W J VAN DER ELST
E O G WILHELM

STUDIES OF HOT AIR RECIRCULATION IN POWER STATION FORCED DRAUGHT COOLING SYSTEMS

Report to the
WATER RESEARCH COMMISSION
by the
DIVISION OF AERONAUTICAL SYSTEMS TECHNOLOGY, CSIR

WRC Report No 335/1/91

CSIR

DIVISION OF AERONAUTICAL SYSTEMS TECHNOLOGY

STUDIES OF HOT AIR RECIRCULATION
IN
POWER STATION FORCED DRAUGHT COOLING SYSTEMS

by

W J van der Elst
and
E O G Wilhelm

Contract report for the
Water Research Commission

Contract Report No. WRC 335/1/91

PRETORIA
March, 1991

ISBN 1 874858 05 5

ACKNOWLEDGEMENT

The research in this report emanated from a project funded by the Water Research Commission and entitled:

STUDIES OF HOT AIR RECIRCULATION
IN
POWER STATION FORCED DRAUGHT COOLING SYSTEMS.

The financing of this project by the Water Research Commission is gratefully acknowledged.

STUDIES OF HOT AIR RECIRCULATION IN POWER STATION FORCED DRAUGHT COOLING SYSTEMS.

EXECUTIVE SUMMARY

Past water tunnel investigations into wind effects on recirculation of hot air in power station forced draught cooling systems dealt with some general aspects of this problem. However, such investigations did not include a systematic study of the effects of various lay-out parameters applicable to power stations. The present work deals with a series of systematic water tunnel studies investigating the occurrence of wind-influenced hot air recirculation in a representative forced draught power station cooling system.

In the model under investigation the basic laws for similarity are fully obeyed and the fluorometer method for establishing the degree of recirculation in any test configuration was very effectively applied.

The five investigations, pertaining to various salient power station layout parameters and wind conditions, were concluded as follows:

(a) The effect of the magnitude of the gap between heat exchanger bank and boiler houses, on the degree of hot air recirculation was systematically investigated. It was conclusively shown that marked reduction in circulation is attainable by increasing this gap.

(b) A series of tests, aimed at investigating the effect of the heat exchanger stack height on hot air recirculation showed that recirculation is drastically increased for low stacks (in the order of 10 m) but as the stack height is increased the occurrence of recirculation dwindles and an increase in height from 20 m to 45 m (a typical present day design height) only slightly reduces the plume recirculation problem.

(c) In all previous power station studies heat exchanger banks were always in the lee of the power station buildings. In this particular study the effect of the prevailing wind blowing directly into the opening of the heat exchanger bank was investigated and it was conclusively found that no recirculation occurs for this particular wind direction.

(d) In order to obtain correlation between experimental results and results from computational fluid flow methods a two-dimensional water tunnel test was executed to again investigate the heat exchanger stack height effect. Results similar to those obtained for the three-dimensional case (described in (b) above) were obtained which can be used conveniently for developing further computational methods suitable for studying problems on wind-affected plume recirculation.

(e) Recirculation tests, limited to two-dimensional models, indicated that for this model operating at a rather low Reynolds number, no recirculation is evident when no external wind is simulated. This result does not at present tally with computational fluid flow results obtained at the University of Stellenbosch and further investigation into this suspected Reynolds number effect is indicated.

In order to illustrate the repeatability of results from this type of model plume recirculation study, results of an early test run, which was repeated in the present test series merely to maintain continuity in the test program, was compared directly with the present results. Although these tests were done by different analysts and although the original test was done more than a year ago the repeatibility was excellent.

In conclusion it is recommended that careful attention be given to the results obtained from the studies on heat exchanger-boiler house gap effects and the effect of heat exchanger height on recirculation problems during the planning stage of future power station installations. It is also recommended that attention be given to the basic model Reynolds number effect which will be of importance when interpreting certain ultra low speed test results in future water tunnel studies.

CONTENTS PAGE

CONTENTS (continued) PAGE

1 INTRODUCTION

Past water tunnel investigations into wind effects on recirculation of hot air in power station forced draught cooling systems ([1] and [2]) dealt with some general aspects of this problem. However, such investigations did not represent a systematic study of the effects of various geometrical layouts of the heat exchanger/boiler house combination such as the separation gap between the heat exchanger and boiler house etc.

The present report deals with a series of systematic water tunnel tests investigating the occurrence of recirculation at various external wind conditions in a typical forced draught power station cooling system. The five layouts and test conditions that were to be considered separately are given in Section 2 below.

2 ENVISAGED TEST SCHEDULE

2.1 Test (a): The Effect of the Gap between Heat Exchanger Bank and Power Station Boiler Houses

Previous tests [2] indicated that the magnitude of the gap between the heat exchanger bank and the row of power station boiler houses (see Figure 1) had a very marked effect on the extent of recirculation of hot air under the influence of external winds. This parameter was to be investigated by selecting equivalent full-scale gaps of 0, 7,5 m, 15 m, 45 m, and 90 m and testing recirculation at equivalent full-scale wind velocities of 2 m/s, 3 m/s, 4 m/s, 5 m/s, 7 m/s and 10 m/s for each gap. For these tests the equivalent full-scale height of the heat exchanger was to be fixed at 45 m.

2.2 Test (b): The Effect of the Heat Exchanger Height

The effect on recirculation of the heat exchanger height was to be investigated by selecting equivalent full-scale heights (defined as the height from the ground to the inlet plane of the fans) of 16 m, 21 m, 31 m and 45 m and testing recirculation at wind speeds of 2 m/s, 3 m/s, 4 m/s, 5 m/s, 7 m/s and 10 m/s for each height.

2.3 Test (c): Wind Effects with Boiler Houses Downstream of Heat Exchanger

All previous investigations were carried out with the heat exchanger bank more or less in the lee of the wind obstructing mass of boiler houses since this was regarded as the general condition where most severe recirculation will take place.

The effect of wind blowing into the opening of the heat exchanger bank when it is positioned upstream of the boiler houses was to be investigated by measuring recirculation at wind speeds of 2 m/s, 3 m/s, 4 m/s, 5 m/s, 7 m/s and 10 m/s.

For these tests no gap is to be allowed between heat exchanger and boiler houses.

2.4 Test (d): Heat Exchanger Height Effect Considering a Two-Dimensional Isolated Heat Exchanger Model

In order to correlate experimental results with numerical predictions [3] recirculation tests were to be carried out on a two-dimensional isolated (without boiler houses) heat exchanger model at equivalent full-scale heat exchanger heights of 16 m, 21 m, 31 m and 45 m. Two-dimensional flow was to be effected by two parallel perspex plates guiding the flow over the heat exchanger model in a direction perpendicular to its long axis. Equivalent full-scale wind speeds of 2 m/s, 3 m/s, 4 m/s, 5 m/s, 7 m/s and 10 m/s were to be considered.

2.5 Test (e): Recirculation Prevalent when no Wind is Blowing over Heat Exchanger

Numerical flow predictions [3] show that, although recirculation appears to dwindle to almost zero at low wind speeds over an isolated (without boiler houses) heat exchanger, this recirculation again manifests itself, in completely calm conditions. Such calm conditions have not as yet been simulated in a water tunnel model. In calm conditions and at very low simulated wind velocities the simulated hot air plume, emanating from the top of the heat exchanger, tends to strike the roof of the water tunnel working section and is deflected downwards again. Thus the possibility arises that false recirculation conditions could be brought about.

Tests on simulated recirculation in calm wind conditions were to be attempted by removing the roof of the water tunnel working section and allowing the plume from the heat exchanger to enter the reservoir above the tunnel working section.

2.6 Note on the Use of "Cladding" in the Model Tests

In a typical heat exchanger system which abuts against the power station boiler houses cladding is used to cover the opening between the tops of the boiler houses and the bottom of the heat exchanger bank (see Figure 1). In the above test schedule the cladding was to be removed for tests (a), (b), (d) and (e). In test (b), where no gap was to be allowed between the model heat exchanger and boiler houses, tests were to be made with and without cladding in position. In test (c) the cladding was to be installed.

3 THEORETICAL BACKGROUND FOR TESTS

The problem dealt with in this report concerned a hot air heat exchanger plume ejected into the free atmosphere where it was acted upon by prevailing wind. This system was simulated by means of a model in a water tunnel working section where the fluid flow represented the natural wind. The plume was simulated by a water-alcohol mixture which could be adjusted so that the plume had the correct reduced density so as to simulate buoyancy.

For such a water tunnel model plume to correctly simulate the dynamic behaviour of the full-scale prototype plume all ratios of forces acting on the model plume must be identical to the corresponding force ratios in the full-scale prototype. Such force ratios can be represented analytically as follows:

Let V = a typical wind velocity
Ve = velocity of efflux from forced draught system
ρ = density of ambient air
ρ' = density of hot air in plume
D = typical linear dimension (say the width of the heat exchanger)
g = acceleration due to gravity
μ = viscosity of working fluid (air in full-scale prototype and water in model)

The significant forces encountered in the plume system may be represented as follows:

(1) Air viscosity forces proportional to μ VD.
(2) Aerodynamic inertia forces of cold air proportional to $\rho V^2 D^2$.
(3) Aerodynamic inertia forces in hot plume proportional to $\rho' V_e^2 D^2$.
(4) Buoyancy forces on plume proportional to $(\rho - \rho')g D^3$.

Taking ratios of these forces result in non-dimensional numbers as follows:

Putting $\frac{(2)}{(1)}$ gives $\frac{\rho V D}{\mu}$ (the Reynolds number)

Putting $\frac{(3)}{(2)}$ gives $\frac{\rho' V_e^2}{\rho V^2}$ (the specific impulse ratio)

Putting $\frac{(4)}{(2)}$ gives $\frac{\rho - \rho'}{\rho} \cdot \frac{g\ D}{V^2}$ (the densimetric Froude number)

It can readily be ascertained by inspection that, since expression (2) is common to the above three ratios, all possible force ratios can be derived from these three ratios. Therefore, if the above three non-dimensional numbers are identical in the model and the full-scale prototype full similarity between model and prototype may be achieved. If it is possible to obtain the same density ratio $\frac{\rho'}{\rho}$ in the model and prototype (as happens to be the case in this investigation) the required non-dimensional numbers may readily be simplified to:

$\frac{\rho'}{\rho}$ (density ratio)

$\frac{V_e^2}{V^2}$ or $\frac{V_e}{V}$ (velocity ratio)

$\frac{g\ D}{V^2}$ (Froude number)

$\frac{\rho\ V\ D}{\mu}$ (Reynolds number)

Unfortunately, as is always the case for wind tunnel and water tunnel investigations on very small-scale models, it is impossible to attain both Froude number and Reynolds number similarity. The reason for this is that, as can be seen from the above expressions for these numbers, the Froude number requires a reduction in model velocity for a small linear scale model whereas the Reynolds number demands an increase in model velocity for the same small-scale model.

It is customary [4] to ignore the Reynolds number in modeling the relatively bluff-shaped buildings and plumes occurring in this investigation. As deduced above the Reynolds number is derived from considering the ratio of fluid viscosity force to aerodynamic inertia force. For such relatively bluff shapes viscosity forces are small compared to aerodynamic inertia forces and buoyancy forces and may be neglected, thus implying that the Reynolds number may be ignored.

Since the hot air leaving the full-scale heat exchanger is at a temperature of 30° C above the assumed ambient air temperature of 20° C a density ratio of $\frac{\rho'}{\rho} = 0{,}91$ is obtained from consideration of the absolute temperature ratio. This density ratio could readily be achieved in the water tunnel model by mixing alcohol with water.

A linear scale of 1:1800 was selected for the model in this investigation and from the Froude number ($\frac{g\ D}{V^2}$), which had to be the same for model and prototype, it readily follows that the velocity scale, i.e. the ratio of full-scale velocity to model velocity, is $\sqrt{1800} = 42{,}4$. Applying this velocity scale to all velocities, i.e. wind velocity and efflux velocity, automatically ensures that the velocity ratio $\frac{V_e}{V}$ is the same for model and prototype.

4 DESCRIPTION OF TEST MODEL

The heat exchanger model was essentially the same system as the one previously used for the Matimba investigation [1].

The heat exchanger system of Matimba power station consists of an array of 72 pillars supporting heat exchangers through which 288 fans force air.

Inspection of the Matimba heat exchanger system indicated that the fans sucked air up from the lower surface of the system and discharged this air into the voids beneath the heat exchangers which simulated a discharge into a plenum chamber. From this plenum chamber, the air flowed upwards uniformly through the heat exchanger fins.

In the water tunnel model, simulated fans were not required, but it was necessary to provide a system where the water could be sucked in at the bottom of the bank of simulated heat exchangers, while a different fluid (in this instance, alcohol and water) representing the less dense efflux, could be uniformly ejected out of the top surface of the heat exchanger. This heat exchanger model, illustrated in Figure 1, was constructed as follows: Each pillar, represented by a thin tube, was used to suck water away from the base of the model heat exchanger through small holes drilled in the base (see Figure 2). Thus, the inflow at the base could be simulated by allowing all the small tubes connected to the 72 pipes to discharge in the tunnel pit at a depth calibrated to give the correct flow rate for the four fans represented by the small holes surrounding each pillar.

The upper compartment of the model heat exchanger was completely separated from the lower compartment from which the water was sucked out. The upper compartment which was covered by a fine gauze contained tubes with suitable holes in the walls to ensure equally distributed efflux of the water/alcohol mixture, as is indicated in Figure 2. This water/alcohol mixture was supplied from header tanks for which the elevation was calibrated so as to give the required rate of efflux from the model heat exchangers. This required rate of efflux was such that an equivalent full-scale efflux velocity of 5 m/s was attained in the model.

The wind was simulated as a flow with a conventional vertical wind profile obtained by fitting "spires" upstream of the model and also small regularly spaced blocks in the model floor upstream of the model so as to retard flow at ground level. These "spires" and blocks were so arranged as to yield a wind velocity distribution over the model power station which approximately obeyed the power law

$$\frac{V}{V_R} = \left[\frac{Z}{Z_R}\right]^{0,13}$$

where V was the velocity of the wind at an elevation Z above the plate representing the ground in the model, and V_R was the velocity at some reference height, Z_R, taken for this model to be 100 mm above the ground plate. The required wind velocity profile and values for wind velocity distribution actually obtained in the model are indicated in Figure 3.

Only a wind direction normal to the longitudinal axis of the heat exchanger was simulated. The models of chimney stacks and all structures upwind of boiler houses were omitted and only the boiler and turbine houses were included as depicted in Figure 1.

It was arranged that the model boiler houses could be displaced relative to the model heat exchanger so that various gaps between these two power station components could be simulated. Suitable perspex spacers were made so that various heights of the heat exchanger relative to the model boiler houses could also be simulated.

5 INSTRUMENTATION AND TESTING PROCEDURE

One of the advantages of water-tunnel testing is the capability of making quantitative measurements of plume dispersion and recirculation. In carrying out these quantitative measurements of recirculation taking place from the upper surface of the heat exchanger system to its lower inlet surface, the Fluorometer system used for previous investigations [1] was again employed. This technique involved the introduction of a known mass of quinine sulphate into the mixture of water and alcohol which represented the efflux plume. A Fluorometer, which can measure the quinine sulphate content in parts per million (ppm) of any sample taken anywhere in the flow field where recirculation of the plume had taken place, was then used to determine the concentration of quinine sulphate at any such desired point. In this way, the percentage recirculation presented at any such sampling point could readily be determined.

For any particular test where the tunnel speed was adjusted to represent a given wind speed and where the exit plume had become stable, three samples, each coming from the three pillar rows in the model heat exchanger, were taken in clean containers. The 72 hollow pillars in the model each sucked fluid away from the underside of the heat exchanger but 24 such suction tubes coming from each of the 3 pillar rows (see Figure 1) were combined thus giving three sampling points.

6 RESULTS, DISCUSSION AND CONCLUSIONS

6.1 Test (a): The Effect on Recirculation of the Gap between a 45 m Heat Exchanger and Boiler Houses

The results of test investigating the influence on recirculation of the gap between heat exchanger stack and boiler houses, are reflected in Figures 4 to 10. In all these figures, except Figure 5, percentage recirculation measured is plotted against the simulated full-scale wind speed. As was found in all past tests on recirculation, these graphs again clearly show that as the wind velocity over the stack is increased from zero, recirculation commences at some threshold velocity (usually in the vicinity of 2 m/s). As the wind velocity further increases these graphs all indicate a progressive increase in recirculation.

As far as illustrating the influence of the gap is concerned Figures 4 and 5 are perhaps the most significant. Figure 4 shows the total average recirculation/wind-speed relationships for all the gaps tested and shows how recirculation diminishes with increased gap. Figure 5, a plot of the total average recirculation versus gap size at a simulated full-scale wind speed of 10 m/s, also illustrates this progressive diminution of recirculation with increase in gap size. It may be concluded from these results that recirculation can be very effectively reduced by separating the heat exchanger stack from the boiler houses.

Figures 6 to 10 represent recirculation/wind-speed relationships at various gap sizes, showing the recirculation distribution relative to the stack supporting pillar positions (see Figure 1). In general it appears that the most recirculation occurs at pillar row 3 (see Figure 1) which is to be expected since this is the location where portions of the plume emitted by the cooling stack tends to re-enter the suction side of the simulated cooling fan bank.

6.2 Test (b): The Effect on Recirculation of the Stack Height of a Heat Exchanger butting against the Power Station Boiler Houses (zero gap)

Figures 11 to 16 depict the effects which various stack heights has on hot plume recirculation for the case where the cooling stack abuts against the power station boiler houses. Figure 11, indicates the usual result of wind action, namely that a threshold wind velocity exists below which no recirculation takes place and above which the recirculation rapidly increases. Figures 11 and 12, the latter showing the relationship between recirculation and stack height at a fixed wind speed of 10 m/s, both clearly illustrate the effect of stack height on hot plume recirculation. It is apparent from these figures that the wind-induced recirculation of a hot air plume in a forced draught cooling stack is severe for low stacks (in the order of 10 m). As the stack height is increased recirculation rapidly diminishes and it is clear that increasing the height from 20 m to 45 m (the design height of a typical stack) only slightly reduces the occurrence of recirculation.

Figures 13 to 16 show the streamwise distribution of recirculation over the three pillar positions (see Figure 1) for all the different stack heights. In general, as is to be expected, recirculation at the downstream edge of the stack (pillar position 3) is the highest since this is where recirculation flow from the efflux plume enters the lower region of the cooling stack.

