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EFFECT OF A WET SCRUBBER TO REDUCE RADIOACTIVE AEROSOL AND DUST CONCENTRATIONS IN UNDERGROUND URANIUM MINES

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ABSTRACT

The effect of a wet scrubber in controlling long-lived and short-lived radionuclides associated with airborne particulate matter in the submicron and respirable ranges was investigated during hard rock crushing operations at a crusher plant in an underground uranium mine. The crusher was located underground. Dust loaded air from crushing operations was fed to the wet scrubber via an intake plenum and ducting system. Measurements were made of long-lived radioactive dust concentration and radon progeny and thoron progeny Working Levels. Additionally, mineral dust and radioactive dust size distributions were also determined by means of 8-stage cascade impactors. Measurements were preferentially conducted at the crusher platform, the scrubber, and in an area adjacent to the crusher. The data show the wet scrubber was very efficient in reducing the concentration of long-lived radioactive dust and in removing radioactive particulate matter of size greater than about 2 μm. A modest reduction in radon progeny and thoron progeny concentration was also noticed during the operation of the wet scrubber. The data indicate the wet scrubber tested was very efficient in controlling long-lived radioactive dust concentrations in underground uranium mine operations.

Key words: Wet scrubber; Uranium mines; Radioactive dust; Emissions.

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EFFET D'UN ÉQUIPEMENT D'ÉPURATION PAR VOIE HUMIDE POUR ÉLIMINER LES AÉROSOLS RADIOACTIFS ET LES CONCENTRATIONS DE POUSSIÈRE DANS LES MINES D'URANIUM SOUTERRAINES

par

J. Bigu*, M. Grenier** et S. Hardcastle**

RÉSUMÉ

On a étudié l'effet d'un équipement d'épuration par voie humide pour contrôler les radionucléides de longue et de courte période. Ces radionucléides sont associés à la matière des particules inhalables aéroportées, en suspension dans l'air. L'étude a été menée pendant des travaux de concassage de roche dure, dans une mine d'uranium souterraine. Le concasseur se trouvait sur les lieux. On a utilisé une chambre de surpression dotée d'une prise d'air et un conduit aéraulique pour acheminer l'air vers l'équipement d'épuration par voie humide. La granulométrie de la poussière radioactive concentrée, de même que celle des descendants du radon et du thoron a été mesurée. De plus, la dimension des particules de poussière minérale et de poussière radioactive a également été déterminée au moyen d'un impacteur à huit étages. Les mesures ont été effectuées sur la plateforme ou se trouvaient le concasseur et l'équipement d'épuration, de préférence à proximité du concasseur. Les données indiquent que l'équipement d'épuration par voie humide est très efficace pour réduire la concentration de poussière radioactive et éliminer les particules dont la dimension est supérieure à environ 2 µm. On a également pu observer une faible diminution des concentrations de descendants du radon et du thoron pendant que l'épurateur était en service. Les données indiquent que l'équipement d'épuration sur lequel a porté l'essai est très efficace pour le contrôle des concentrations de poussière radioactive dans les mines d'uranium souterraines.

Mots-clé : équipement d'épuration par voie humide; mines d'uranium; poussière radioactive; émissions.

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INTRODUCTION

Significant amounts of dust in the respirable range (<1-10 μm) and greater than 10 μm size are generated in mining operations and activities associated with mining operations (1). The inhalation of such dusts poses a potential health hazard (1). The inhalation of dust containing radionuclides can pose an even greater potential occupational health concern (2).

In underground uranium mines, dust emissions contain certain radionuclides. These radionuclides have been identified by a variety of methods, such as α- and γ-spectrometry, and neutron activation analysis (3,4). The radionuclides identified include the parents of the natural uranium and thorium decay chains (^{238}U, ^{235}U, ^{232}Th) and their short-lived and long-lived decay products, e.g., ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn, ^{228}Ra, ^{228}Th, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb, ^{212}Bi, ^{210}Pb and ^{210}Po (3,4). Methods for reducing and controlling exposure to dust emissions with these radionuclides are thus of paramount importance from the standpoint of providing healthy working conditions.

Various methods and techniques have been developed to reduce or control airborne dust emissions. These include mechanical filtration, wetting (e.g., water sprays), scrubbing and electrostatic precipitation (1,5,6). This study reports the effectiveness of a wet scrubber on reducing the short-lived and long-lived radioactivity associated with aerosols and dusts generated from a rock crushing operation in an underground uranium mine.

EXPERIMENTAL SITE

The study was conducted in a crushing plant located in an underground hard rock uranium mine. A view of the mine area where the study was conducted is shown in Figure 1. The crusher was fed by two ore passes and one waste pass, which joined as an open flow of muck to feed the screen and the crusher.

The muck flow fed a surge bin which was drawn by an operator at the tail pulley of a belt conveyor in a drift approximately 15 m below. On average, the plant crushed about 1.4 x 10^3 kg of ore or waste during the sampling periods. The ore to waste ratio was approximately constant for each sampling period (about 6 hours).

The wet scrubber was an 8.7 m^3/s unit, 4.5 m in length, 1.5 m in width, and 2.0 m in height. Dusty air was fed to the dust collector via an intake plenum and ducts, from four dust producing areas, namely:

a) below the crusher screen and jaws;

b) the crusher pit;

c) a hood extracting dusty air from the open ore pass junction above the crusher platform; and

d) a hood at the tail pulley transfer point.

The wet scrubber operated on a continuous basis and was flushed daily at the beginning of the working shift. The scrubber was equipped with a special fabric filter at the exhaust which was cleaned on a weekly basis as part of the regular crusher maintenance schedule. The appropriate water level for optimum operation was maintained by an automatic overflow valve system. The wet scrubber is shown in schematic form in Figure 2. The crusher plant was ventilated with air (9.4 m^3/s) coming from working sites of an upper level. The wet scrubber replaced a 7.1 m^3/s bag collector which drew air from underneath the crusher jaws, and from the tail pulley transfer point dust collection hood, exhausting it into an adjacent ore pass. (The bag collector was replaced because of mechanical and engineering problems.)

EXPERIMENTAL PROCEDURE

The performance of the wet scrubber for air quality control purposes was evaluated during a period of eleven weeks. Experimental data were collected before and after the installation and operation of the wet scrubber for evaluating its radioactive dust collection efficiency and assessing its impact on air quality in the crusher plant.

Measurements were preferentially done at the wet scrubber itself, the crusher platform, i.e., crusher operator work station, and the crusher plant floor, i.e., mechanic's work bench. In addition, measurements were also made at the air intake of the crusher plant, the ore passes feeding the crusher, and the return air path going to the tail pulley area.

The radioactivity measurements included:

a) the short-lived decay products of thoron and long-lived α-particle radioactivity associated with dust samples;

b) the airborne radon progeny and thoron progeny concentration levels from air samples, i.e., radon and thoron progeny activity concentrations and radon progeny Working Level WL(Rn), and thoron progeny Working Level WL(Tn).

The short-lived and long-lived α-radioactivity associated with dust were measured from samples collected by means of cascade impactors, nylon cyclones and CAMPEDS (gravimetry dust samplers (7)), using conventional α-particle scalers (model Tri-Met 372A from TriMet, Winnipeg, Canada) using ZnS(Ag) 'screens' optically coupled to a photomultiplier tube.

