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INVESTIGATION OF PERFORMANCE OF PERSONAL SAMPLERS IN INDUSTRIAL WORKPLACES

by

RA Botham, G Hughson, I Parker, D Mark, JH Vincent

FINAL REPORT ON HSE CONTRACT 2191/R42.12

Duration of project: July 1986 to March 1988

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SUMMARY

A life-size model of a human worker has been built to enable the performances of personal dust samplers in industrial workplaces to be assessed in relation to inspirability. The aim was to provide a system whereby the actual dust levels experienced by the worker could be measured by both the simulated worker and by personal samplers mounted on his body. The work is a direct progression from recent studies on personal sampler performance that have been carried out in the 'ideal' conditions found in laboratory wind tunnels.

The model, which is mounted on a trolley for moving around the workplace, is based on an anthropomorphic robotic arm, shrouded by a mannequin torso and with a head fixed to the robot 'wrist'. The robotic arm provides limited movements to enable simulations to be made of the range of typical body movements displayed by workers in the course of their work. Simulated breathing through the mouth or nose is provided by a electronically-controlled breathing machine consisting of a pump, and a series of critical orifices and solenoid valves.

As the development proceeded, a number of compromises were made in the design and operation of the model in relation to the fully-automated model first envisaged. Firstly, an operator is required to transport the model around the workplace, to operate the body movements and to ensure that the flowrate is maintained at the specified level. In addition it was not practicable to mimic the precise movements of individual workers. Nevertheless, with the model worker, a means has been provided, for the first time, of evaluating the performances of personal dust samplers in relation to dust exposure in industrial workplaces.

Investigations were carried out in five different industrial workplaces chosen to represent a range of industrial processes, environmental conditions, and types of dust. At lease ten repeat samples were taken at each workplace to enable meaningful conclusions about sampler performances to be made, whilst covering as many industries as possible.

Several broad conclusions were drawn from the statistifcal analysis of the data obtained. The IOM personal inspirable dust sampler performed satisfactorily in relation to inspirability, but this performance varied between the industries. The HSE seven-hole personal sampler signficantly underestimated inspirable dust exposure, but was not as affected by varying industrial conditions as the IOM personal sampler. In general both personal samplers collect more dust when

exposed to fine particles than when exposed to the coarser ones. This effect was found to be more marked for the HSE sampler.

Finally, the problems associated with using static samplers for estimating dust exposures were highlighted by the performance of the IOM static inspirable dust sampler which in general underestimated dust exposure, with performance varying from workplace to workplace.

Whilst we have developed a means by which the performance of dust samplers, in relation to inspirability, can be evaluated in industrial workplaces, it was possible to carry out only limited field investigations. Further work is therefore required before decisions concerning sampler suitability can be made.

1. BACKGROUND

Recently a number of studies have been reported in which the sampling performances of personal samplers for 'total' dust have been determined in laboratory wind tunnels (Mark and Vincent, 1986, Buchan *et al*, 1986, Chung *et al*, 1987). In these studies, it was recognised that for personal sampler evaluation it is necessary to mount them on the torso of the worker or a tailor's mannequin, that is in the intended mode of use. Tests where personal samplers are evaluated in isolation from the torso may be invalid because the local aerodynamic field around the sampler is substantially influenced by the presence of the body on which it is mounted. Indeed, Buchan *et al* (1986) showed substantial improvement in the efficiency of a 37 mm filter cassette when mounted on a torso compared to the unit's efficiency when in isolation. It was also recognised that, since when using personal samplers we are interested in health effects, the criterion against which performance should be judged is inspirability (Vincent and Armbruster, 1981, ACGIH 1985) - a health-related definition of total dust.

Two different methods of evaluating sampler performance were employed. Buchan *et al* (1986) and Chung *et al* (1987) assessed performance by comparing the concentration of particles of a given aerodynamic diameter collected by the personal sampler with the true total dust concentration in the air approaching the mannequin as measured by a number of isokinetic probes. These results are then compared with the inspirability criterion. A more direct approach was applied by Mark and Vincent. In their study, the tailor's mannequin was equipped with filter holders in the mouth through which air was drawn by a breathing machine at rates and patterns similar to those of a typical worker. Performance was then assessed by comparing directly the concentration of dust particles of given aerodynamic diameter collected by the personal sampler with that which enters the mouth during simulated breathing. Here, it was not necessary to know the true total dust concentration.

Whilst these studies have provided very valuable information about the performances of the various personal samplers currently used (and in one study led to the development of a personal sampler specifically for inspirable dust), they were carried out in idealised conditions of uniform dust concentration and velocity profile. Very few studies have been reported in which the basic performances of personal samplers in actual workplaces have been investigated. In workplaces, non-uniform dust concentration and air velocity conditions prevail, due to - for instance - point dust sources and local exhaust ventilation. It may not be appropriate, therefore, to apply results gained in the uniform conditions prevalent in wind tunnel studies to the workplace situation. In those workplace studies that have been performed the dust concentrations given by various personal samplers are compared either to evaluate the relationship between the different types, or to investigate the effect of sampler position on the torso. In none of the studies has the actual performance relative to either true total dust or inspirability been determined. It is the broad objective of this project to develop methodology to enable these studies to be carried out.

2. AIMS OF THE PROJECT

The main aim of this project is to investigate the performance in workplaces of a number of personal samplers for 'total' dust in relation to the inspirability criterion. The specific aims were:-

1) to design and construct a life-size model of a human worker having simulated breathing and capable of limited movement;

2) to investigate in a limited number of industrial workplaces the relationship between the airborne dust inspired by the model and that sampled by a range of relevant personal samplers mounted on its torso.

3. MODEL SPECIFICATION

The broad requirement is that the model should be a life–size, portable representation of a human worker, consisting (for aerodynamic similarity) of head and torso. It should be mechanised to simulate the range of movement and breathing parameters displayed by human workers.

In particular:–

1) the design should be based on a life–size tailor's mannequin, maintaining simplicity yet providing easy, reliable operation;

2) the model should be capable of breathing through the mouth or nose, the inspired dust being deposited onto a filter for subsequent analysis;

3) breathing should be executed by a breathing machine capable of providing a representative range of breath patterns and frequencies, mounted with the model;

4) the model should be self–contained and capable of a range of movements (translation, rotation and attitude) similar to those used by an actual worker. It should be mounted on a solid base, which itself should be mounted on wheels to facilitate its movement around the workplace, and should be electronically controlled.

5) for preference it should be battery–operated and capable of repetitive programmed movements.

4. DESIGN OF THE MODEL

The overriding requirements are that the model should aspirate particle-laden air through the nose and mouth similarly to what happens in man. Consequently, for aerodynamic similarity, that process must not be compromised by the presence of the breathing machine, the mechanism or the controls. At the outset it was envisaged that the model would be based on a microprocessor-controlled anthropomorphic robot arm, shrouded by a mannequin torso and with a head fixed to the robot 'wrist'. This would then be set on a trolley carrying the breathing machine and controls. A suitable choice of robot arm length would allow the robot shoulder to represent the waist, and the 'wrist' would become the model neck.

When actual working practices were examined in detail, it became clear that the original concept of having the robot repeat a programmed series of movements was neither appropriate nor necessary. Firstly, in the industries to be studied no process required such repetitive work. Secondly, it was impracticable, for reasons of safety or access, to position such a programmed robot closely adjacent to a worker. As workers generally move around a machine or around an area of plant in a way which is not predetermined, there are two ways in which the robot may be used. Either an operator might attempt to control and move it in such a way that it copied a particular worker's movement. Alternatively, after studying the worker's movements, the robot may be arranged to spend the same proportions of time in the various positions and attitudes adopted on average by the worker. The latter is simpler and more convenient, and was the method adopted for the workplace studies.

The requirement therefore reduces to that of the robot being moved relatively infrequently into different postures under operator control. There is then no need for microprocessor control, but the ability to move the arm remotely without interference is clearly an advantage. The power required by the breathing machine makes battery operation impracticable, so this aspect of the specification was dropped. This was not found to limit the machines use on industrial sites, as 110 or 240v supplies were readily available.

4.1 The Robot Arm

To model the human torso movements at waist and neck calls for a robot arm with 500 mm between 'shoulder' and 'wrist' axes. The lifting capacity of the robot arm is another constraint. When the torso, head, pipework, and safety helmet are fitted a minimum lifting capacity of 1.5 kg is required. In order to achieve this, the torso (based on a plastic shop display model) was reduced in weight by cutting away unnecessary bulk of plastic to leave just a skeleton frame. The resultant holes were covered when the torso was 'dressed' in a laboratory white coat. A survey of manufacturers showed that few arms met these desired dimensional requirements. When constraints of size and portability were included only one supplier could provide an acceptable arm. After long delays caused by company financial problems, an arm was eventually delivered and commissioned, but needed further modifications to carry the load reliably. During commissioning, intermittent faults appeared in the microprocessor controller, but as this form of control was found to be unnecessary, the microprocessor controller was bypassed and two joysticks were employed to give direct control of the motor functions. This has the distinct advantage of being very simple, and operators found this a convenient control mechanism. Figure 4.1 is a schematic diagram of the robot arm assembly, illustrating the available movements.

4.2 The Model Head

To minimise the load on the robot arm, a lightweight (but strong) head of 1.5 mm thick ABS plastic was chosen. It is dimensionally similar to a human head, and was cut to provide openings for the mouth and nostrils and internal access. The head slips over a frame carrying a 47 mm polycarbonate filter holder, which may be positioned behind either the nose or mouth, and a second pipe which carries the exhaled air to the outside via the unused orifice. The filter holders are connected to the breathing machine by lightweight flexible tubing. This arrangement is shown in Figure 4.2.

4.3 The Breathing Machine

4.3.1 Basic Design

The outline design requirements for the breathing machine are that it should be portable, be capable of simulating a wide range of breathing patterns and be usable with the normal range of filter materials. Inhalation, normally through the mouth, is followed by exhalation through the nose to disturb any stagnant air surrounding the mouth, as would be the case for the real worker.

Most existing breathing machines are of the cam-driven piston type. Here the rigidity requirements result in heavy and bulky machines in which breath volume and breathing waveform are essentially fixed. Moreover, it is virtually impossible to compensate for pressure drops in the filter. For these reasons an alternative machine has been developed having greater flexibility in use and smaller dimensions.

Figure 4.3. is a schematic diagram of the design adopted. A vacuum pump draws air through six critical orifices connected in parallel, each being enabled by a solenoid valve in series. Flow rates through the orifices are arranged in a binary progression from 2 to 64 l/min enabling, in theory, the selection of flow rates corresponding to any even number from 2 to 126 l/min. Other valves direct airflow so that exhalation takes place through the nose via an orifice which limits the flow to 40 l/min.

4.3.2 Machine Control

Data held in a read-only memory (EPROM) controls the solenoid valves (see Figure 4.4). Six bits of each word control the critical orifice solenoids, and two bits select flow direction. As the inhalation phase is described by 16 such words, the waveform realised by the machine has 16 steps. Clearly by using more words a more accurate representation of the waveform could be achieved. However the sixteen step waveform was felt to be adequate for the present application. An approximately sinusoidal waveform has been adopted for the inhalation phase, in line with that used in the wind tunnel studies of Mark and Vincent (1986). There is adequate memory space available if other alternative waveforms are required. The exhalation phase is also described by 16 words, but here the words are identical, so that only solenoids 7 and 8 are opened and a 40 l/min airflow is directed to the nose.

Stepping through the 32 word pattern generates the breathing cycle, and the timing pulses which control the stepping may be varied to alter the breathing rate. This results in a high degree of flexibility; for example, it would be a relatively simple matter to copy the breathing pattern adopted during a particular task, such as bending or lifting, or that associated with an impaired lung function. It should also be possible, if desired, to make the breathing pattern appropriate to different phases of a cyclical task.

4.3.3 Critical Orifices

Clearly the critical orifices are crucial to the success of the device. They have been described theoretically by Mercer (1973). Kotrappa *et al* (1977), using hypodermic needle tubes, found that the flow was reasonably constant with a pressure drop of 0.5 bar, but was affected by orifice aspect ratio. A low length/diameter ratio exhibits a characteristic with a better defined plateau. As we needed to adjust orifice flows to required values, the orifices were made from brass rod, drilled undersize and counter bored to form a thin plate at one end (as shown in Figure 4.5). The flowrate through the orifices was measured using a bubble meter for the lower flowrates and a calibrated gasmeter for the higher ones. Higher flowrates were achieved by incrementally opening the hole in the thin end plate with a watchmaker's tapered reamer until the required flow was attained. Typical performance curves of these critical orifices are shown in Figure 4.6, and well-defined plateaux are evident. Also it can be seen that, in order to be able to operate in this region, a vacuum pump must be chosen that has the minimum specified capability above about 60 l/min at a pressure of at least 0.5 bar.