Figures 11 to 16 reflect recirculation test results for the case where the cladding, normally covering the aperture between the fan bank of the heat exchanger and the boiler house roofs, had been removed (see Section 2 of report). Since in past investigations the presence or absence of this cladding had a marked effect on the magnitude of recirculation, it was decided to repeat the test series reflected in Figures 11 to 16, this time including the cladding in the model. Figures 17 to 22, reflecting the results of this study, follow the same general trends as Figures 11 to 16 and will not be discussed in detail again. It is sufficient to point out that except for low stacks the general effect of the cladding is to increase the plume recirculation. This substantiates results obtained in previous investigations [1].

6.3 Test (c): Recirculation Tests with the Forced Draught Cooling Stack situated Upwind of the Boiler Houses

This investigation into the nature of plume recirculation behaviour when the natural wind blows in the opposite direction to that simulated in all previous investigations, yielded very conclusive results. It was found that when wind blows onto the cooling stack (situated upwind of the boiler houses) no circulation whatever takes place. This test was done with the heat exchanger butting against the boiler houses and with the cladding between the stack top and the boiler house roofs, mentioned in tests 6.2 above, fixed into position. Figures 23, 24 and 25 depict the appearance of the windblown plumes for each of three different wind speeds. It is clear from these photographs that the occurrence of any recirculation is very unlikely. This was substantiated by fluorometer recirculation tests.

6.4 Test (d): Studies of the Stack Height Effect on Recirculation, applied to an Isolated Two-Dimensional Heat Exchanger Model

As stated in Section 2 the sole purpose of this particular test series was to obtain two-dimensional recirculation flow results on an isolated stack (no boiler houses) of variable height, in order to study correlation with corresponding numerical fluid flow computations carried out at the University of Stellenbosch [3]. Such analytical work can in future prove very useful in studying flow and circulation problems in connection with forced draught cooling stacks.

Figures 26 to 30 reflect the general results of this test in a similar way as Figures 11 to 16 reflect the results of test (b) (the three-dimensional case). Recirculation measured in this two-dimensional model was markedly less than in the three-dimensional case since the boiler house buildings were removed. This tallies with the results of test (a) which show that the further the stack is separated from the boiler houses, the less the recirculation becomes. Figure 26 show that the recirculation present in the 10 m stack height case rapidly dwindles to very small values (less than 0,8%) when the stack height is increased. Figures 27 to 30 again show that recirculation mostly occur at the downstream edge of the heat exchanger bank (i.e. at the location of pillar row 3).

6.5 Test (e): Investigation of Recirculation in a Heat Exchanger Bank at Various Heights with no Wind Blowing

Recirculation tests, limited to two-dimensional models of various heights indicated that for this water tunnel model no recirculation takes place in simulated calm conditions. Figures 31 to 34 illustrate these results, which do not agree with computational fluid flow results obtained at the University of Stellenbosch. These computational results do show a small recirculation taking place under calm conditions.

The reason for the failure to obtain correlation may possibly be the very low Reynolds number at which such small-scale tunnel tests are unavoidably carried out (see Section 3). However, this can only be established by further experimental and theoretical investigations.

6.6 The Repeatability of the Tests as Illustrated by a Typical Example

In the present test series some tests done previously [2] were repeated in order to maintain continuity in the test program. This repetition affords the opportunity to obtain some idea of the repeatability of such water tunnel recirculation tests which were done with a time lapse of more than one year between particular test series.

Figure 35 shows some results obtained in Test (a) as given under section 6.1 above, as well as results obtained in previous investigations [2] done more than a year ago. These graphs show the variation of percentage recirculation with wind speed for no gap between heat exchanger bank and power station boiler houses. It is clear that results obtained from two distinctly different test series show the same trends of behaviour, but a certain amount of scatter of results exist about a mean line which is shown in Figure 35. In this figure the recirculation at 4 m/s is shown to be 4% for the present test series but only 2% for the same test done a year ago. It is wrong to say that the results of the two tests are in error by a factor of two. The correct definition of the discrepancy of results is to state that the test was repeated within a tolerance of measured percentage recirculation of plus or minus one.

If a great number of percentage recirculation values are obtained for each test wind velocity it is possible to determine statistically a so-called "confidence belt" around the mean recirculation-velocity curve such that, for example, it can be stated that it is 95% certain recirculation will lie somewhere within the confines of such a "confidence belt". The costs involved in carrying out this type of recirculation test precluded the repetition of tests for a great number of times, so that statistical analysis of result repeatability was not possible but Figure 35 does give an indication of the repeatability of results.

Recirculation can be measured accurately by the fluorometer method to within a fraction of a percent so that the scattering of results as indicated above do not arise from this source. Scattering of results are caused by the unsteady nature of the wind and plume flow in this type of test and best results are obviously attained by running a particular test as long as possible. A typical test duration giving results as depicted in Figure 35 is approximately 20 seconds.

7 RECOMMENDATIONS

It is recommended that attention be given to establishing gaps or spaces between heat exchanger stacks and power station building in future power station layouts. Such a spacing will very drastically reduce recirculation if winds blow over the power station buildings on to the heat exchanger stack.

Furthermore it is recommended that careful consideration be given to the minimum stack height required for future power station installations.

It is suggested that the effect of the test Reynolds number magnitude on recirculation results at very low simulated wind speeds or at zero wind speeds be investigated in order to obtain clarity regarding the correlation between work done at the University of Stellenbosch and the CSIR.

REFERENCES

[1] Van Der Elst, W J - "Water tunnel tests on a forced-draught cooling system for a power station". Parts I, II and III (Contract Reports, ME 1966/9, Nov 1986, ME2035, May 1987 and ME 2029/4, Nov 1987.

[2] Van Der Elst, W J - "Model tests on factors influencing hot air recirculation in a force-draught cooling system". Report DAST 88/124, January 1989.

[3] Kröger, D G - "Numerical predictions of air flow about air-cooled heat exchangers". Under preparation.

[4] Poreh, M and Kacherginsky, A - "Simulation of plume rise using small wind tunnel models." Journal of Wind Engineering and Industrial Aerodynamics, Vol 17, No 1, January 1981.

[5] Tielman, H W; Reinhold, T A and Marshall, R D - "On the wind tunnel simulation of the atmospheric surface layer for the study of wind loads on low-rise buildings." Journal of Wind Engineering and Industrial Aerodynamics, Vol 3, No 1, March 1978.

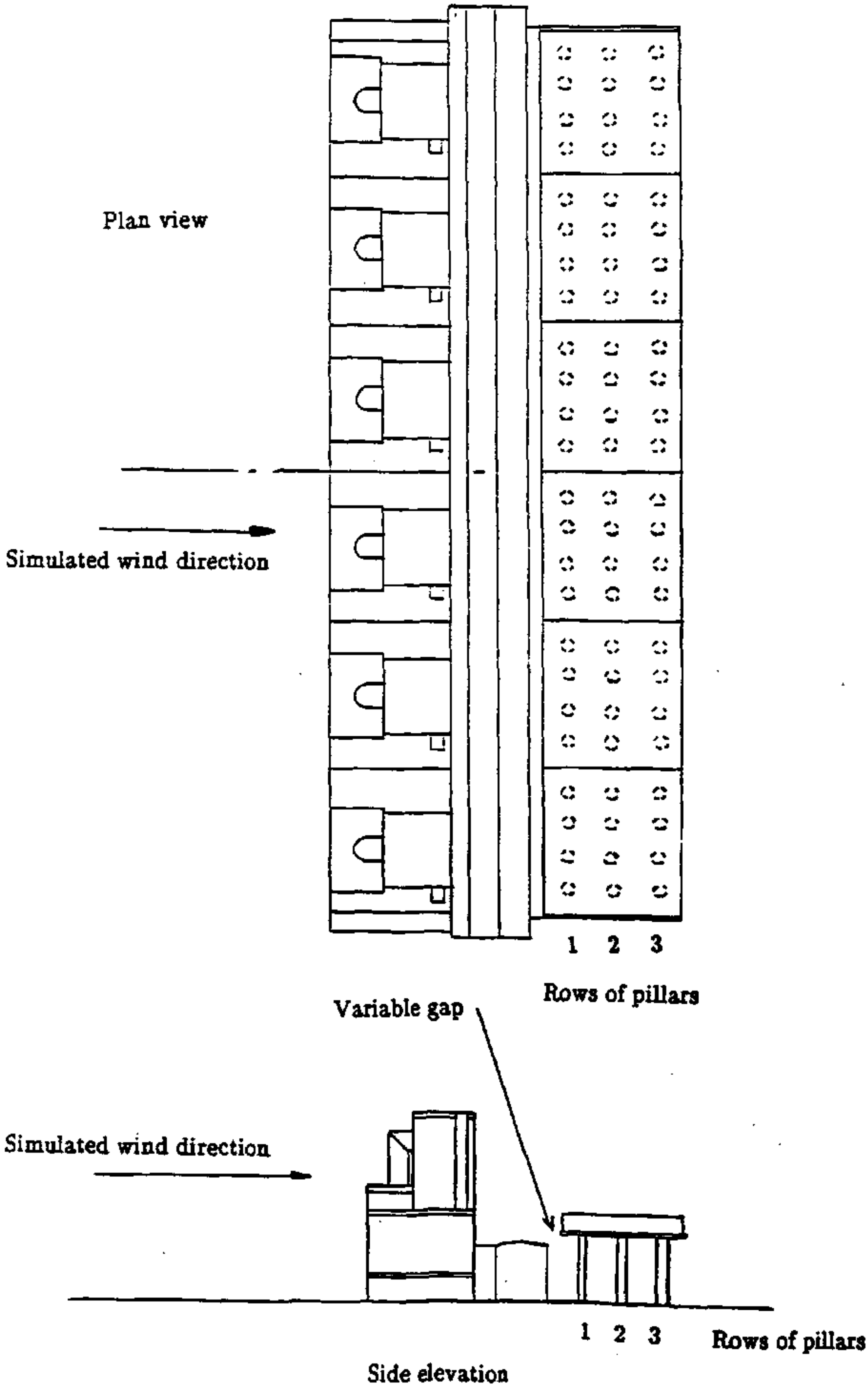

Figure 1: Layout of power station model.

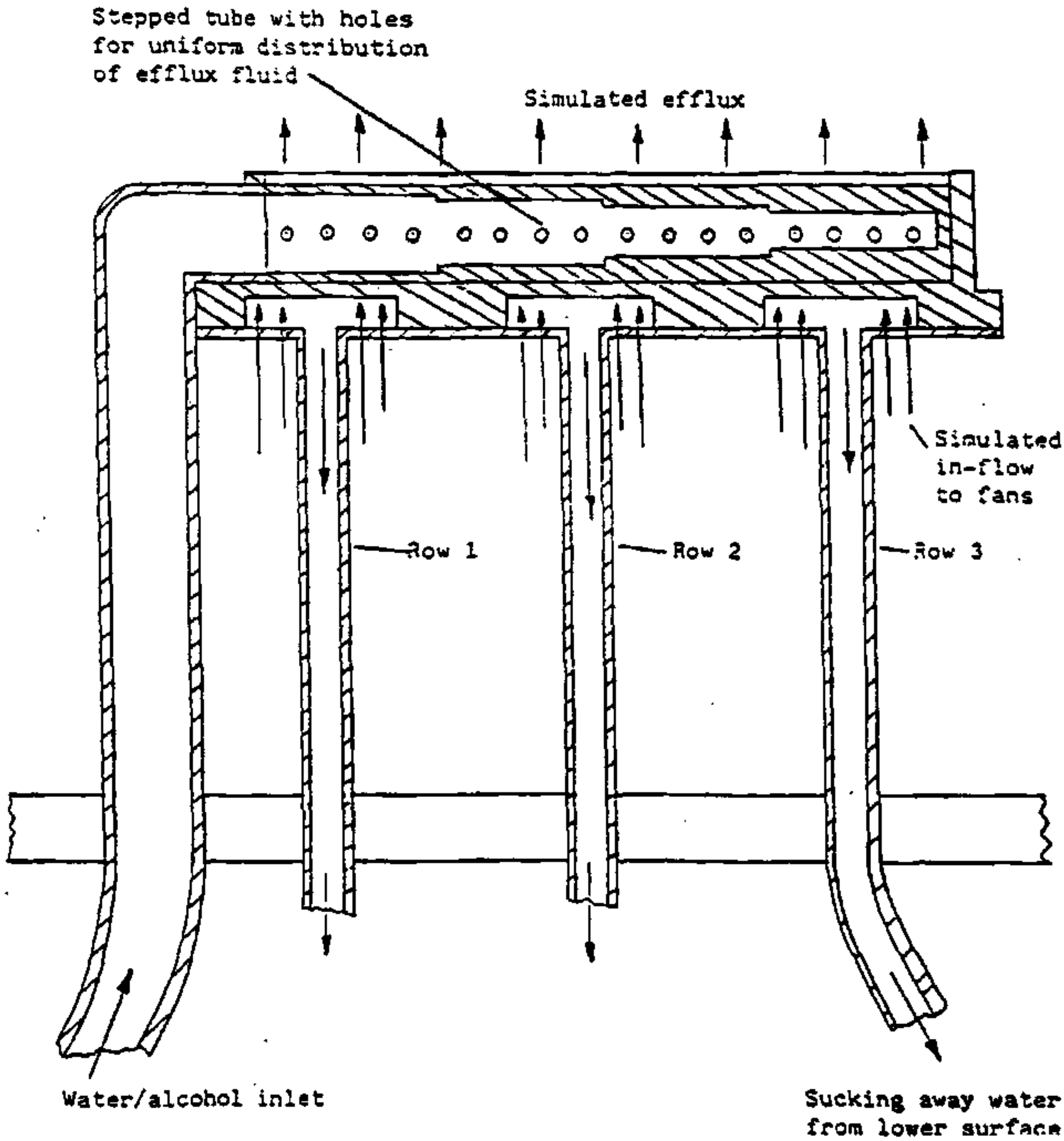

Figure 2: Cross-sectional side elevation of model heat exchanger.

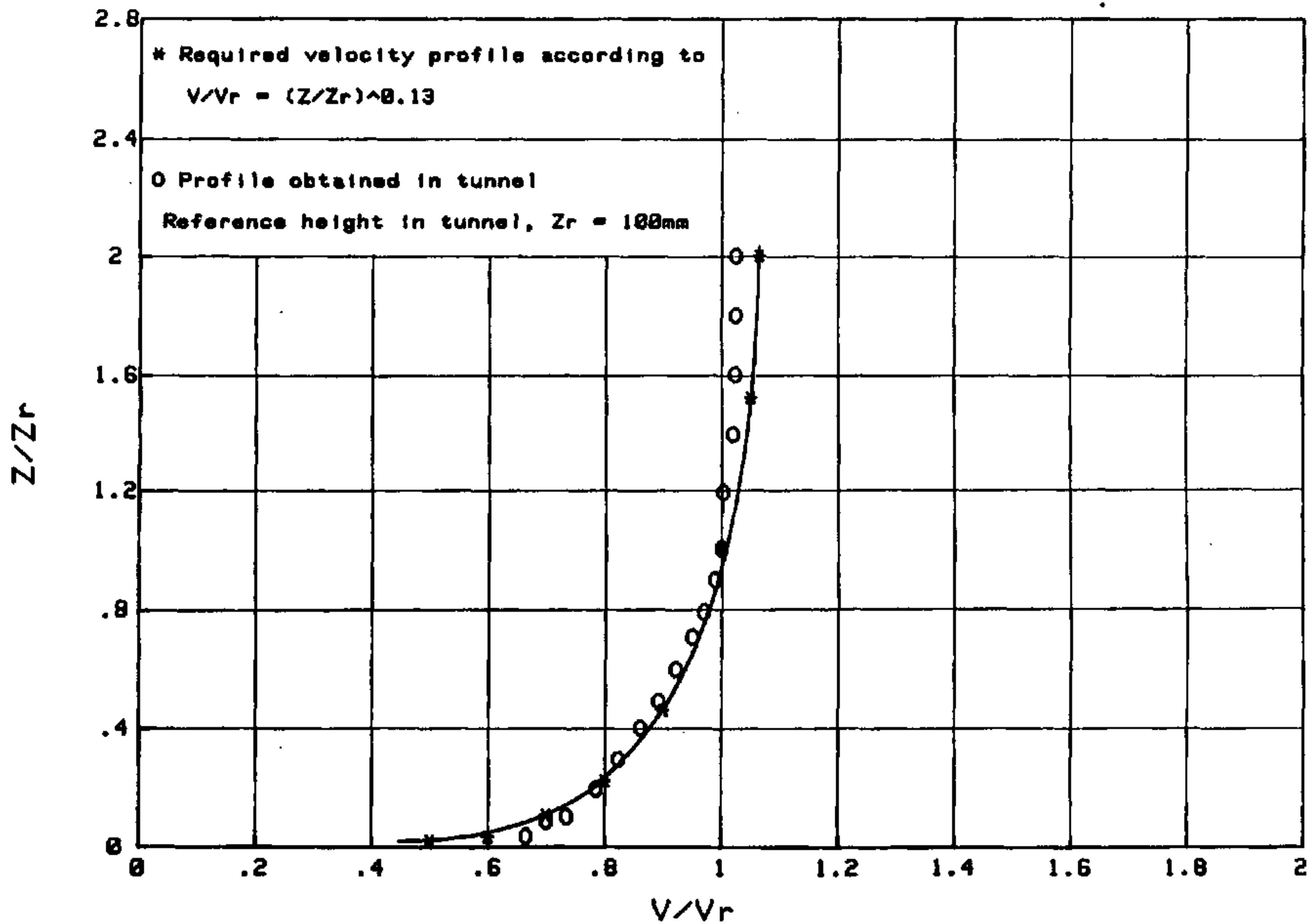

Fig 3. Wind velocity profile simulated in the water tunnel.