Radon progeny and thoron progeny Working Levels were measured using grab-sampling methods (8,9). Measurements of WL(Rn) and WL(Tn) were made preferentially at the mechanic's work bench. It should be noted that the terminology, short-lived decay products of radon, radon daughters, and radon progeny are equivalent. However, in keeping with more recent trends, the terminology, radon progeny, is used, and preferred, in this paper rather than the more historical terminology, radon daughters. The same applies to thoron and its decay products.

Short-lived and long-lived radioactive dust concentration and size distribution were measured using 10-stage cascade impactors Model 210 manufactured by Sierra Instruments U.S.A., now Andersen (U.S.A.). The impactors were operated with 8 stages, instead of 10 stages, at a nominal air flow-rate of 13 L/min. The last two impactor stages were removed at the expense of losing some size distribution information but with the benefit of substantially increasing the amount of dust collected on the remaining 8 impactor stages. The calculated cut-off size of the impactor stages at a nominal operating sampling flowrate of 13 L/min are given in Table 1.

The procedures followed to determine dust concentration and size distribution from cascade impactor data have been amply documented elsewhere (4,10) and will not be discussed here. However, some definitions often encountered in this paper are given below.

The Equivalent Aerodynamic Diameter (EAD) is defined as the size of a spherical particle of density 1 g/cm^3 which has the same terminal settling velocity as the sampled particle. The variable $D_{P,50}$ is defined as the particle size cut-off at 50% collection efficiency for spherical particles. Mass Median Aerodynamic Diameter, Activity Median Aerodynamic Diameter and geometric standard deviation are abbreviated, respectively, MMAD, AMAD, and σ_g. The MMAD and AMAD indicate, respectively, the median of dust mass distribution and the median of the radioactivity distribution associated with the dust, with respect to aerodynamic diameter.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental data have been summarized in Tables II to V, and Figures 3 to 9. Dust size distribution data were obtained with two identical cascade impactors (labelled EMR and C for internal identification purposes) at the same operating conditions, and hence the cut-off sizes were the same. The

Long-Lived Radioactive Dust activity referred to in this paper corresponds to the total α-activity from all long-lived radionuclides in the dust. The long-lived α-activity of dust was measured well after the airborne short-lived decay products of radon and thoron collected in the filter substrates had decayed away completely.

Table II shows Long-Lived Radioactive Dust (LLRD) concentration, [LLRD], data for two different locations at the crusher plant, i.e., crusher platform and mechanic's work bench, before and after the operation of the wet scrubber. Also shown in the table is [LLRD] measured at the intake and exhaust of the scrubber. Measurements in this case were conducted through special isokinetic sampling ports designed for the purpose as described elsewhere (11). (Square brackets are used in this paper to indicate α-activity concentration.)

The data of Table II show a large difference in [LLRD] between the crusher platform and the mechanic's work bench before the wet scrubber went into operation. This difference is attributed to the fact that the mechanic's work bench is located in the relatively fresh air intake path, and hence is not so severely affected by crushing operations. Although the difference in [LLRD] between the crusher platform and mechanic's work bench during the operation of the wet scrubber was less accentuated than when the scrubber was not operating, the difference was, nevertheless, very substantial. This suggests that the dust collector also had quite a significant effect on the work bench area.

Table II also shows that the wet scrubber reduced the long-lived radioactive dust concentration, [LLRD], by about 68% in the crusher platform, and by approximately 39% at the mechanic's work bench location. The [LLRD] reduction at the crusher itself was slightly over 87%.

Table III and Figures 3 to 7 summarize MMAD for dust and AMAD data for long-lived radioactive dust, and thoron progeny before and during operation of the wet scrubber. (The Figures show the percentage cumulative α-particle activity or dust mass versus the Equivalent Aerodynamic Diameter, EAD ($D_{p,50}$). The straight line in Figures 3 to 5 and 7 represent the best fitted lined through the experimental data by linear regression analysis.

The data of Table III and Figures 3 to 7 show the following features of interest:

1. The LLRD AMAD was significantly larger than the MMAD corresponding to the carrier dust (Table III and Figure 4), an experimental finding in full agreement with previous work (4).
2. On average, the LLRD AMAD and the dust MMAD at the crusher platform were larger than the corresponding values at the mechanic's work bench. This was true before the installation of the wet scrubber and during the operation of the scrubber (see Table III and Figure 3). This simply reflects the effect of crushing operations in the neighbourhood of the crusher.
3. The LLRD AMAD was greatly reduced during the operation of the wet scrubber: from 5.3 μm to 2.75 μm at the crusher platform, and from 4.9 μm to 2.59 μm at the mechanic's work bench. Similarly, the MMAD was also correspondingly reduced from 4.4 μm to 1.6 μm, and from 2.40 μm to 1.1 μm for the crusher platform and the mechanic's word bench, respectively (see Table III and Figures 4 and 5).
4. The LLRD AMAD at the wet scrubber itself was greatly reduced from 2.5 μm at the intake to 0.44 μm at the exhaust (see Table III and Figure 6).
5. Only slight variations in the LLRD AMAD corresponding to the thoron progeny, AMAF(TnD), were observed. Table III and Figure 7 show that thoron progeny attach themselves preferentially to particulate matter in the submicron range, i.e., in the range 0.14 to 0.19 μm in the crusher

area, e.g., crusher platform and the mechanic's work bench. Attachment of thoron and radon progeny to submicron particulates has been amply documented elsewhere (12,13). A modest decrease in AMAD(TnD) was noticed during the operation of the wet scrubber at the crusher platform (see Table III and Figure 7). An even smaller difference in AMAD(TnD) was observed at the mechanic's work bench. Some difference in AMAD(TnD) was also observed between the crusher platform and the mechanic's work bench prior to the installation and operation of the wet scrubber. The differences in LLRD AMAD indicated above are to be expected because of location and air flow condition differences between the crusher platform and the mechanic's work bench.

Figures 8 and 9 show percentage (%) of the total α-particle activity measured on the different stages of cascade impactor samplers versus impactor stage cut-off size. These Figures show data prior to, and during, the operation of the wet scrubber for the crusher platform (Figure 8), and for the mechanic's work bench (Figure 9). Figures 8 and 9 show the following features:

a) a maximum (peak) percentage α-particle activity at a given cut-off size;

b) a rapid increase in percentage α-particle activity from small particle size ($\lesssim$0.2 μm) to the maximum percentage activity;

c) a less rapid increase in percentage α-particle activity from the maximum percentage activity to the coarser particle size range (up to $\gtrsim$13 μm).

In addition, Figures 8 and 9 show the following:

i) the maximum percentage α-activity measured during the operation of the wet scrubber (curves B) was lower, in percentage value, and displaced to lower cut-off size, as compared with data taken prior to the operation of the scrubber (curves A);

ii) the percentage α-activity data obtained during the operation of the scrubber were higher than those measured before the scrubber operation for values of particle cut-off size less than that corresponding, in each case, to the maximum percentage α-activity;

iii) The converse of item (ii) was true for particle cut-off sizes larger than that corresponding to the maximum percentage α-activity.

Futhermore,a comparison of Figures 8 and 9 show that for the crusher platform, as opposed to the mechanic's work bench:

1) the peaks, i.e., maxima, were more sharply defined;

2) percentage α-particle activity measurements were higher;

3) a much lower value for the particle cut-off size corresponding to the maximum percentage α-activity, i.e., 1.8 μm as compared with 3.3 μm (no scrubber). For the mechanic's work bench the particle cut-off sizes corresponding to the maximum percentage activity were not much different, i.e., ~3.0 μm (wet scrubber) and ~3.3 μm (no scrubber).