The solenoid valves have been selected to introduce a low pressure drop, and have a switching time which is much less than the waveform step time. Examples of use quoted by the supplier indicated an adequate life expectancy.

4.3.4 Effect of Filter Characteristics

According to Mercer (1973), the airflow through such an orifice is a linear function of the upstream pressure if the downstream pressure is below a required level. As the pressure drop across small pore size filters is high and variable (dependent on the type of filter), some form of correction is needed. This is achieved very simply by changing the 32-word memory block which determines the breathing cycle. The EPROM was programmed specifically for Whatman GFA filters, but the performance is virtually identical if Gelman VM1 PVC 5 μm pore size, or Sartorius 8 μm pore size cellulose nitrate filters are substituted. However the use of a 1.2 μm pore size Sartorius cellulose nitrate filter reduces the minute volume by 17% and a 0.8 μm pore size filter of the same type reduces it by 25%.

4.3.5 Performance of Breathing Machine

In initial tests it was found that as dust load on the filter increased, the flowrate through it dropped due to the extra pressure drop produced by the dust. To compensate for this, a piezo-resistive transducer is mounted upstream of the breathing machine, and the peak pressure displayed on a specially-designed meter (see Figure 4.7 for the circuit). A multi-position switch is used to select the required combination of solenoid valves to be open so that the flowrate is restored. This adjustment was not automated as it was not expected to be needed at the majority of workplaces to be visited. A table of switch positions for given loadings was constructed for use with the device (see Table 4.1).

Hot wire anemometry was used to measure the airflow at the entry to the breathing machine and revealed a stepped waveform with large amplitude switching pulses. The introduction of a filter into the entry (as would be the case in actual use) reduced the pulse amplitude and, as the pressure drop increased, an exponential rise appeared on the steps and the airflow dropped. An example of a typical waveform is given in Figure 4.8 where the flowrate quoted is that obtained by integrating over a number of cycles with a gasmeter. While it was possible to maintain a sinusoidal waveform for low pressure drop filters, the use of small-pore membrane filters dictates a waveform approaching a square wave at the higher sampling flowrates (i.e., >18 l/min).

4.4 The Complete Assembly

To give the robot a height similar to that of an average man (1.8 m), it is mounted on a trolley which, apart from providing a firm base for the robot, encloses the breathing machine, power supplies and voltage selectors. It is illustrated in Figure 4.9. A console, which may be placed inside for storage, carries the joystick arm controls and breathing machine switches. In use, it sits behind the robot on the trolley top. A 50 m spring-return extension reel removes the need for external cable reels, and the machine operates on either 110 or 240 volts. If the machine is inadvertantly connected to 240 v when set for 110 v, crowbar circuits on the control panel are designed to blow the fuses rapidly, thus protecting the machine (see Figure 4.10). For operator safety, power is supplied through a residual current circuit breaker. Towards the end of the workplace trials six ports, from which air at 2 l/min could be drawn, were incorporated as a convenient means of operating personal samplers.

The robot may be easily removed from the trolley for transportation, making the trolley an easy lift for two men. The heaviest item within it is the breathing machine pump at 11 kg.

4.5 Laboratory Testing of Model Worker

A number of operators were asked to make the model follow the movements of a colleague working in the laboratory. Whilst all found the joystick control easy to use after a short familiarisation period, all agreed that the aim of following a worker's detailed actual movements was not realistic. It was also apparent that, if realistic, representative rates of movement were used, then the model would become a safety hazard in the workplace. Having decided that the project objectives could be achieved without copying worker's movements exactly, the rates of movement were reduced to safe levels by fitting limit switches and incorporating motor current limiters.

5. WORKPLACE INVESTIGATIONS

5.1 Introduction

It was apparent from the outset that a compromise must be made between the desire to sample as wide a range of dusts as possible and the need to obtain, at each site, a statistically useful amount of data. Of the industries specifically mentioned in the contract, some could not be studied due to difficulties in obtaining access to factories within the time-scale of the project, or sometimes difficulties in achieving access with the model worker itself. Ultimately however, sites were chosen to give a wide range of industrial dusts and environmental conditions. Occasionally more than one type of dust was available for study on a given site.

As the operation of the equipment had still to be proved outside the laboratory, sites close to Edinburgh were preferred. In order to use the limited resources efficiently, dusty locations were preferred, enabling data to be collected relatively quickly.

5.2 Description of Working Sites

Five industrial sites were selected for study: chemicals, flax, rubber, cement production and quarrying. Of these, only quarrying enabled the effect of wind speed as a parameter to be studied; at the other sampling sites the wind speed was generally well below 1 m/s. Sketches of the site layouts are given in Figures 5.1 to 5.5, including identification of sampling positions.

5.2.1 Fertiliser Factory

Mineral acids are produced for direct sale and as a feedstock for the main product, agricultural fertilisers. In the manufacture of 'superphosphate' fertiliser, calcium phosphate rock is crushed prior to use. The crushing is done in two mills, their output being transported by pneumatic and mechanical conveyors to the reaction vessel.

The mills are set on the ground floor of a high building which houses associated conveyors, cyclones etc., and whilst double doors adjacent to the mills allow through draughts, there is little air movement in the sampling zone near the mills. During operation, dust is released into the air by leaks in casings and conveyor ducts. The plant requires little attendance other than to adjust baffles and clean up dust piles.

5.2.2 Flax Spinning

This plant is housed in a purpose-built, single-storey factory, taking in bales of flax stems and producing a spun thread ready for weaving. The flax stems are reduced to a clean, fibrous state by processes termed 'carding' and 'hackling'; thread is then spun from this in a separate part of the building. It is essential to maintain high humidity or the flax becomes brittle, so typical atmospheric conditions were 24 ^{0}C and 70% relative humidity.

Flax bales are opened and loaded into the carding and hackling machines manually, a process causing high dust levels close to the operator, but one difficult to approach sufficiently closely with the robot. Detritus from the machine drops to the floor from where it is swept out and removed manually, again generating a lot of dust. In the spinning hall, dust levels are generally lower as it is possible to fit dust extraction ducts close to the generation points. In addition, few manual jobs make dust, with the notable exception of the use of compressed air to clean machines and clothing.

5.2.3 Cement Manufacture

Portland cement is produced at this plant from locally-quarried raw materials: limestone, clay and shale. These three materials, in suitable proportions, are mixed and formed into granules which then pass into large, rotating, coal-fired kilns. As the granules move through the kiln, they are heated to about 1400 °C forming a clinker. After leaving the kiln, it goes through a 'clinker cooler' before the finishing processes. The site provided three locations suitable for sampling, each with different conditions and types of dust: the granulation plant, where the dust is from the feedstock; the kiln area, where coal dust predominates; and the clinker coolers, characterised by hot updraughts and where the dust is mainly cement. The plant is controlled remotely, and employees do not spend more than a fraction of their shift at any one of the various locations.

5.2.4 Rubber Manufacture

Rubber mats, belting, seals and other products are made in a range of natural and synthetic rubbers. The physical properties of the product are determined by a number of additives mixed with the raw material prior to curing. As these additives are generally powders, dust is generated by both weighing them out and mixing them with the raw rubber. Mixing is achieved by mastication followed by rolling into sheet, the machines being fed manually and, during this, the rubber heats sufficiently to produce a fume. Later processes, in which the rubber is pressed into its final form and cured by heat generate more rubber fume. But being batch processes, the fume is produced intermittently and is awkward to sample using the robot. Hence sampling was restricted to the weighing and mixing zones.

5.2.5 Quarrying

The particular quarry selected for the study produces graded and tarred stone for road building and repair. Dolerite rock is piled up in the open after blasting. Eventually it is fed to crushing machines to yield stone of the required size. In wet weather, there is enough water on the rock fed to the crushers to suppress dust formation almost entirely, but high concentrations arise around the crushers in dry weather. Of the three crushers installed, the most suitable and accessible for sampling with the robot was the tertiary crusher. This is housed about 4 m above ground level in a small, open-ended shed, so that while it is well shielded from rain, it is fully exposed to wind. The crusher bowl, about 1.3 m in diameter, is fed from above by a conveyor; men visit the shed to check or adjust the machine, otherwise it runs unattended. As the quarry is on a moor about 300 m above sea level, and the buildings receive little protection from the quarry walls, the crushers generally have a strong through draught. This enabled data to be obtained with wind speed as a parameter, and luckily during sampling, the wind was either well under 1 m/s, or was a steady 3 to 4 m/s.

5.3 Sampling Strategy

In order to obtain statistically-significant conclusions about sampler performance from the workplace trials it is desirable to take a lot of repeat measurements. However in this short project, in which a major part of the work has involved the design and construction of the model worker, there was insufficient time and resources to achieve this aim. It was decided therefore to design the workplace trials so that they would provide an indication of the sort of results to expect from a much larger study to be carried out in the future. The programme consisted of taking at least ten repeat measurements in each of five different industries. Where different processes were identified within a given industry a target of at least three repeat measurements were attempted. The time taken to achieve at least ten repeat samples varied from industry to industry dependent on the dust concentration. At some sites it was possible to take as many as 5 samples in one day.

The main purpose of the work was to compare the performances of two personal samplers in relation to inspirability, using those dusts found in industrial processes. In that sense it does not matter whether or not the mannequin copies the exact movement of a man, or whether people routinely work in the chosen site. Indeed, at some of the sites chosen, dust levels were too high for continuous occupation. For this reason, quarry crushers are frequently unattended, using closed-circuit television to monitor conditions. In such places, where workers went infrequently, the mannequin was set to adopt the postures and positions used by a worker when he was there. In none of the sites visited was it possible to follow a worker in the way envisaged when the work was first being discussed.

In the initial work on the fertiliser plant, one personal sampler of each type was fitted to the model, and one of each type to the operator. In all subsequent work, however, all four were fitted to the model, on opposite shoulders, to reduce directional effects. It had by this time become apparent that samplers fitted to workers would not receive exposures similar to those on the model, as their movements could not be copied by the model. Subsequently, personal samplers were only used on workers in the flax industry study, where it was felt that a more legitimate comparison could be made.

5.4 Sampling Methods

Two types of personal sampler were mounted on the model torso for comparison with the model; these were the seven-hole sampler, Casella Model T13077, (the so-called 'HSE sampler') and the IOM Personal Inspirable Dust Sampler (the so-called 'IOM sampler'). The former was recommended by the Health and Safety Executive for sampling total particulate airborne material (HSE, 1983), and in a later version of the document MDHS14 (HSE, 1986) is presently recommended for sampling inspirable dust (which the document refers to as 'total inhalable particulate'). The second sampler (IOM) has been described by Mark and Vincent (1986) and is designed specifically to sample inspirable dust, avoiding entry and wall losses by depositing dust onto a filter inside a light cassette which may be weighed.

Where possible, samples were also taken with the IOM Static Inspirable Dust Sampler, described by Mark *et al* (1985). Here again, dust is deposited on a filter inside a weighed cassette. While sampling in the Flax works, a high volume static sampler was also used (Rotheroe and Mitchell Model L60), air being drawn through a wire mesh in accordance with cotton sampling practice described in document EH25 (1980). Similar wire mesh grids were also fitted to some of the personal samplers in the Flax study to investigate whether this affected performance.

An assessment of the particle aerodynamic size distributions was obtained at all sites (except the fertiliser factory) using the IOM Personal Inspirable Dust Spectrometer (PIDS) described by Gibson *et al* (1987). This device was mounted on the torso of the mannequin in the lapel position similar to the other personal samplers. At least one measurement was taken for each different process in the industries studied.

Personal samplers, static samplers and the filter holder of the mannequin all used Whatman GFA glass fibre filters. All weighing was performed using a Sartorius 5-place balance, and control filters were used to minimise the effects of environmental changes. The airflow for personal samplers was provided by Casella type AFC 123 flow-controlled pumps. The flowrates through the personal sampler entries were set, prior to sampling, to 2 l/min +/- 5% with a calibrated flowmeter. In the quarry work only, the airflow was derived from the sampling ports built into the trolley. After weighing, sampler entries were protected by a plastic cap which was removed during the sampling period.