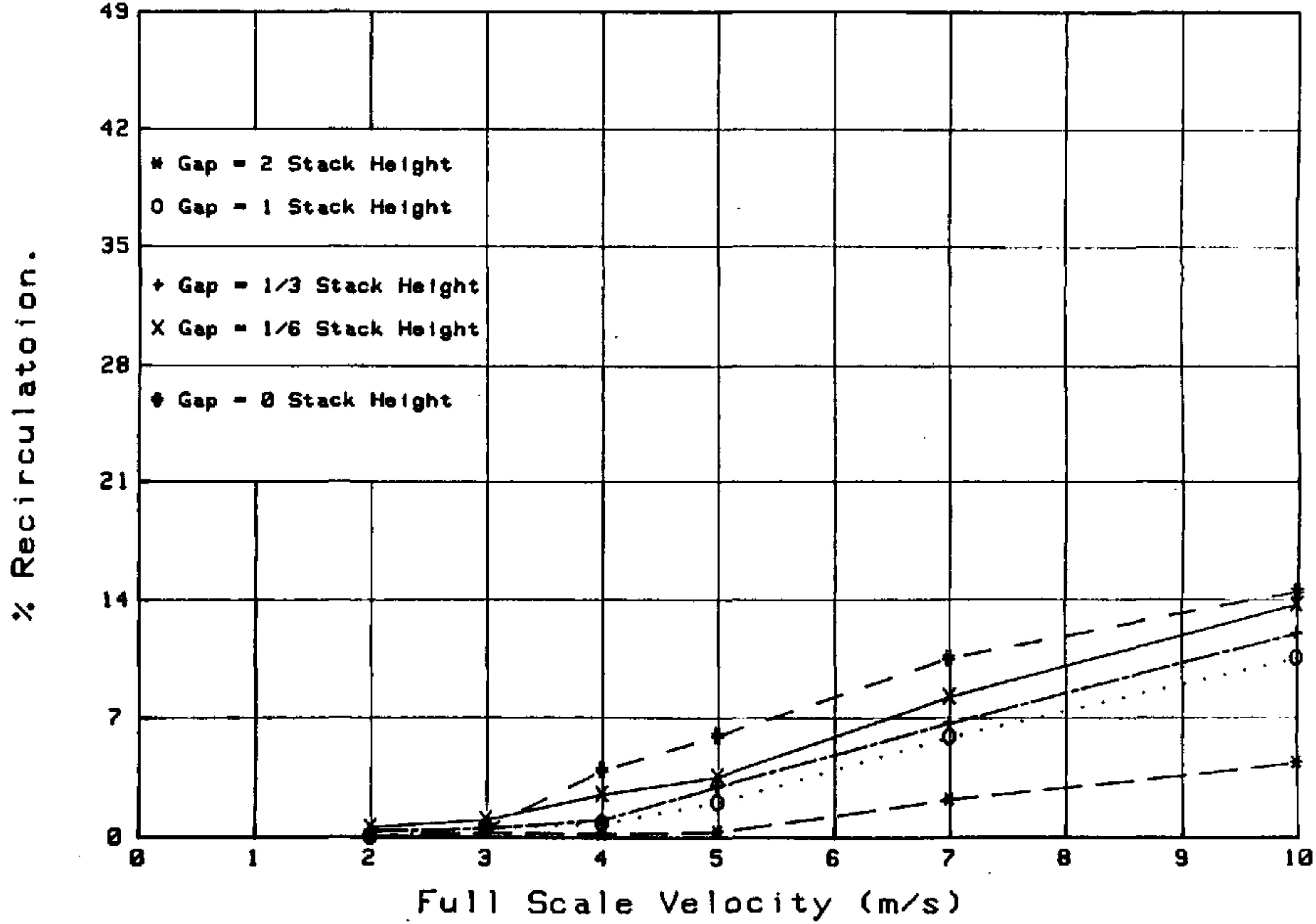

Fig 4. Test a. Effects of gap between heat exchanger and boiler houses

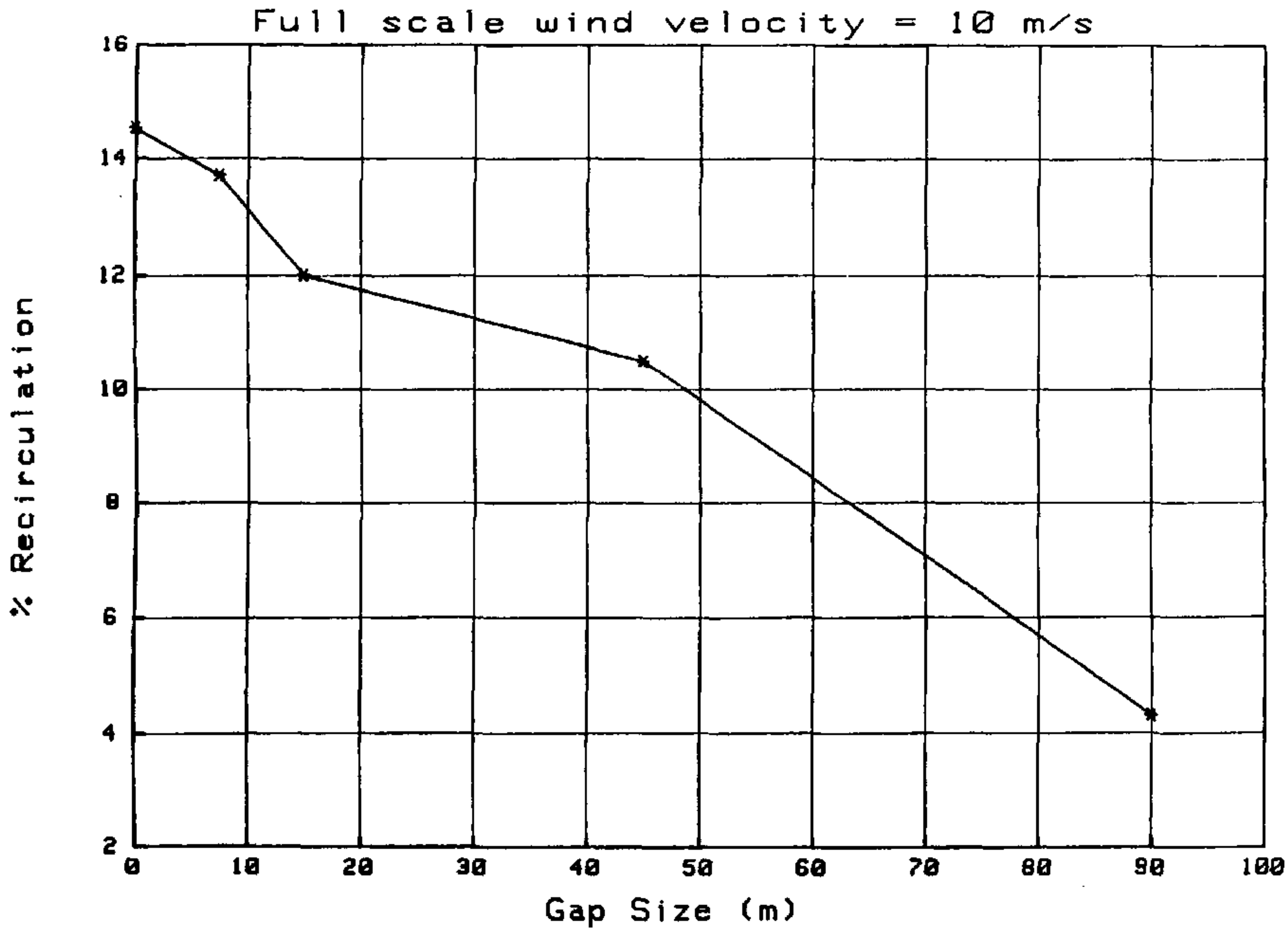

Fig 5. Test a. Effect of gap between heat exchanger and boiler house.