The discussion above can be summarized quite simply by stating that the wet scrubber was relatively inefficient in removing long-lived radioactive dust of size below approximately 1.8 μm, but quite efficient in removing long-lived radioactive dust of size above 2 to 3 μm.

Table IV summarizes radon progeny and thoron progeny Working Level data, i.e., WL(Rn) and WL(Tn), respectively. Data were taken at the mechanic's work bench before, and after, the installation and operation of the wet scrubber. The Table show that WL(Rn) and WL(Tn) were reduced, respectively, by about 13% and 23% during the operation of the scrubber. The ratio WL(Tn)/WL(Rn) was also reduced, although only marginally at best, i.e., $\lesssim$8%.

Table V summarizes data previously discussed regarding the performance of the wet scrubber in reducing the concentration levels of long-lived radioactive dust, and other variables of interest, in the crusher area.

CONCLUSIONS

The wet scrubber substantially reduced the concentration of airborne long-lived radioactive dust in the crusher area, i.e., 68% in the crusher platform, and 39% at the mechanic's work bench. At the scrubber itself, the removal efficiency was about 88%.

The scrubber was quite efficient in removing long-lived radioactive dust of size greater than about 2 μm. However, the efficiency decreased very rapidly with decreasing particle size. Removal efficiency for submicron particulate matter was rather poor.

The LLRD AMAD corresponding to the long-lived radioactive dust was significantly reduced during the operation of the wet scrubber. Modest reduction in airborne radon progeny and thoron progeny Working Levels was brought about by the scrubber.

In summary, a significant reduction in respirable dust concentration, long-lived radioactive dust concentration,[LLRD], dust MMAD, LLRD AMAD, and radon progeny and thoron progeny concentration was quite evident during the operation of the dust collector (scrubber). Because respirable dust and long-lived, as well as short-lived, airborne radionuclides may pose a potentially serious environmental and occupational hazard, the installation of the wet scrubber is expected to result in much improved and desirable environmental conditions from the dust concentration standpoint. It should be noted that as a reduction in LLRD AMAD increases the radiation dose per unit exposure (14) it is at present not clear what effect a reduction in AMAD may have compared with the decrease in radiation dose resulting from a reduction of long-lived radioactive dust concentration. However, the potential health effects associated with the above data are beyond the scope of the paper.

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LIST OF ILLUSTRATIONS

AMAD(EMR). (The symbols EMR and C represent codes for internal identification purposes.)

Figure 7 - Percentage cumulative α-particle activity (thoron progeny) versus EAD($D_{p,50}$) at the crusher, AMAD(EMR), encircled dots, and at the mechanic's work bench, AMAD(C), crosses, before the operation of the wet scrubber. Also shown is the α-particle activity at the the crusher and mechanic's work bench during operation of the wet scrubber, AMAD(EMR+C), dots. (The symbols EMR and C represent codes for internal identification purposes.) The symbol EMR+C indicates data taken with both cascade impactors.

Figure 8 - Percentage α-particle activity (LLRD) versus impactor stage cut-off size measured at the crusher before (A) and during (B) operation of the wet scrubber.

Figure 9 - Percentage α-particle activity (LLRD) versus impactor stage cut-off measured at the mechanic's work bench before (A) and during (B) operation of the wet scrubber.

Table I - Cut-off size of cascade impactor stages at a sampling flow rate of 13.1 L/min.*

Impactor Stage	Cut-off Size μm
1	13.17
2	7.85
3	3.16
4	1.89
5	1.20
6	0.66
7	0.35
8	0.17

*Calculated for the corresponding operating air flow rate, temperature and barometric pressure.

Table II - Effect of the wet scrubber on Long-lived Radioactive Dust (LLRD) concentration at the crusher plant.

Wet Scrubber in operation	Impactor Location	[LLRD]* mBq/m^3	Date
No	Crusher platform	126.3±25.1	June 16-20
No	Mechanic's work bench	34.9±17.8	" "
Yes	Crusher platform	40.3±14.4	Aug. 25-27
Yes	Mechanic's work bench	21.3±8.1	" "
Yes	Crusher intake	226.0	Aug. 28-29
Yes	Crusher exhaust	28.0	" "

*Square brackets indicate activity concentration. The notation LLRD indicates long-lived radioactive dust.

Note: The [LLRD] was calculated by adding the dust collected in each impactor stage and dividing by the total air volume sampled. The approximate cascade impactor sampling period was 6h per run. The values given in the table represent mean (arithmetic) values and their corresponding standard deviations, whenever applicable. [LLRD] values without standard deviation represent the average values of two sampling periods (runs). Values with standard deviations represent the mean values of 8 sampling periods (runs).

Table III - Effect of the wet scrubber on Mass Median Aerodynamic Diameter (MMAD) and Activity Median Aerodynamic Diameter (AMAD) at the crusher plant. Data in the table represent average values.

Wet Scrubber in Operation	Impactor Location	MMAD µm	σ_g µg	AMAD (LLRD) µm	σ_g µm	AMAD (TnD) µm	σ_g µm
No	Crusher platform[1]	4.40	2.90	5.30	2.84	0.19	3.00
No	Mechanic's work bench[2]	2.40	5.40	4.90	3.18	0.15	2.87
Yes	Crusher platform[1]	1.60	5.30	2.75	3.98	0.14	3.20
Yes	Mechanic's work bench[2]	1.10	6.50	2.59	4.21	0.14	3.19
Yes	Scrubber intake[3]	-	-	2.50	~2.00	0.17	3.08
Yes	Scrubber exhaust[3]	-	-	0.44	3.01	0.17	2.82

Notes: MMAD and AMAD stand, respectively, for mass median aerodynamic diameter and activity median aerodynamic diameter. The symbols TnD and σ_g stand, respectively, for thoron progeny and geometric standard deviation.

[1,2] Number of sampling periods (runs): 8 (see table II)

[3] Number of sampling periods (runs): 2 (see table II)

Table IV - Effect of the wet scrubber on short-lived radioactivity concentration (radon progeny Working Level, WL(Rn), and thoron progeny Working Level WL(Tn) at the crusher plant. Sampling was conducted at the mechanic's work bench.

Wet Scrubber in Operation	WL(Rn)	WL(Tn)	WL(Tn)/WL(Rn)
No	0.17±0.01	0.16±0.01	0.94
Yes	0.15±0.01	0.13±0.01	0.87

Note: The values given above for EL(Rn and WL(Tn) represent mean (arithmetic)and standard deviation values calculated from measurements during the wet scrubber operation(August) and prior to the operation of the wet scrubber (June). WL(Rn) and WL(Tn) stand, respectively, for radon progeny Working Leveland thoron progeny Working Level. The total number of samples taken was 50. Each sample was used to determine both WL(Rn) and WL(Tn).

Table V - Percentage reduction for several variables of interest brought about by the operation of the wet scrubber.