To determine the total quantity of dust entering the mouth of the mannequin it is essential to include that dust deposited on the sampler walls, its 'O'-ring seal and the mouthpiece. Brushing these parts was found to be impracticable on site and as the balance can cope with large tare weights up to 160 g, the entire housing (weighing about 89 g) was weighed before and after sampling, taking care to remove dust on the outer surfaces of the filter holder.

6. DATA AND ANALYSIS

6.1 Description of Data

The data obtained at the five sites is presented in Tables 6.1 to 6.5. These tables include inspirable dust concentrations measured by the IOM static samplers and the PIDS, as well as data for the IOM and HSE personal samplers. In order to obtain a 'feel' for the data, scatterplots of the performances of the various personal samplers in relation to the mannequin are presented in Figure 6.1. Particle aerodynamic size distributions determined using the PIDS are displayed in Figure 6.2. Within each industry, apart from the Fertiliser factory, the data are grouped for statistical analysis according to two different working conditions. These groupings, which are identified in the tables, are suggested either according to process where particle sizes differ (Flax, Rubber, Cement) or windspeed (Quarry).

Experience at the first site (Fertiliser) showed that point sources of dust, resulting in a concentration gradient across the model, caused problems in obtaining a comparison between head and personal sampler. In subsequent work, two personal samplers of each type were used, one on each shoulder. It was not possible at this site to make measurements with either the IOM static sampler or the PIDS.

Intense point sources of dust are again common in the flax industry where workers routinely used compressed air to clean machines, and cleared rejected material from hackling and carding machines generated dense local clouds. For these reasons the workers' personal samplers generally returned results well in excess of those on the model. A similar problem from a local source is apparent in the drug-weighing results from the rubber industry.

6.2 Statistical Methods

The investigation of the performance of the IOM and HSE personal samplers is formulated as a regression analysis. The mannequin mouth is the reference sampler and the assumption is made that its measurments are not subject to random variation. Thus the mouth measurement may be regarded as a 'predictor variable' in relation to the personal sampler measurement, and the interest is in how the changes to the first measurement affect the second. The two measurements are linked via a straight-line relationship through the origin which is fitted by the method of least squares. The slope is unknown and must be estimated.

A slope of 1 represents a 1:1 relationship and a perfect comparison. A slope greater than 1 means that the personal sampler is over-estimating the dust level. Similarly, a slope less than 1 means that it is under-estimating the dust level.

A t-test can be carried out to examine how close the slope is to the desired 1. The t-test involves calculating a t-statistic and judging how likely the calculated value, known as the t-value, is to have occurred by chance. The t-statistic is based on the difference between the observed data and the data that would be expected if the slope were truly 1. The significance level is the probability that the t-value or a more extreme one could have arisen by chance if the slope were

1. The smaller the significance level the less likely the slope is to be 1. A significance level of 0.10, 0.05 or 0.01 is traditionally chosen as a criterion. The t–statistic has a t–distribution when the slope is 1 and the significance level corresponding to the t–value can be obtained from tabulated percentage points of the t–distribution.

The goodness–of–fit of the straight line fitted through the origin is assessed by calculating the proportion of variation in the personal sampler measurement about the mean which is explained by the straight line. This proportion is in fact the square of the correlation between the observed measurement and that predicted by the straight–line relationship, expressed as a percentage, and as such is referred to as R–squared. The closer R–squared is to 100% the better is the fit of the straight line. For approximate guidance, R–squared greater than 60% represents a satisfactory fit, while R–squared greater than 80% indicates a very good fit.

The effect of working conditions within an industry on sampler performance is investigated by means of F–tests. An F–statistic, which has the F–distribution if the working conditions have no effect, is calculated for the data. The significance level of the F–value may be evaluated along the lines of that already described for the t–test. A signficance level of 0.05 is chosen as a criterion. A regression model with separate slopes for the two working conditions can be fitted to the data. Two separate t–tests can be carried out to test how close the slopes are to the desired 1.

This regression analysis assesses the performance of the personal samplers against the mannequin mouth. It can be applied identically to investigate the performance of the IOM sampler with the HSE sampler as reference and its measurement as predictor variable in the regression.

The personal sampler data used in the regression analysis comprised the mean values, for each type of sampler, of the dust concentrations recorded on the left and right shoulders. This was because there were indications of an unresolved bias between the values obtained on each shoulder which could have been caused by differences in sampler operation – the respective positions of each sampler on the mannequin torso were kept constant throughout the workplace trials. In hindsight, it would have been better to have randomised the sampler positions.

The results of the regression analyses are given in Table 6.6 for each of the five industries. Each 4–line entry consists of:–

(i) the slope of the fitted line through the origin;
(ii) the t–value (and significance level) for testing that the slope is 1 (i.e., testing the 1:1 relationship);
(iii) R–squared (i.e., the percentage variation in the personal sampler measurement explained by the fitted line);
(iv) the F–value (and significance level) for testing the effect of working conditions.

The extra row of entries in Table 6.6. corresponds to the regression analysis for the combined data from all industries treated as a single data set. The F–values (and signficance levels) recorded test whether the different industries affect the performances of the personal samplers.

The results from fitting regression models with separate slopes for the two working conditions are detailed in Table 6.7 for each industry. Each 2–line entry in the table consists of the estimated slope for the fitted line and the t-value (and significance level) for testing that the slope is 1.

Finally, the results of the regression analysis investigating the performance of the static sampler with the mannequin mouth as reference are given in Table 6.8.

The regression analyses were carried out using the GENSTAT statistical package (Alvey *et al*, 1982) on a Prime 750 computer. The results of the regression analyses are discussed in full in the next section.

6.3 Performance of Personal Samplers

Referring to the results of Table 6.6 for the combined data from all industries treated as a single data set the IOM sampler is seen to perform satisfactorily, but a significant F-value of 6.73 indicates that the performance varies over the industries. In comparison, the HSE sampler significantly underestimates the likely dust exposure but its performance does not appear to be as significantly affected by the differing conditions in the various industries investigated. In the following paragraphs the performance of the two samplers will be discussed with reference to both Tables 6.6 and 6.7.

In the fertilizer factory, the IOM and HSE samplers consistently and significantly over-estimate the dust exposure, IOM more so than HSE. As only one process was sampled and no size distribution information is available from this site no more comments are possible. Windspeeds were generally below 1 m/s.

In the Flax factory, the two personal samplers perform very similarly when the wire grid (described in Section 5.4) is not used. Both samplers significantly overestimate the dust exposure and there appears to be an effect of process on performance. Even when separated into the two processes their performances are similar, with both devices underestimating dust exposure in process A, where the particles are large (mass median aerodynamic diameter (mmdae)=40 μm), and overestimating in process B, where smaller particles are prevalent (mmdae=11 μm). In both areas windspeeds were low (<1 m/s). When equipped with grids designed to eliminate 'fly' the efficiency of the HSE sampler is improved, and it performs satisfactorily, but the IOM sampler still significantly overestimates dust exposure. However the results for the two processes show that whilst for the IOM sampler there is no evidence to suggest an effect of process on performance, for the HSE sampler particle size effects still appear to be playing a role in performance.

In the Rubber factory, the IOM sampler performs satisfactorily but with more variability than in the industries discussed so far. The data for the HSE sampler is not well fitted by a straight-line relationship and when the slope of the regression is calculated it shows an underestimation of exposure. When the results for the two processes are analysed separately both samplers overestimate dust exposure for the smaller particles of process (A) (mmdae=20 μm), whilst for process B, where the particles are larger (mmdae=30–50 μm), the IOM sampler performs well and the HSE underestimates exposure.

At the Cement works, the IOM sampler performs reasonably well in general and is affected only to a small degree by changes in particle size within the different processes. The HSE sampler, however, underestimates dust exposure in both processes, and this underestimation is again worse for the larger particles found at process A.

At the Quarry, both personal samplers underestimate dust exposure in general. However, the measurements are not well fitted by the straight line relationships, and show a lot of scatter. Whilst all measurements were taken at the same process (the tertiary crusher), the windspeeds changed from day to day and it is instructive to consider the results for two windspeed classifications. For low windspeeds (<1 m/s) both samplers overestimate dust exposure, whilst at the windspeeds of 3–4 m/s both samplers signficantly underestimate dust exposure. The estimated particle size distributions were similar for both windspeeds.

6.4 Performance of Static Samplers

Whilst not part of the original aims of the project, the opportunity was taken to assess the performances of static samplers in relation to dust exposure as measured by the mannequin. The IOM static inspirable dust sampler was generally used and, as can be seen from Table 6.8 it almost invariably underestimates actual dust exposure.

Its performance in the Flax industry is quite good although it does underestimate dust exposure for the spinning and winding processes. It very–signficantly underestimates dust exposure in the Rubber factory, and the data are not well fitted by the straight line relationship. The same is also true for the Cement data where, singificantly, different performances in the two processes lead to two completely different data sets. At the Quarry, windspeed signficantly affects the relationship between the IOM static sampler and the mannequin. The general behaviour is similar to that experienced by the personal samplers.

In the Flax industry, the performance of a second static sampler, the Rotheroe and Mitchell L60 (recommended for use in the cotton industry), was assessed. The performance is considerably worse than for the IOM static sampler, displaying both significant underestimation of dust exposure and considerable variability of performance.

7. CONCLUDING REMARKS

7.1 The Model Worker

The full-scale model of a human worker has been built to enable the performances of personal dust samplers in industrial workplaces to be assessed. The aim was to provide a system whereby the actual dust levels experienced by the worker could be measured by both the simulated worker and by the personal samplers mounted on his body. As the development proceeded, a number of compromises were made in the design and operation of the model with respect to the fully automated version first envisaged. Firstly the model requires an operator for transportation around the workplace, for operation of the body movements, and for ensuring that the required flowrate is maintained in workplaces where dust concentrations are high. In addition, in most workplaces studied, the aim of mimicking the precise movements and actions of individual workers was not practicable. However, the model worker has provided, for the first time, a means of evaluating the performances of personal samplers in relation to dust exposure in industrial workplaces.

7.2 Workplace Investigations

Investigations have been carried out in five different industrial workplaces. Whilst the number of repeat sampling runs have been relatively low, several broad conclusions may be drawn:-

1) The IOM personal sampler performs satisfactorily in relation to inspirable dust exposure but this performance varies between industries.

2) The HSE personal sampler signficantly underestimates inspirable dust exposure, but this performance is not as affected by varying industrial conditions as the IOM sampler.

3) For both personal samplers, performance appears to be dependent upon particle size distribution and windspeed. In general, they collect more dust when exposed to fine particles than when exposed to the coarser ones. This effect is more marked for the HSE sampler and confirms results found in the laboratory wind tunnel (Mark and Vincent, 1986).

4) The IOM static sampler generally underestimates inspirable dust exposure with performance varying both at a given workplace and from workplace to workplace. However, the performance of the Rotheroe and Mitchell L60 static sampler was worse at the one site visited. This highlights the problems of static sampling for health-related dust exposure measurements.

7.3 Further Work

The aim of dust sampler evaluation is to assess how well a given sampler performs in relation to its required task or criterion. This then provides information to enable decisions to be made as to whether the sampler is suitable for the task of whether a different one should be chosen and, if necessary developed. From the limited investigations described above such decisions are not yet possible and so further work is needed. There are two ways in which progress could be made, both of which will provide complementary information:

a) Carry out further, more extensive workplace investigations both in the same industries as those already studied as well as additional ones.

b) Carry out laboratory studies where realistic simulations of workplaces may be constructed and sampler performance evaluated systematically.

Finally, the performances of other personal samplers currently recommended and used to measure dust exposures (e.g., the single-hole sampler recommended by HSE for lead (HSE, 1986), the American 37 mm cassette, etc.) should be investigated in a similar manner.

ACKNOWLEDGEMENTS

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Filter Load mg	Memory Switch Posn.	Pressure Meter*	Minute Volume l	Memory Switch Posn.	Pressure Meter*	Minute Volume l
0	4	3.0	20.0	4	3.0	20.0
20	4	4.0	19.2	6	4.5	20.5
35	6	5.5	20.0	-	-	-
60	6	7.0	18.0	8	7.5	20.0
70	8	8.0	18.6	12	8.0	20.2
100	12	8.5	19.0	15	9.0	20.0
120	15	9.5	19.8	16	9.5	20.0

GFA Filter loaded with 5 micron alumina powder.

