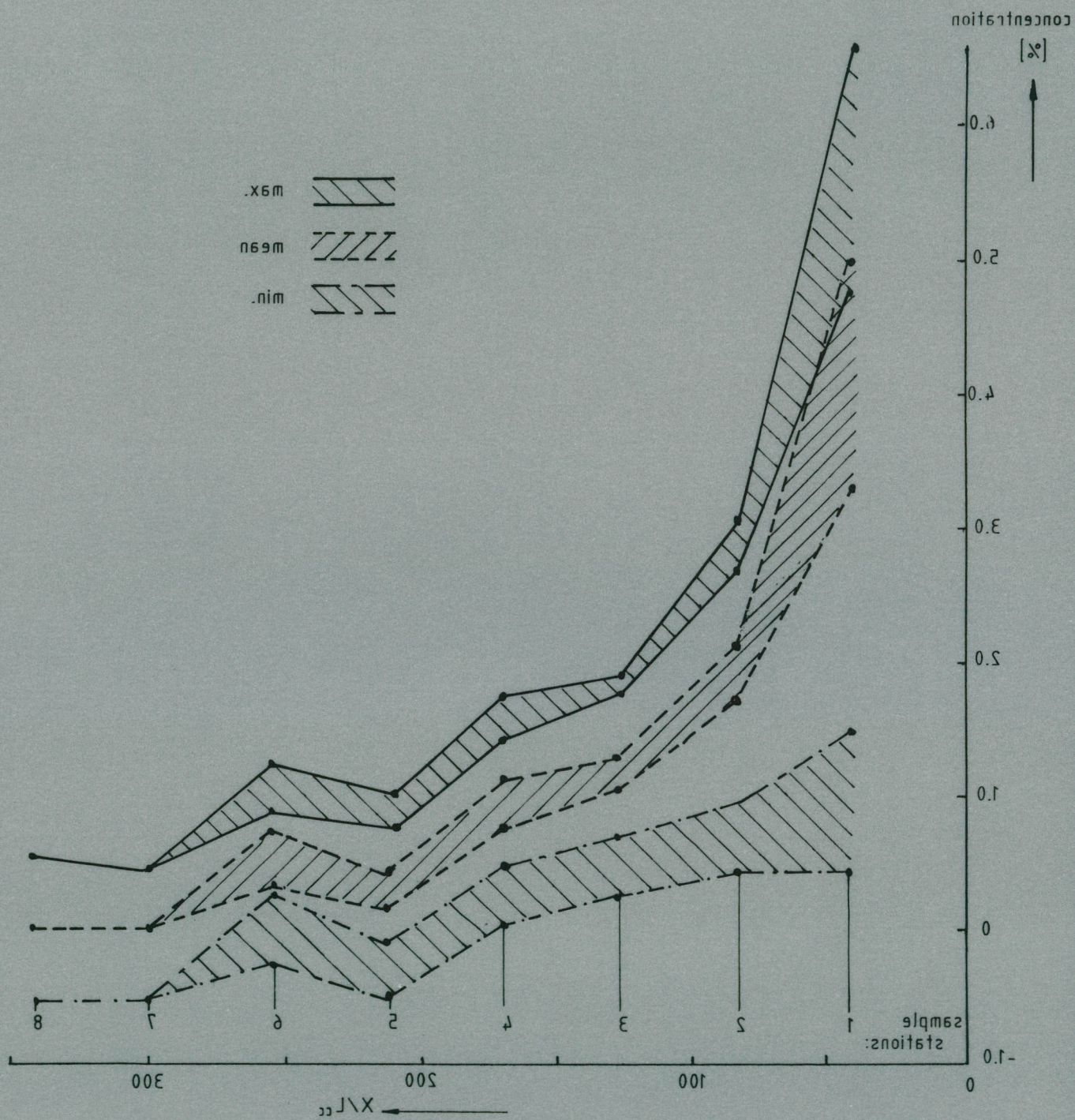
Example result of the continuous release.

Fig. 12
91 - 026
MT - TNO



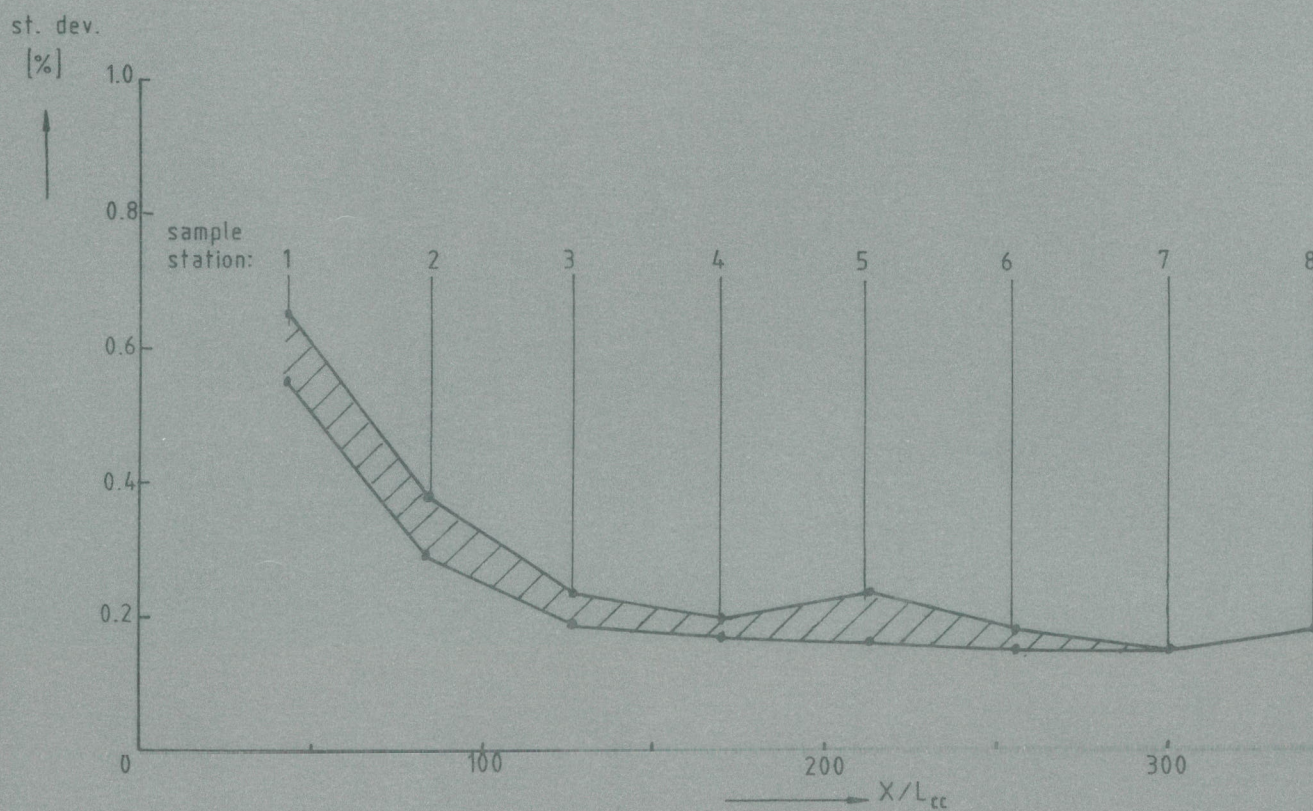
Mean, minimum and maximum concentrations for the continuous release test.

MT-TNO
91-026
Fig. 13



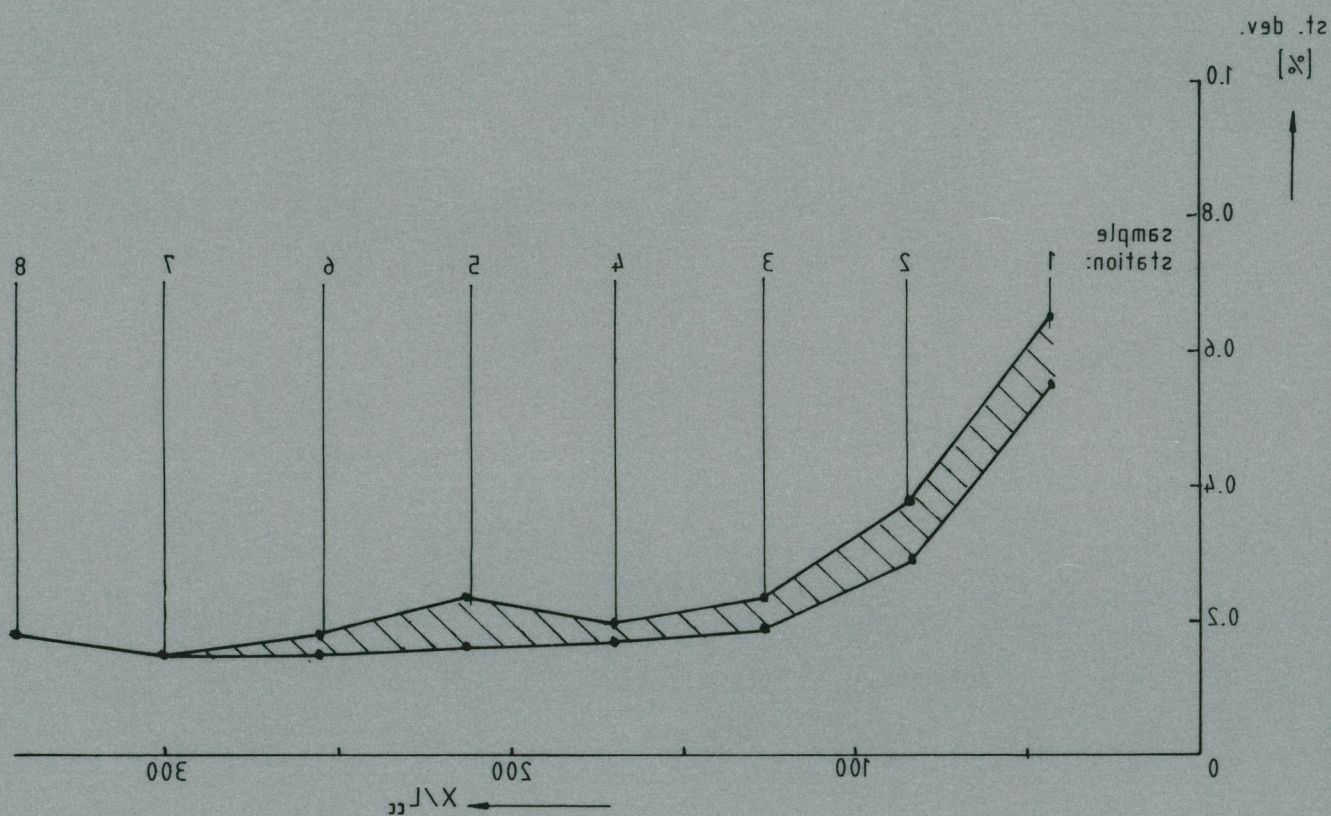
ONT-TM
850-18
Fig. 13

Mean, minimum and maximum concentrations for the continuous release test.



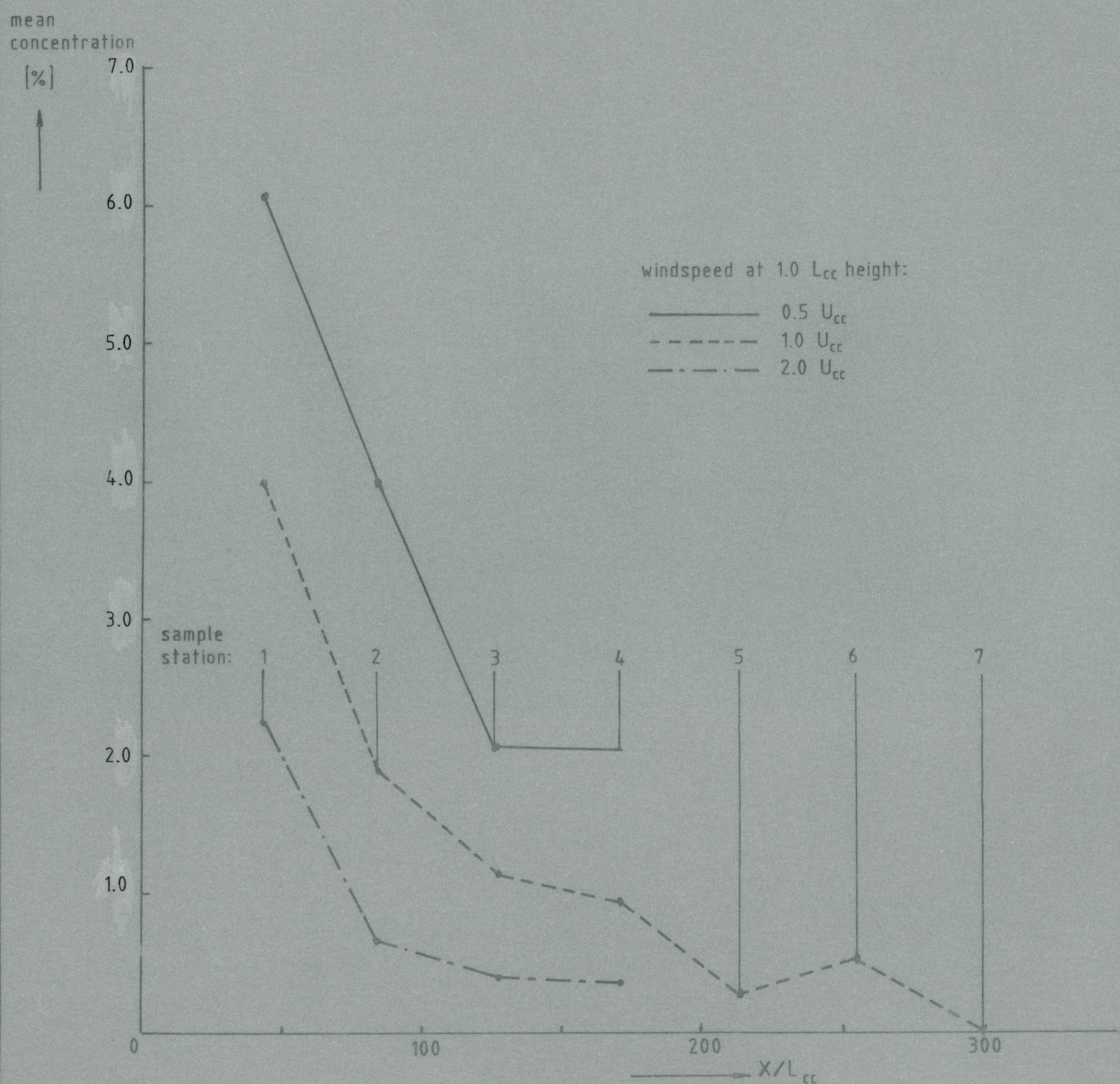
Standard deviation for the continuous release test.