Variable	% Reduction When Wet Scrubber On	Location
[LLRD]	68.1	Crusher platform
	39.0	Mechanic's work bench
	87.6	Crusher itself
MMAD	63.6	Crusher platform
	54.2	Mechanic's work bench
AMAD	48.1	Crusher platform
	47.1	Mechanic's work bench
WL(Rn)	11.4	Mechanic's work bench
WL(Tn)	16.7	Mechanic's work bench

Note: [LLRD], MMAD, AMAD, WL(Rn) and WL(Tn) stand, respectively, for long-lived radioactive dust concentration, mass median aerodyamic diameter, activity median aerodynamic diameter, radon progeny Working level, and thoron progeny Working Level.

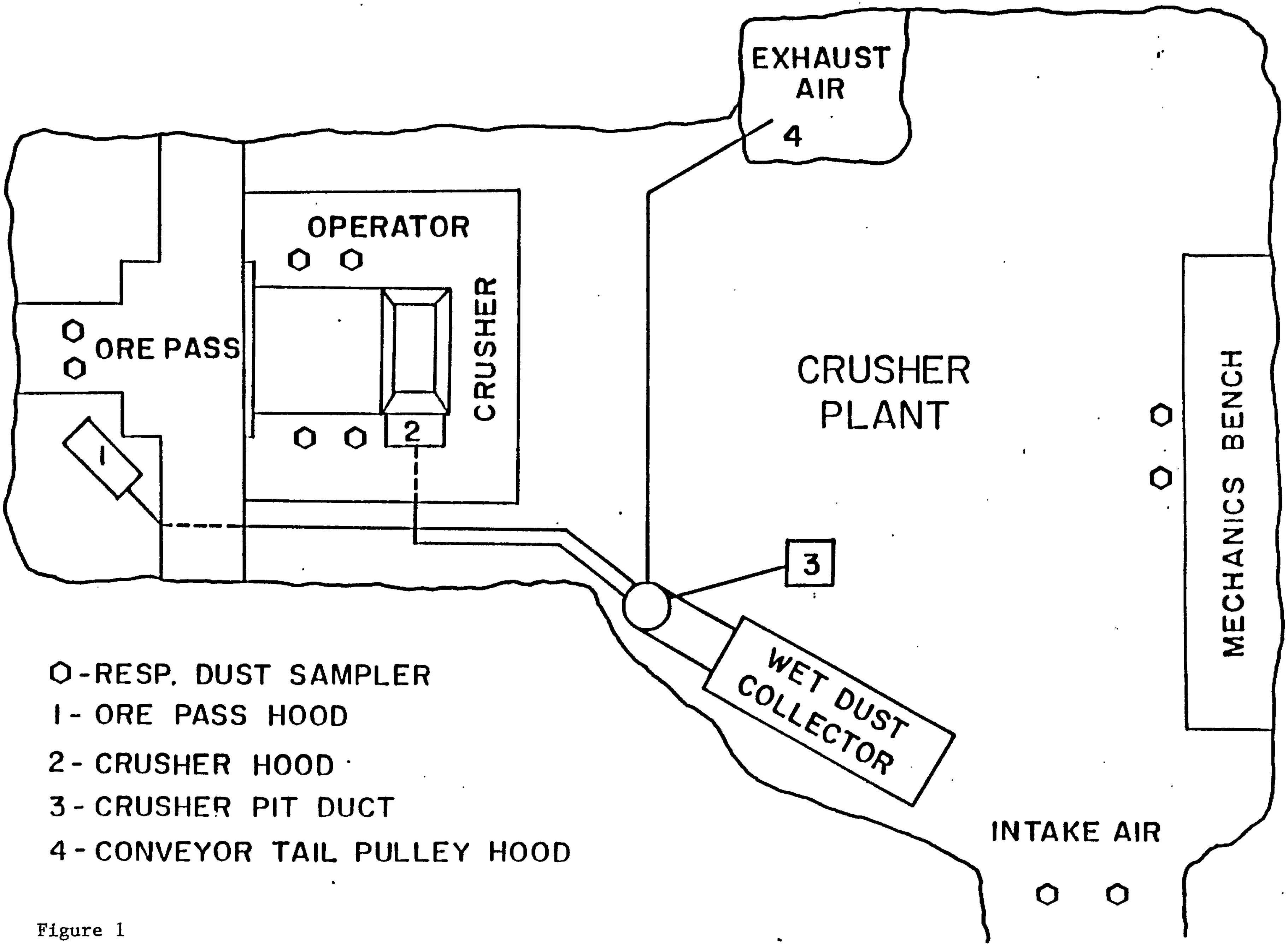
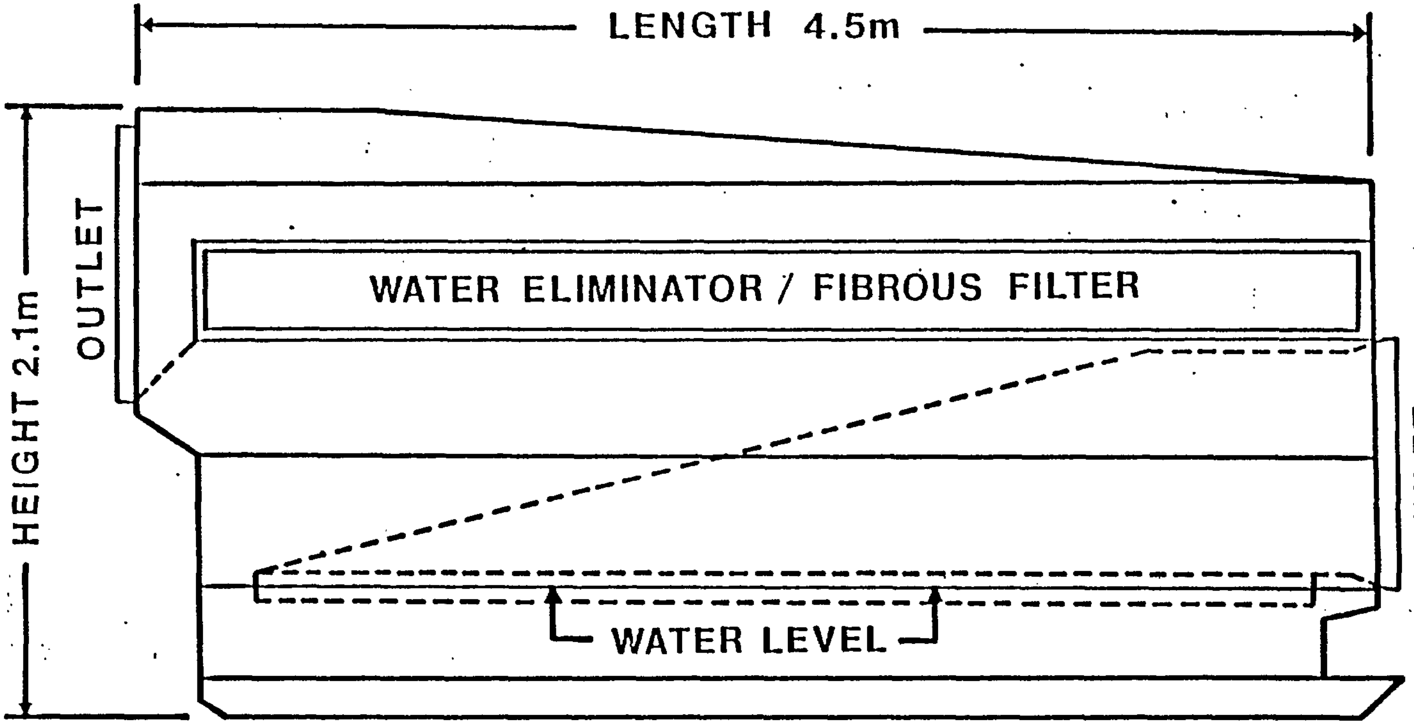