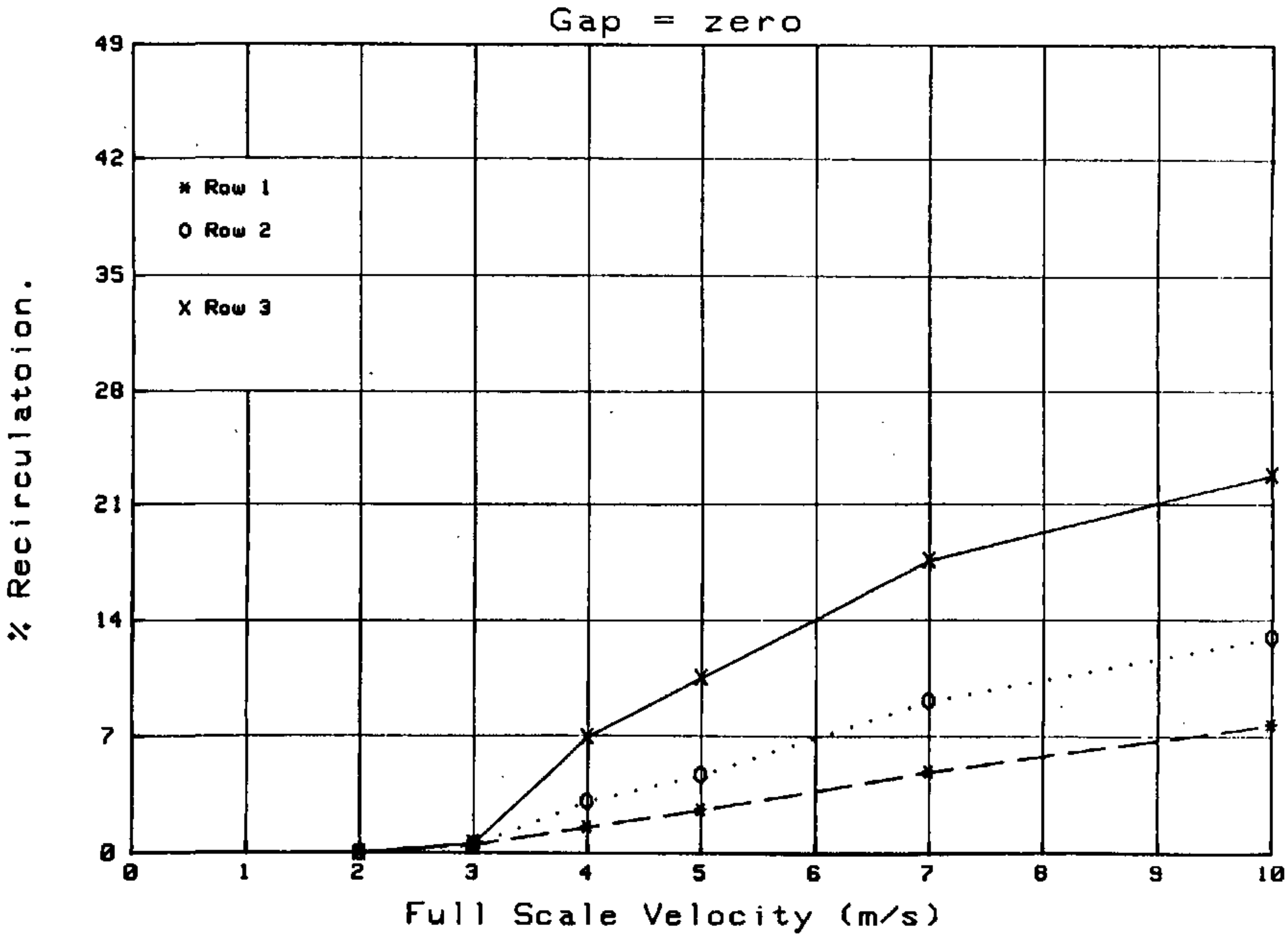

Fig 6. Test a. Effect of gap between heat exchanger and boiler house

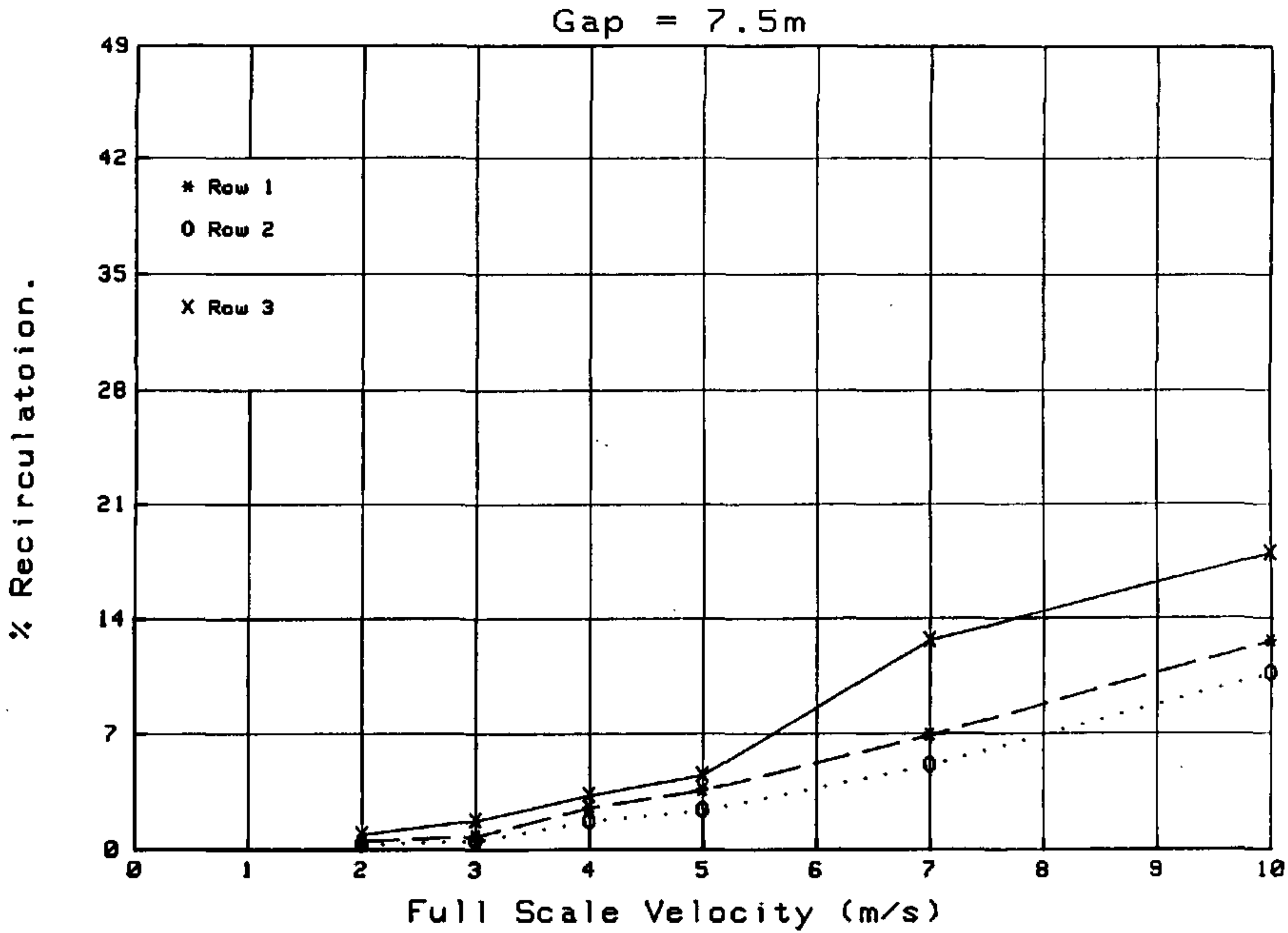

Fig 7. Test a. Effect of gap between heat exchanger and boiler house

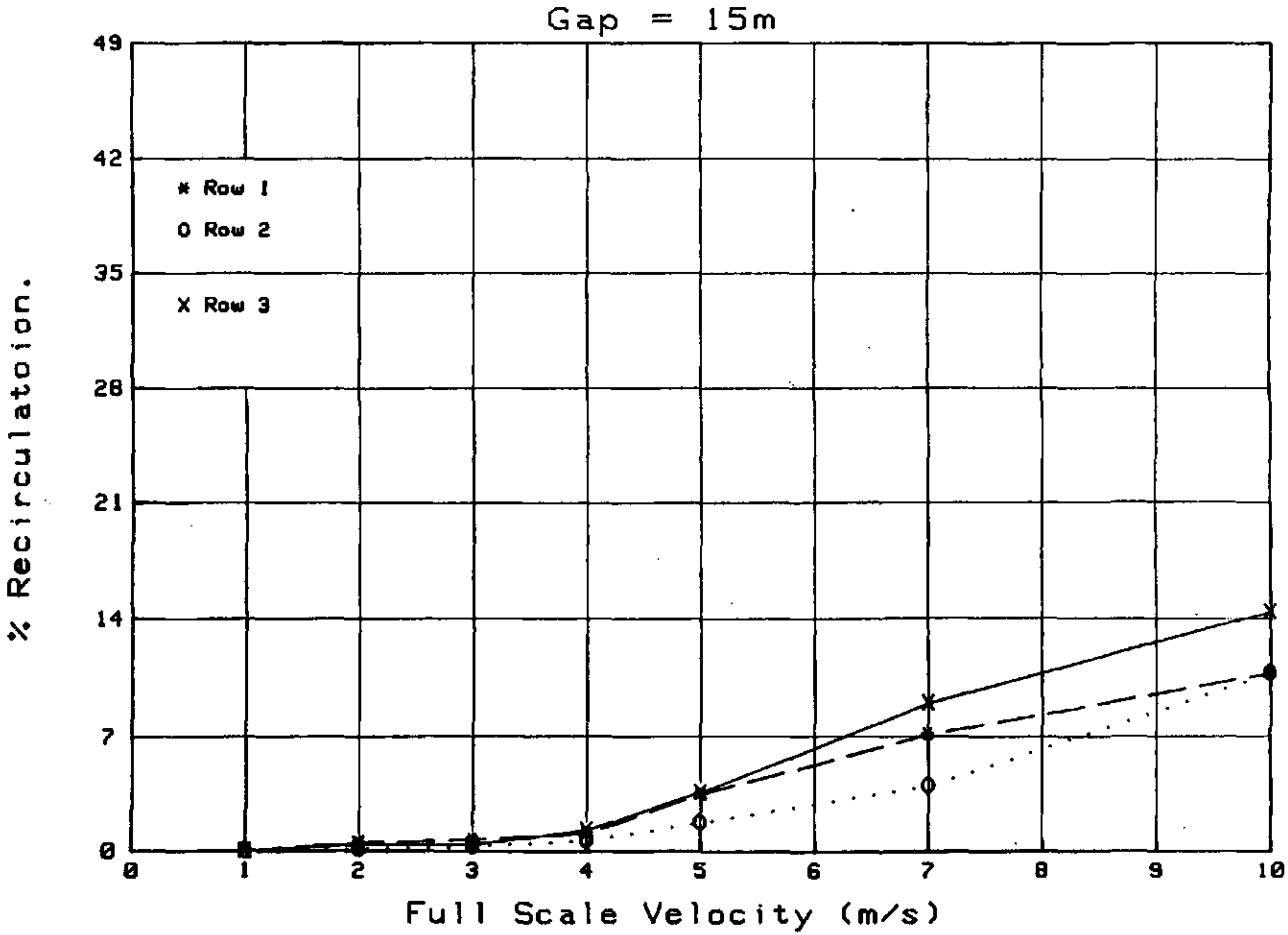

Fig 8. Test a. Effect of gap between heat exchanger and boiler house

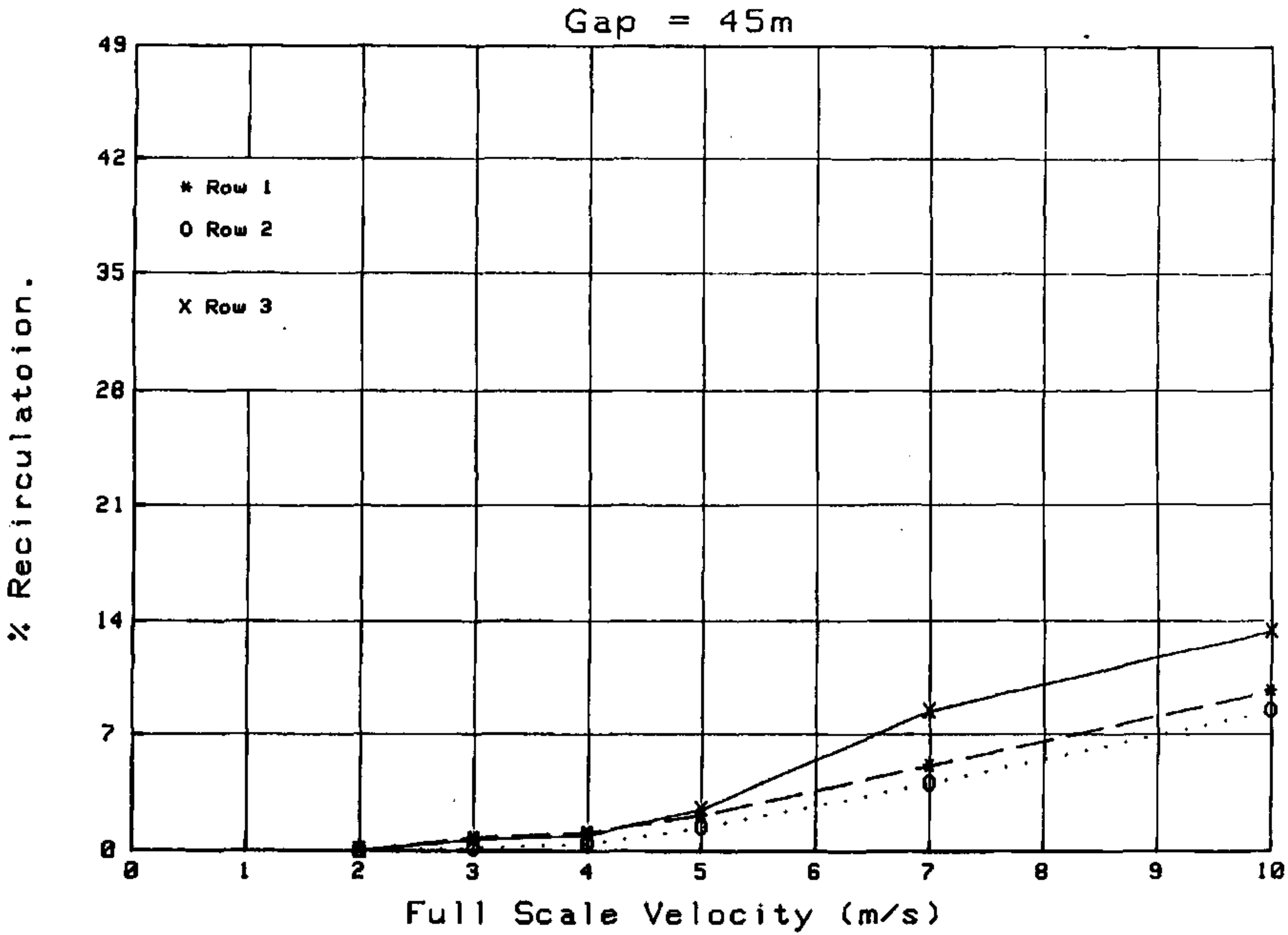

Fig 9. Test a. Effect of gap between heat exchanger and boiler house

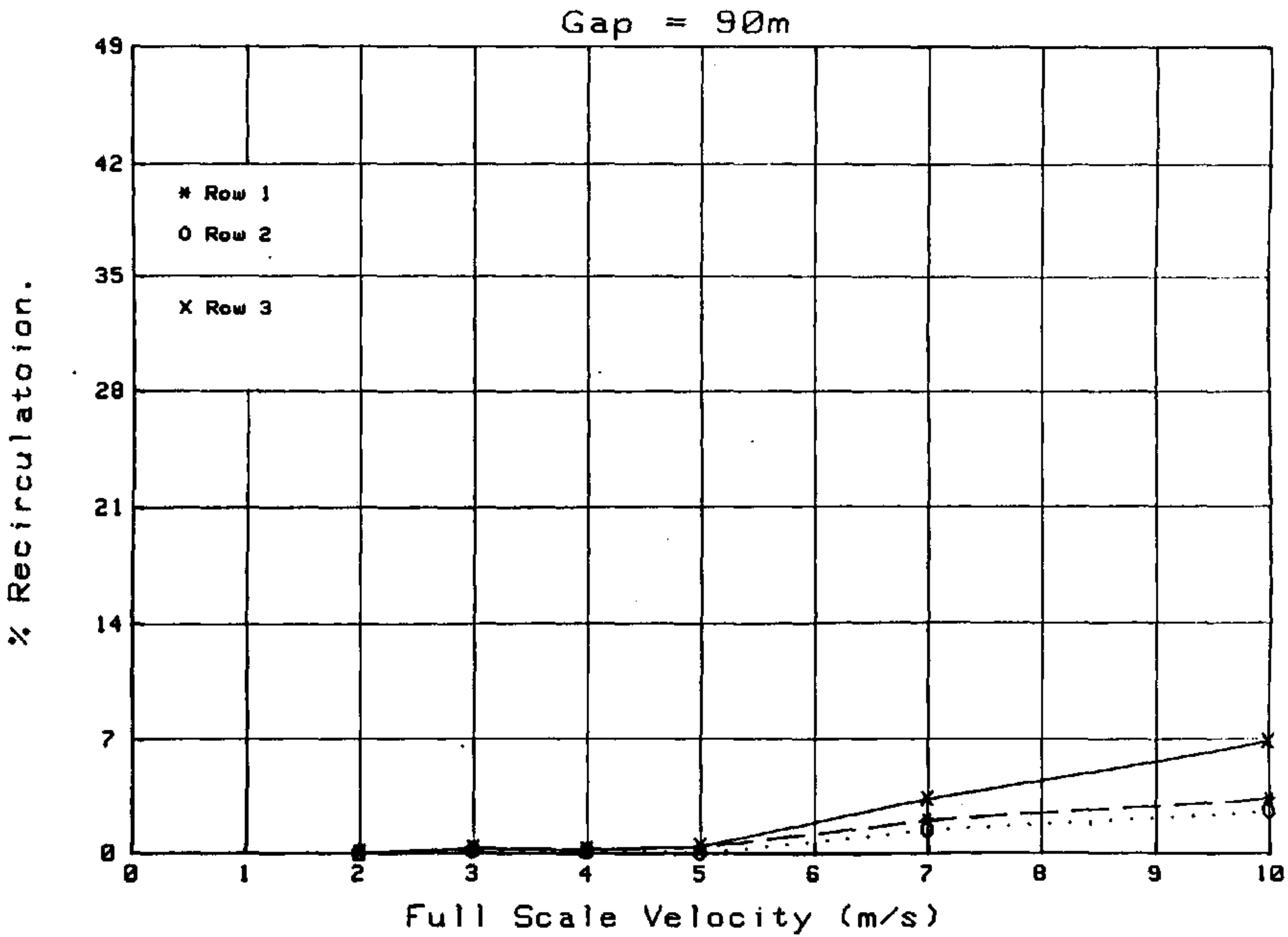

Fig 10. Test a. Effect of gap between heat exchanger and boiler house

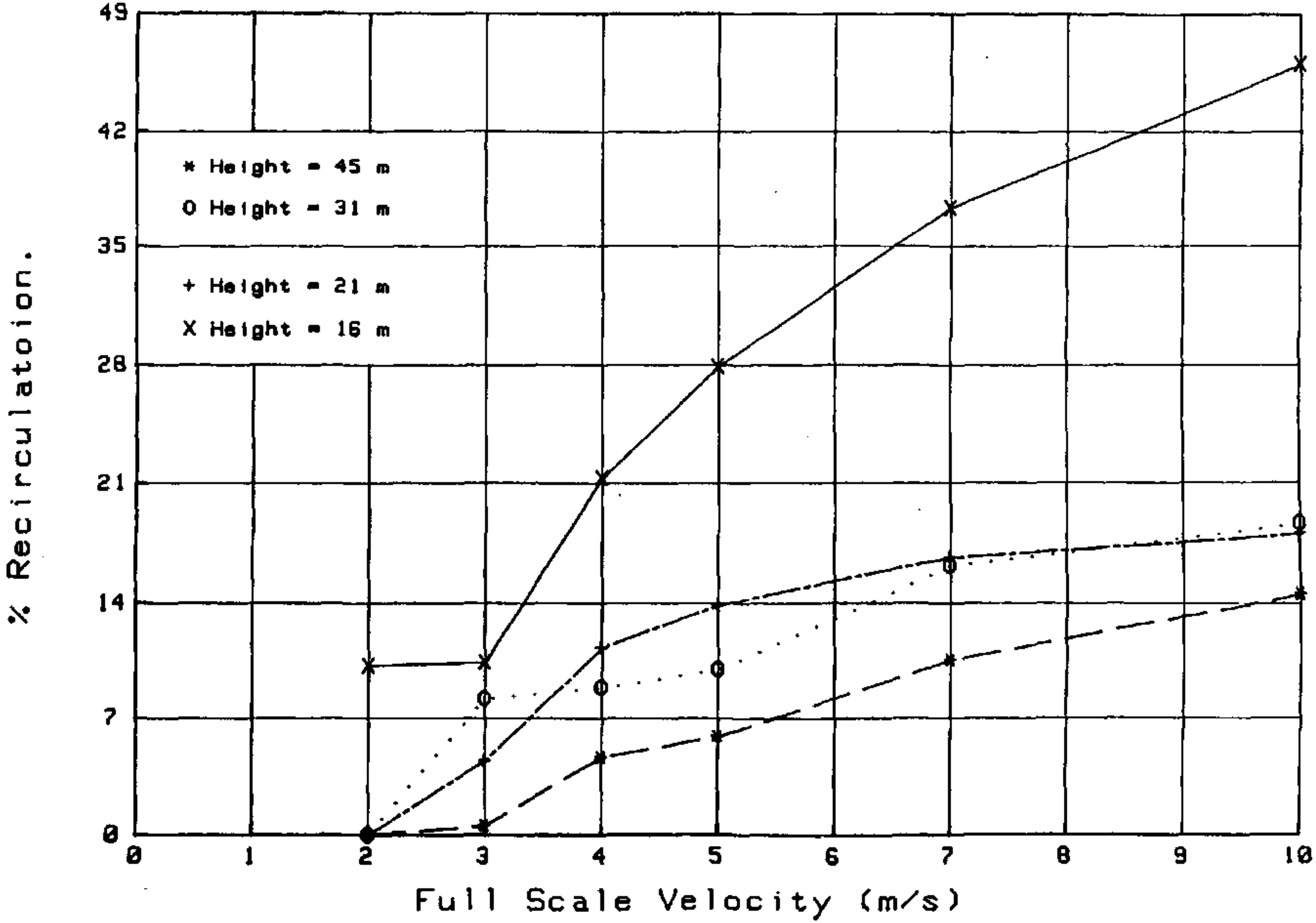

Fig 11. Test . Effects of stack height. (no cladding).

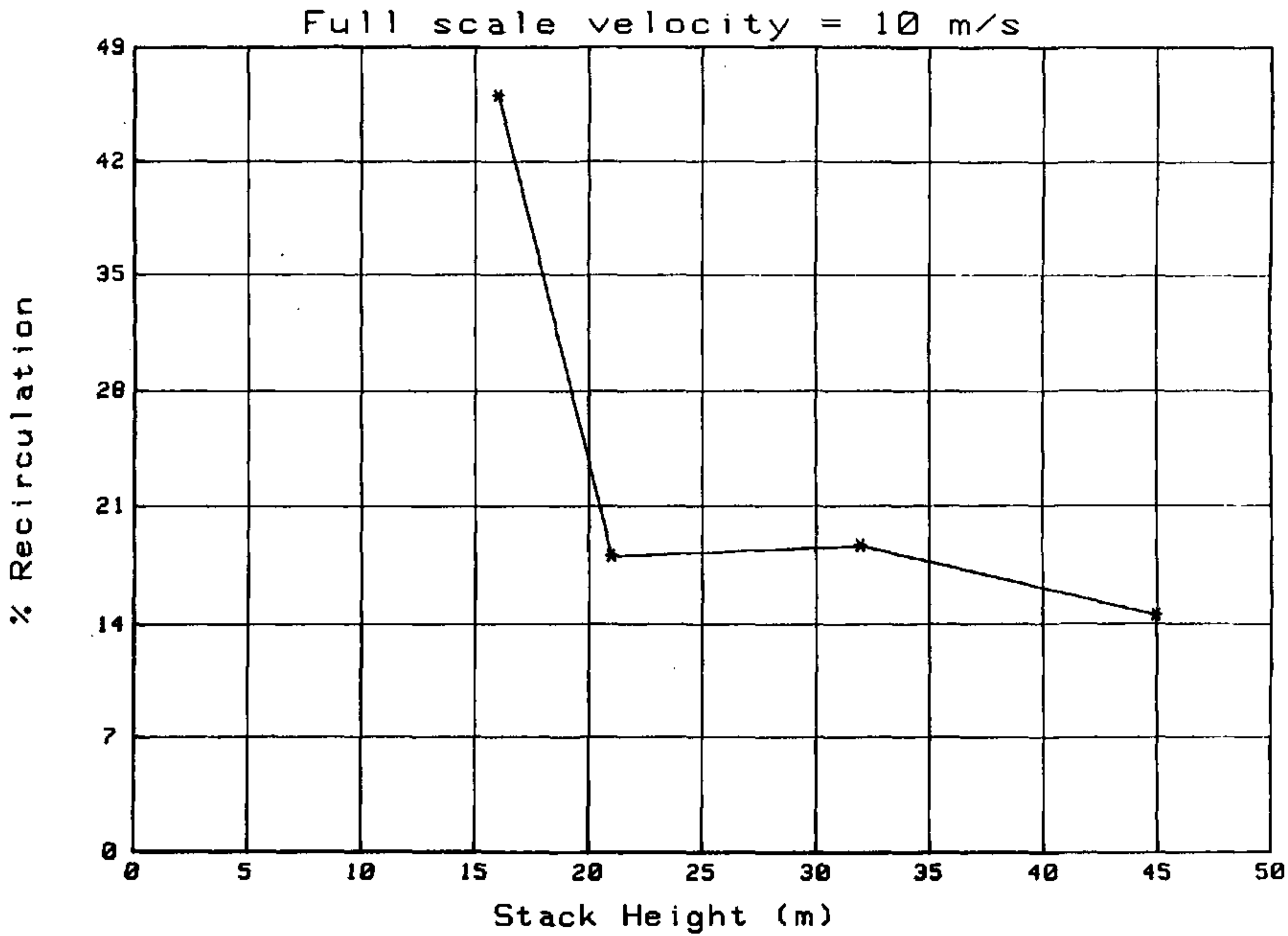

Fig 12. Test b. Effect of stack height. (no cladding).

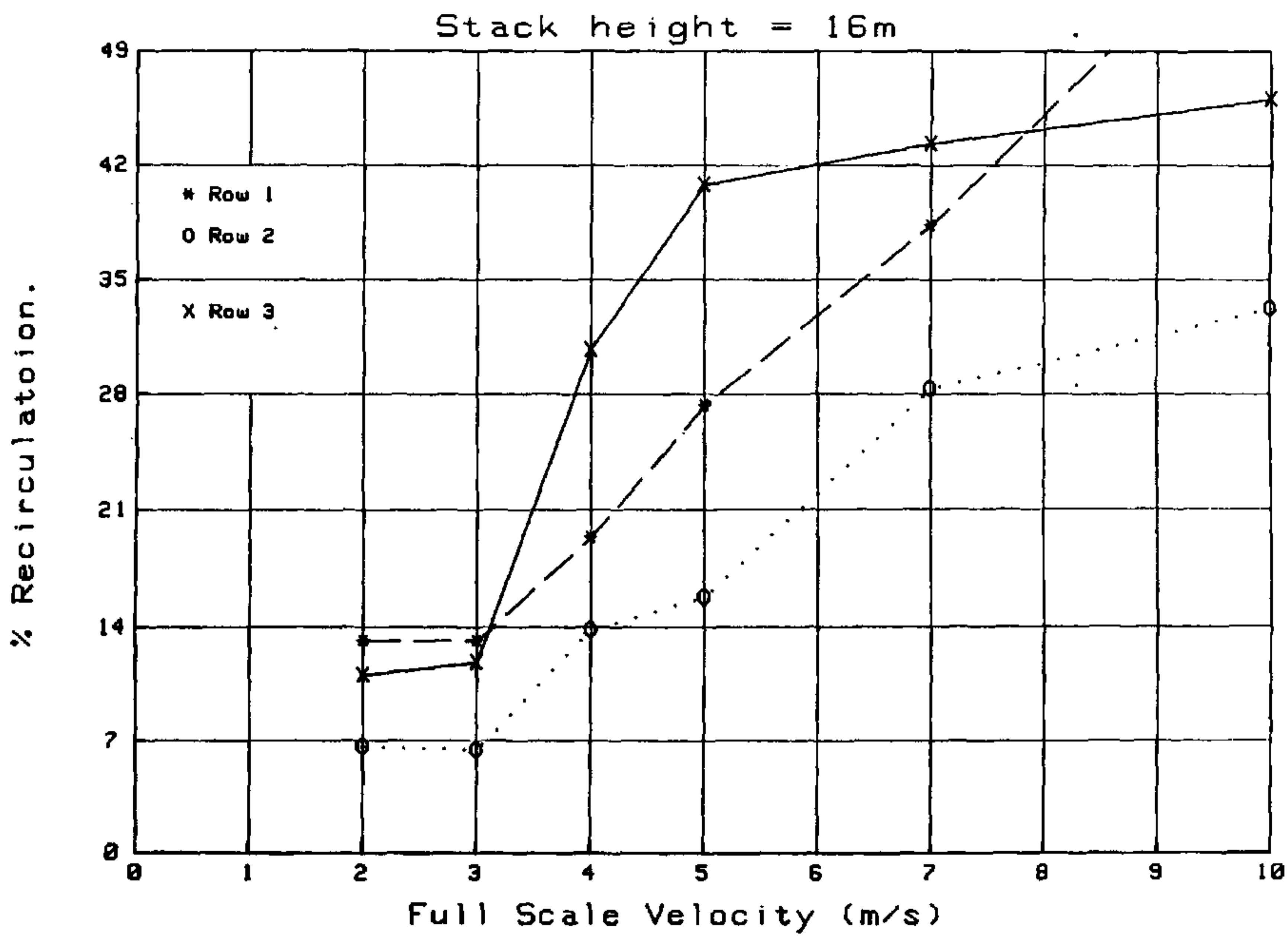

Fig 13. Test b. Effect of stack height. (no cladding).