MT-TNO
91-026
Fig. 14



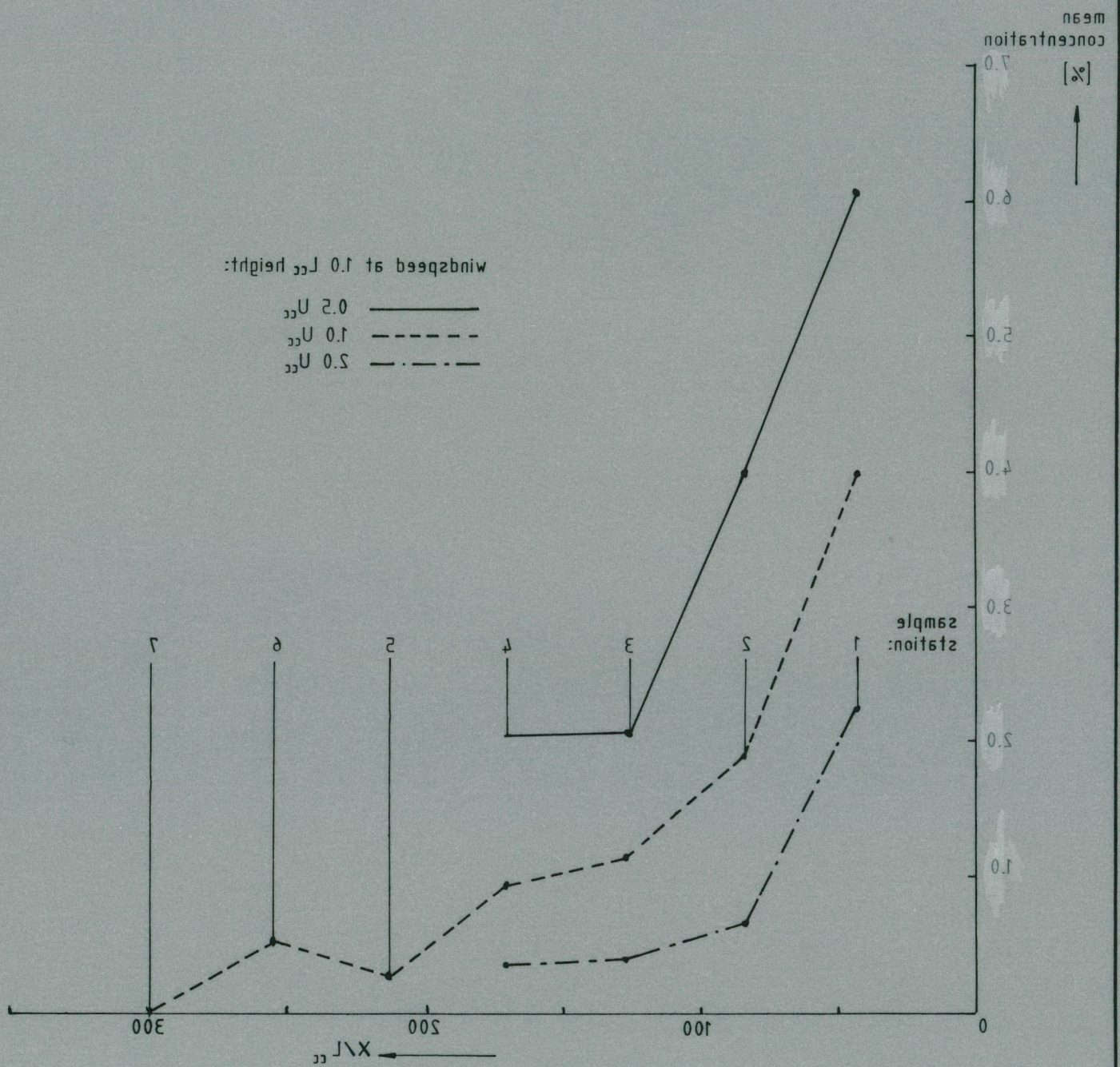
Standard deviation for the continuous release test.

MT-TNO
91-056
Fig. 14



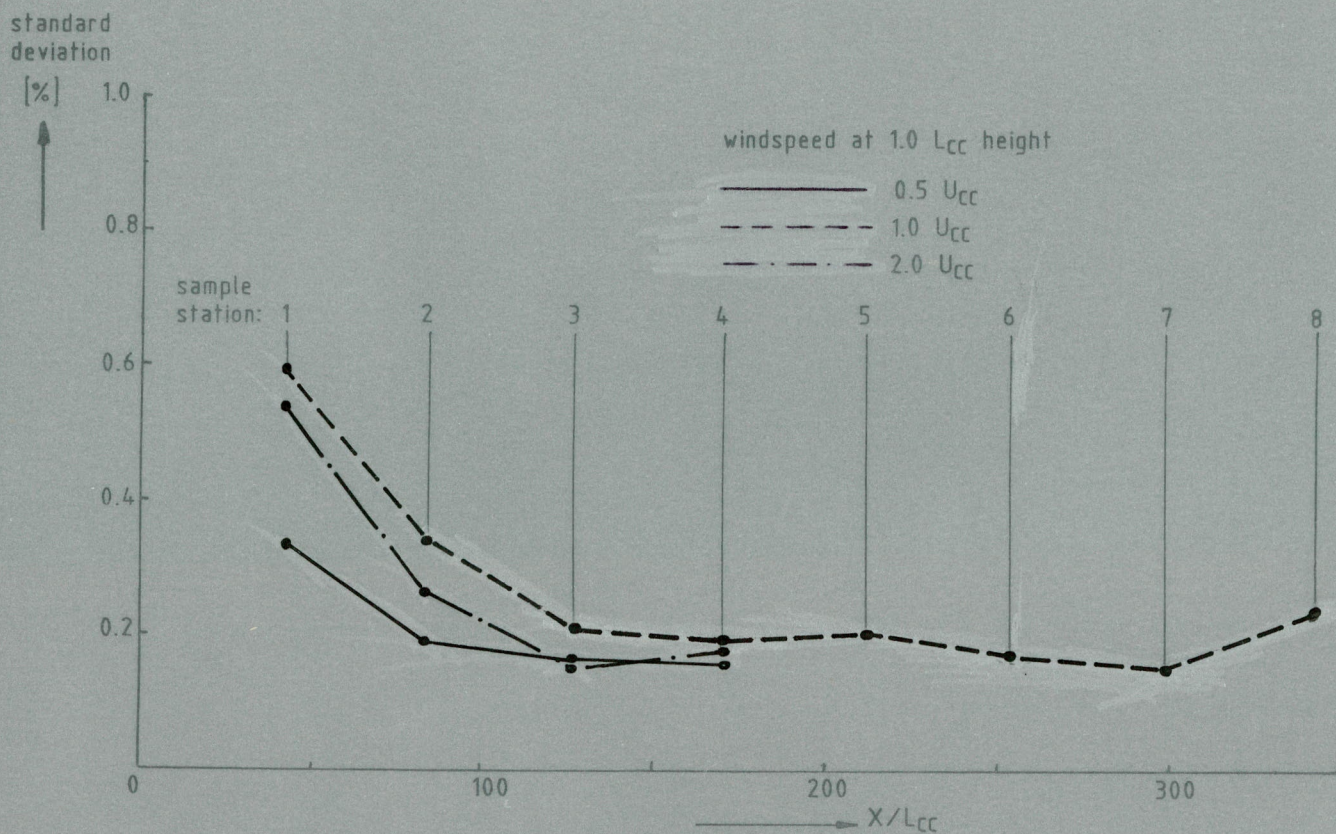
Mean concentration for the intercomparison continuous test and both additional test.

MT-TNO
91-026
Fig.15



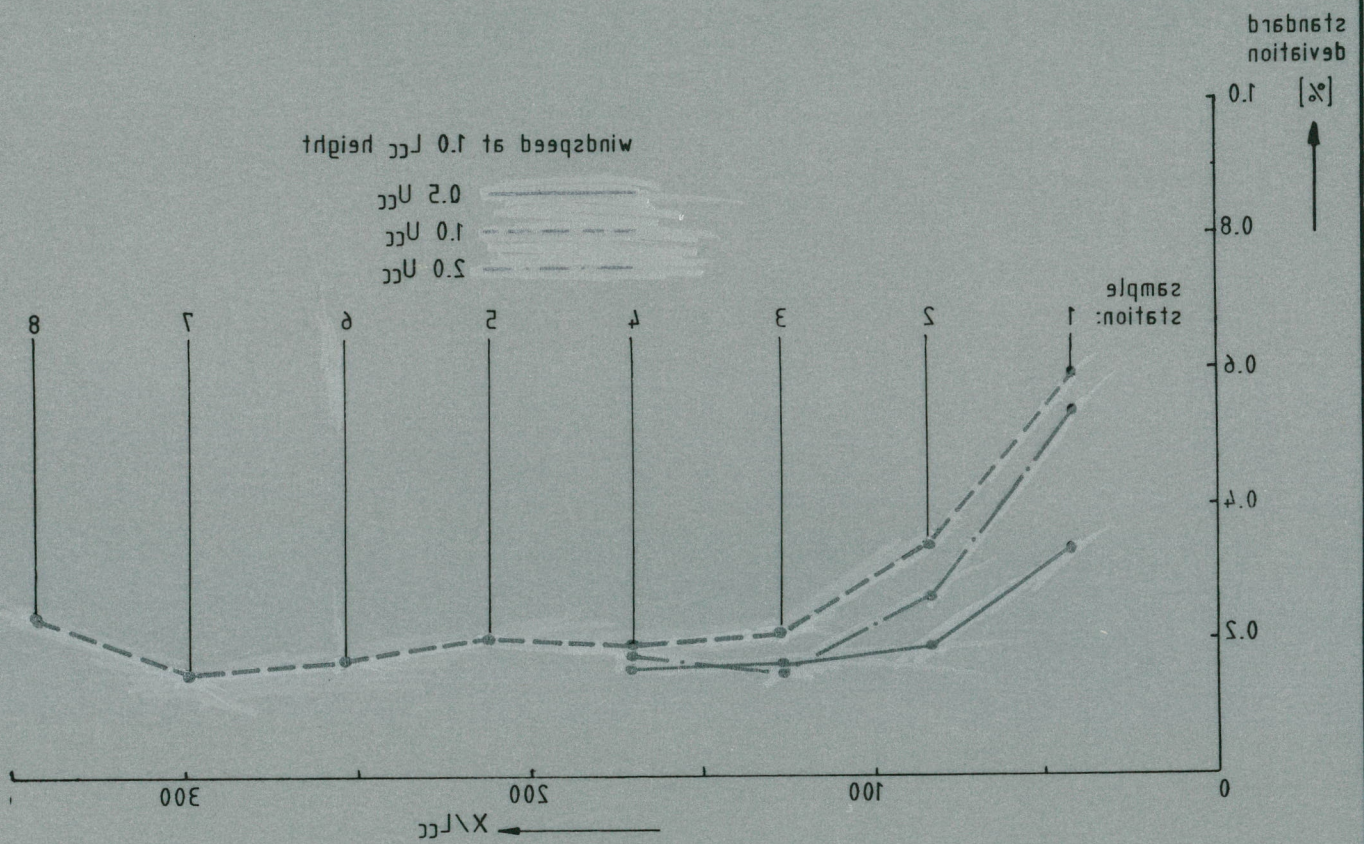
Mean concentration for the intercomparison continuous test and both additional test.

MT-TM
91-056
Fig. 12



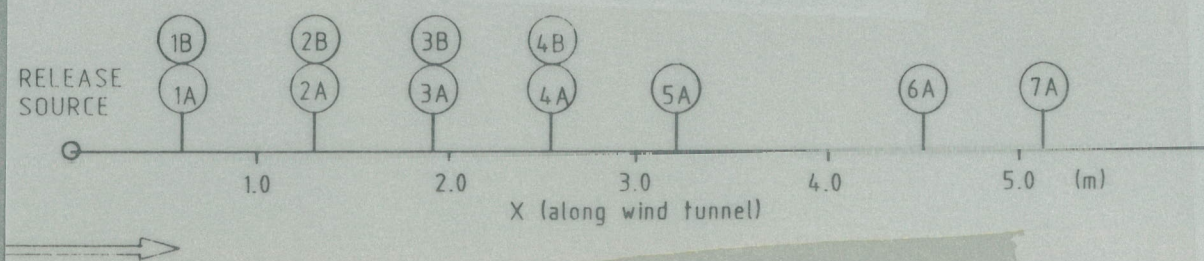
Standard deviation for the intercomparison continuous test and both additional tests.

MT-TNO
91-026
Fig.16



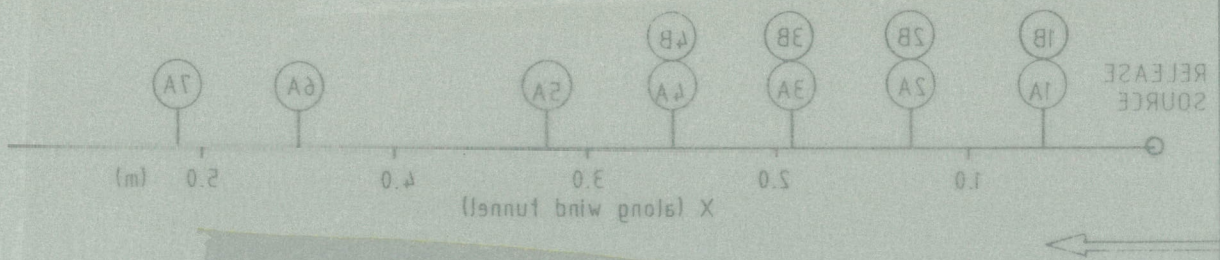
Standard deviation for the intercomparison continuous test
and both additional tests.

MT-TNO
91-056
Fig. 16



Sampling station for case A (628l/h) and case B (127l/h)