* – arbitrary units

TABLE 4.1 Switch positions to maintain required flowrate on breathing machine.

SAMPLES	1	2	3	4	5	6	7	8	9	10	11	12
MOUTH	60.8	66.4	75.5	91.5	90.4	279	196	76.4	64.1	47.4	84.5	58.8
HSE L	58.3	////	////	////	106	302	229	77.4	66.8	46.3	82.4	59.3
HSE R	////	85.7	70.6	75.5	////	///	///	92.9	82.8	53.9	70.4	64.8
IOM L	////	81.0	118	119	////	///	///	89.2	82.8	40.6	95.8	57.4
IOM R	63.4	////	////	////	102	407	340	94.1	86.7	52.0	100	60.8
OPERATOR												
HSE	48.5	24.7	97.6	94.0	127	242	342	////	////	////	////	////
IOM	58.6	36.2	192	133	207	253	578	////	////	////	////	////

It was not possible to obtain static sampler or PIDS measurements at this site.

* ALL SAMPLES WERE OBTAINED IN THE MILL AREA.

TABLE 6.1 Dust concentration measurements (in mg/m^3) from Fertiliser factory.

SAMPLER	SPINNING			CARDING					HACKLING			WINDING		PREPARATION	
MOUTH	5.1	5.2	7.4	13.2	22.8	20.6	12.8	15.2	13.3	8.9	10.6	3.2	////	3.2	////
HSE.L	2.8	3.6g	3.9g	14.8	23.6g	18.5g	16.7	13.8g	17.2	10.2g	11.6g	3.5g	////	2.5	////
HSE.R	3.8g	6.2	5.1	14.5g	28.1	19.5	14.6g	17.3	14.6g	10.2	13.8	3.4	////	3.1	////
IOM.L	3.3	5.1g	6.0g	16.2	29.4	20.5	16.5	15.9g	14.2	10.4g	12.4g	3.6g	////	2.7	////
IOM.R	5.6g	5.0	4.9	15.3g	27.2g	29.3g	15.9g	17.1	15.6g	13.2	14.6	4.0	////	4.4	////
OPERATOR:															
HSE	18.4	////	////	64.0	20.2	139.0	98.0	////	32.2	////	////	4.6	////	11.4	////
IOM	5.8	////	////	30.7	////	52.8	27.6	////	36.6	22.8	45.0	4.4	3.5	5.7	////
PIDS		7.6				14.8				21.2					
STATIC:															
L 60	1.2	5.0	3.9	////	////	////	////	5.8	5.7	7.4	12.3	3.2	1.3	3.1	1.2
IOM	1.7	6.7	4.1	13.4	////	////	////	15.2	12.4	////	13.4	2.8	1.4	2.3	////

g indicates that a grid was attached to the personal sampler. All operator samplers were fitted with grids.

PROCESS A = Spinning and Winding : PROCESS B = Carding and Hackling

TABLE 6.2 Dust concentration measurements (in mg/m^3) from Flax factory.

SAMPLER	KILN PLATFORM		CLINKER COOLER						GRANULATION PLANT							
MOUTH	3.2	4.0	6.0	34.9	33.7	11.9	147	39.2	1.8	104	6.0	163	64.4	10.9	7.6	2.2
HSE L	5.0	4.6	9.5	56.4	28.5	13.8	77.5	26.4	2.6	142	3.6	105	113	9.0	11.7	3.3
HSE R	5.1	4.0	10.0	50.6	26.0	10.0	56.5	20.9	2.4	73.1	10.8	115	52.4	8.3	8.2	5.6
IOM L	5.1	5.3	17.0	64.0	43.4	34.2	89.6	26.5	3.6	155	7.0	167	179	11.8	14.5	3.8
IOM R	6.4	5.8	16.7	58.4	42.3	18.3	118	34.9	3.7	87.5	19.3	92.8	69.8	11.8	10.0	2.8
PIDS	7.1		33.7							107.3						
STATIC:																
IOM	3.2	4.9	11.6	44.1	17.4	8.9	300	27.2	3.9	13.2	2.2	2.0	33.2	////	16.8	9.2

PROCESS A = Kiln Platform and Clinker Cooler : PROCESS B = Granulation Plant

TABLE 6.3 Dust concentration measurements (in mg/m^3) from Cement Works.

SAMPLER	DRUG WEIGHING			DRUG HANDLING		RUBBER MASTICATION										
MOUTH	9.8	1.3	2.9	2.8	4.8	13.2	7.5	3.9	5.5	11.6	19.6	7.7	3.3	4.6	8.8	7.6
HSE L	12.6	0.5	0.7	3.9	4.8	13.0	7.0	5.1	3.6	7.2	12.4	5.9	5.7	2.5	4.8	13.9
HSE R	12.2	0.7	0.9	5.4	3.9	8.7	11.5	4.8	3.9	9.9	12.3	10.2	6.9	2.6	4.4	20.9
IOM L	13.2	0.9	0.5	2.7	3.7	12.9	8.1	5.2	3.8	10.7	15.6	9.9	5.1	2.3	5.8	18.9
IOM R	12.8	0.7	0.9	4.3	6.5	16.9	8.0	6.6	6.2	9.6	17.9	6.2	6.5	5.9	5.2	19.0
OPERATOR																
I/H/H/I	77.7	10.5	3.8	////	////	7.8	////	////	////	////	////	////	////	////	////	////
PIDS	<—— 6.1 ——>						<—— 9.2 ——>					<—— 6.4 ——>				
STATIC:																
IOM	5.1	1.6	0.2	3.8	2.7	4.0	1.9	3.1	2.4	4.8	6.7	1.9	0.7	1.1	1.6	2.6

PROCESS A = Drug Weighing and Handling : PROCESS B = Rubber Mastication.

TABLE 6.4 Dust concentration measurements (in mg/m^3) from Rubber works.

							TERTIARY CRUSHER							
SAMPLER	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MOUTH	2.1	2.2	10.0	43.0	67.7	4.6	243	192	25.5	112	50.1	196	300	98.9
HSE L	5.3	6.0	13.2	53.1	41.4	3.0	438	178	35.1	183	28.2	65.0	89.3	40.2
HSE R	1.3	5.7	17.9	71.8	50.7	1.4	364	165	28.9	152	25.9	58.2	103	21.6
IOM L	5.4	17.7	18.6	118	49.9	4.9	360	209	41.5	189	33.1	68.3	91.2	24.3
IOM R	3.3	11.3	16.7	110	89.0	6.5	402	191	44.4	189	42.4	98.0	138	45.8
PIDS		<—14.8—>							71.4					
STATIC:														
IOM	////	2.7	9.2	19.4	47.3	6.8	315	228	51.0	216	34.1	154	132	40.2

CONDITION A (Windspeed = <1 m/s) = Samples 7–10
CONDITION B (Windspeed = 3–4 m/s) = Samples 1–6, 11–14

TABLE 6.5 Dust concentration measurements (in mg/m^3) from Quarry.

INDUSTRY	IOM sampler and MOUTH	HSE sampler and MOUTH	IOM Sampler and HSE sampler
FERTILISER	1.448	1.328	1.087
	7.14 (0.001)	5.93 (0.001)	3.01 (0.02)
	94.9%	95.3%	97.6%
	-	-	-
FLAX without grid	1.166	1.137	1.022
	3.31 (0.01)	2.93 (0.02)	0.78 (0.45)
	91.8%	92.8%	96.5%
	3.84 (0.08)	3.92 (0.08)	0.05 (0.90)
FLAX with grid	1.102	0.996	1.102
	2.99 (0.01)	0.11 (0.90)	4.89 (0.001)
	95.5%	93.9%	98.3%
	1.82 (0.20)	8.12 (0.02)	5.76 (0.04)
RUBBER	1.041	0.835	1.164
	0.41 (0.70)	1.50 (0.17)	2.72 (0.02)
	60.9%	38.0%	87.9%
	0.17 (0.65)	1.14 (0.30)	1.85 (0.20)
CEMENT	0.928	0.714	1.273
	0.82 (0.45)	4.04 (0.001)	5.73 (0.001)
	77.4%	77.6%	96.0%
	1.39 (0.15)	5.52 (0.04)	3.13 (0.10)
QUARRY	0.854	0.785	1.036
	0.96 (0.40)	1.37 (0.20)	0.85 (0.40)
	45.8%	45.3%	96.0%
	36.12 (0.001)	48.74 (0.001)	10.24 (0.009)
ALL DATA	1.068	0.880	1.177
	1.11 (0.30)	2.22 (0.03)	6.70 (0.001)
	73.0%	70.6%	95.0%
	6.73 (0.005)	2.12 (0.10)	11.65 (0.001)

TABLE 6.6 Results of regression analysis for the personal dust samplers to show effect of working conditions.

INDUSTRY/ PROCESS	WINDSPEED m/s	ESTIMATED MASS MEDIAN AERODYNAMIC DIAMETER µm	IOM sampler and MOUTH	HSE sampler and MOUTH
FLAX / A without grid	<1	44	0.826 0.97 (0.40)	0.819 1.09 (0.35)
FLAX / B without grid	<1	11	1.190 4.06 (0.005)	1.159 3.67 (0.01)
RUBBER/ A	1	20	1.154 0.51 (0.65)	1.153 0.48 (0.65)
RUBBER/ B	<1	30-50	1.025 0.23 (0.80)	0.792 1.79 (0.10)
CEMENT/ A	1	25	0.799 1.45 (0.20)	0.537 4.69 (0.002)
CEMENT/ B	1	50	1.008 0.07 (0.98)	0.831 2.17 (0.08)
QUARRY/ A	1	43	1.405 5.33 (0.02)	1.375 3.38 (0.04)
QUARRY/ B	3-4	45	0.446 3.35 (0.008)	0.348 6.79 (0.001)

TABLE 6.7 Results of regression analysis for the personal dust samplers to show effect of working conditions.

INDUSTRY	IOM static sampler and MOUTH (all data)	IOM static sampler and MOUTH	
		Condition A	Condition B
FLAX	0.978 0.30 (0.80) 86.2% 3.60 (0.10)	0.703 1.88 (0.15)	1.029 0.43 (0.79)
RUBBER	0.354 18.34 (0.001) 52.9% 5.81 (0.001)	0.555 5.01 (0.08)	0.327 20.63 (0.001)
CEMENT	0.765 0.97 (0.35) 29.2% 93.90 (0.001)	1.848 5.97 (0.001)	0.096 8.07 (0.001)
QUARRY	0.879 0.96 (0.40) 61.2% 47.47 (0.001)	1.336 3.84 (0.04)	0.541 6.09 (0.001)
FLAX for R & M L60 static sampler	0.606 3.72 (0.008) 19.4% 0.01 (0.25)	0.632 1.36 (0.25)	0.601 3.19 (0.05)

TABLE 6.8 Results of regression analysis for the static dust samplers.