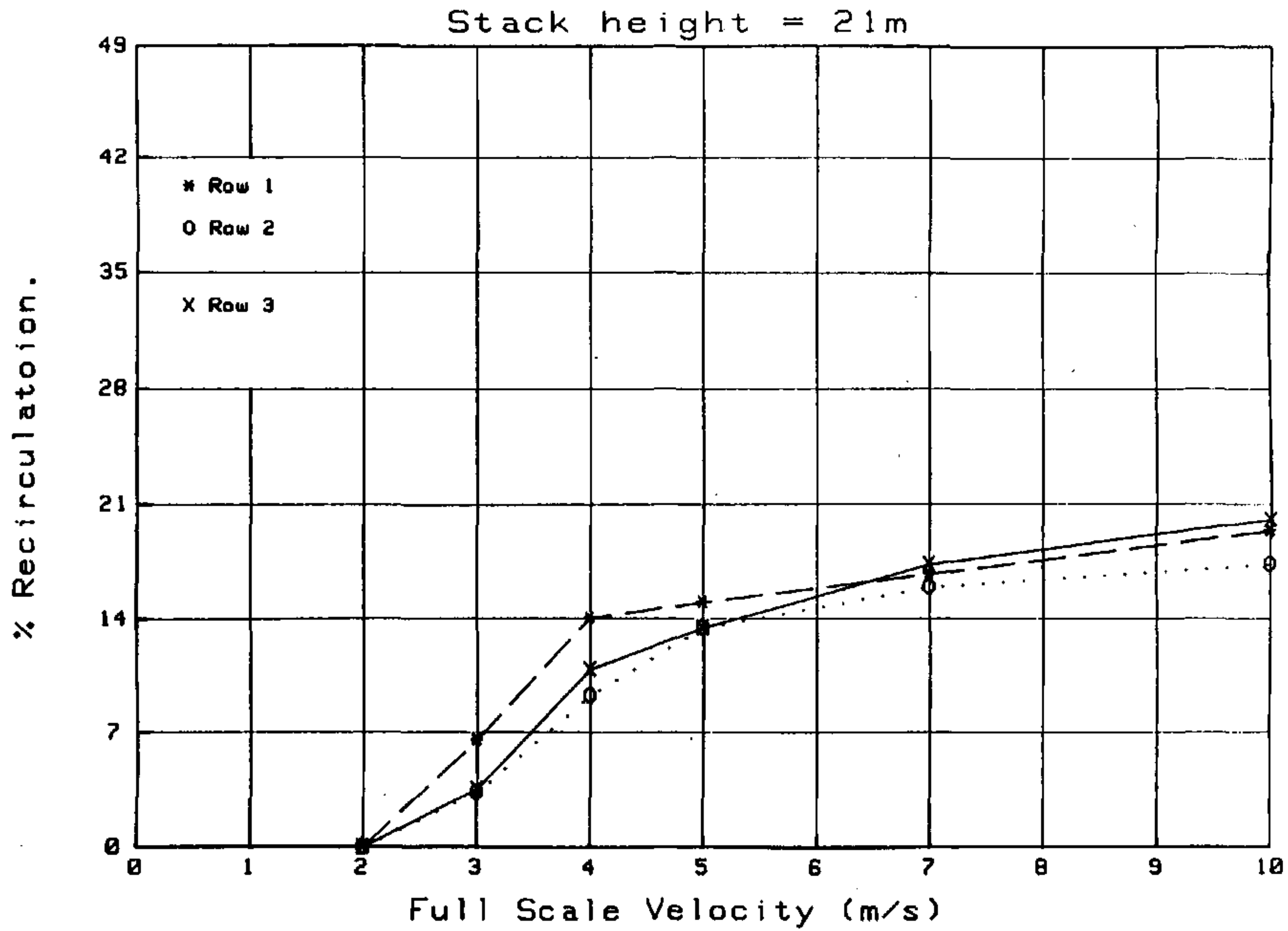

Fig 14. Test b. Effect of stack height. (no cladding).

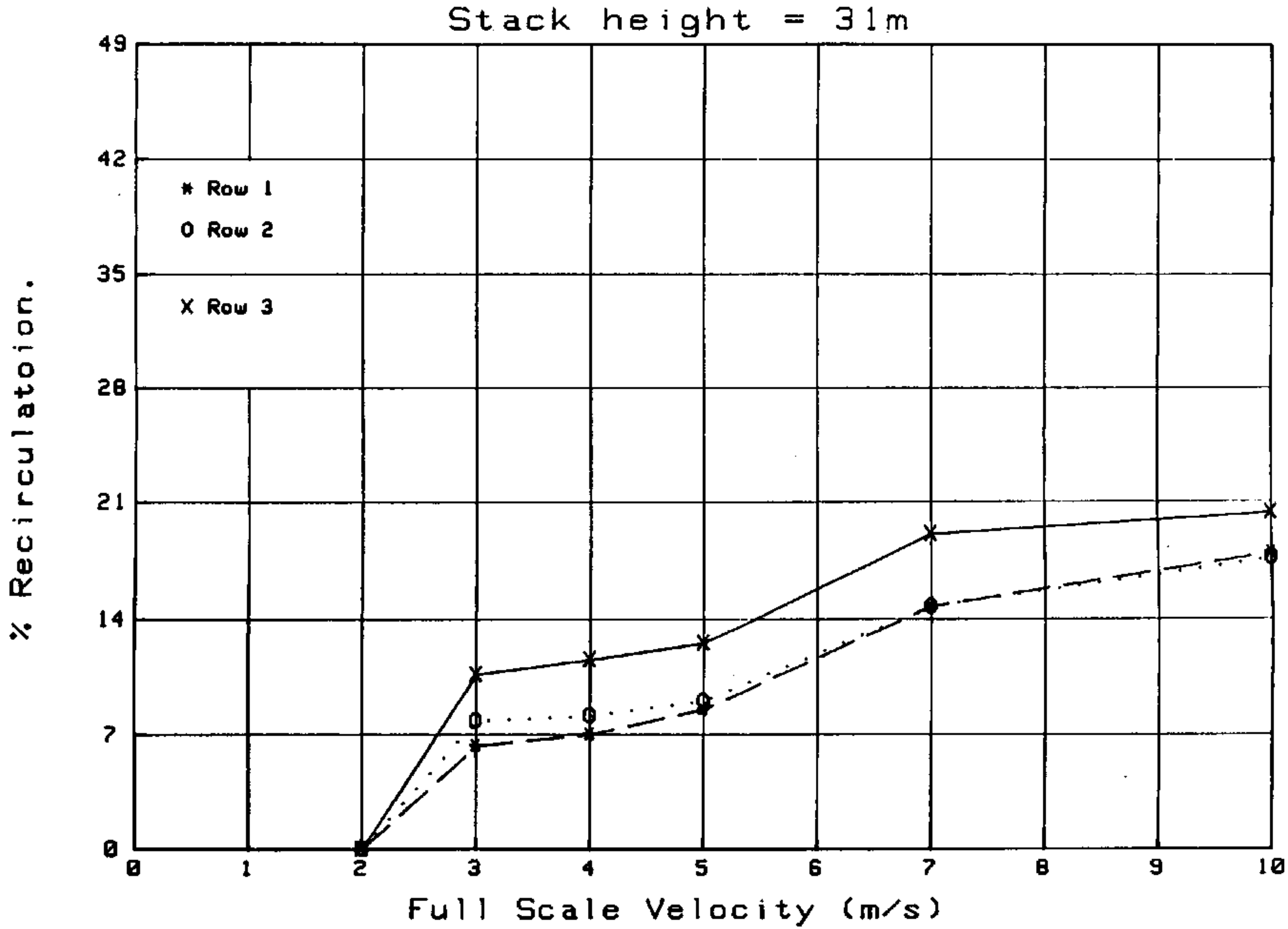

Fig 15. Test b. Effect of stack height. (no cladding).

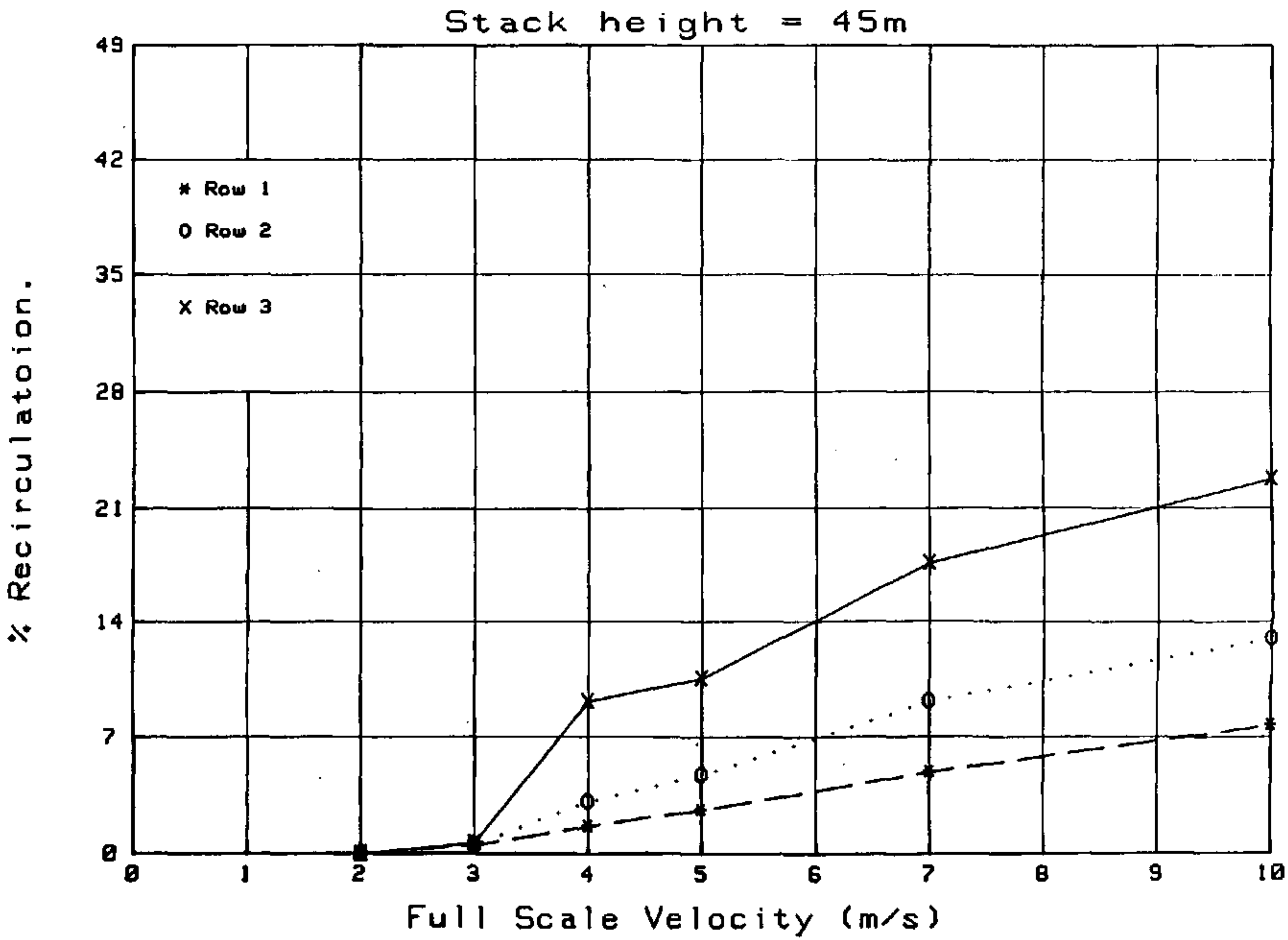

Fig 16. Test b. Effect of stack height. (no cladding).

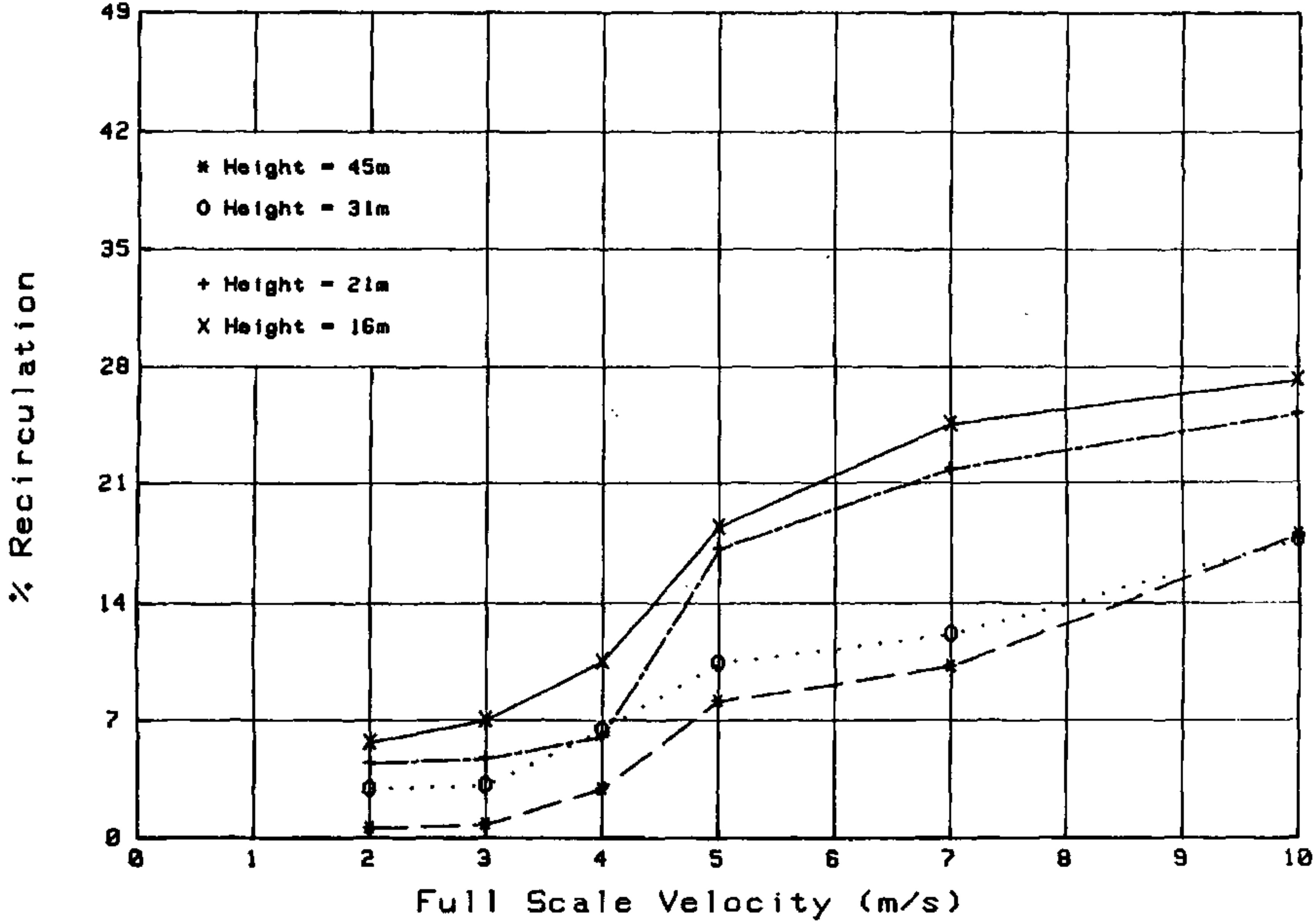

Fig 17. Test b. Effects of stack height. (with cladding).