EXHAUST AIR
4
OPERATOR
CRUSHER
ORE PASS
2
1
CRUSHER PLANT
MECHANICS BENCH
3
WET DUST COLLECTOR
INTAKE AIR
⬡ - RESP. DUST SAMPLER
1 - ORE PASS HOOD
2 - CRUSHER HOOD
3 - CRUSHER PIT DUCT
4 - CONVEYOR TAIL PULLEY HOOD

Figure 1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HEIGHT 2.1m
OUTLET
WATER ELIMINATOR / FIBROUS FILTER
INLET
WATER LEVEL

Figure 2

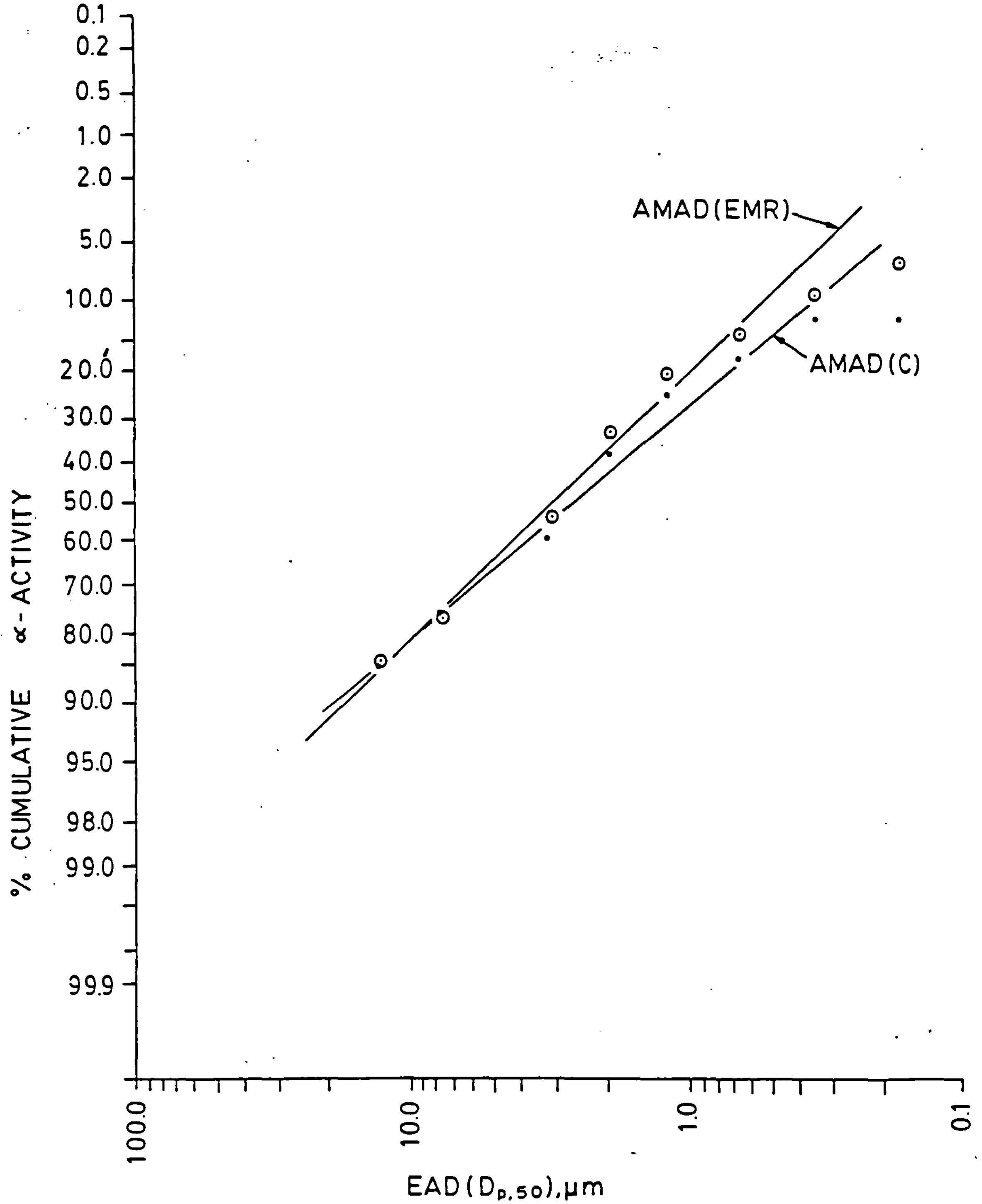

AMAD(EMR)
AMAD(C)
% CUMULATIVE α- ACTIVITY
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
95.0
98.0
99.0
99.9
100.0
10.0
1.0
0.1
EAD(D$_{p,50}$),µm