MT - TNO
91 - 026
Fig. 17

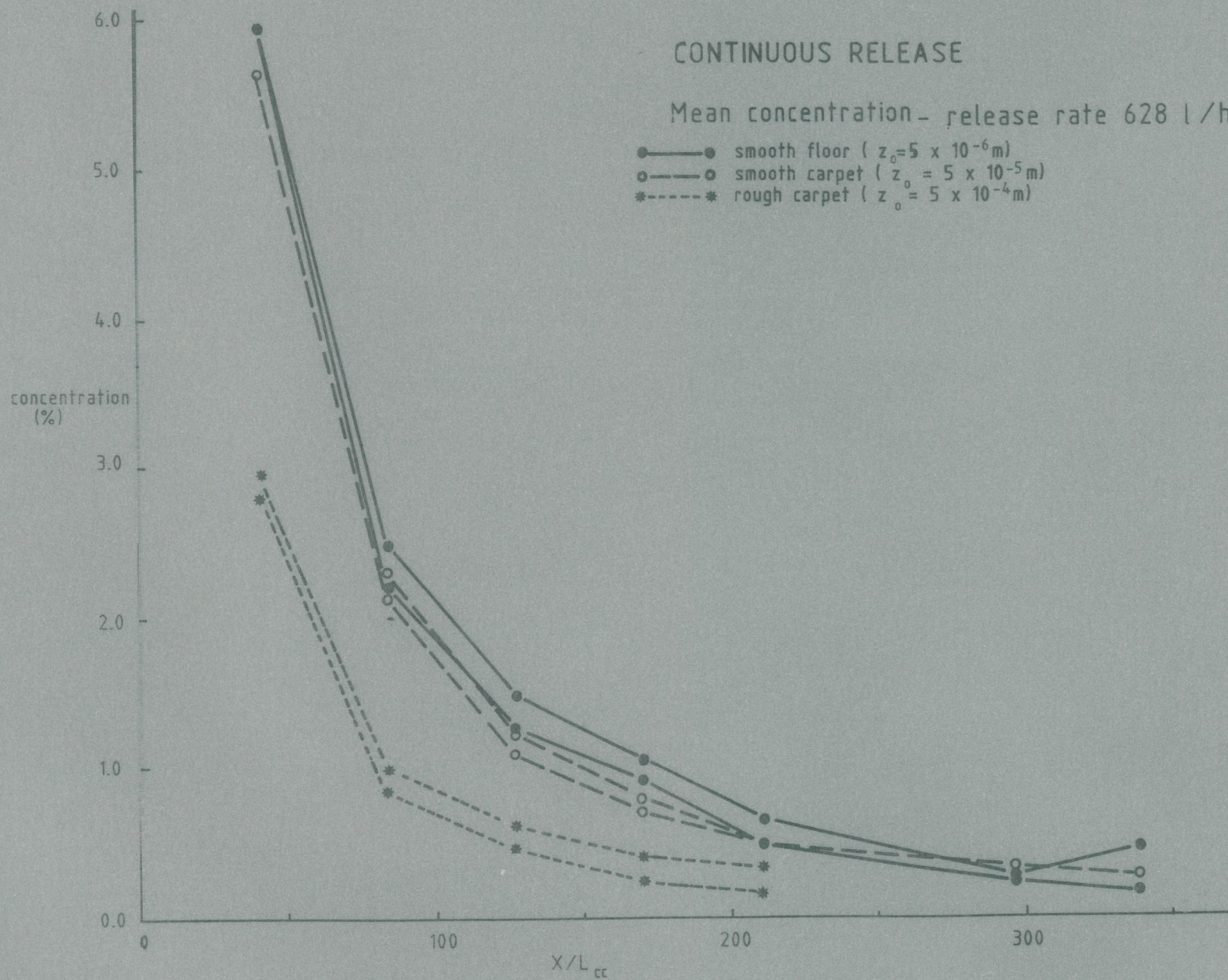


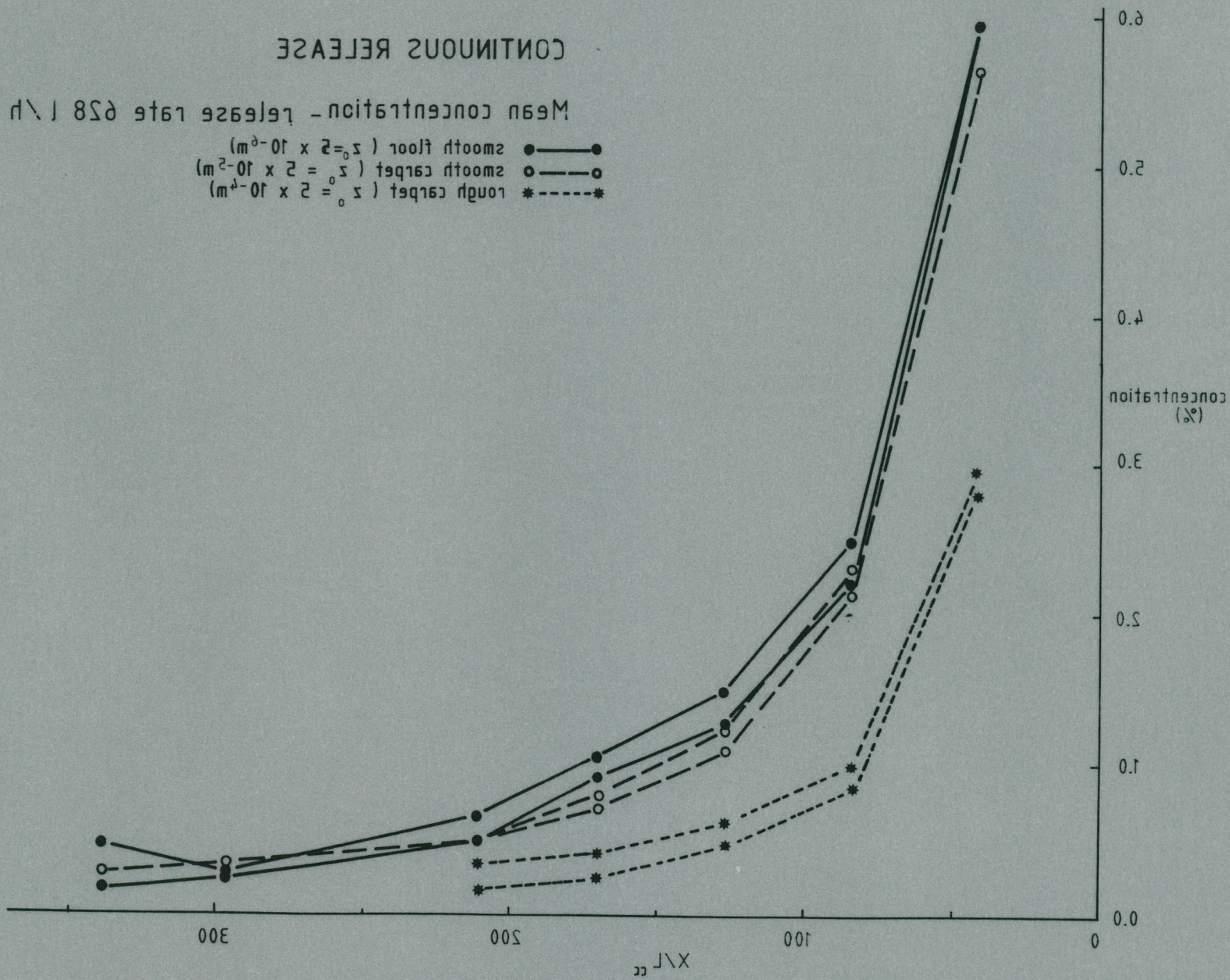
Sampling station for case A (6281/h) and case B (1271/h)

Fig. 12
91 - 026
MT - TNO

Mean concentrations for a release rate of 628 l/h

MT - TNO
91-026
Fig. 18

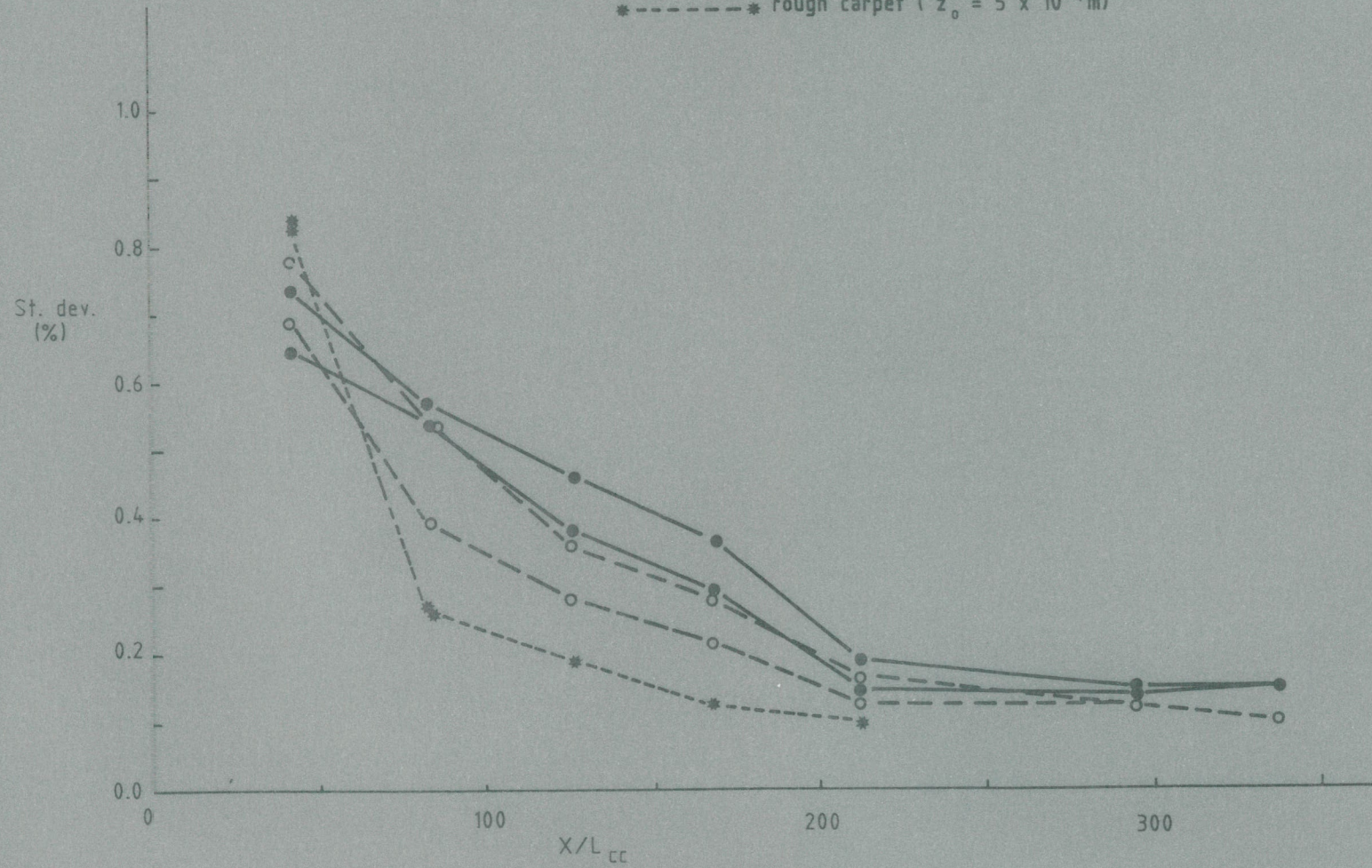




CONTINUOUS RELEASE

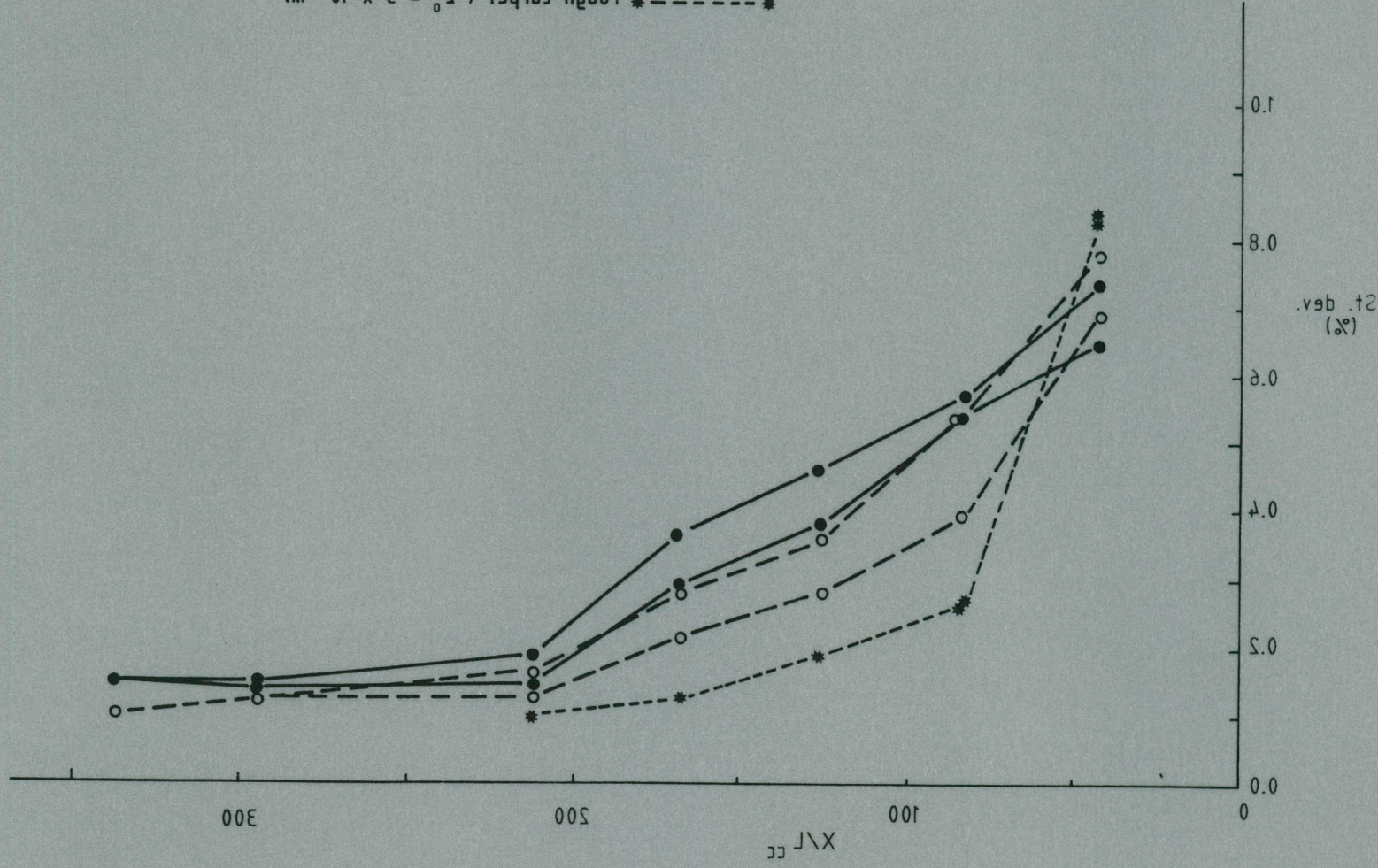
Standard deviation - release rate 628 l/h

- — smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- — smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- * - - - rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)



Standard deviations for a release rate of 628 l/h

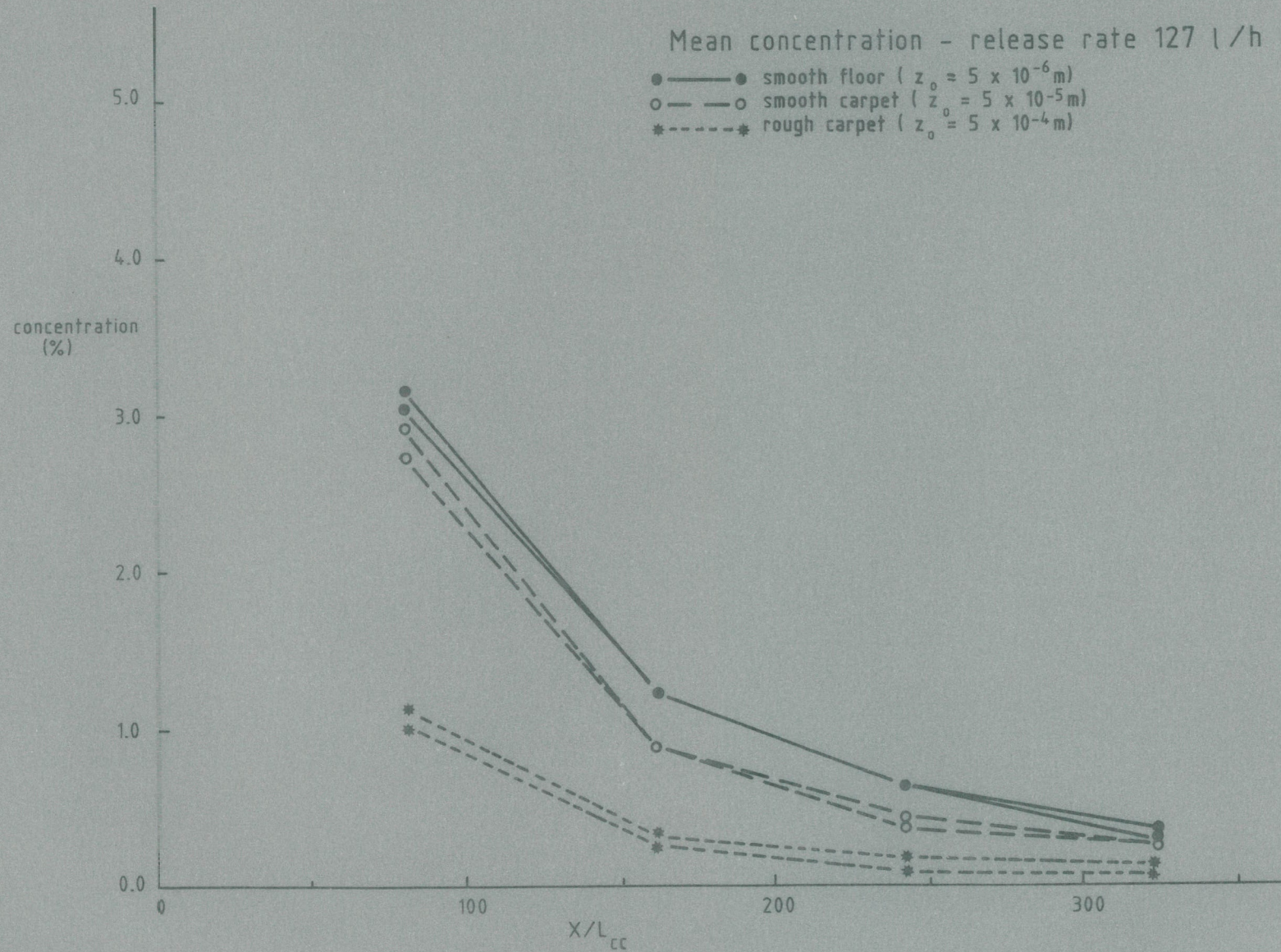
MT - TNO
91-026
Fig. 19



CONTINUOUS RELEASE

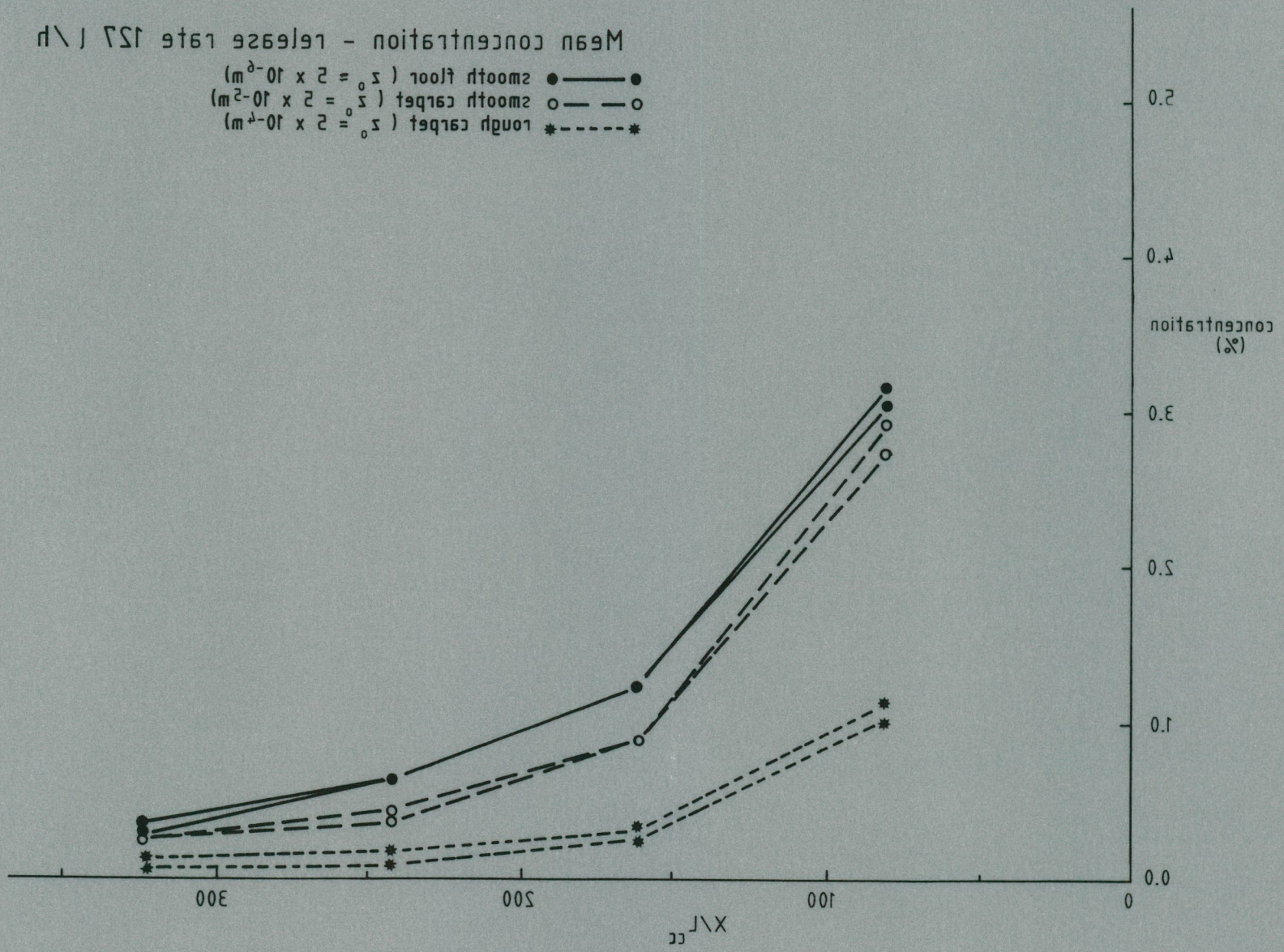
Mean concentration - release rate 127 l/h