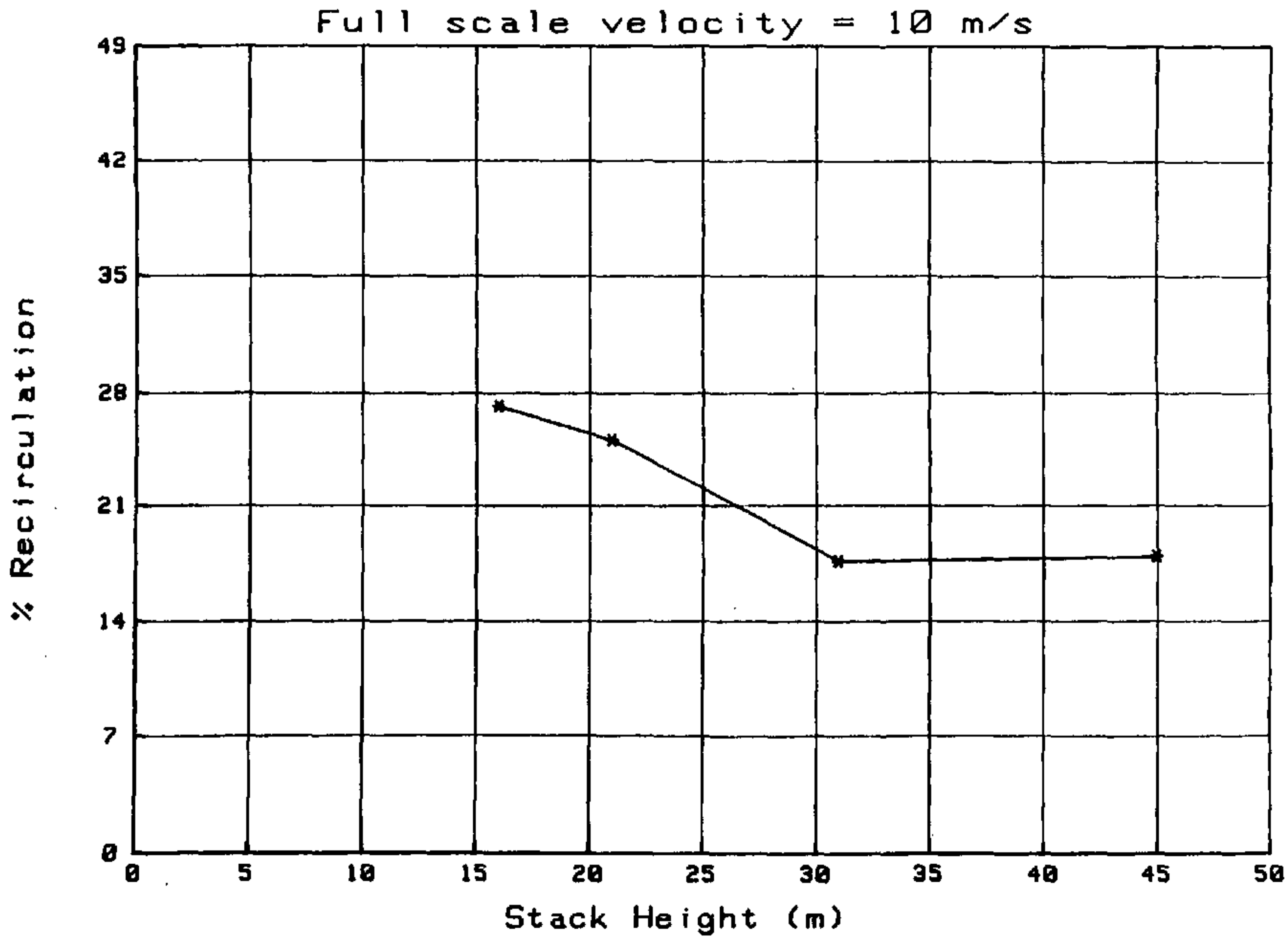

Fig 18. Test b. Effect of stack height. (with cladding).

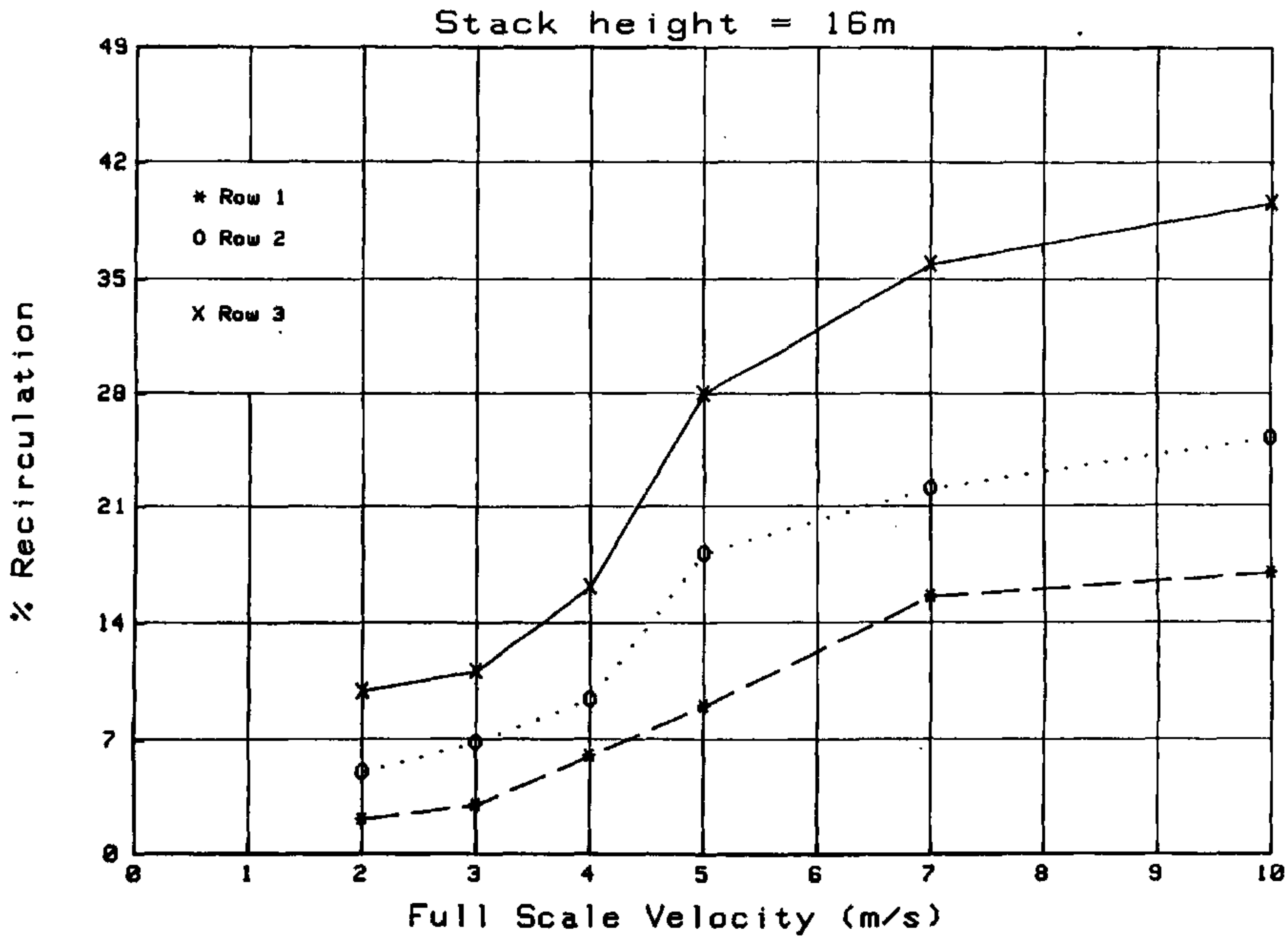

Fig 19. Test b. Effect of stack height. (with cladding).

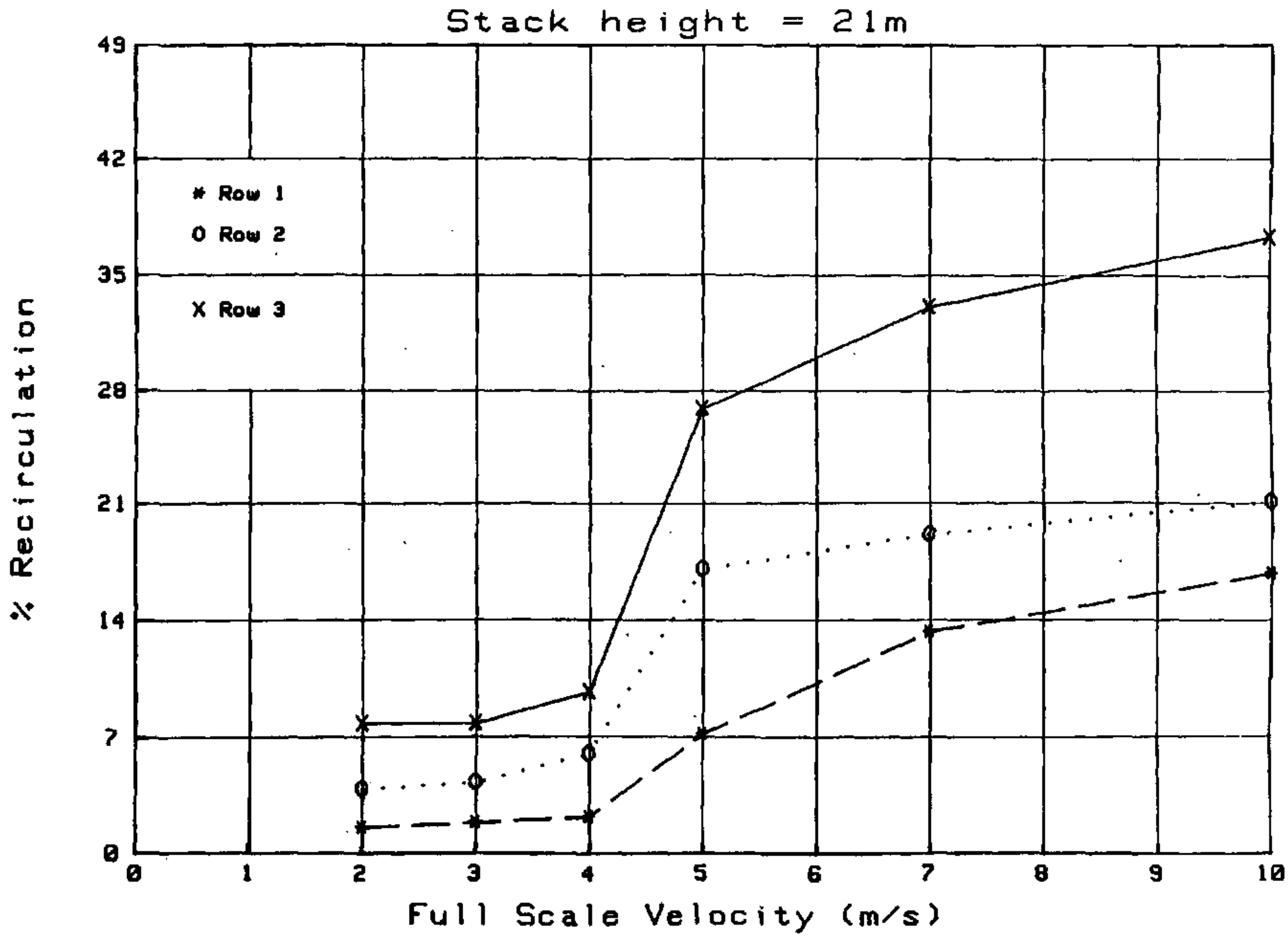

Fig 20. Test b. Effect of stack height. (with cladding).

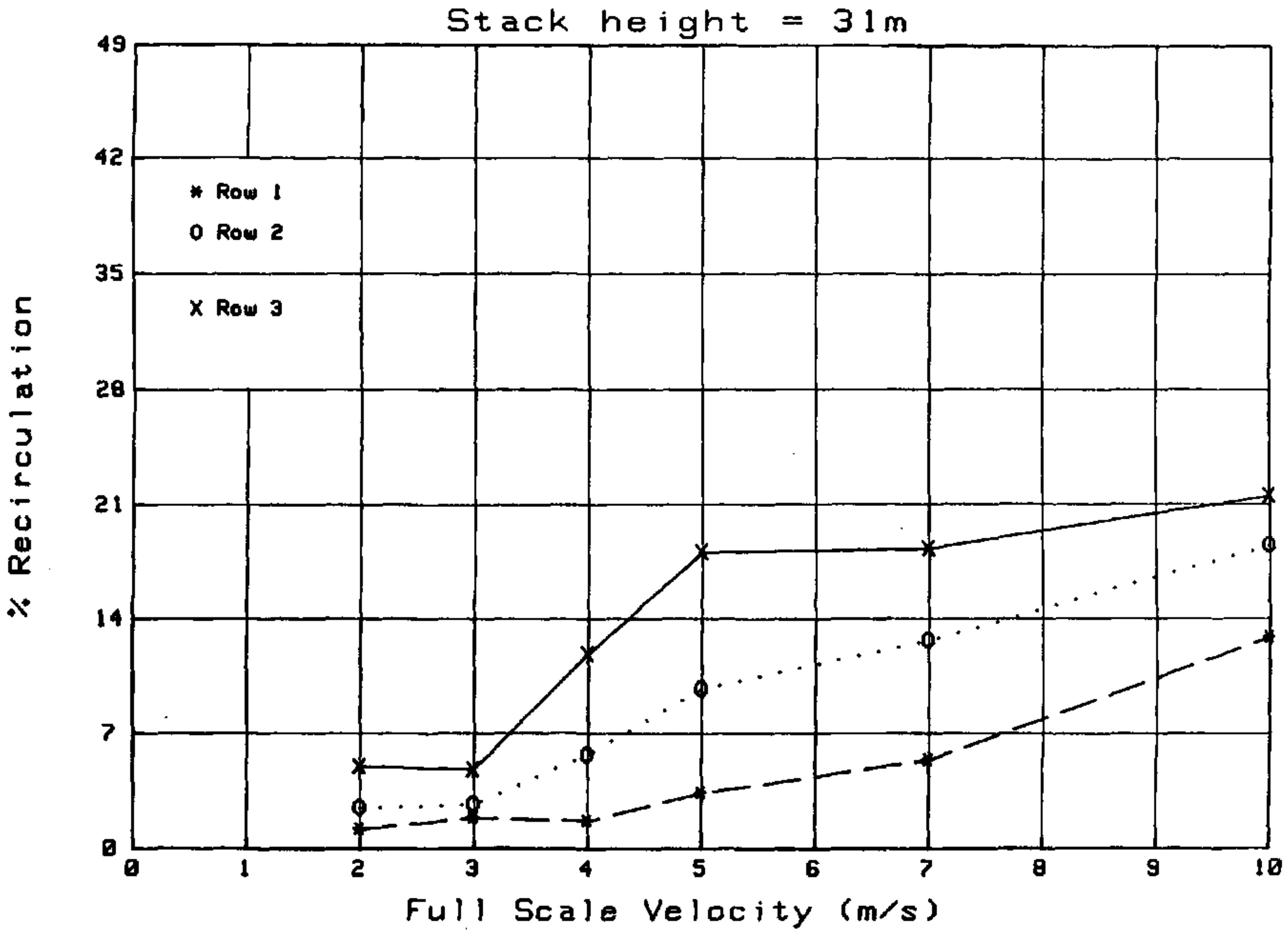

Fig 21. Test b. Effect of stack height. (with cladding).

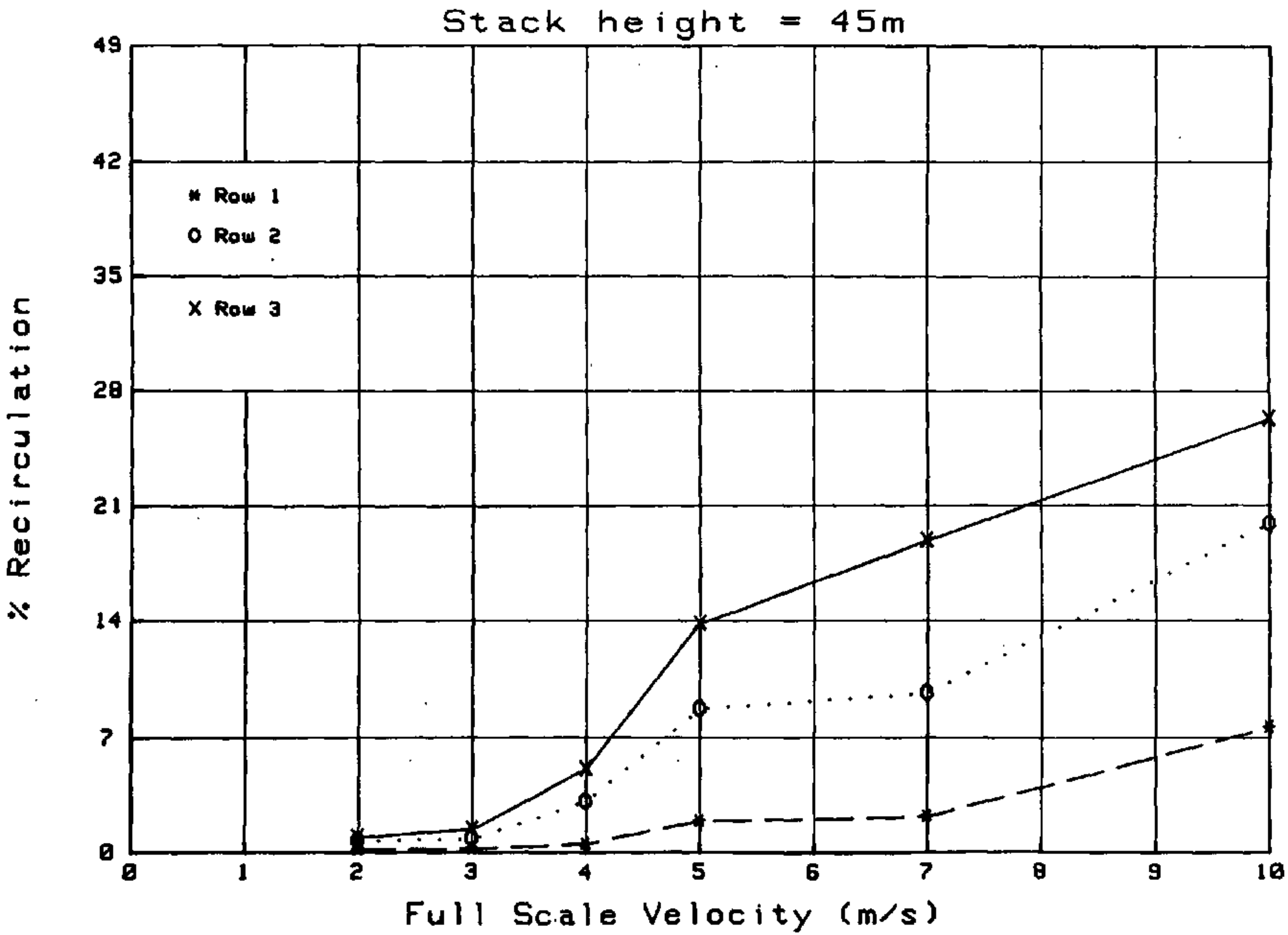

Fig 22. Test b. Effect of stack height. (with cladding).