Figure 3

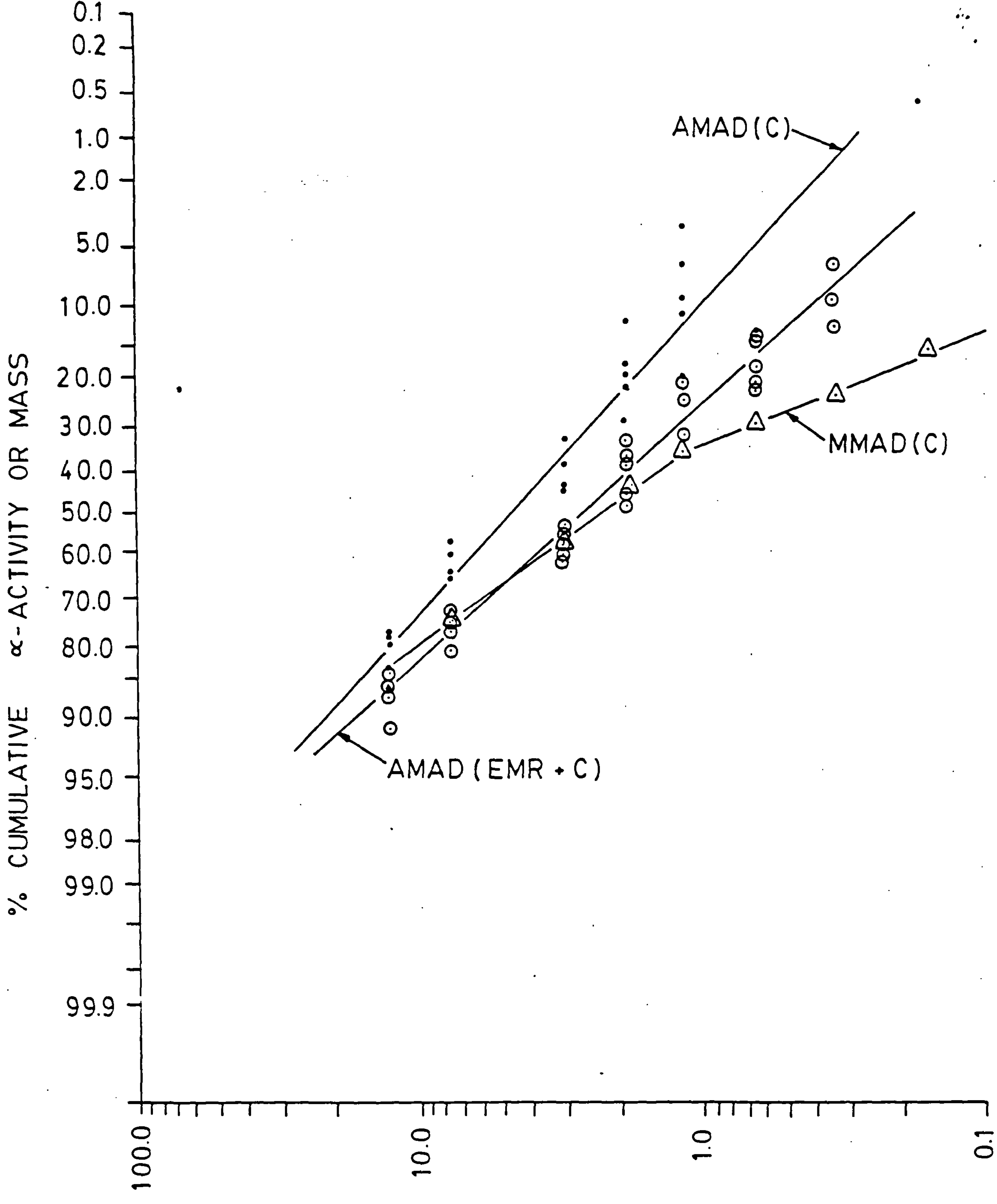

AMAD(C)
MMAD(C)
AMAD(EMR + C)
% CUMULATIVE α-ACTIVITY OR MASS
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
95.0
98.0
99.0
99.9
100.0
10.0
1.0
0.1
EAD($D_{p,50}$), μm

Figure 4

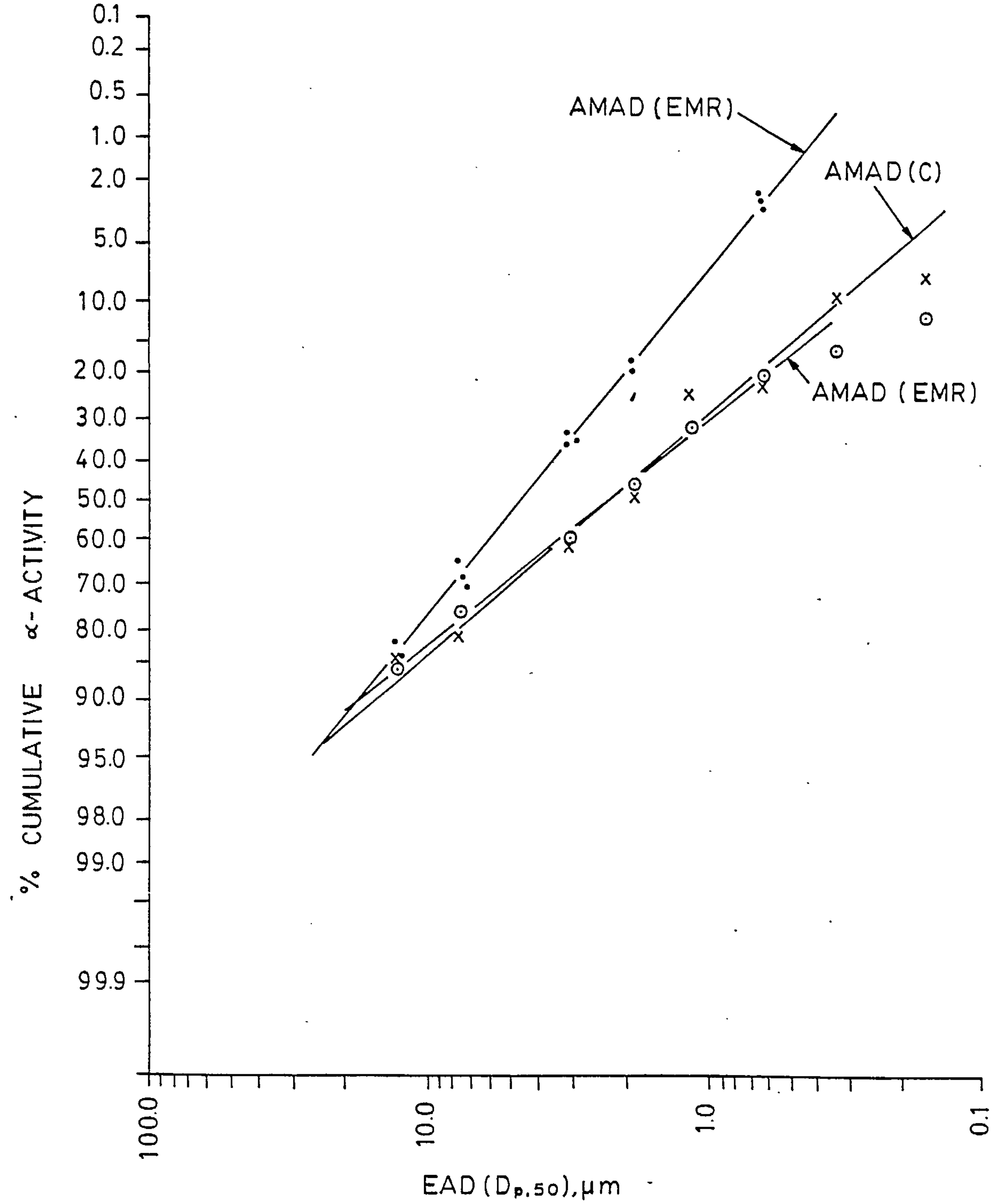
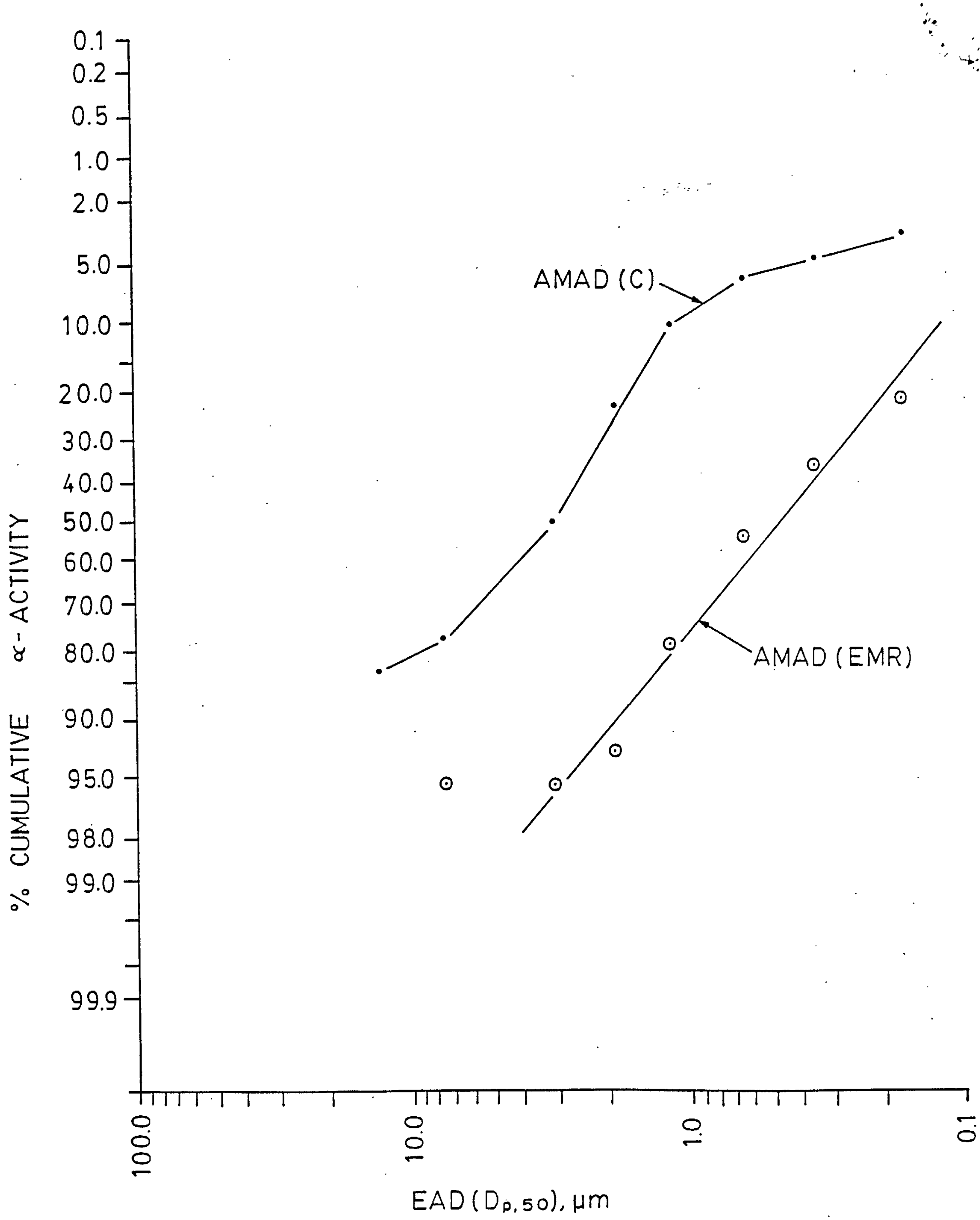