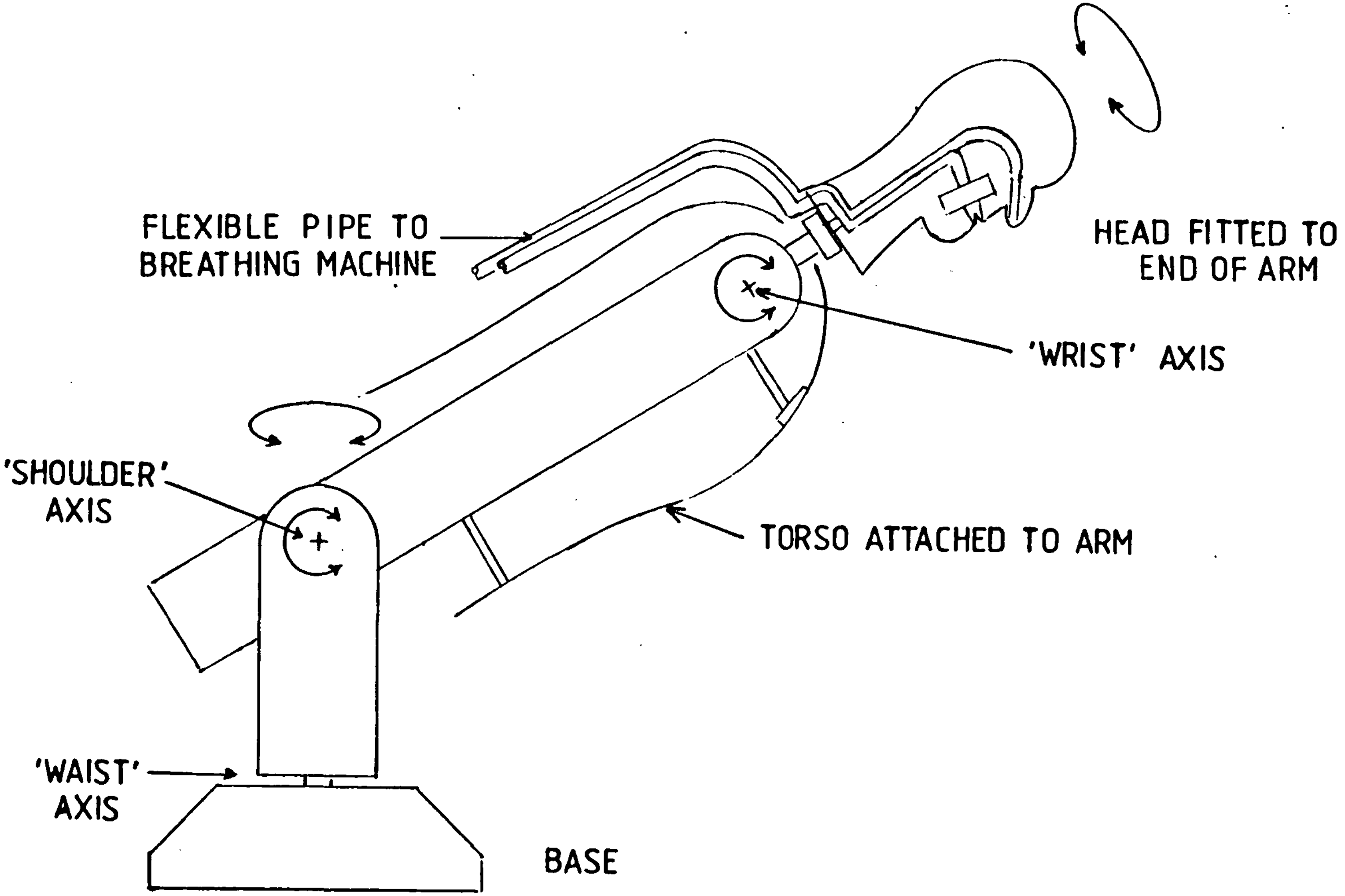


Figure 4.1 Schematic diagram of robotic arm assembly, illustrating available movements.

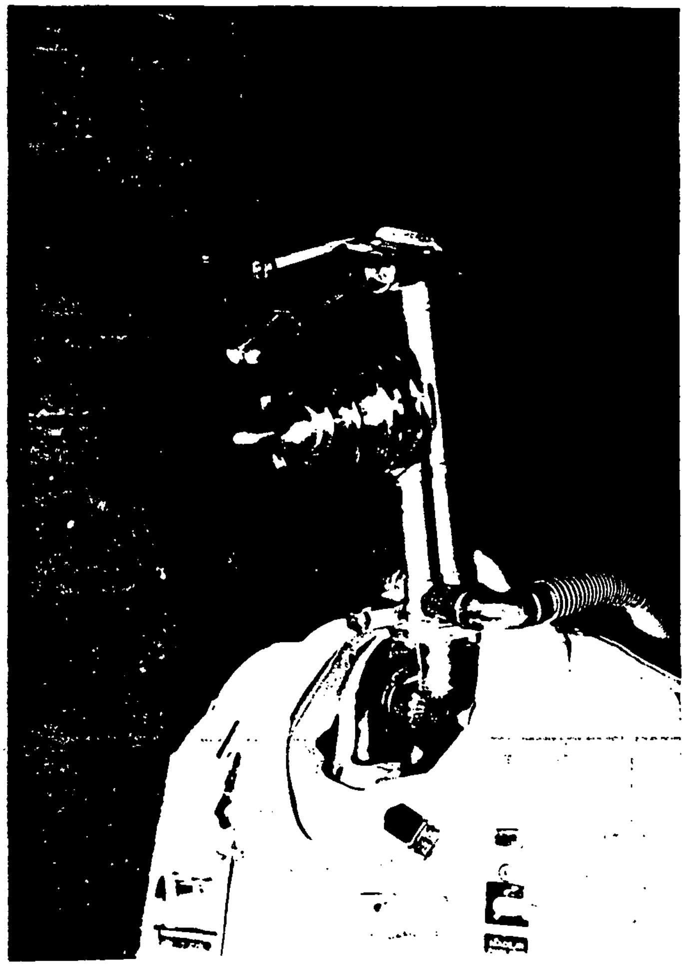


Figure 4.2 Arrangement of filter holder and connecting pipework for model head.

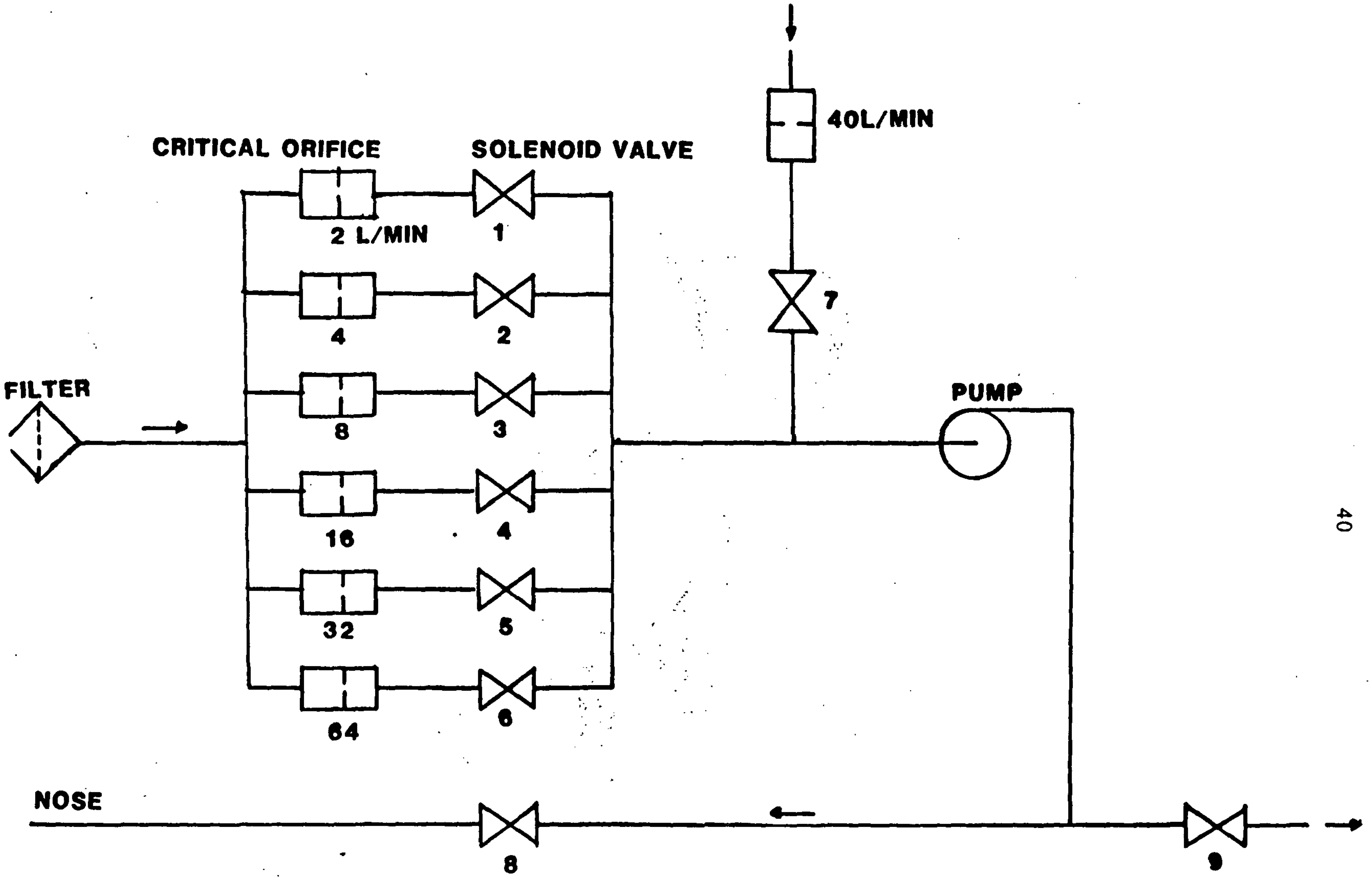
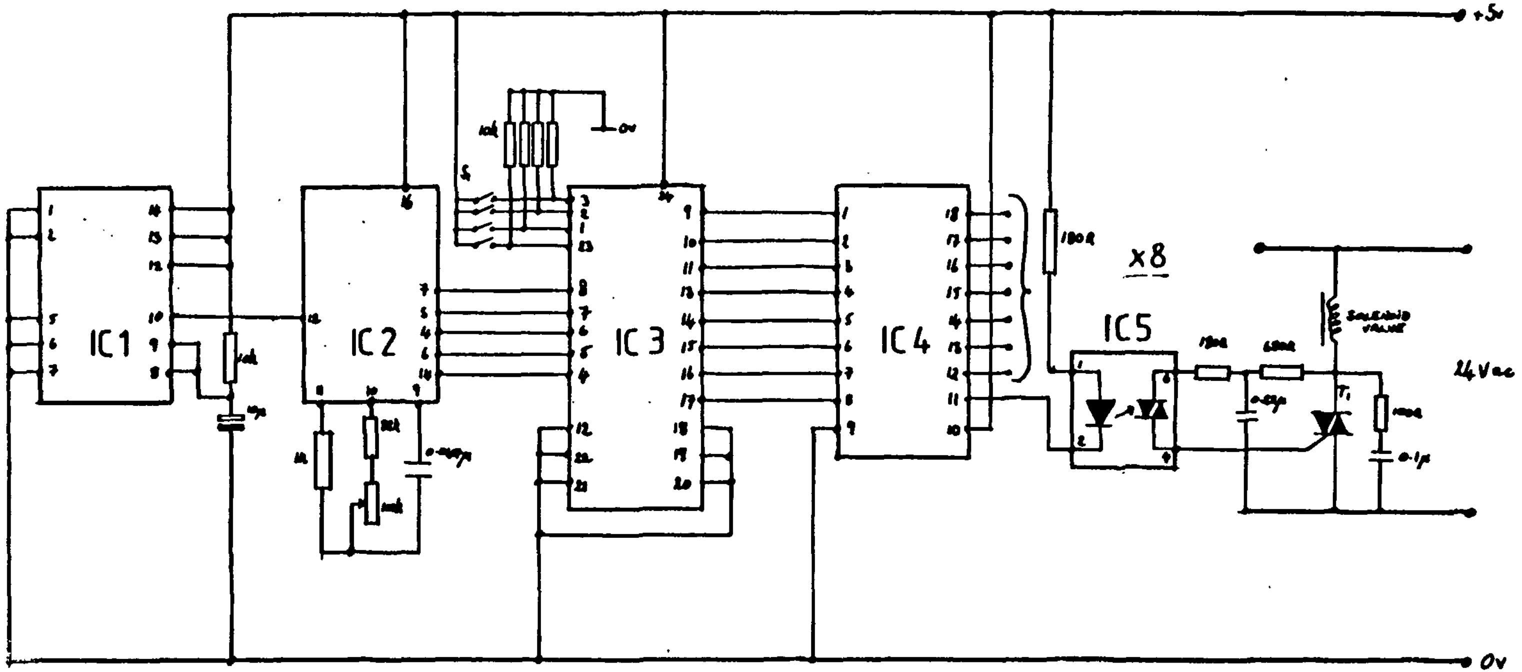


Figure 4.3 Schematic diagram of breathing machine.



IC 1: CD 4011
IC 2: CD 4060
IC 3: M2732 EPROM
IC 4: ULN 2803A OCTAL DRIVER
IC 5: MOC 3020
T1: BT136-600

Figure 4.4 Driver circuit for breathing machine solenoid valves.