- —● smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- —○ smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- * - - * rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)



Mean concentration for a release rate of 127 l/h

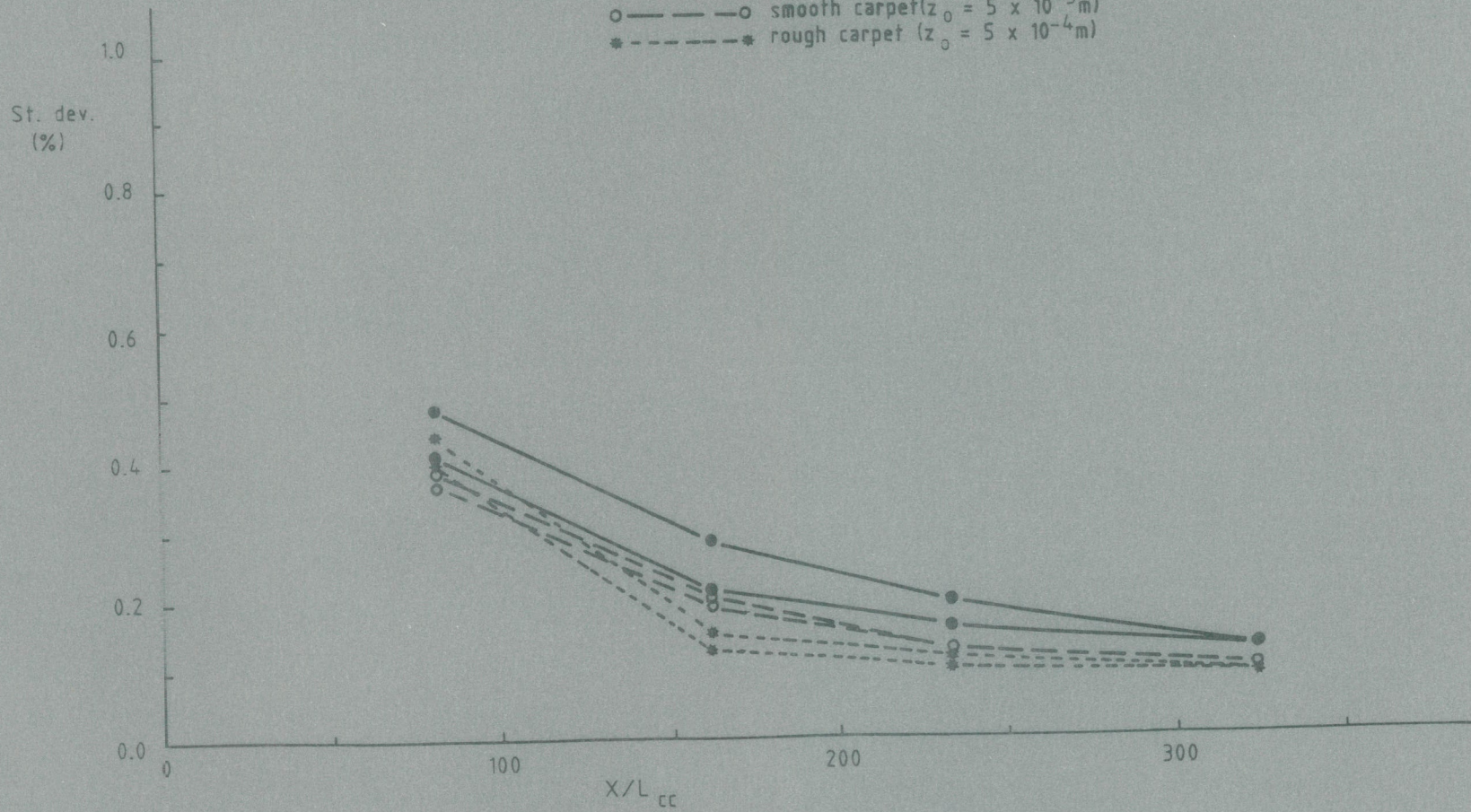
MT - TNO
91-026
fig. 20



CONTINUOUS RELEASE

Standard deviation - release rate 127 l/h

- — smooth floor ($z_0 = 5 \times 10^{-6} \text{ m}$)
- — smooth carpet ($z_0 = 5 \times 10^{-5} \text{ m}$)
- * - - - rough carpet ($z_0 = 5 \times 10^{-4} \text{ m}$)

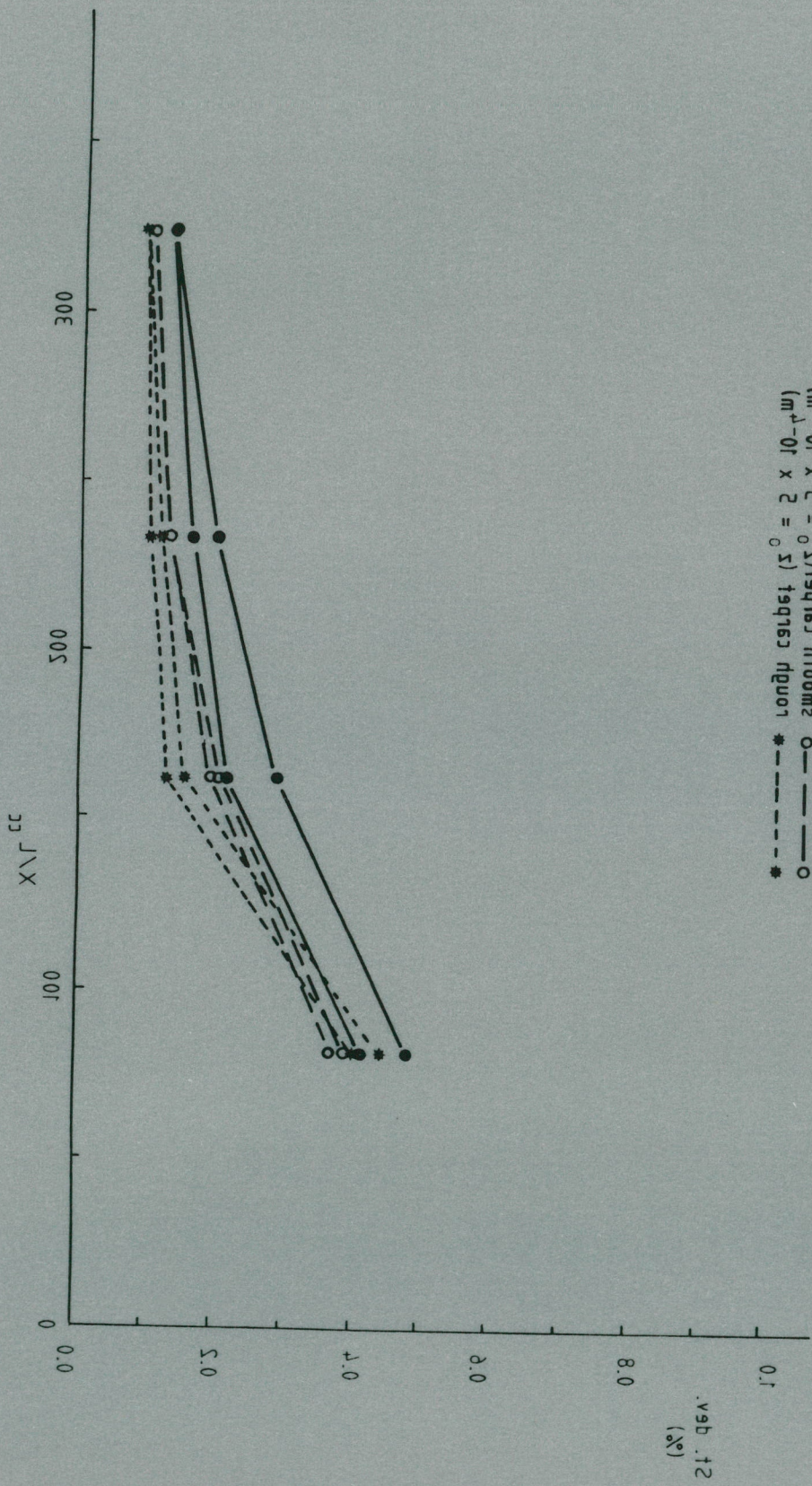


Standard deviation for a release rate of 127 l/h

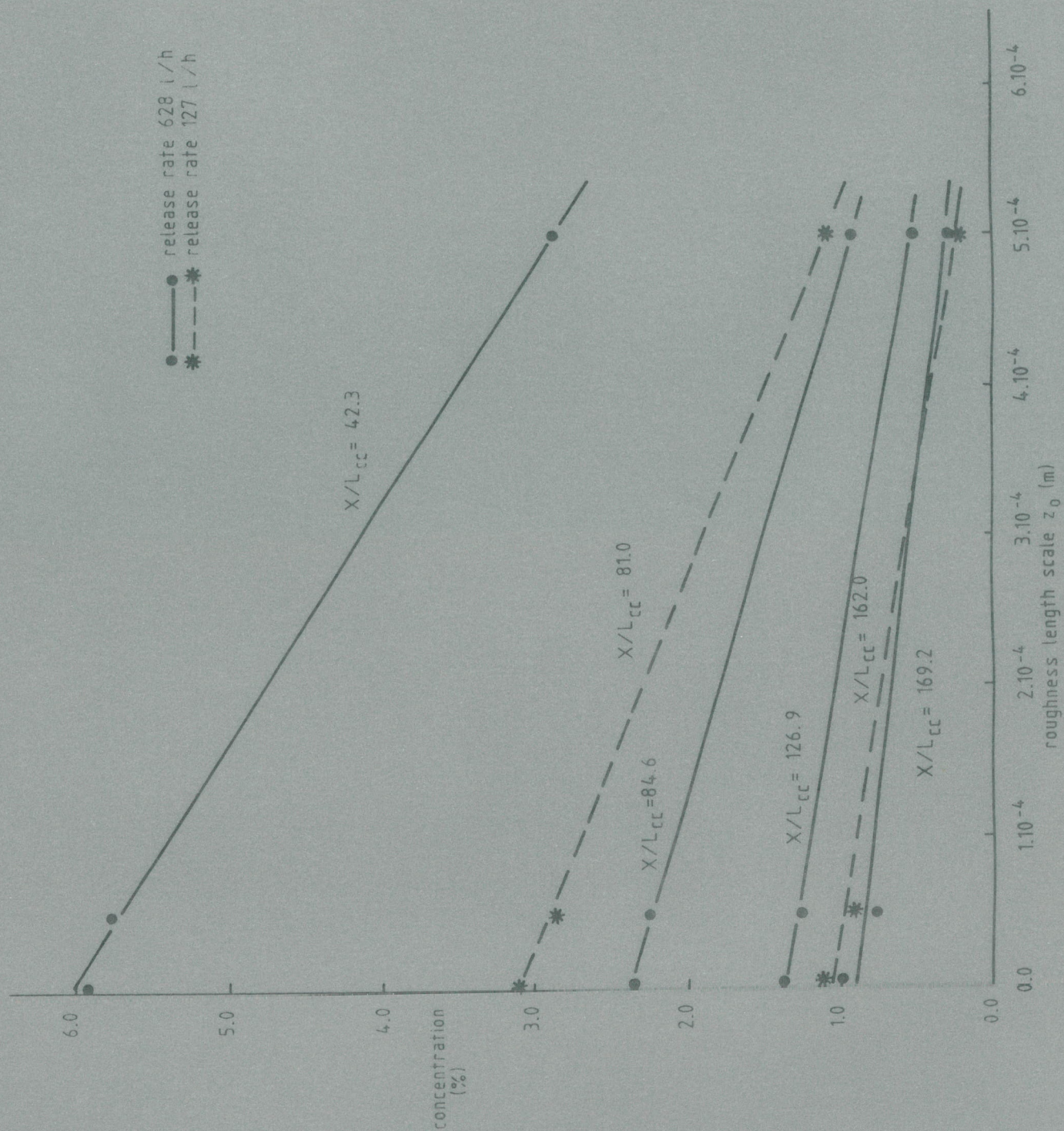
STANDARD DEVIATION

Standard deviation for a release rate of 15% per hour

$(m^2 - 0.01 \times 2 = 0.01)$ room
 $(m^2 - 0.01 \times 2 = 0.01)$ room
 $(m^2 - 0.01 \times 2 = 0.01)$ room



Standard deviation for a release rate of 15% per hour



Mean concentration as function of the roughness length scale.