AMAD (EMR)
AMAD (C)
AMAD (EMR)
% CUMULATIVE α- ACTIVITY
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
95.0
98.0
99.0
99.9
100.0
10.0
1.0
0.1
EAD (Dp.50), μm

Figure 5



% CUMULATIVE α - ACTIVITY
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
95.0
98.0
99.0
99.9
AMAD (C)
AMAD (EMR)
100.0
10.0
1.0
0.1
EAD ($D_{p,50}$), μm

Figure 6

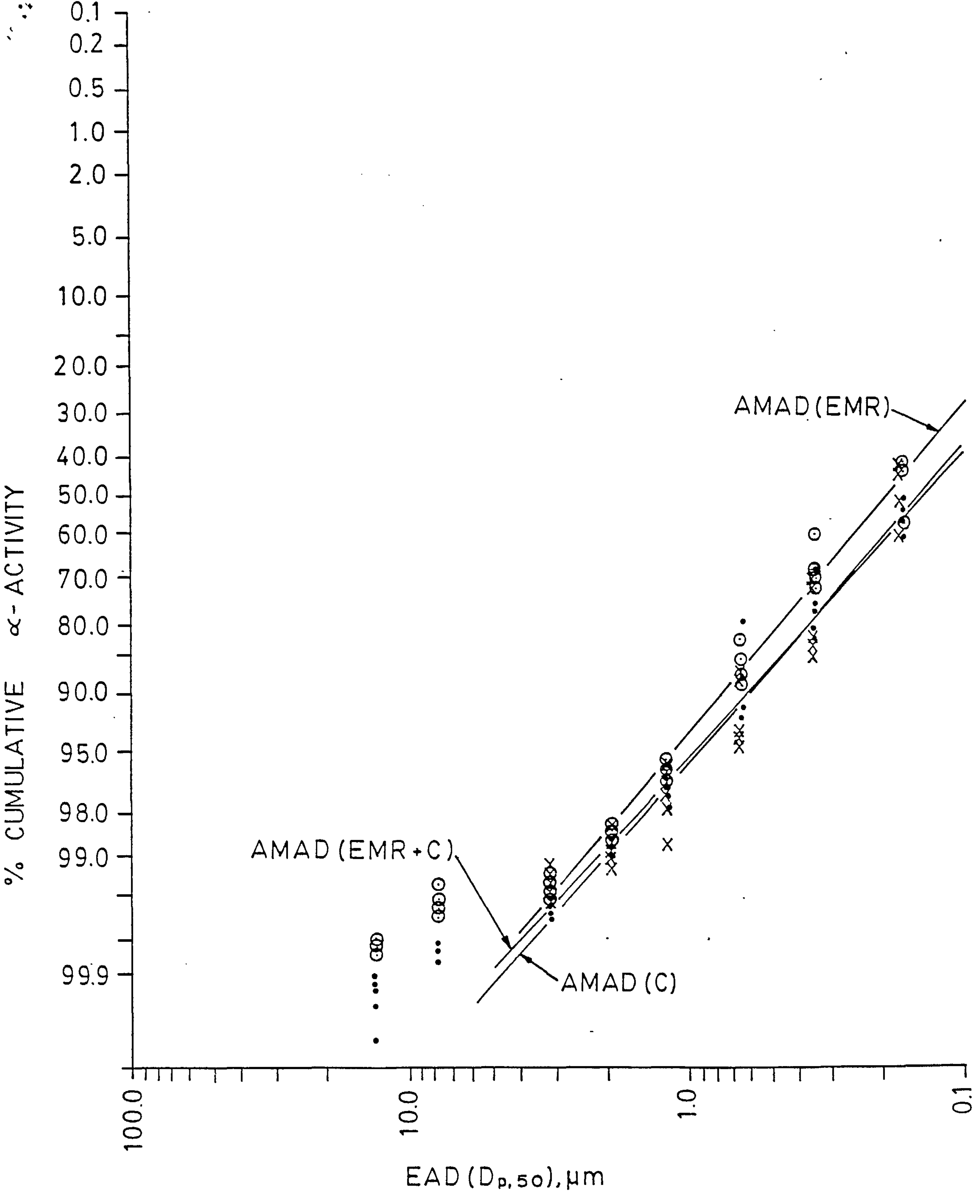

0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
95.0
98.0
99.0
99.9
% CUMULATIVE α- ACTIVITY
AMAD (EMR)
AMAD (EMR + C)
AMAD (C)
100.0
10.0
1.0
0.1
EAD (Dp,50), µm