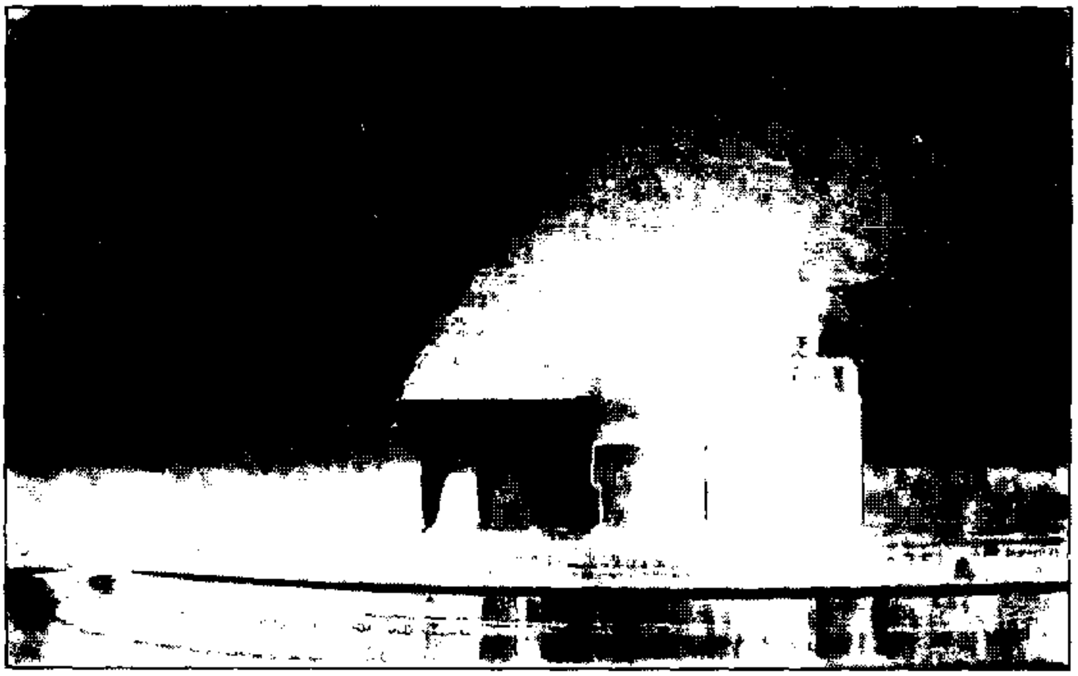

Figure 23: Test c: Appearance of simulated plume with heat exchanger upwind of boiler house. Wind speed of 4 m/s simulated.

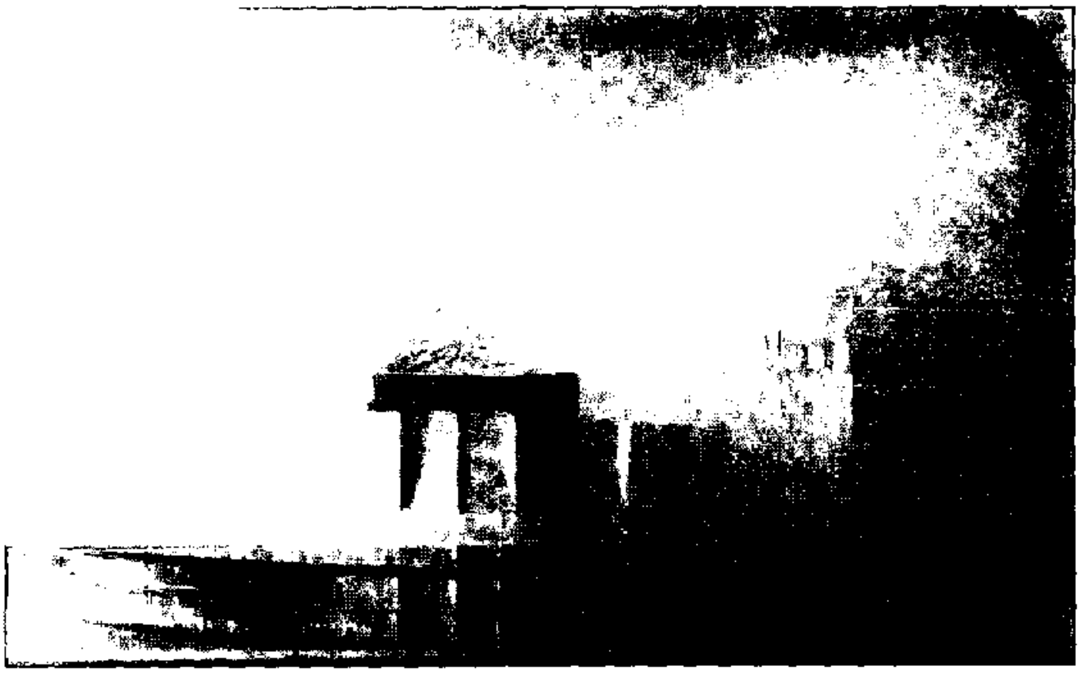

Figure 24: Test c: Appearance of simulated plume with heat exchanger upstream of boiler house. Wind speed of 6 m/s simulated.

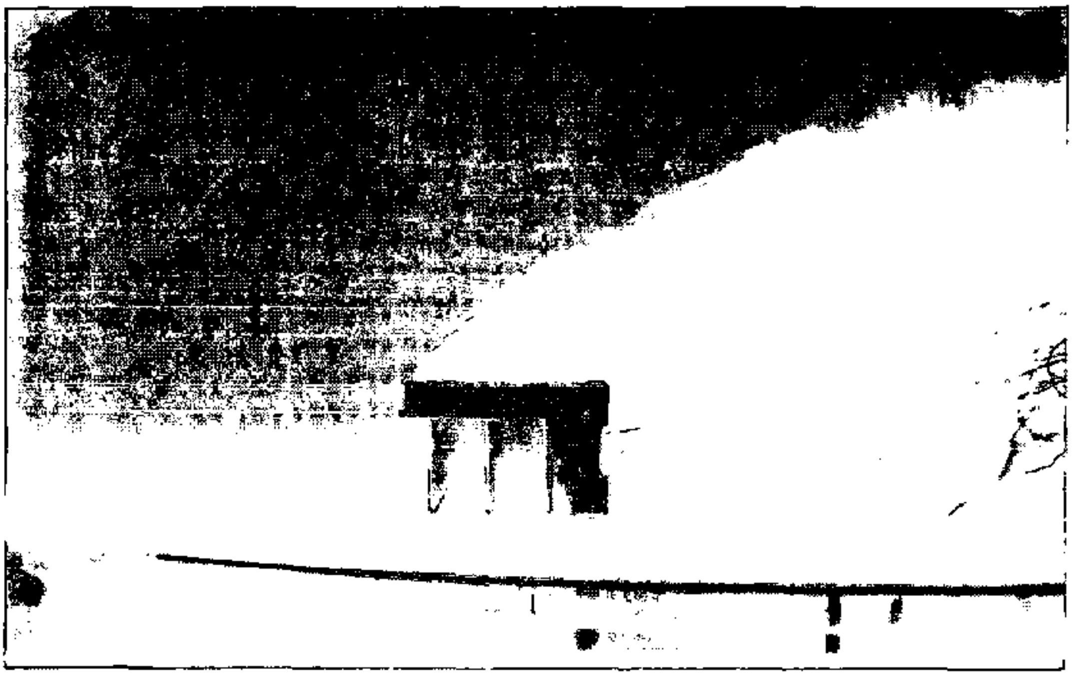

Figure 25: Test c: Appearance of simulated plume with heat exchanger upwind of boiler house. Wind speed of 10 m/s simulated.

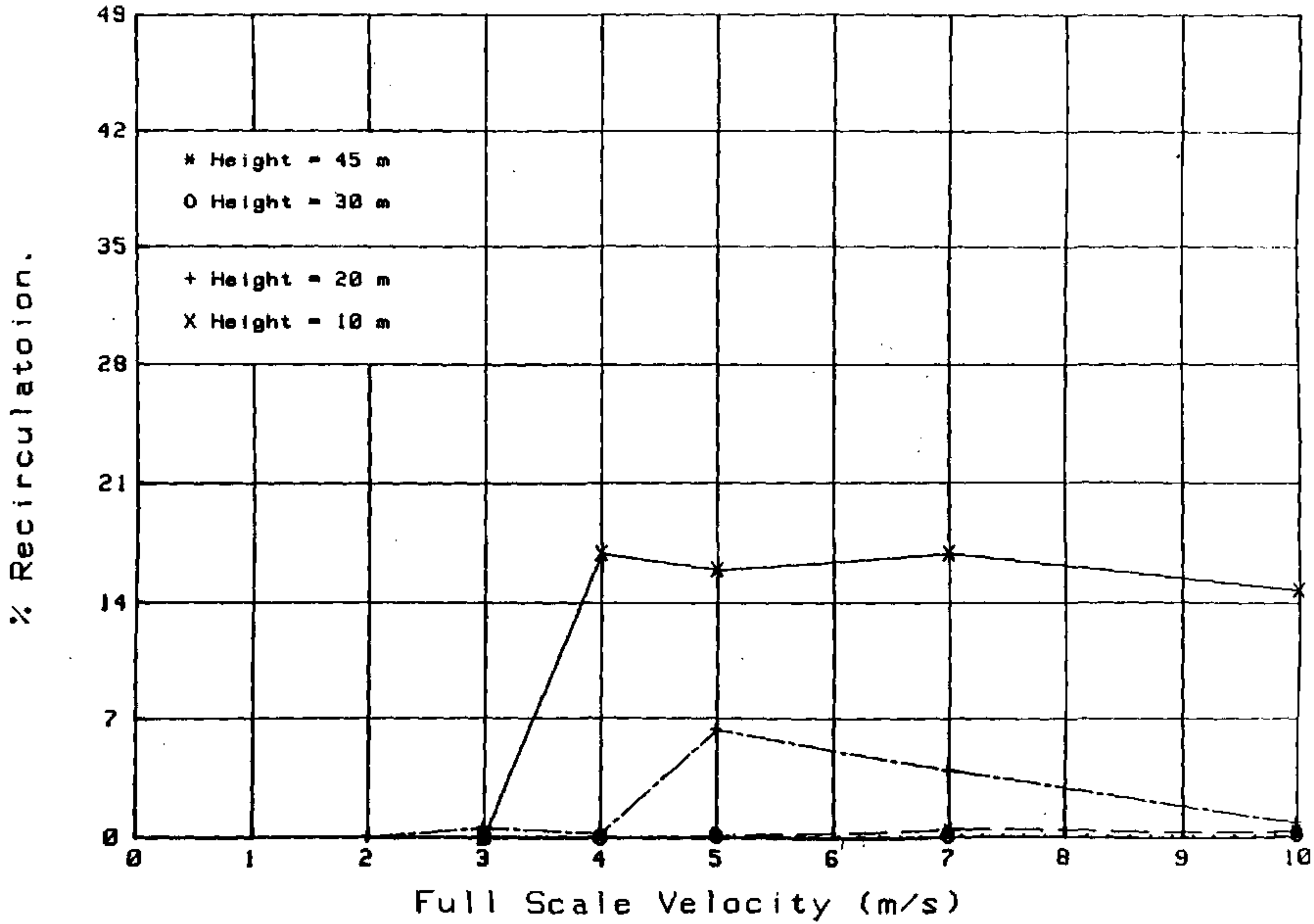

Fig 26. Test d. Effect of stack height for isolated two-dimensional heat exchanger.

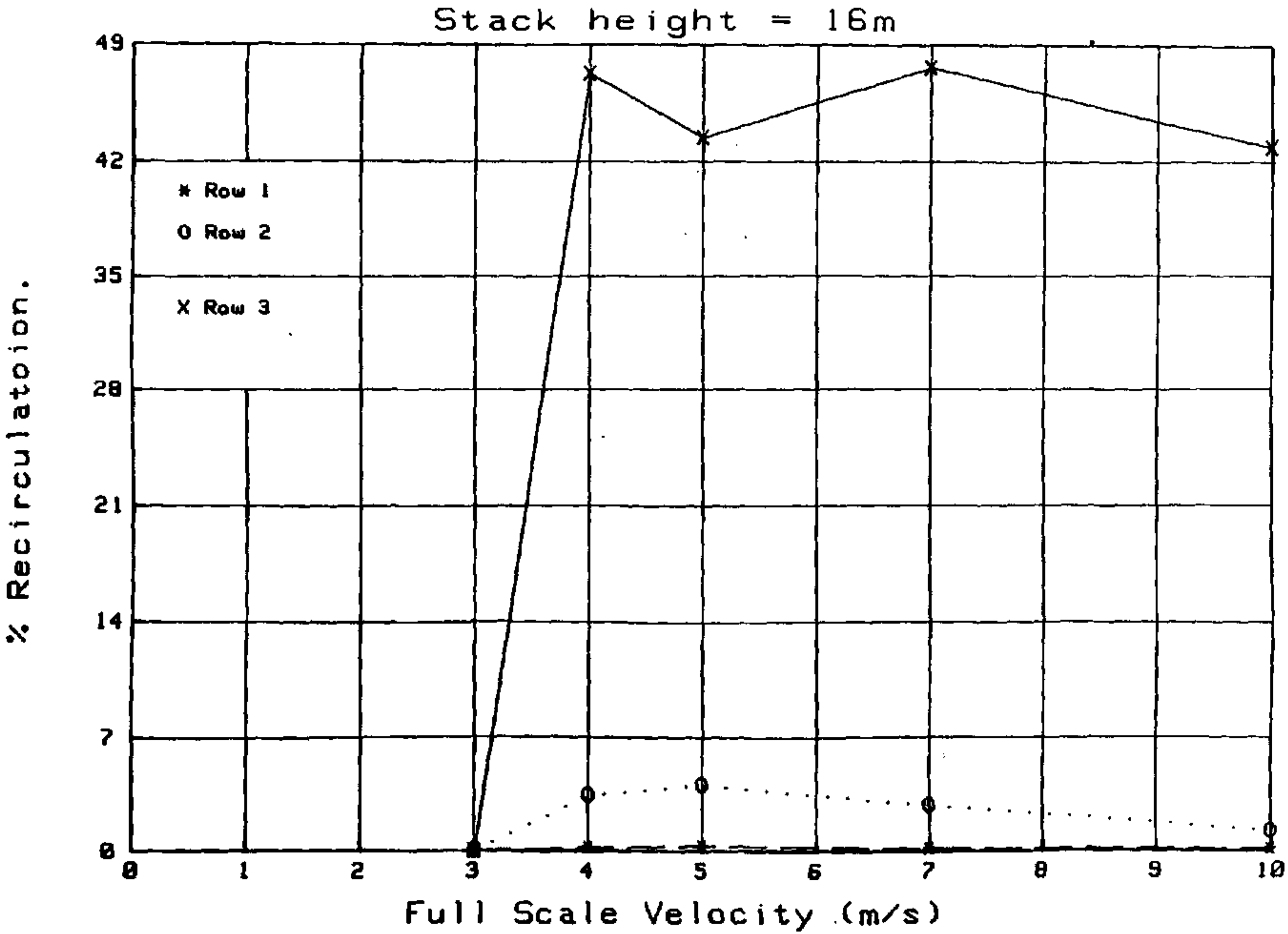

Fig 27. Test d. Effect of stack height for isolated two-dimensional heat exchanger.

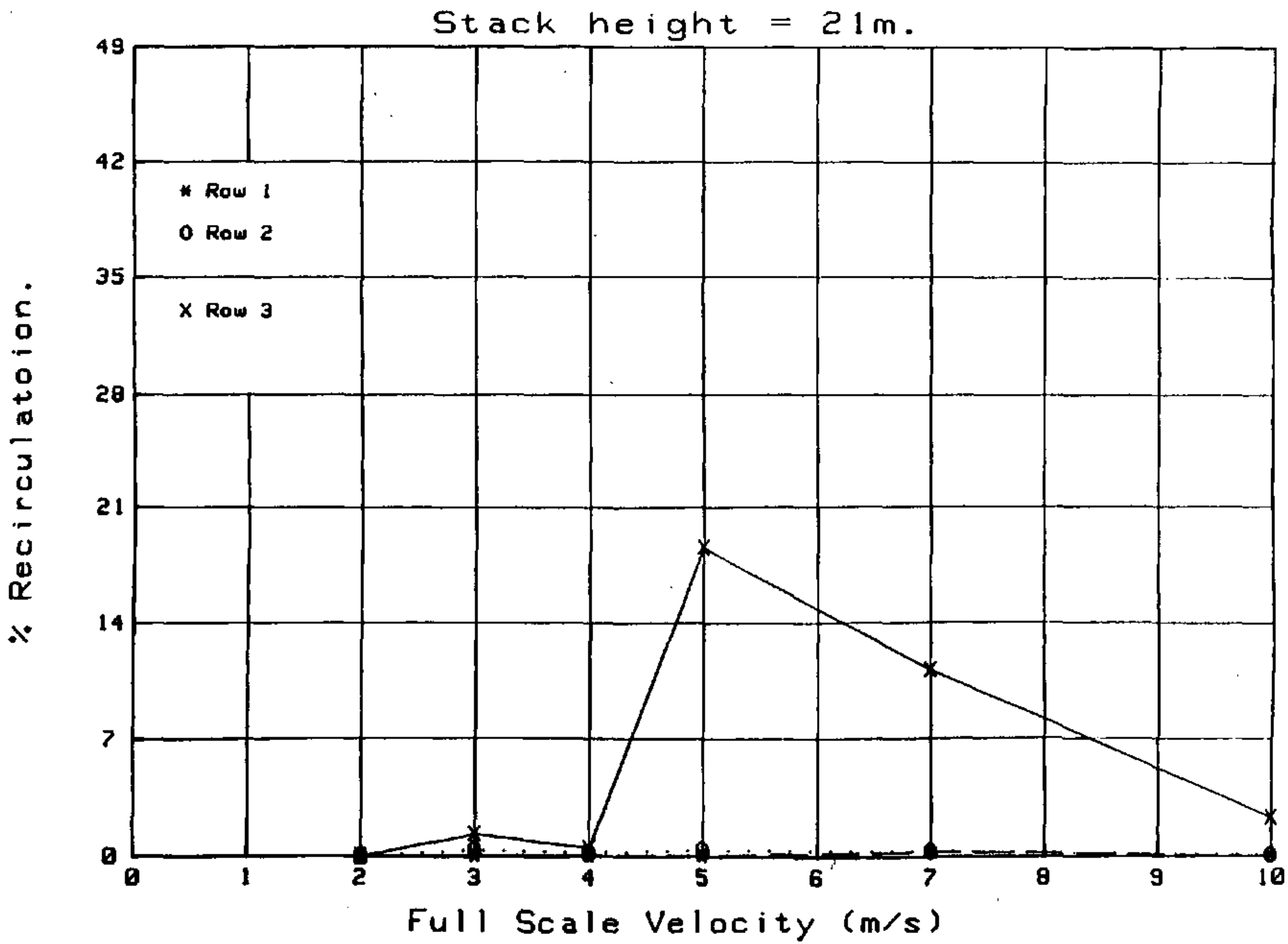

Fig 28. Test d. Effect of stack height for isolated two-dimensional heat exchanger.