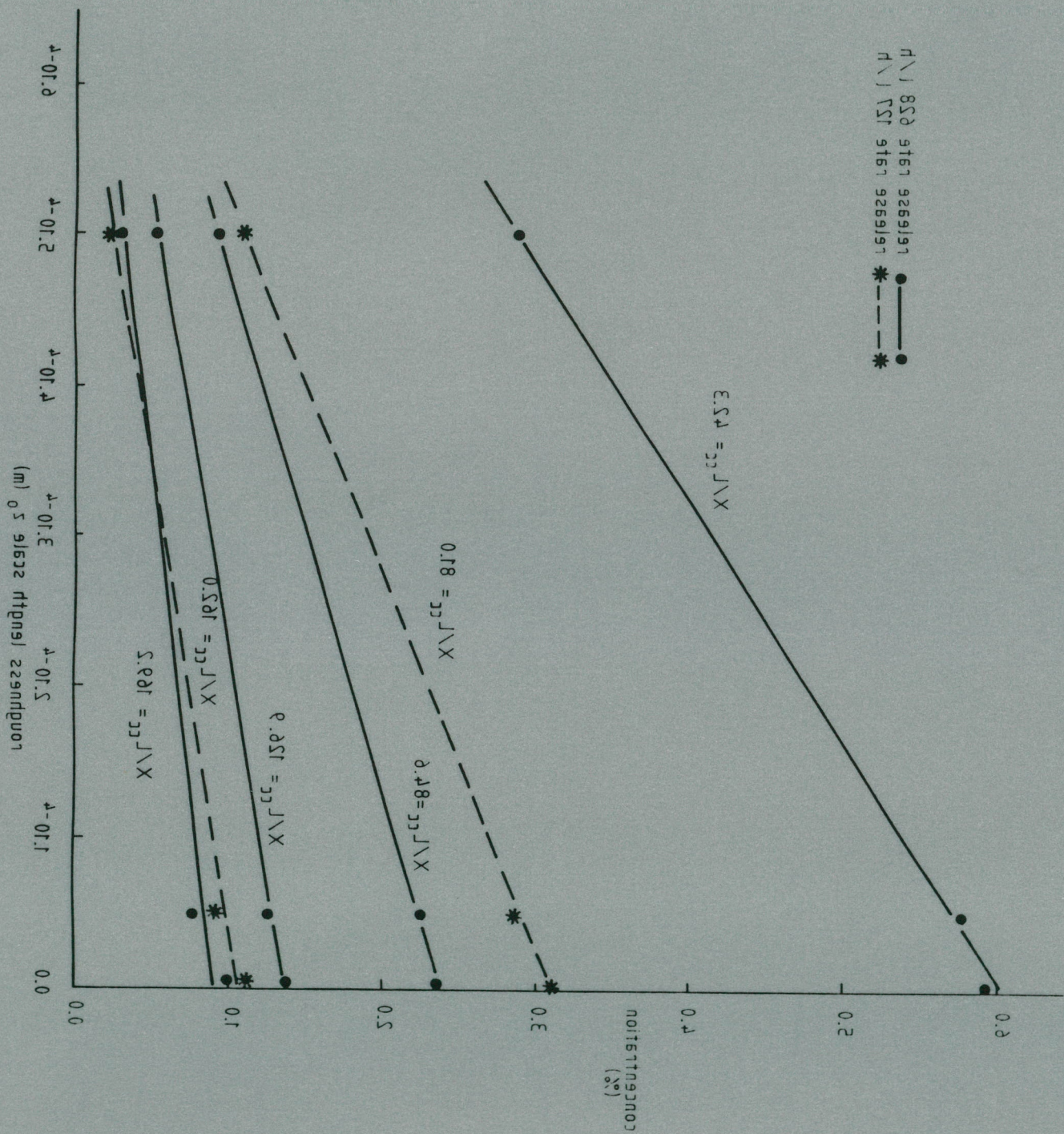
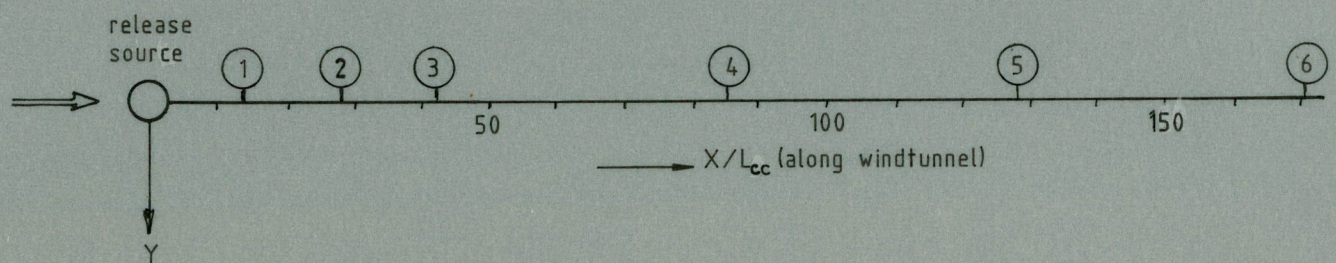


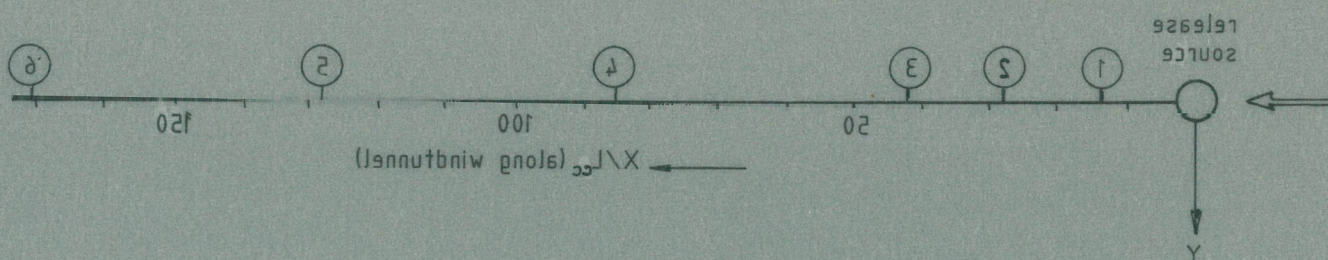
Fig. 55
91-058
MT - TM
TNO

Mean concentration as function of the roughness length



Positions for velocity profile measurements.

MT-TNO
91-026
Fig.23

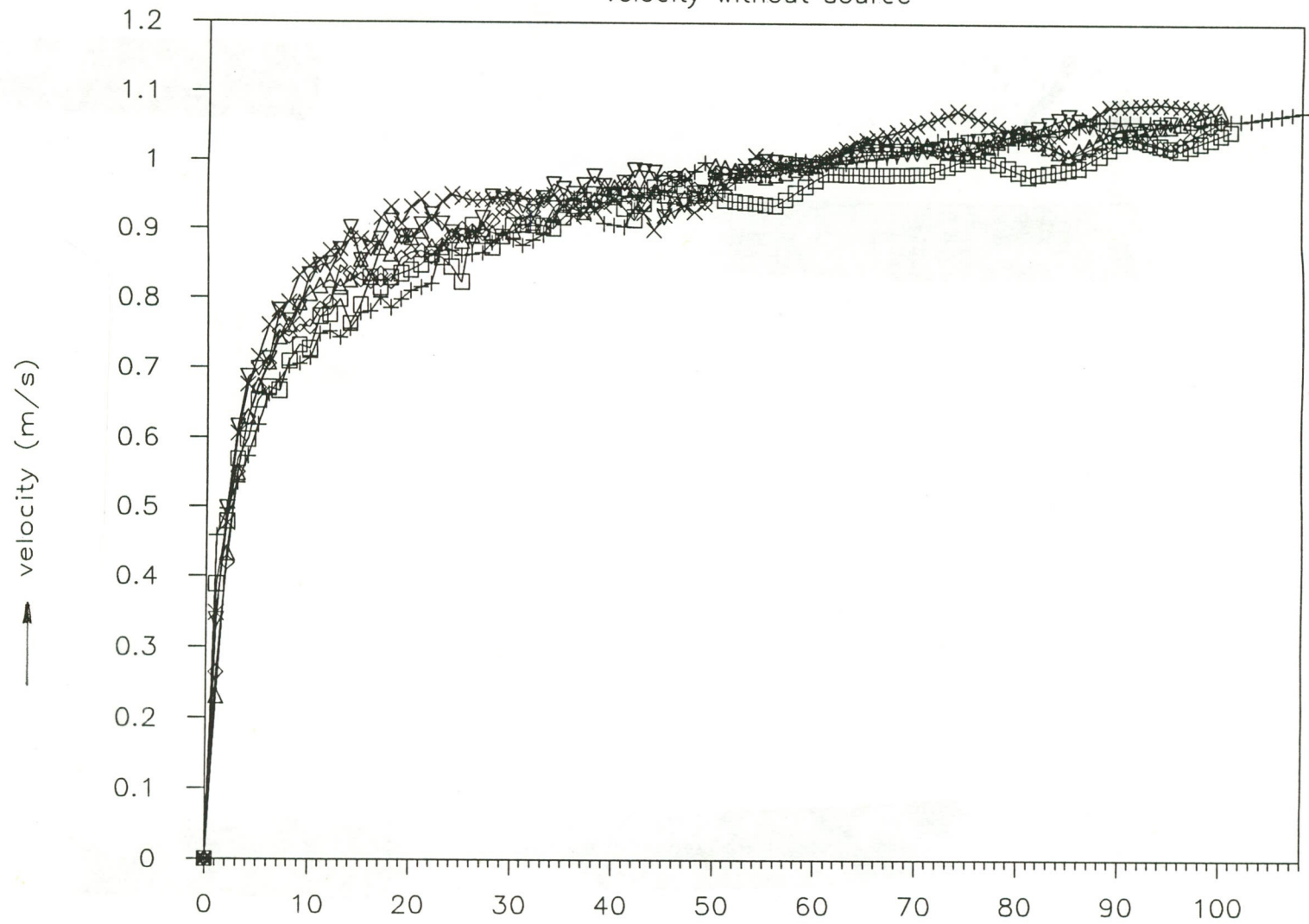


Positions for velocity profile measurements.