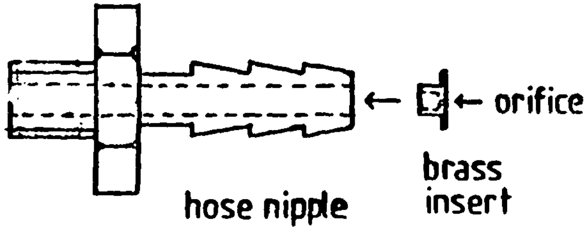


Figure 4.5 Construction of critical orifices.

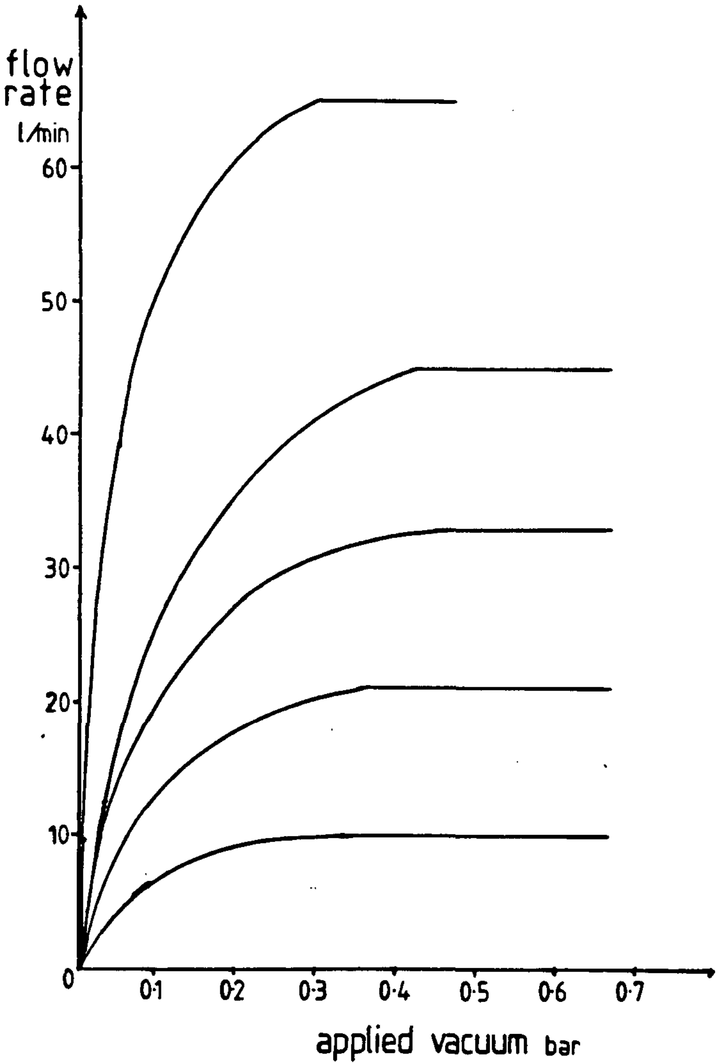
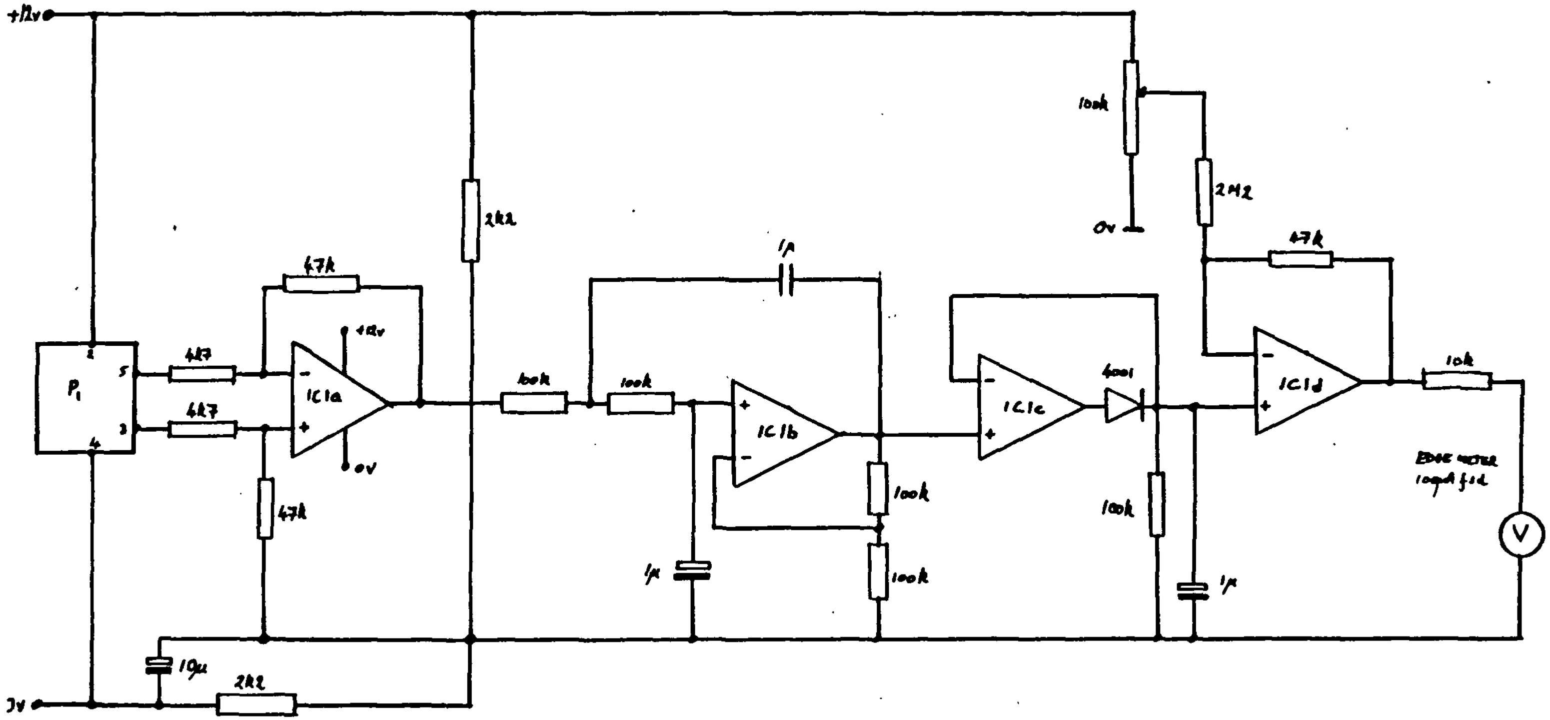


Figure 4.6 Flowrate as a function of applied vacuum for critical orifices.



IC1: LM324
P1: SCX 15 DNC

Figure 4.7 Circuit for peak pressure meter.

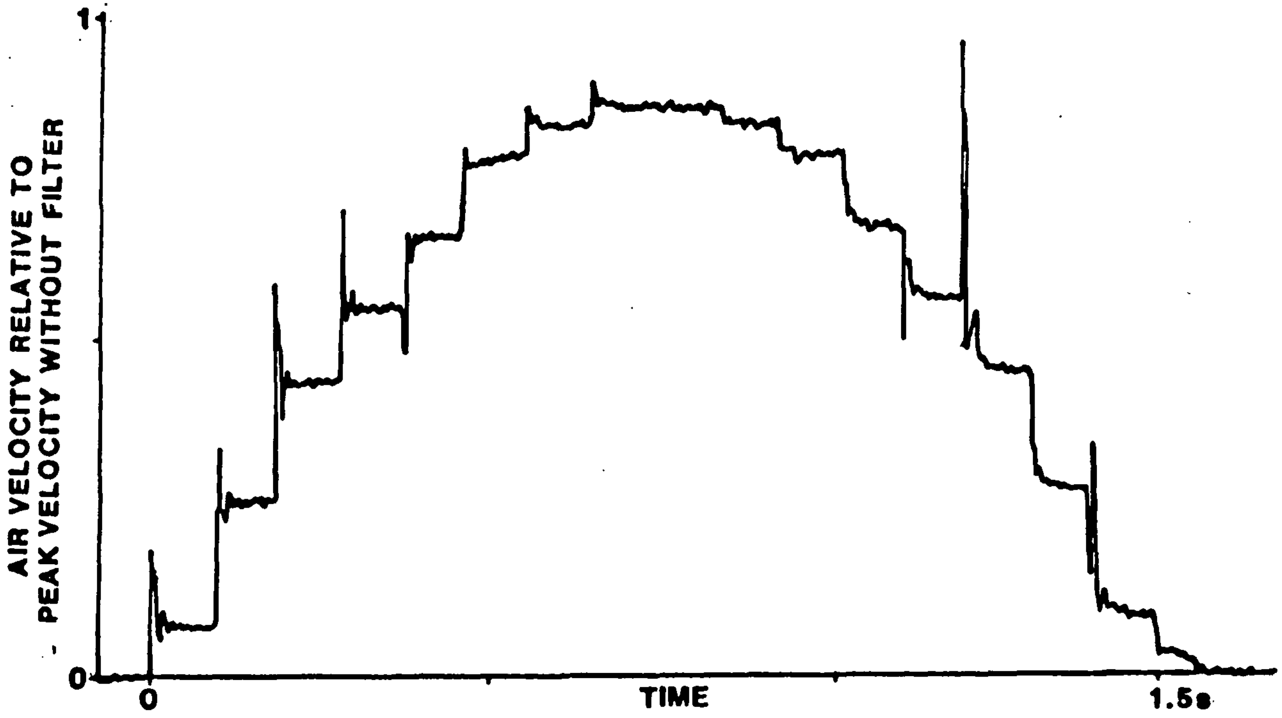


Figure 4.8 Typical waveform produced by breathing machine (through Whatman GF/A filter at a flowrate of 16.8 l/min).

Figure 4.9 Model worker complete.

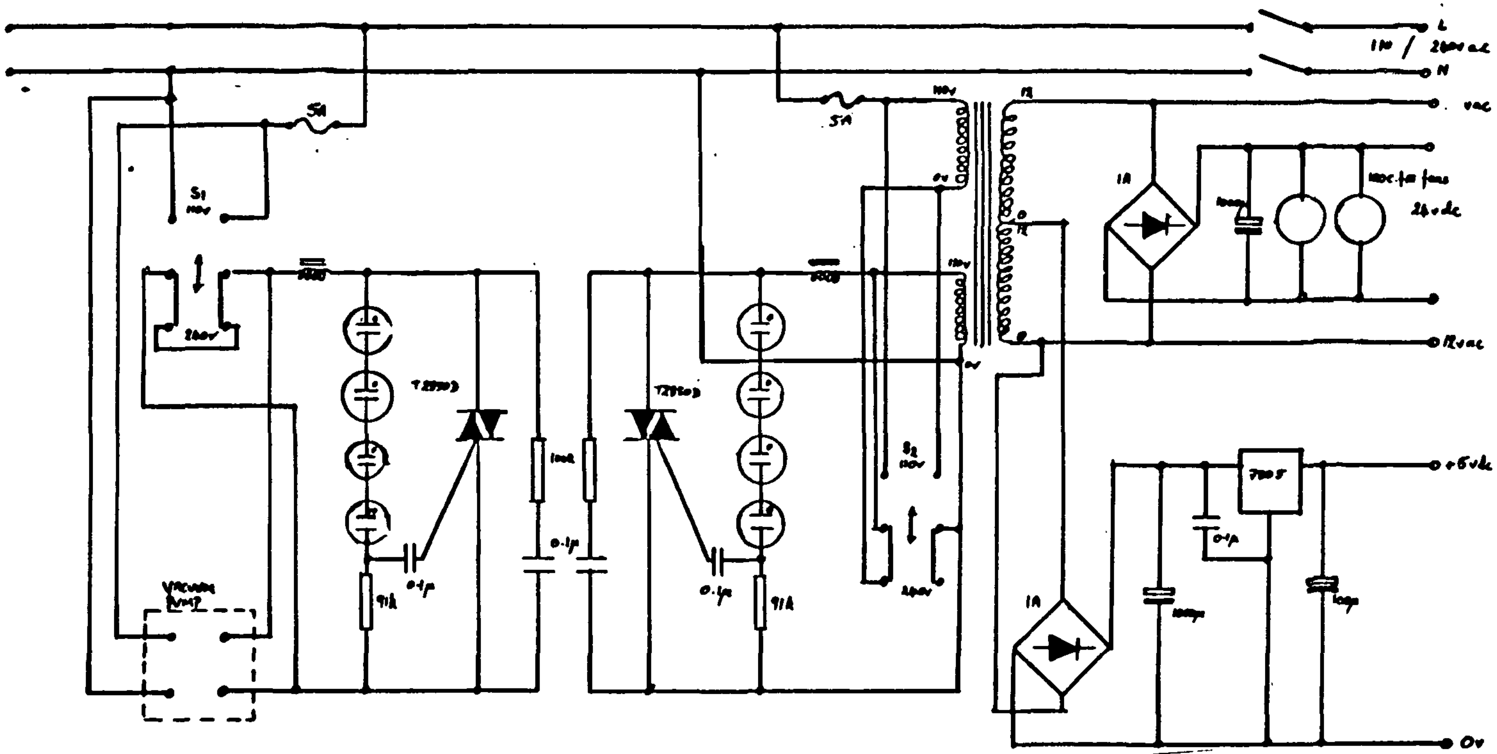


Figure 4.10 Power supply and 'crowbar' protection circuits.