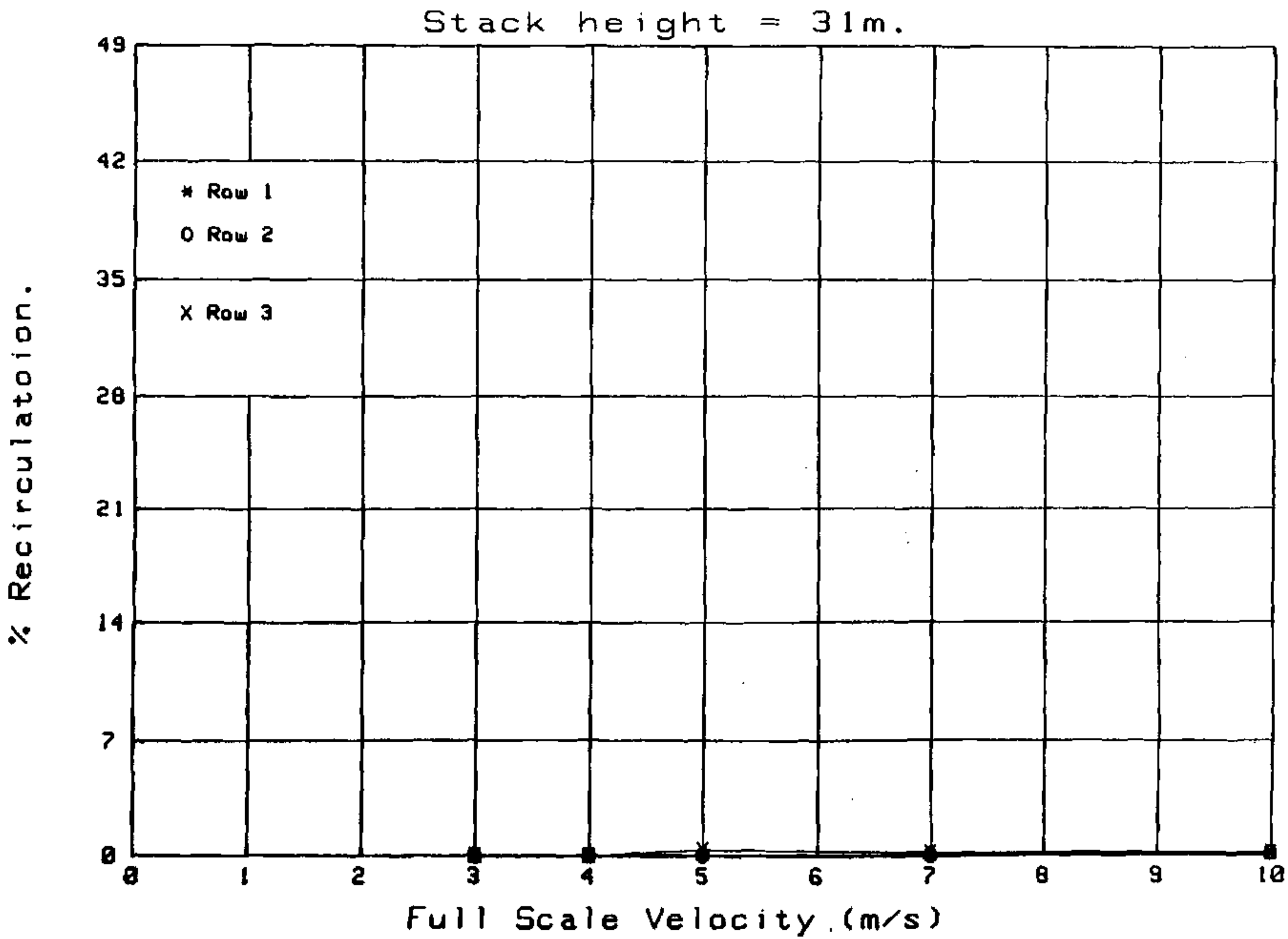

Fig 29. Test d. Effect of stack height for isolated two-dimensional heat exchanger.

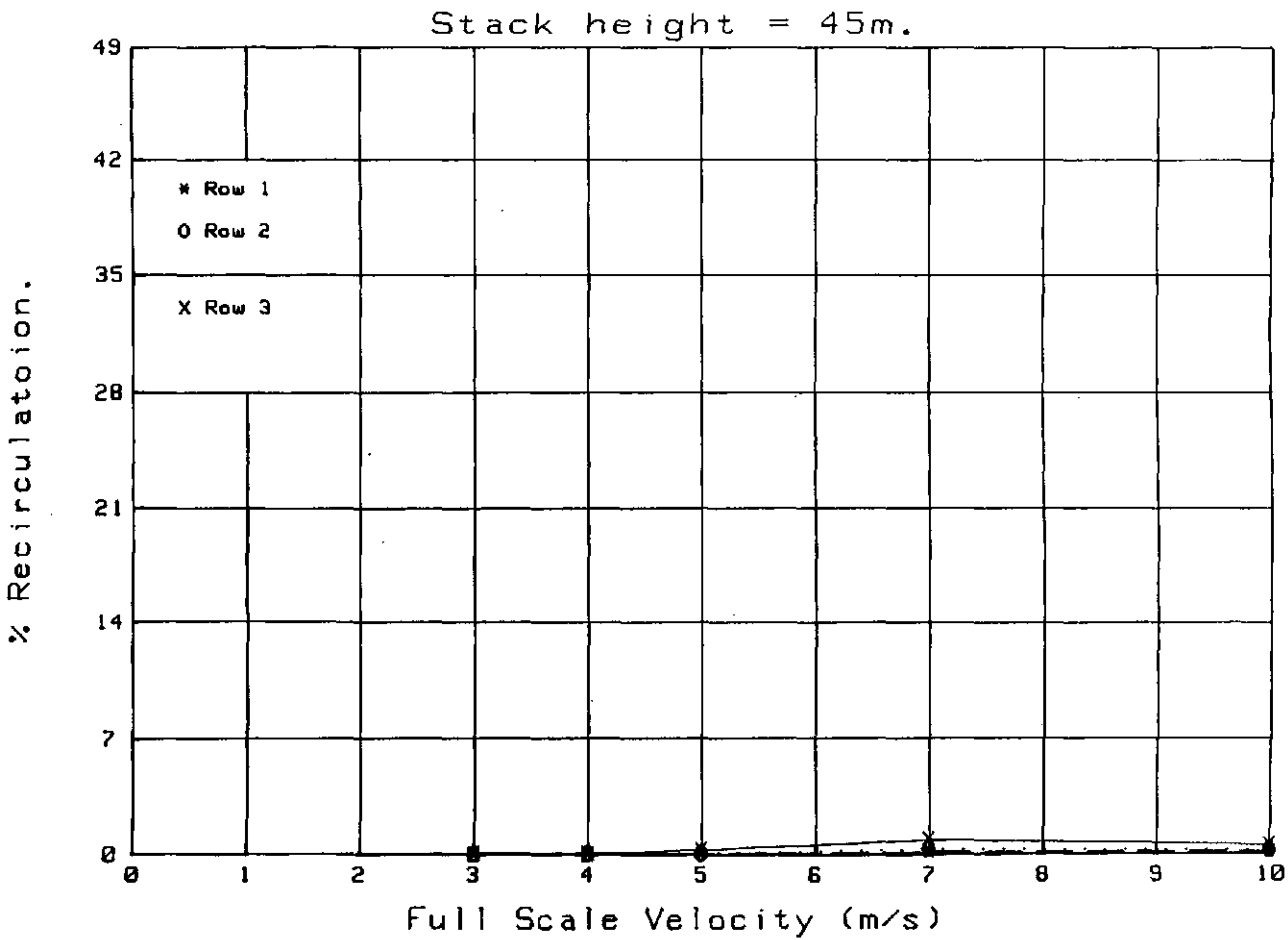

Fig 30. Test d. Effect of stack height for isolated two-dimensional heat exchanger.

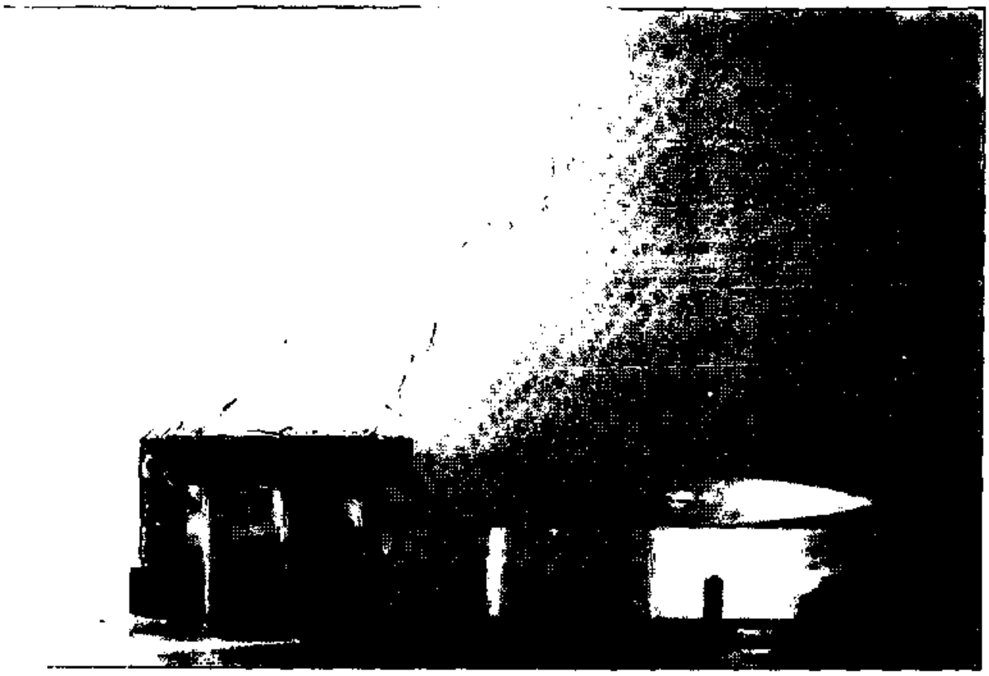

Figure 31: Test e: Two-dimensional model under calm conditions for stack height of 16 m.

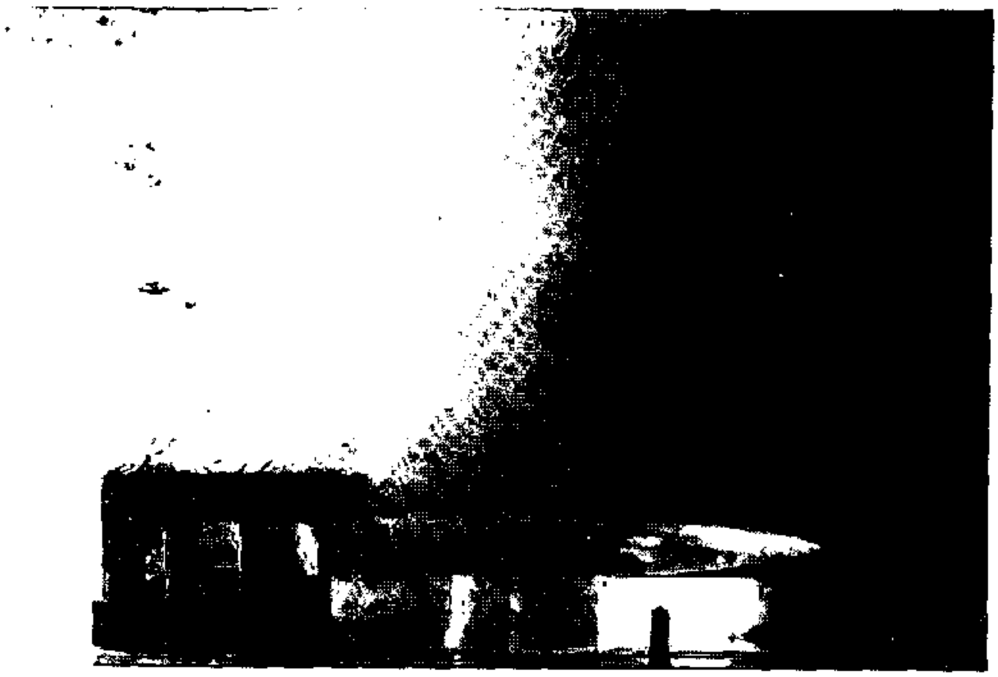

Figure 32: Test e: Two-dimensional model under calm conditions for stack height of 21 m.

Figure 33: Test e: Two-dimensional model under calm conditions for stack height of 31 m.

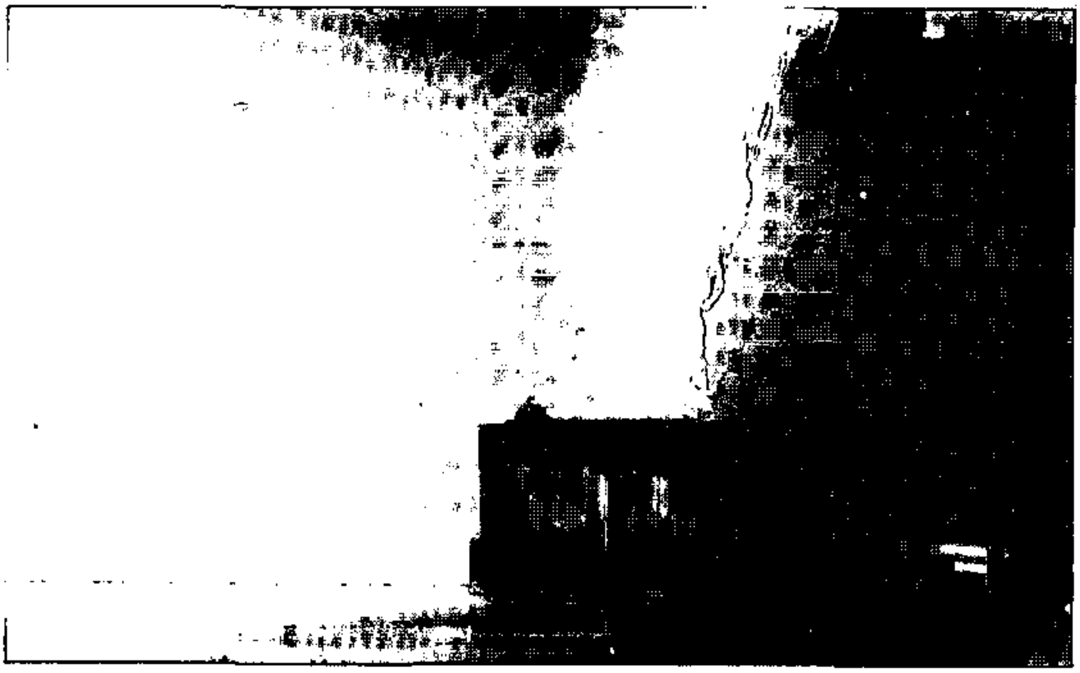

Figure 34: Test e: Two-dimensional model under calm conditions for stack height of 45 m.

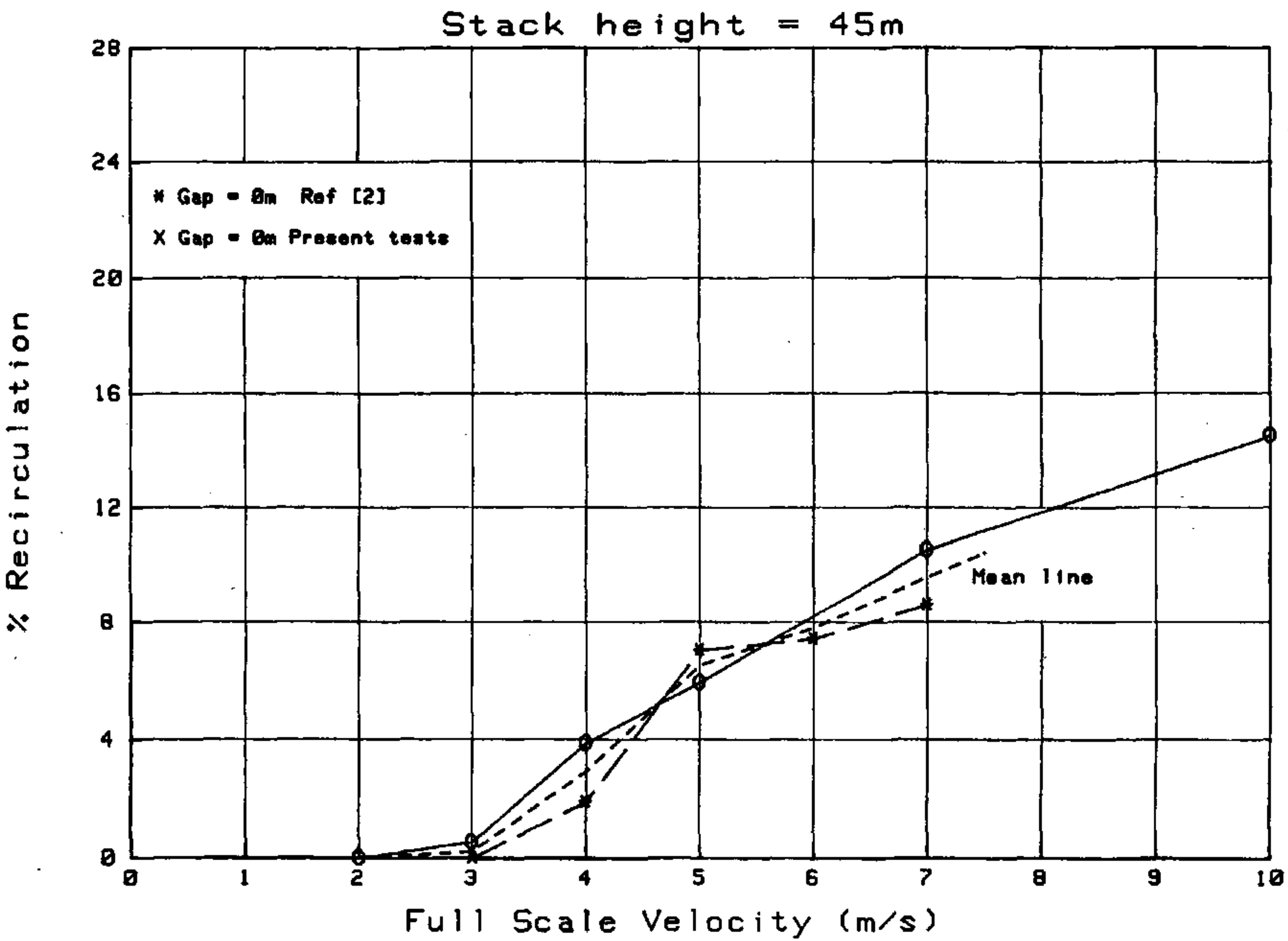

Fig 35. Comparison between current and previous results.