MT-TNO
91-026
Fig. 23

HEAVY GAS – FOLDA measurements

velocity without source



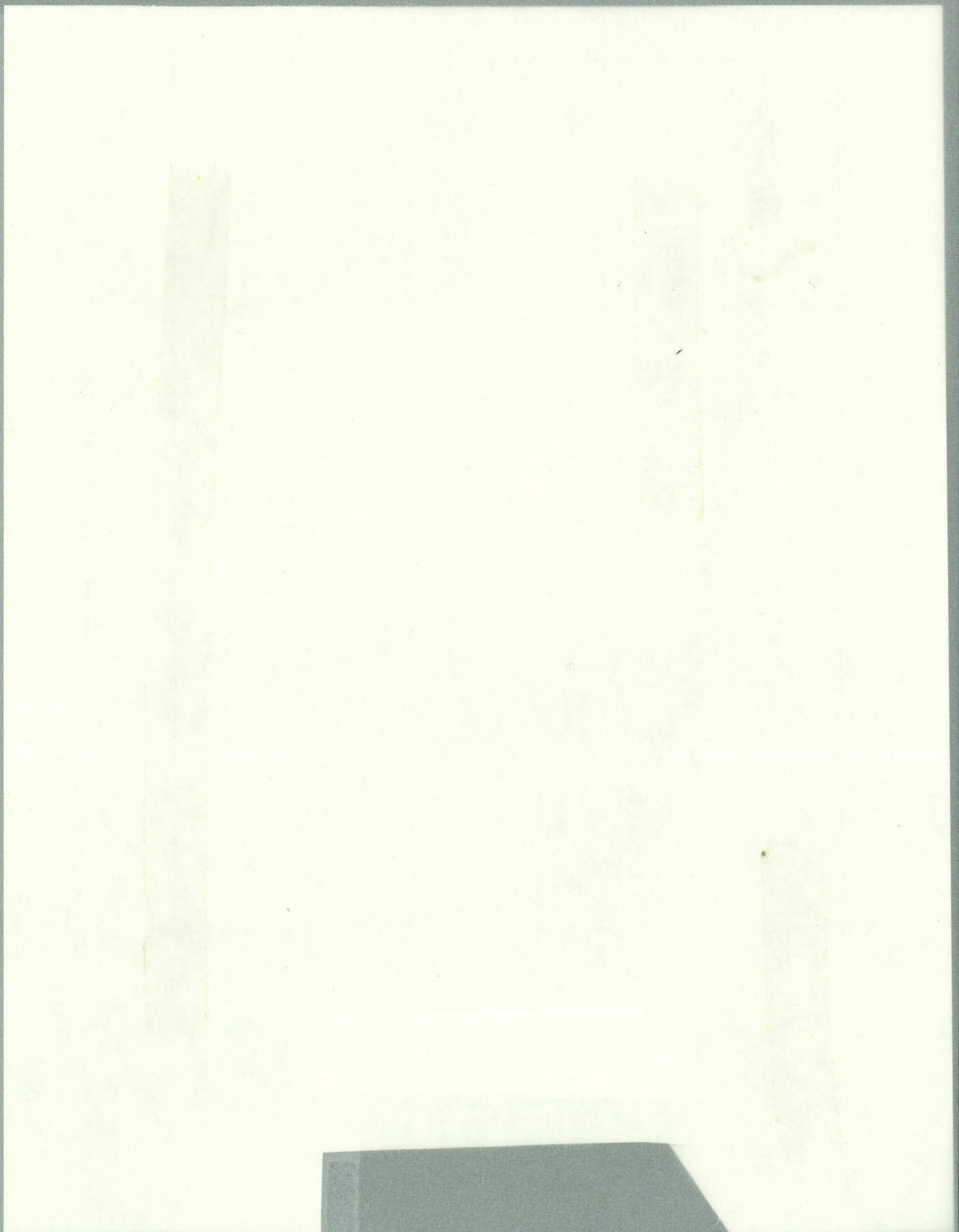
□ = 14.0 Lcc
 Δ = 85.3 Lcc

+ = 28.5 Lcc
 × = 128.0 Lcc

◇ = 42.7 Lcc
 ∇ = 170.7 Lcc

Velocity profiles (without source) at different positions

MT - TNO
 91 - 026
 Fig. 24a

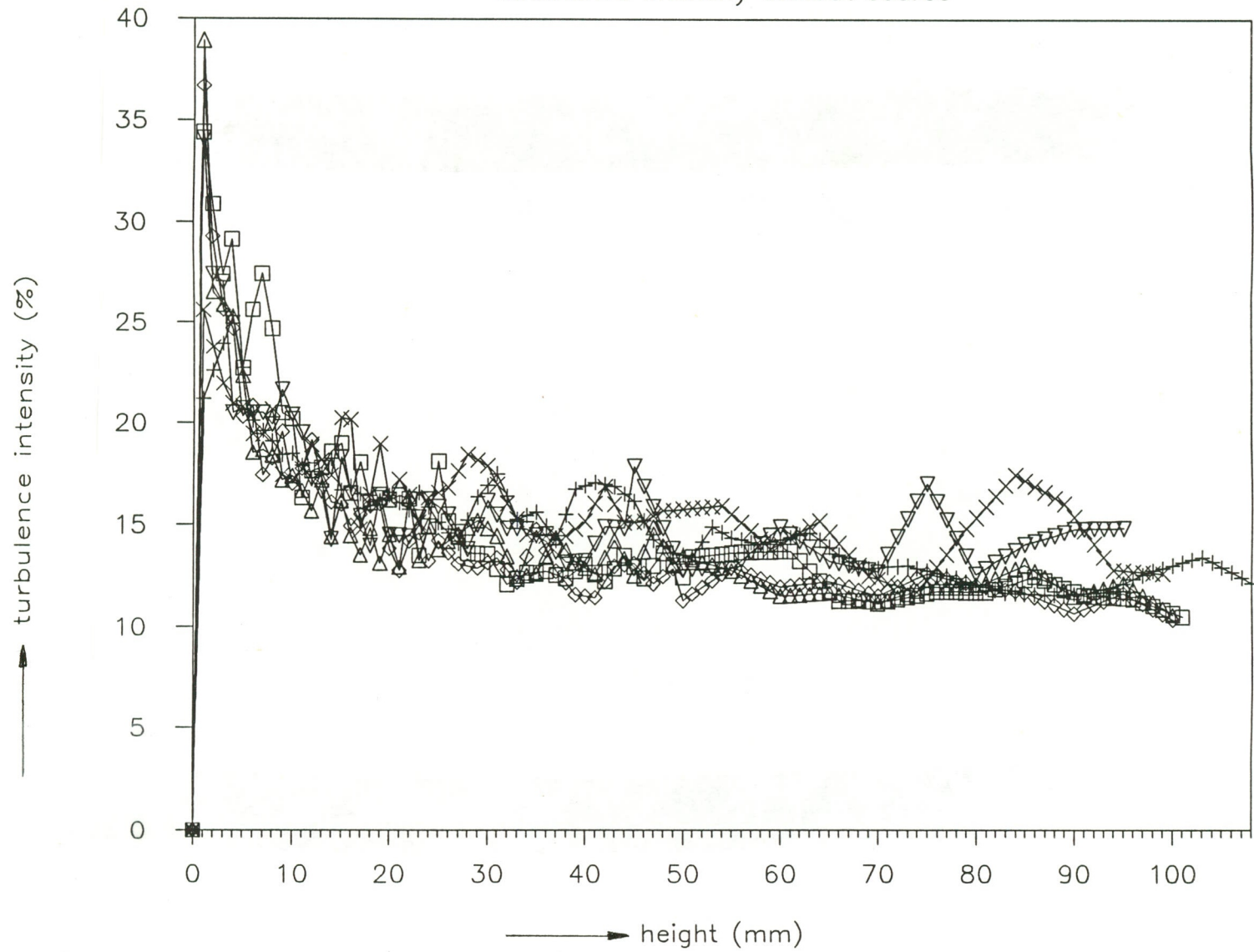


Velocity profiles (without source) at different positions

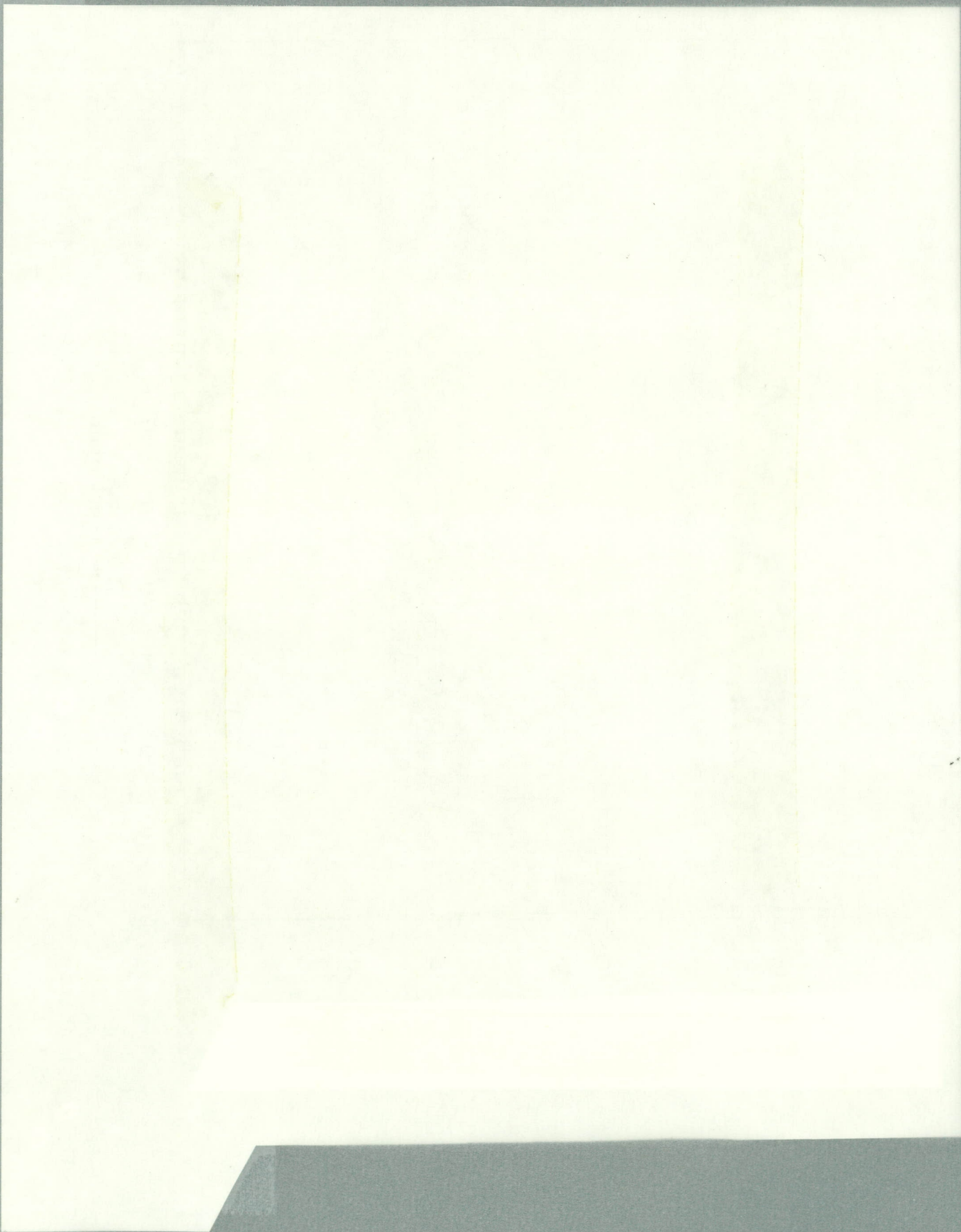
Fig. 24a
91 - 026
MT - TM

HEAVY GAS – FOLDA measurements

turbulence intensity without source



□ = 14.0 Lcc	+ = 28.5 Lcc	◇ = 42.7 Lcc
Δ = 85.3 Lcc	× = 128.0 Lcc	▽ = 170.7 Lcc

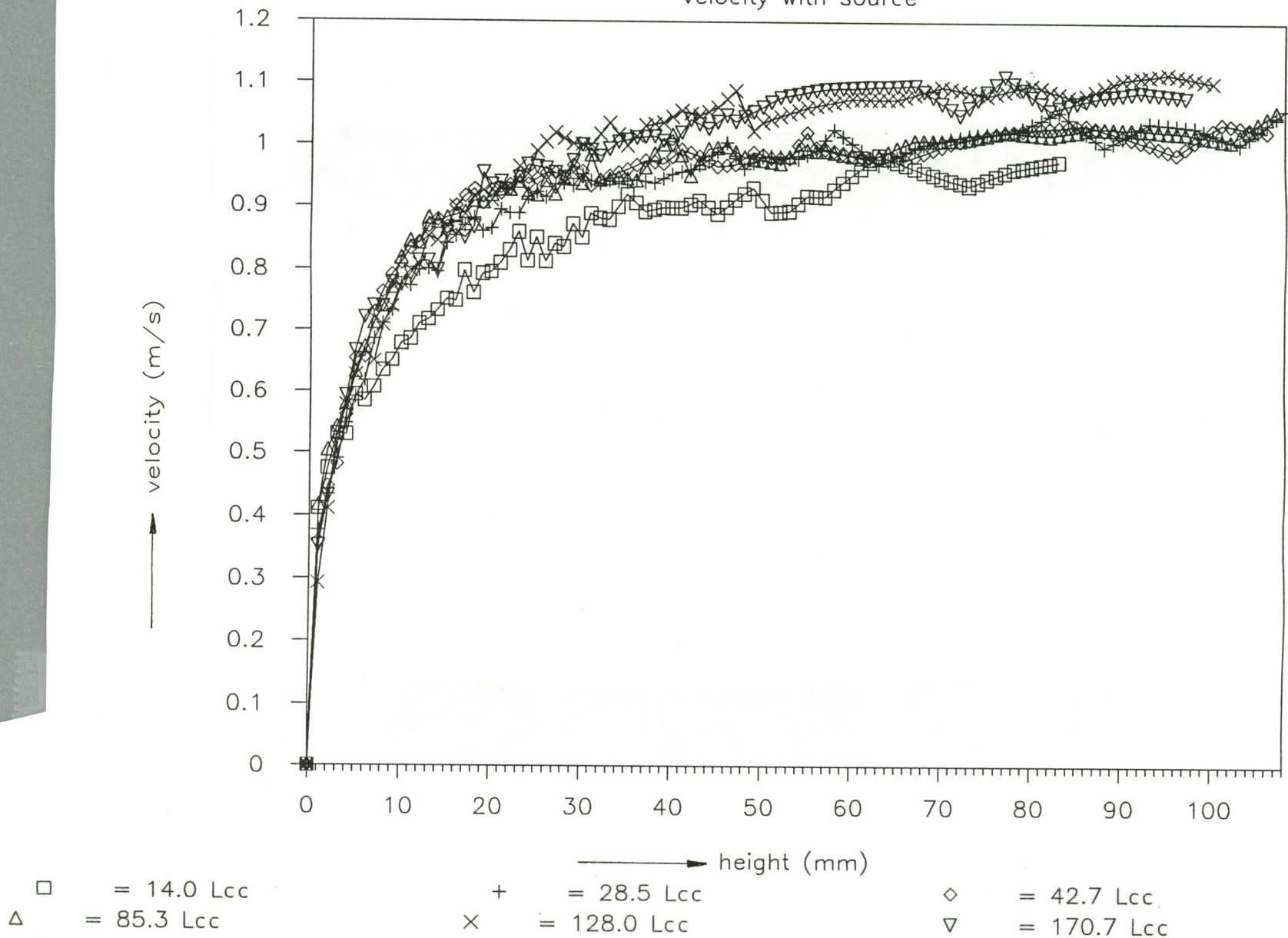


Profiles of turbulence intensity (without source) at different positions.

Fig. 24b
91 - 026
MT - TNO

HEAVY GAS - FOLDA measurements

velocity with source

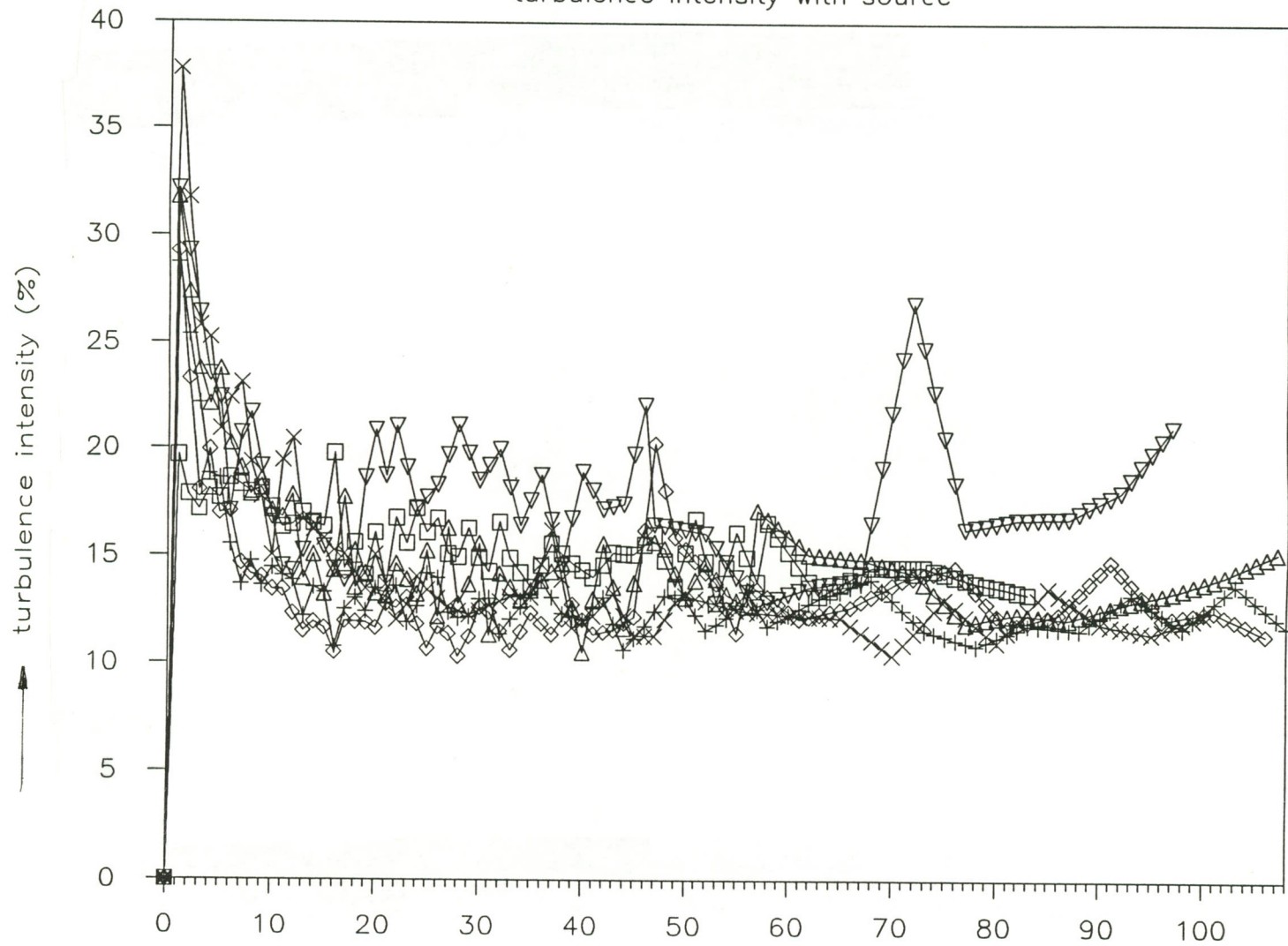


Velocity profiles at positions downwind from the source.

Fig. 22a
91 - 026
MT - TNO

HEAVY GAS – FOLDA measurements

turbulence intensity with source



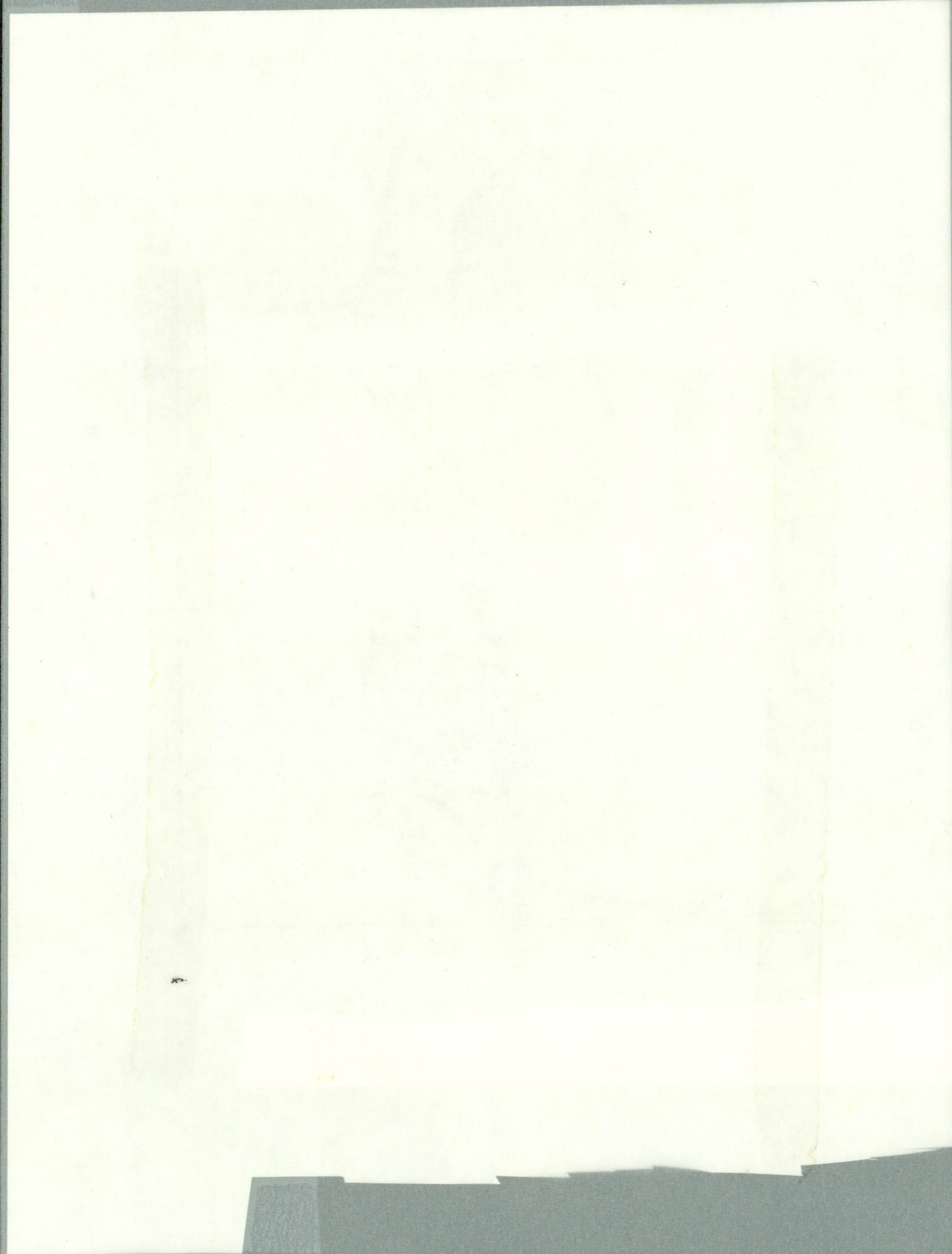
$\square$ = 14.0 Lcc
 Δ = 85.3 Lcc

$+$ = 28.5 Lcc
 $\times$ = 128.0 Lcc

$\diamond$ = 42.7 Lcc
 ∇ = 170.7 Lcc

Profiles of turbulence intensity at positions downwind from the source.