Figure 7

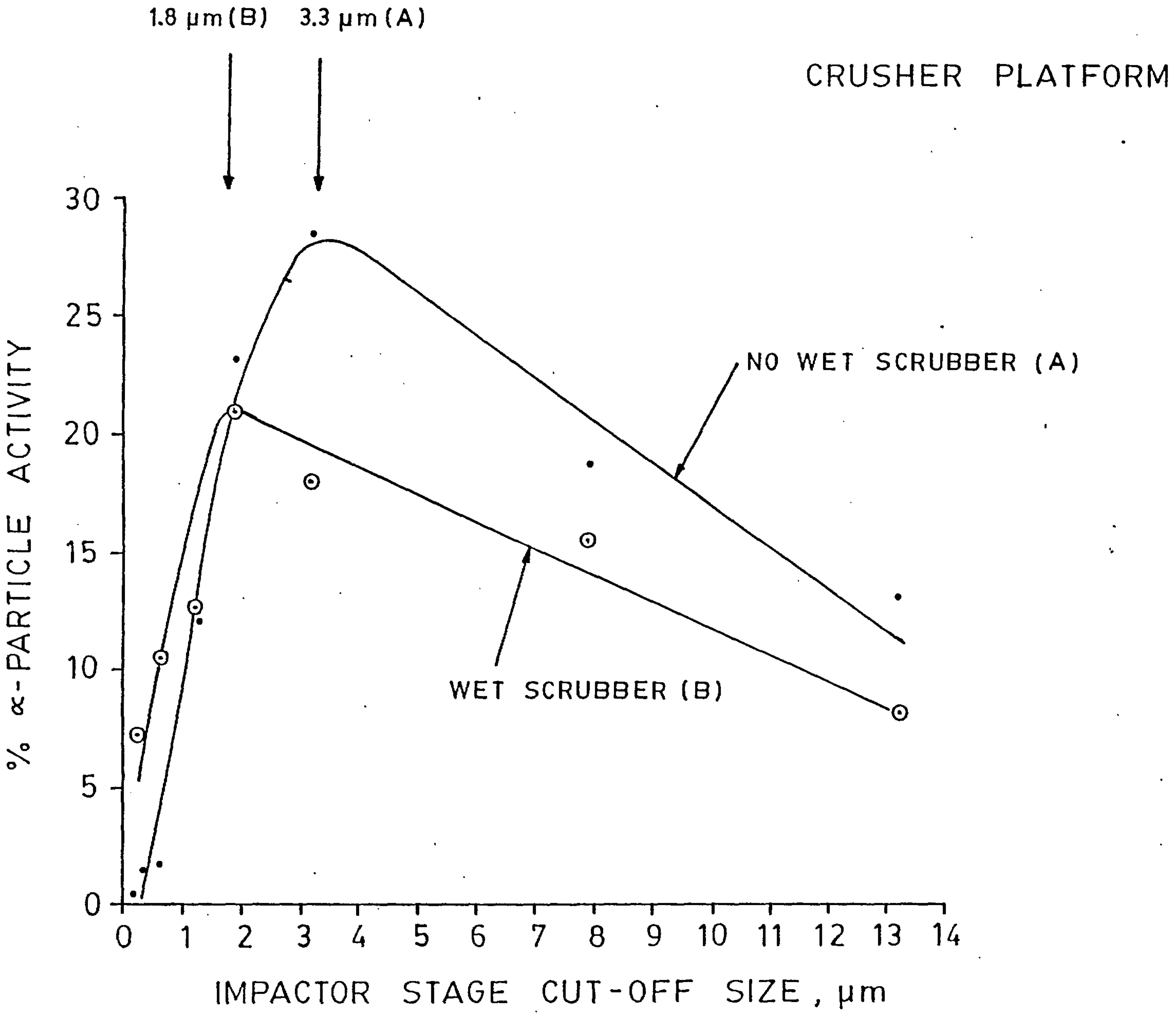
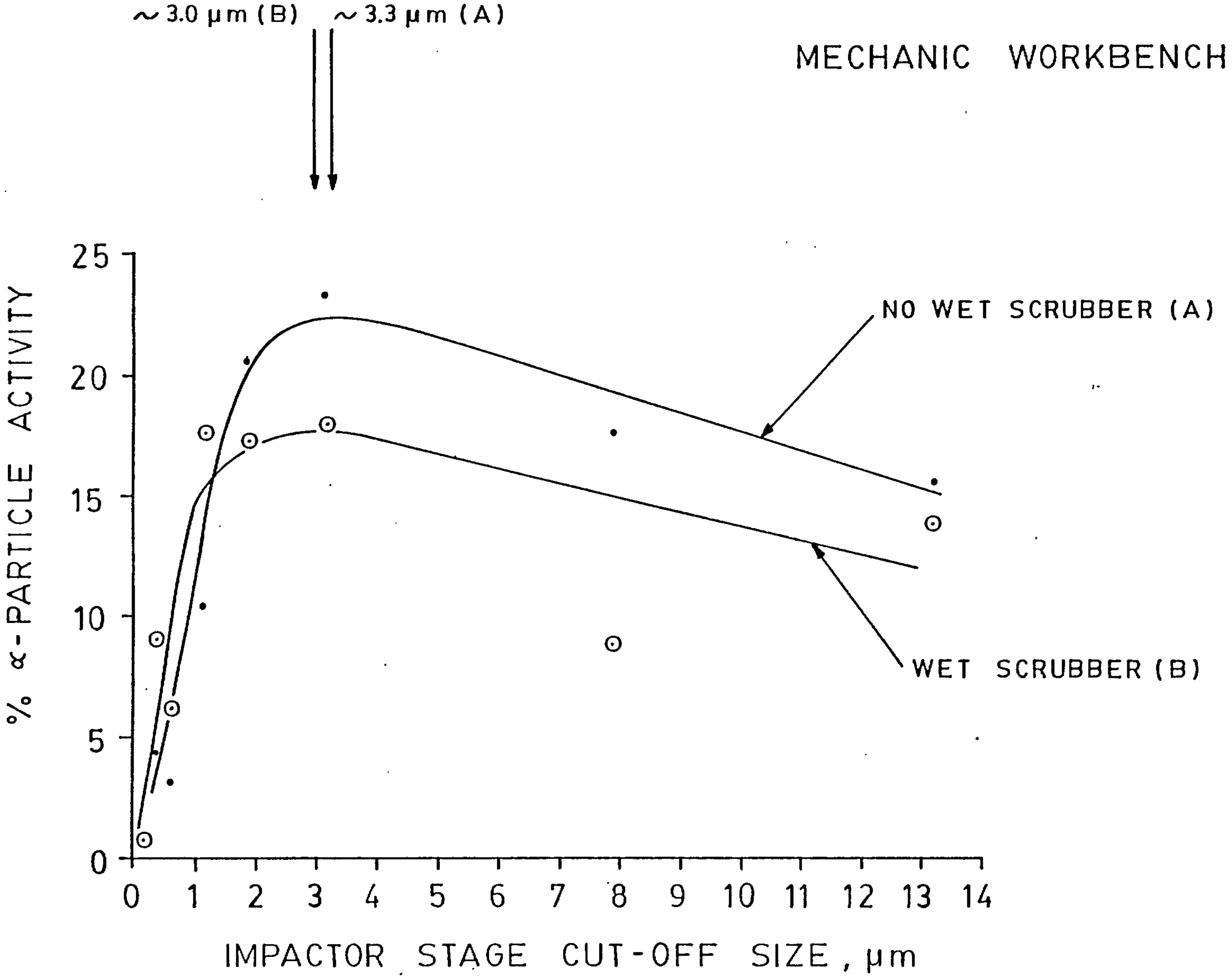

1.8 µm (B)
3.3 µm (A)
CRUSHER PLATFORM
% α-PARTICLE ACTIVITY
30
25
20
15
10
5
0
NO WET SCRUBBER (A)
WET SCRUBBER (B)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
IMPACTOR STAGE CUT-OFF SIZE, µm

Figure 8



~3.0 µm (B)
~3.3 µm (A)
MECHANIC WORKBENCH
NO WET SCRUBBER (A)
WET SCRUBBER (B)
% α-PARTICLE ACTIVITY
0
5
10
15
20
25
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
IMPACTOR STAGE CUT-OFF SIZE, µm

Figure 9