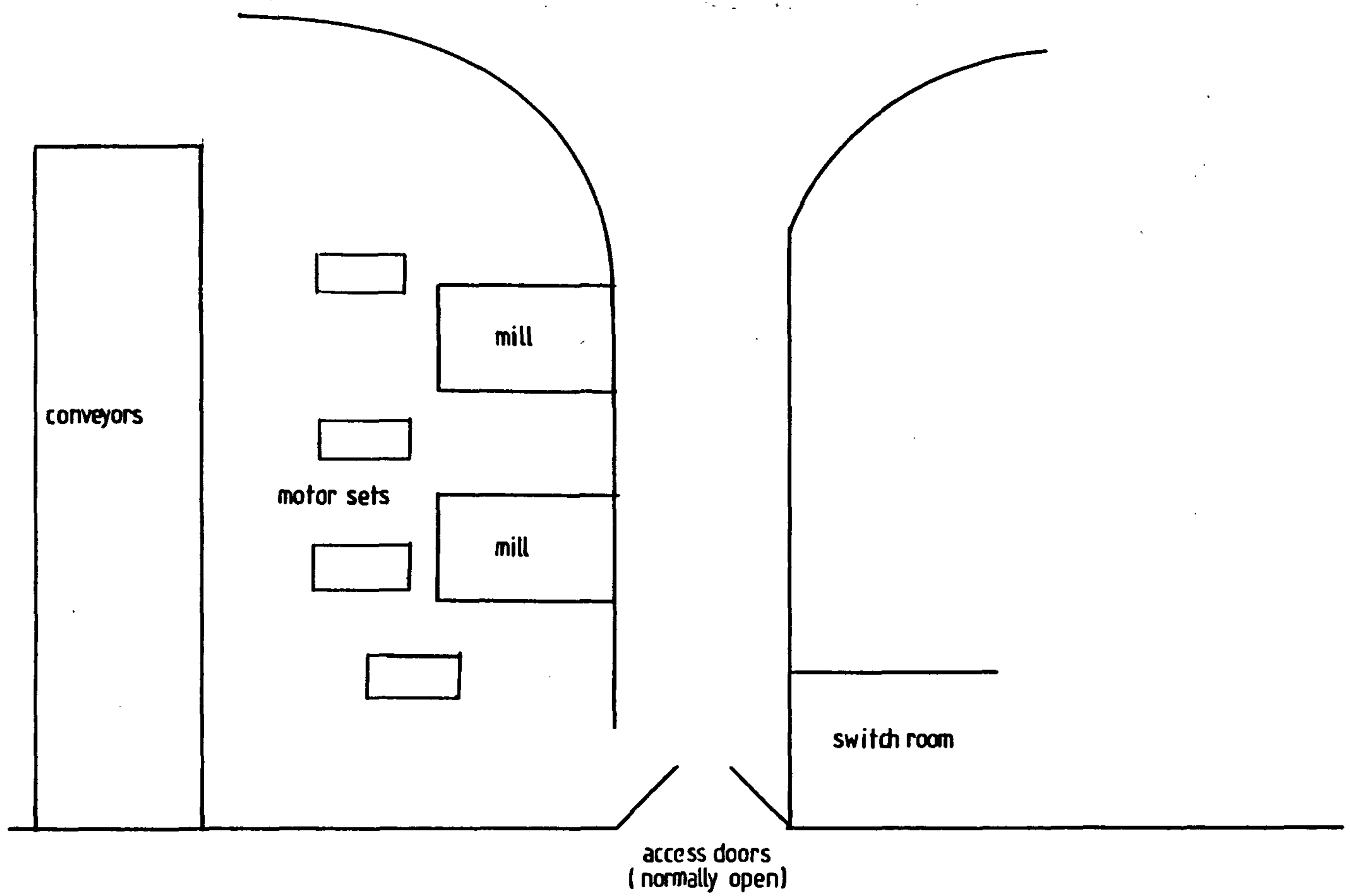


Figure 5.1 Generalised floor plan of phosphoric acid plant at Fertiliser factory.

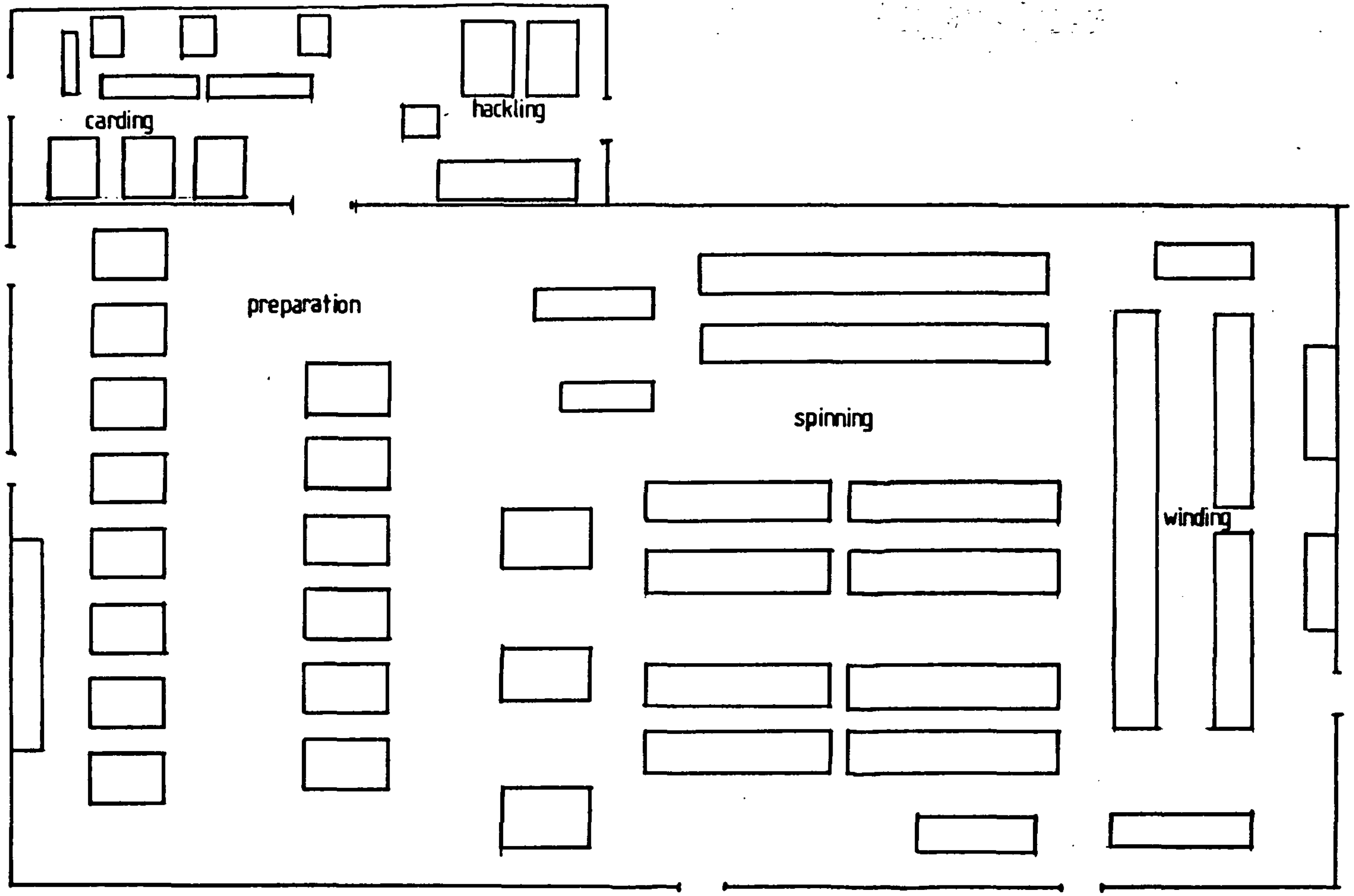


Figure 5.2 Plan view of Flax spinning factory.

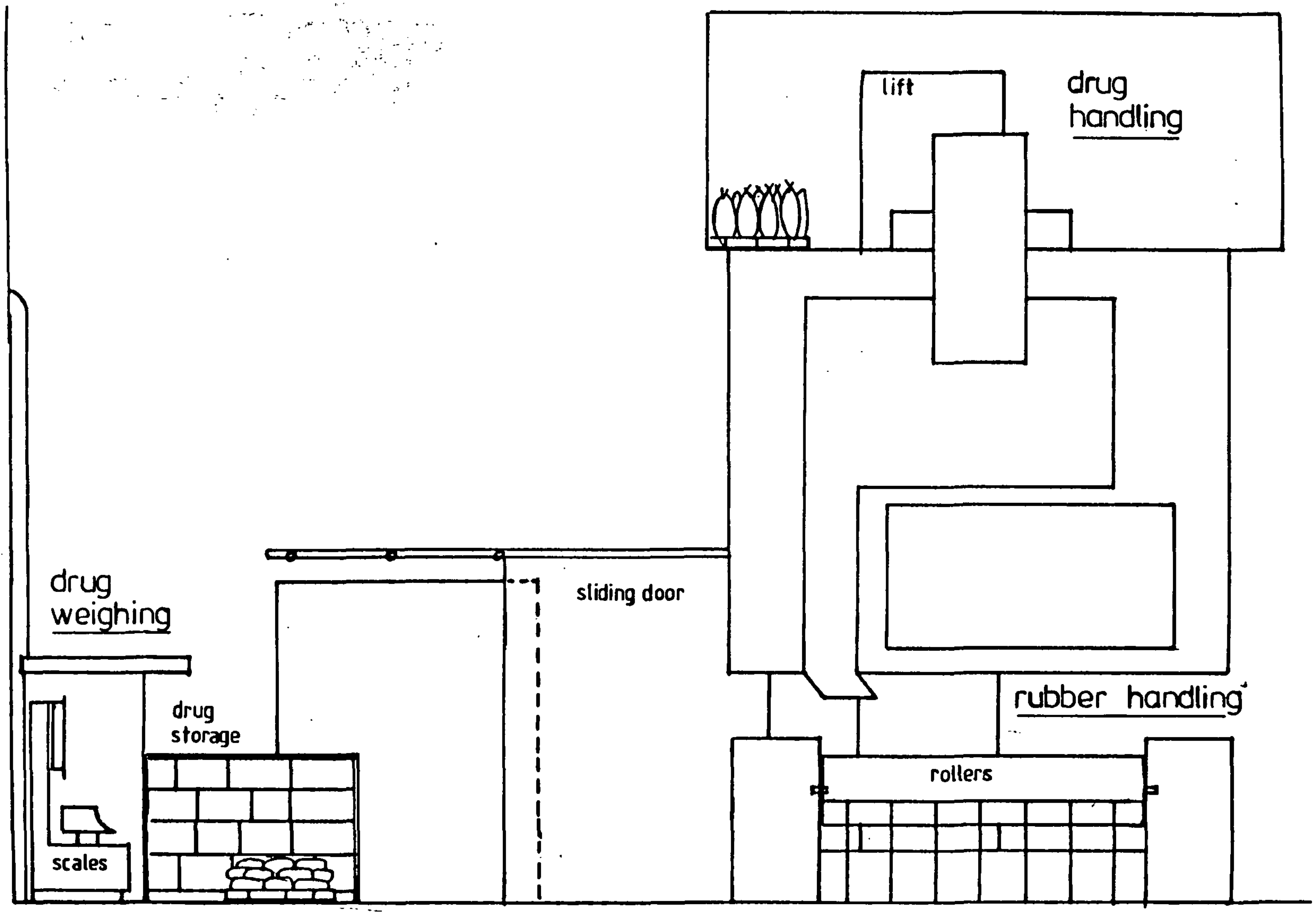


Figure 5.3 General layout of 'Banbury' rubber treatment plant at Rubber works.