MT - TNO
 91 - 026
 Fig. 25b

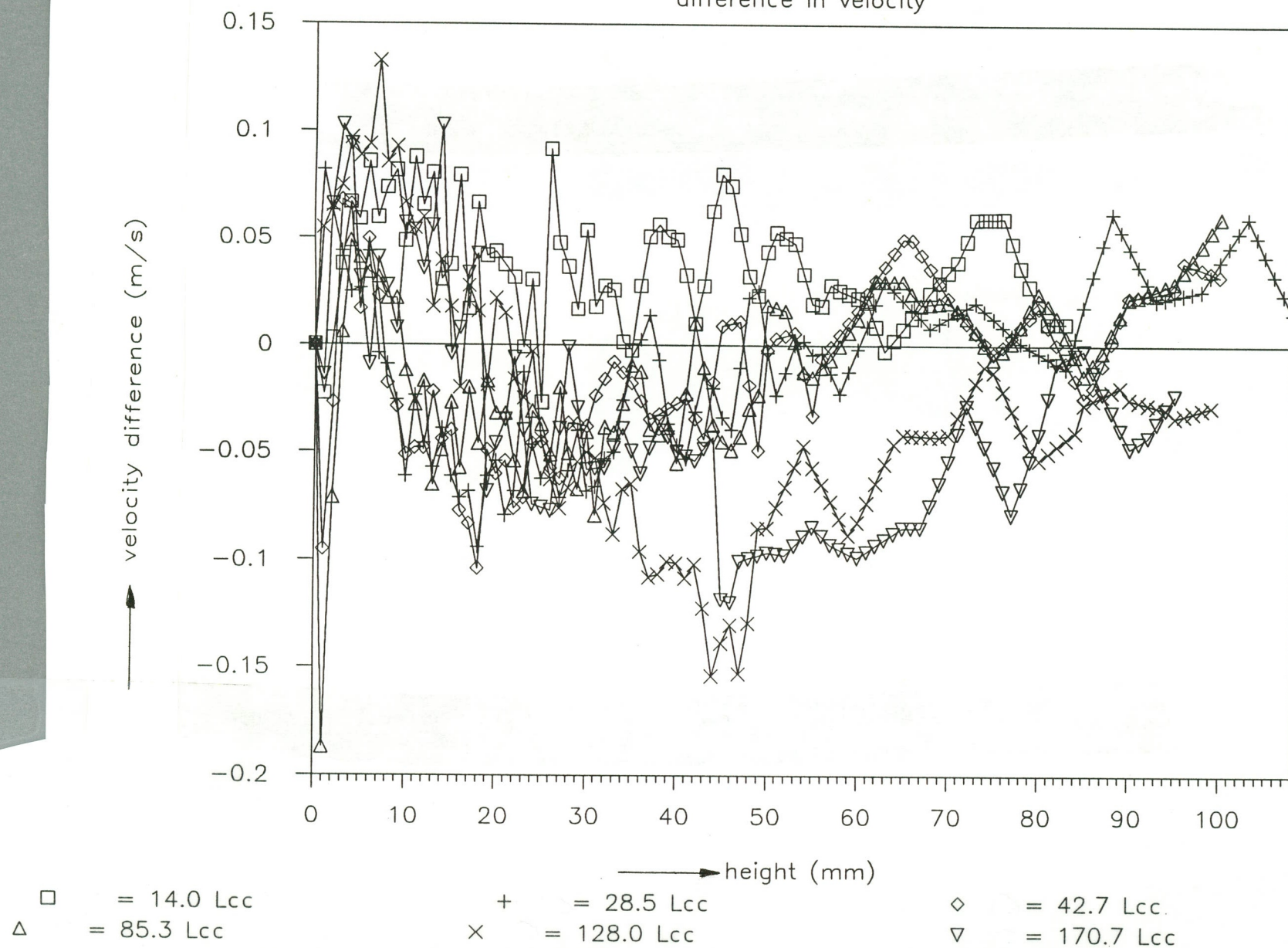


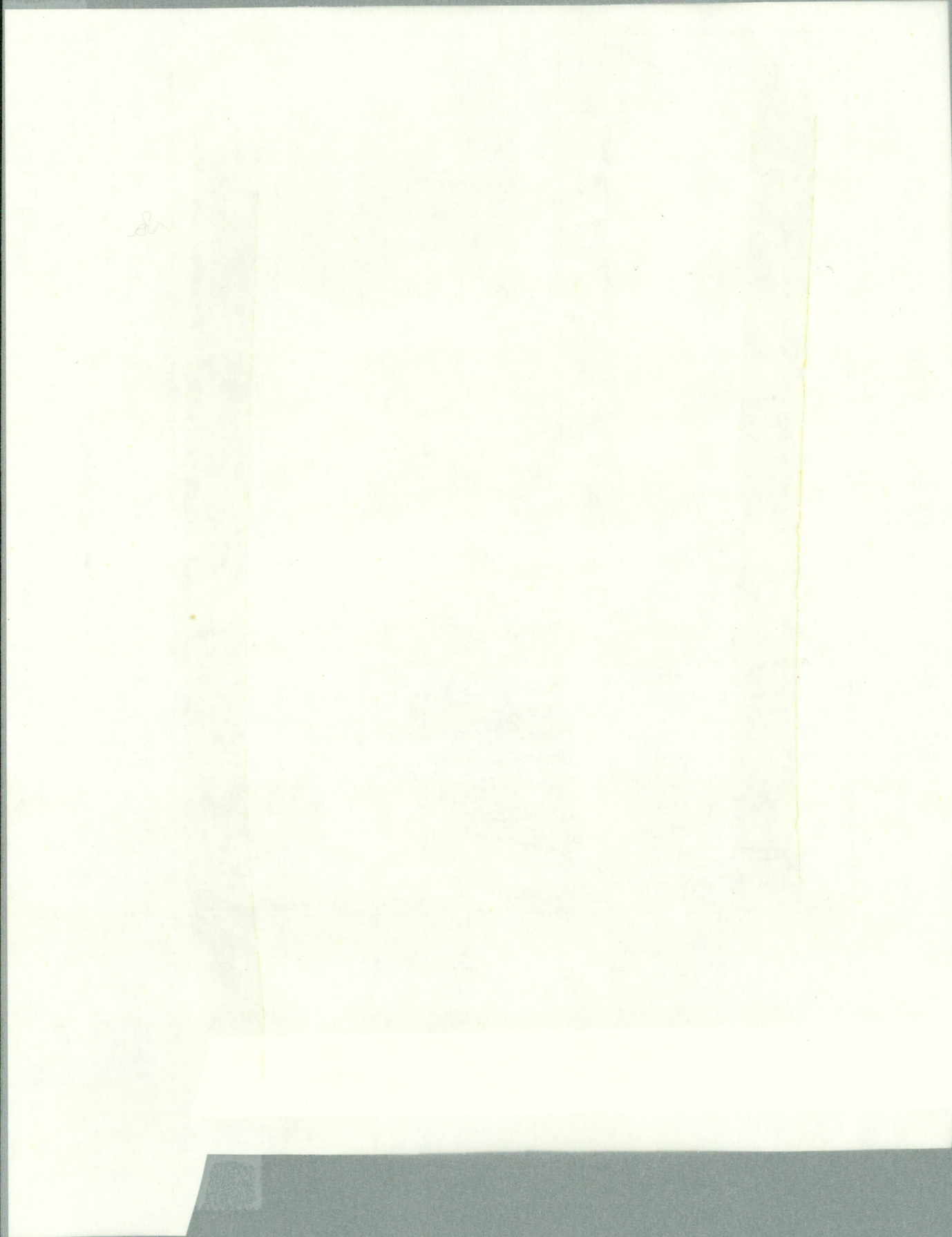
Profiles of turbulence intensity at positions downwind from
the source.

Fig. 22b
91 - 026
MT - TNO

HEAVY GAS - FOLDA measurements

difference in velocity



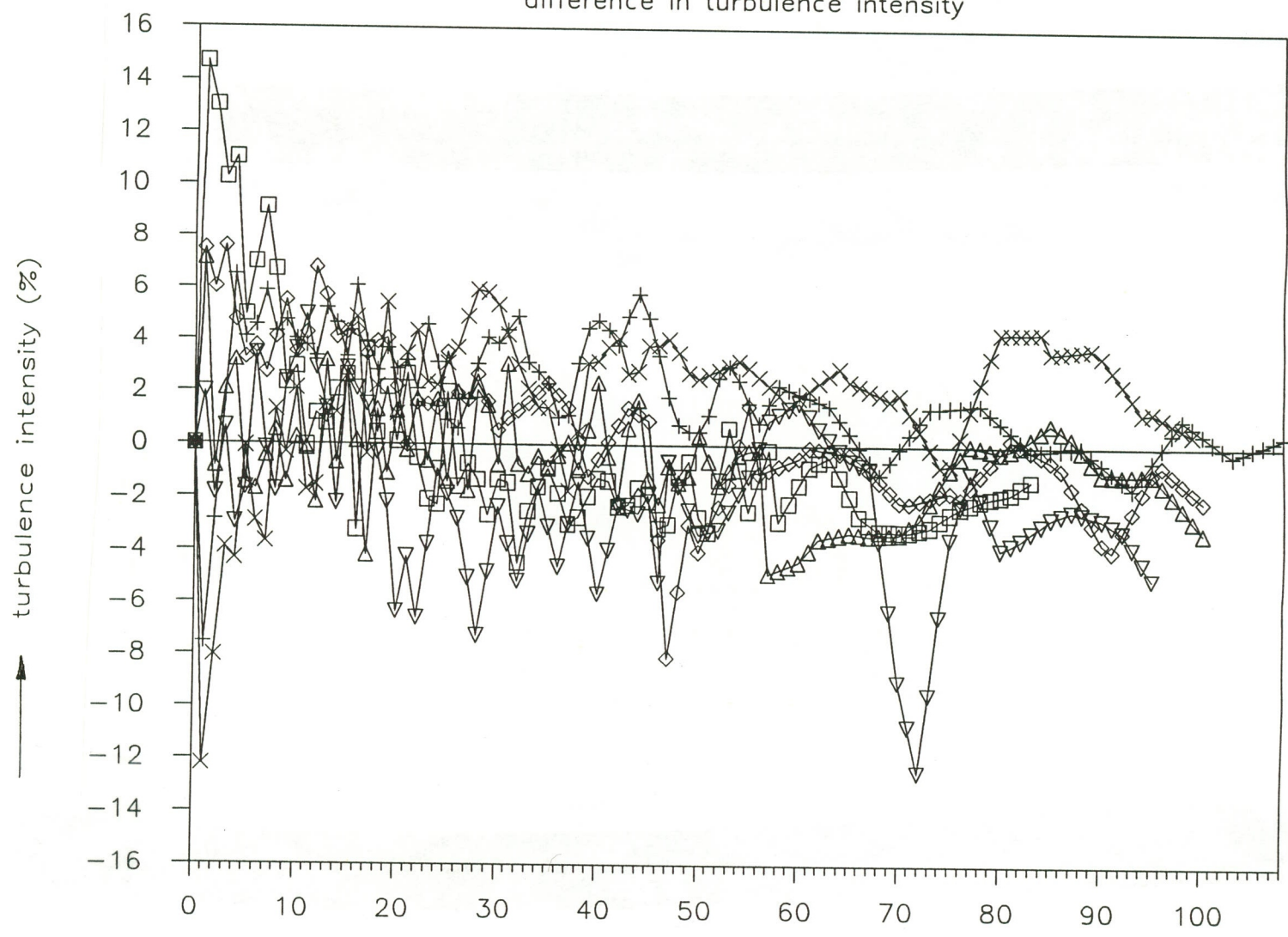


Profiles of velocity difference (without source-with source)

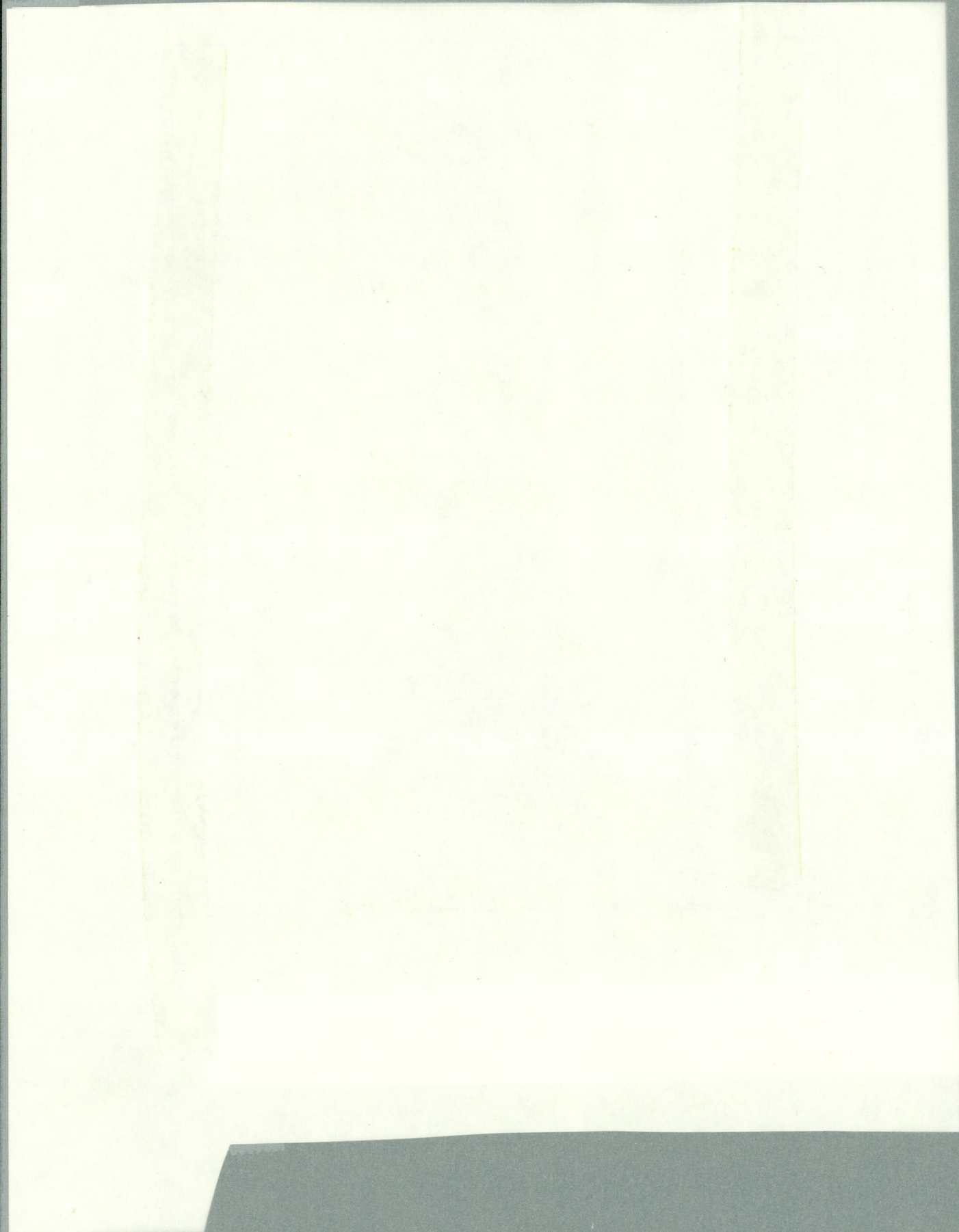
Fig. 26a
91 - 026
MT - TNO

HEAVY GAS - FOLDA measurements

difference in turbulence intensity

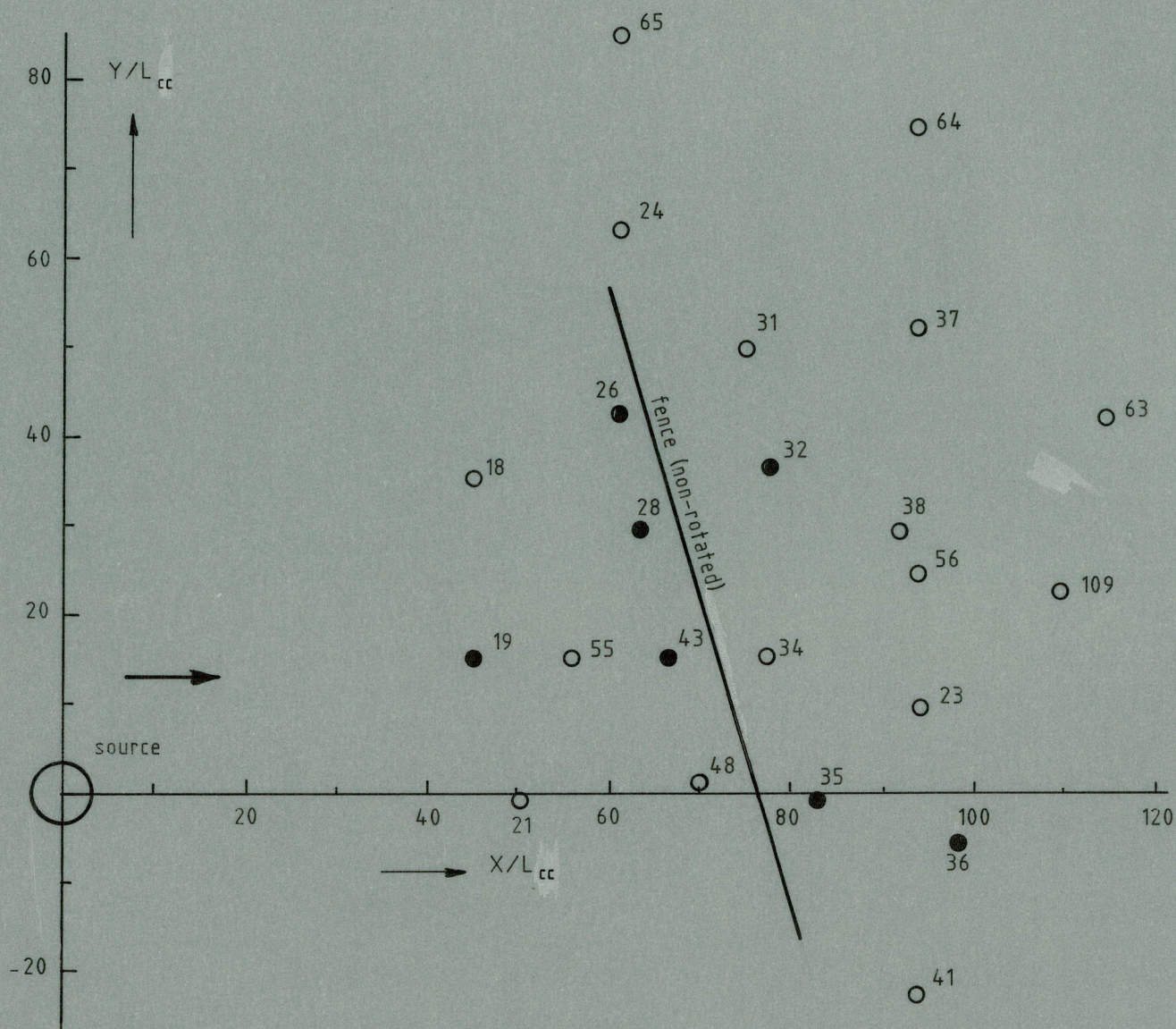


- | | | | | | |
|---|------------|---|-------------|---|-------------|
| □ | = 14.0 Lcc | + | = 28.5 Lcc | ◇ | = 42.7 Lcc |
| Δ | = 85.3 Lcc | × | = 128.0 Lcc | ▽ | = 170.7 Lcc |



Profiles of turbulence intensity difference (without source-
with source)

Fig. 26b
91 - 026
MT - TNO



(closed symbols indicate the wind tunnel measuring stations)

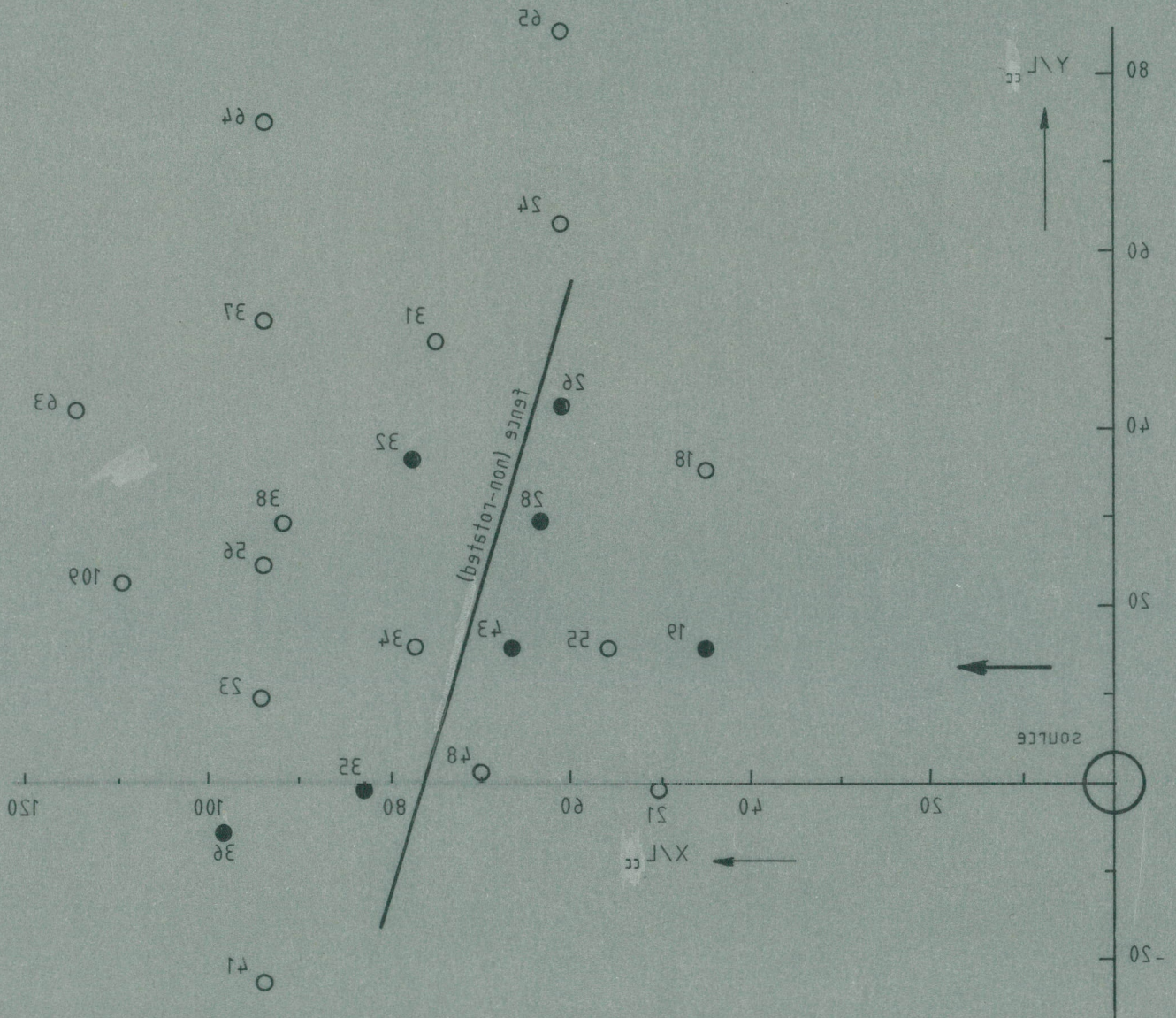
Position of source, fence and probes for the full-scale test EEC 57.

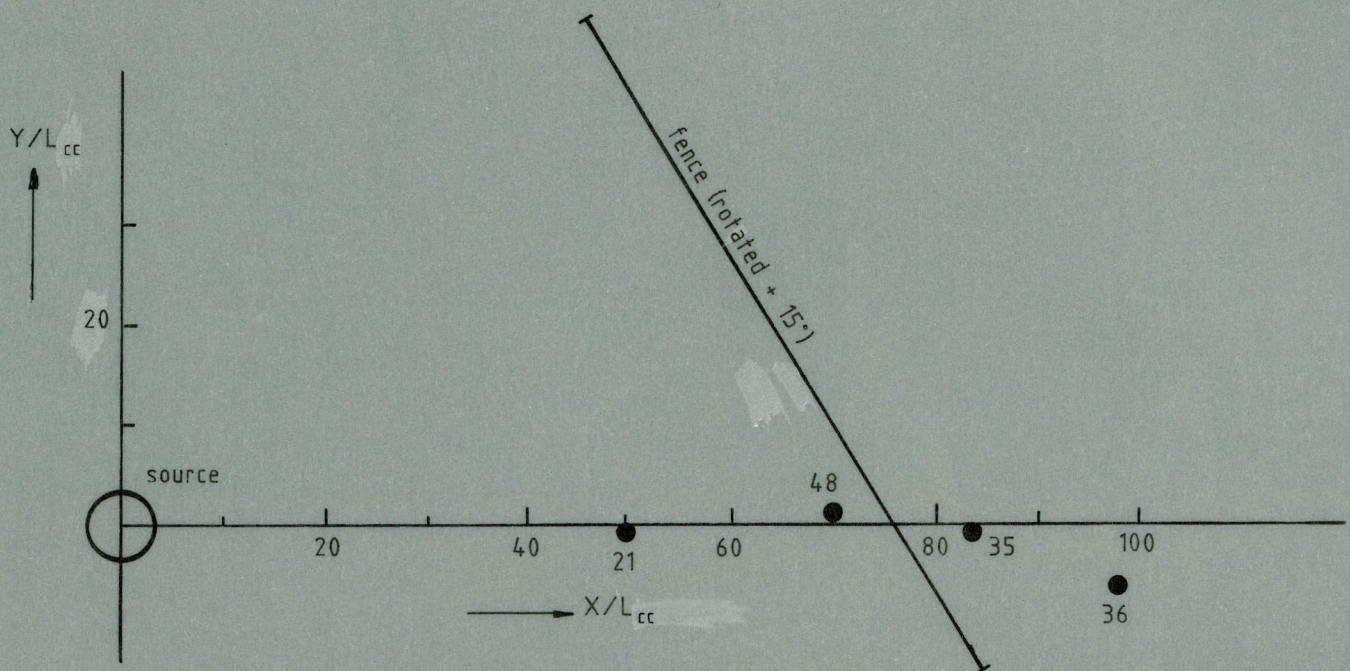
MT TNO
91 - 026
Fig. 27

test EEC 27.
Position of source, fence and probes for the full-scale

Fig. 27
91 - 026
MT TNO

(closed symbols indicate the wind tunnel measuring stations)



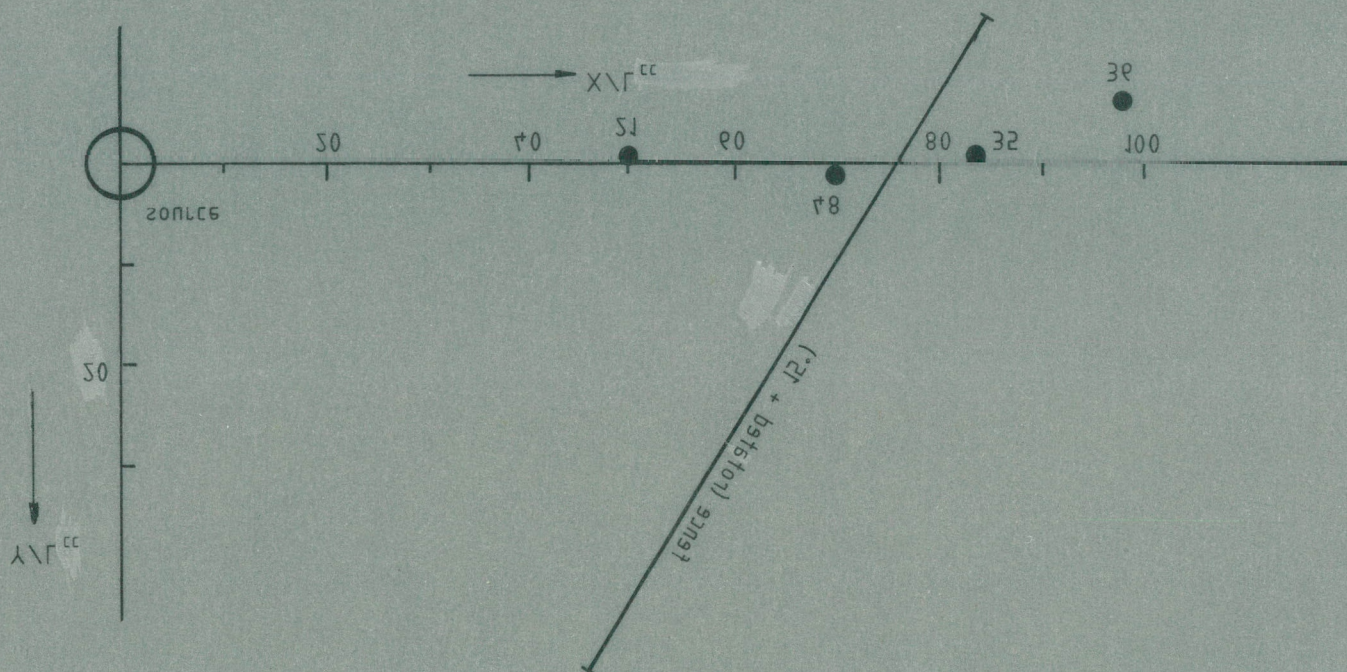


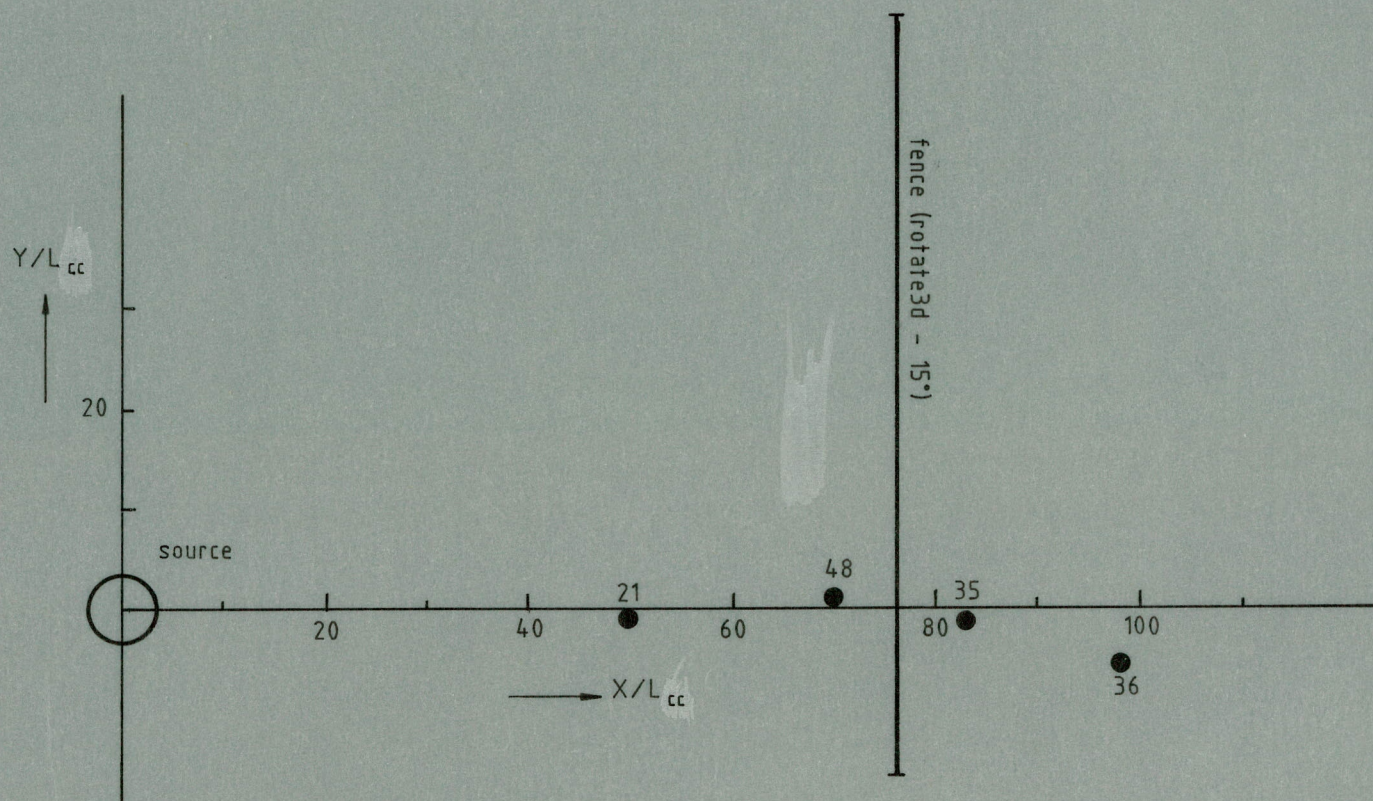
Position of probes for a fence rotation of $+15^\circ$

MT - TNO
91 - 026
Fig. 35

Position of probes for a fence rotation of + 12°.

Fig. 32
 81 - 050
 M1 - 110





Position of probes for a fence rotation of -15°

MT - TNO
91 - 026
Fig. 40