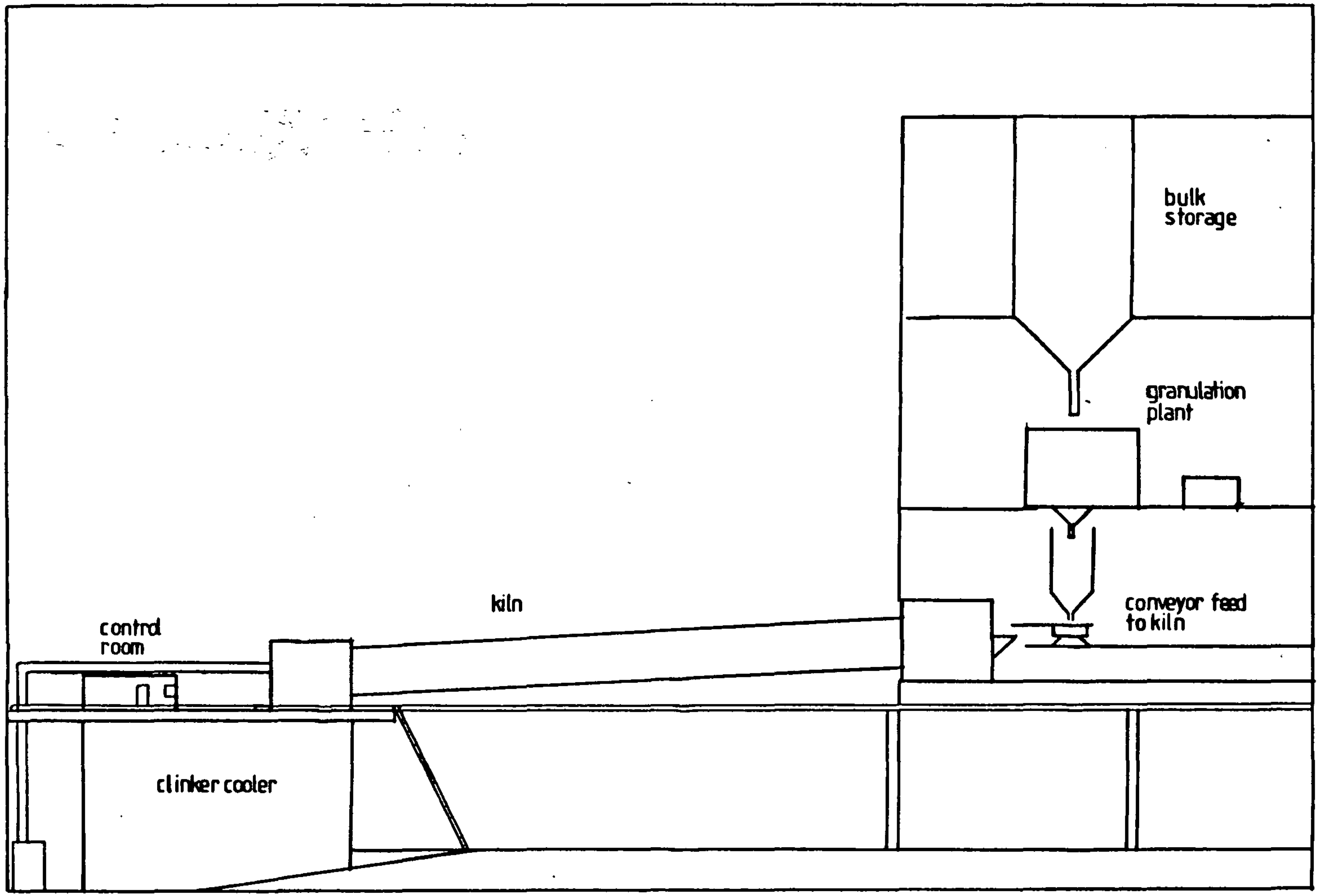


Figure 5.4 General layout of kiln house at Cement factory.

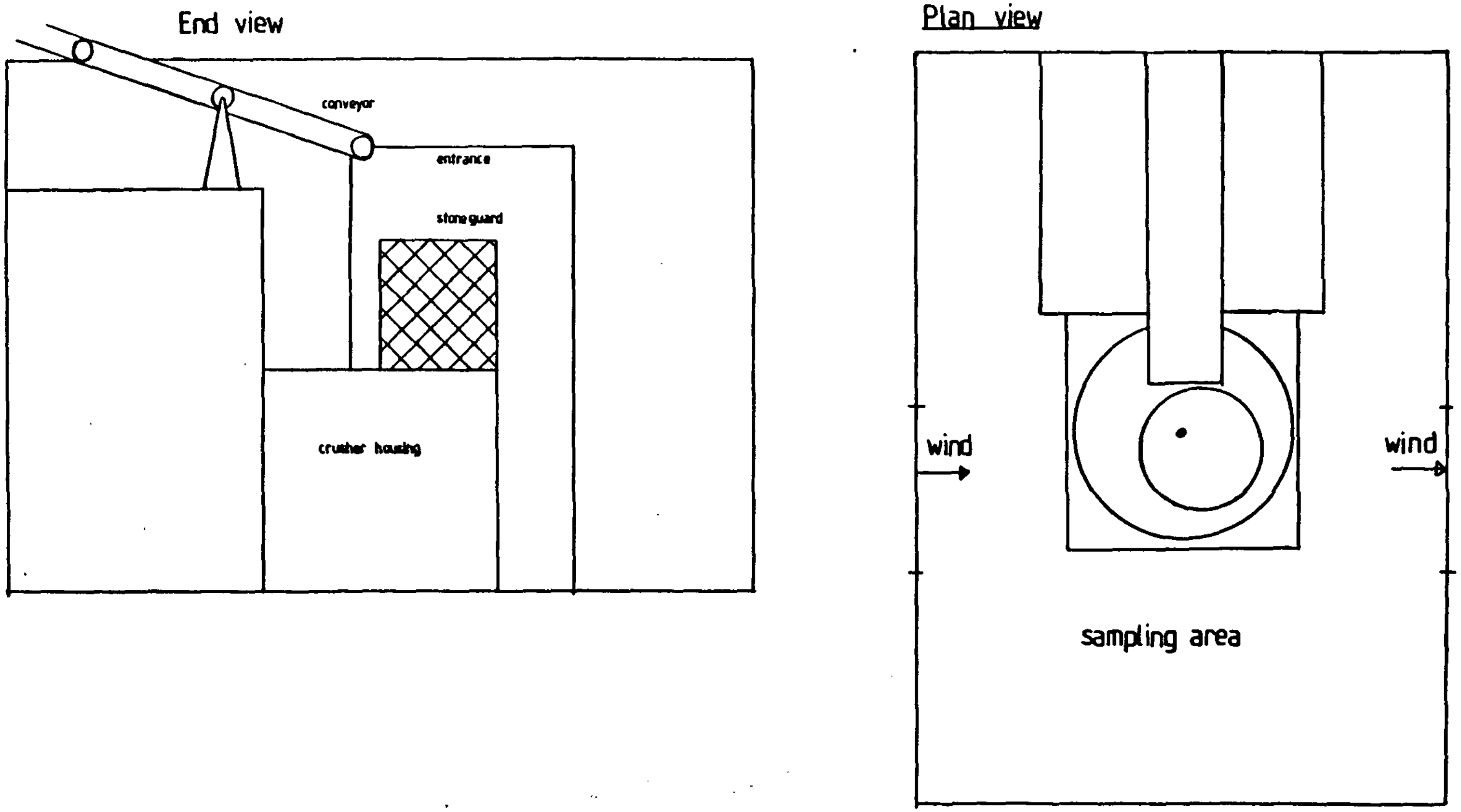


Figure 5.5 General layout of tertiary crusher at Quarry.

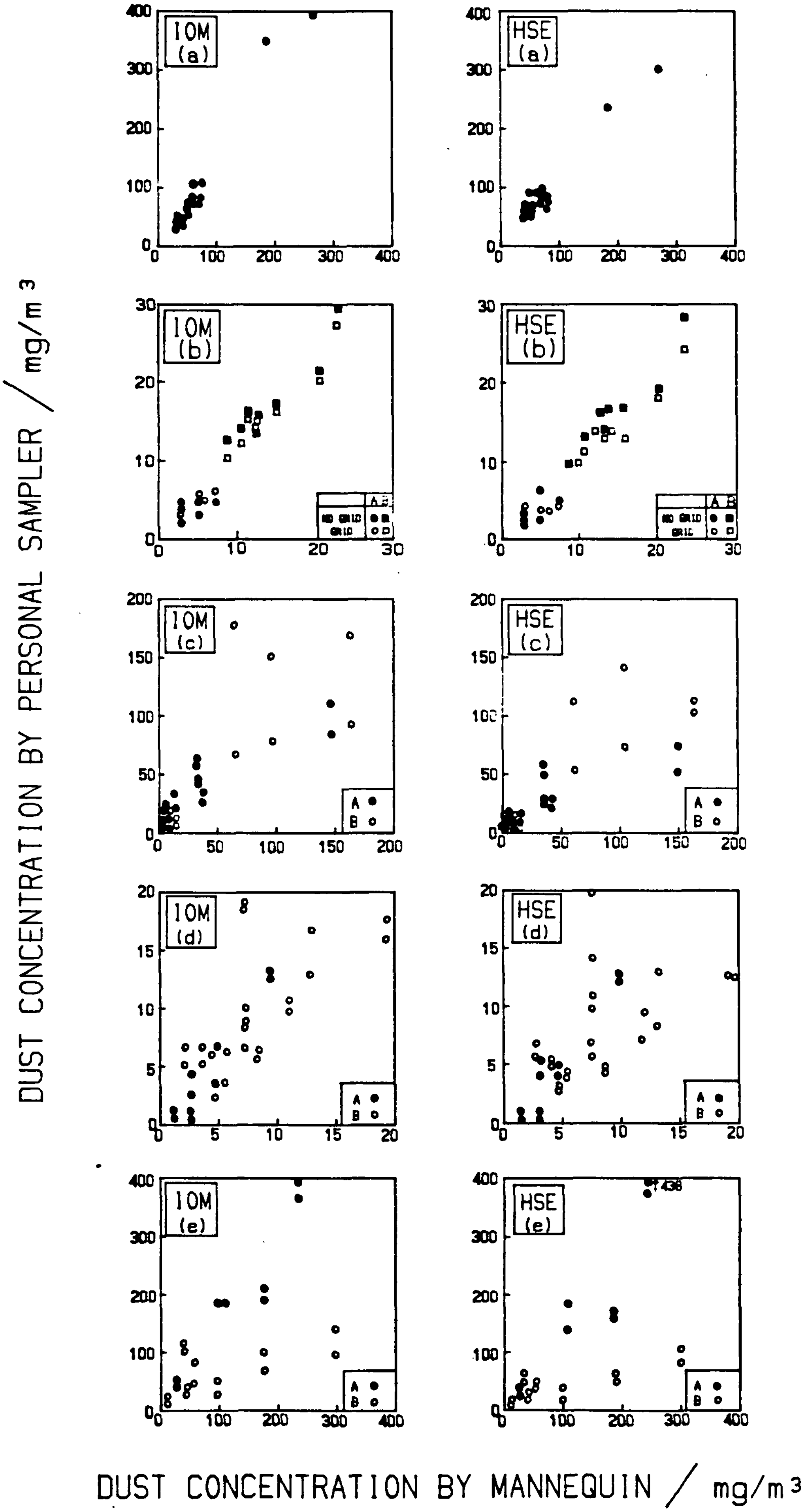


Figure 6.1 **Relationship between dust measurements taken by personal dust samplers and model worker; a) Fertiliser factory, b) Flax spinning factory, c) Cement factory, d) Rubber works, e) Quarry.**

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