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British Occupational Hygiene Society
Technical Guide No. 5

The Selection and Use of Personal Sampling Pumps

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by

The B.O.H.S. Technology Committee

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BOHS TECHNICAL GUIDE NO. 5 SAMPLING PUMPS Science Reviews Ltd.

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The Selection and Use of Personal Sampling Pumps

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The views expressed in this Technical Guide are those of the Authors and are not necessarily those of the Society.

CONTENTS

ABSTRACT

This Guide covers self-contained personal sampling pumps of two basic types:

(a) low flow rate pumps typically used for sampling gases and vapours (flow rates up to 500 cm^3 min^{-1}),

(b) high flow rate, flow stabilized pumps typically used for sampling particulates (flow rates up to 4 litres min^{-1}).

It contains sections on desirable design and performance features and a users' guide which includes:

selection criteria; safety requirements; battery management; maintenance; flow measurement and calibration; and sampling procedures.

It also includes a range of tests which were carried out on many of the makes of pump commercially available in the United Kingdom over the past few years. The tests were undertaken as projects at The University of Aston in Birmingham on seven low flow and eight high flow pumps. The tests cover:

(a) flow stability with time, temperature and orientation;

(b) operational range of flow rate and back pressure characteristics;

(c) battery life;

(d) noise emission levels;

(e) pulsation.

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1 INTRODUCTION

Most European countries have legislation for the protection of the health and safety of persons at work. In the United Kingdom (UK) this provision is made through the Health and Safety at Work etc. Act 1974, and through supportive Codes of Practice and Regulations.

Many industrial processes may use or produce substances that give rise to gases, vapours, fumes or particulates which may be harmful to health. An important aspect of securing the health of persons with the potential for exposure to such compounds is to ensure that airborne contaminants are maintained below acceptable levels by monitoring the workplace atmosphere.

Exposure of persons to any airborne contaminant, whether it has proven toxic effects or not, should be reduced to the lowest level that it is reasonably practicable to achieve, by means of effective methods of control. For many substances there is published information on exposure standards, usually expressed as full shift time weighted average limits and, in addition for some substances, as short term limits.

For good management of occupational health and hygiene, monitoring of workroom air is essential (a) to ensure compliance with the legislation and the published air quality standards, (b) to ensure that engineering controls are effectively maintained, and (c) to collect adequate occupational hygiene data, to assist with the revision of existing limits and preparation of new standards.

The majority of workplace air quality standards in the UK relate to individual exposure of persons, e.g. the Control of Lead at Work Regulations 1980 require the use of personal sampling techniques. For sampling in the workplace, a small portable battery operated pump is worn by the worker and is connected to a suitable sampling device by a flexible hose. The sampling device usually consists of either a vapour adsorption (VA) tube, a bubbler/impinger, a gas bag or a dust sampling head. The sampling device is normally attached t the lapel of the worker, in an attempt to obtain a sample representative of the air breathed by the person, although the monitoring equipment can also be used at fixed locations within the workplace.

Flow rates typically in the range 5 to 500 $cm^3 min^{-1}$ are employed for the collection of gases and vapours whilst for dust sampling they are typically 0.5-4.0 $l min^{-1}$.

Obtaining an accurate measurement of airborne contaminants therefore not only requires reliable sample collection devices and analysis procedures but also a pump that is capable of sampling air at a constant rate within acceptable limits of the set flow rate.

Several designs of battery powered pumps are commercially available for personal sampling in the workplace. However, little information has been published in connexion with the technical evaluation of sampling pumps to assist the practising occupational hygienist in the selection of the one most suitable for a particular application. Published material includes Linch (1974), Akesson et al. (1980), Beaulieu (1980), and a review of dust sampling pumps by Wood (1977).

Because of the widespread use and variety, the Technology Committee of the British Occupational Hygiene Society set up a working group to produce a Guide, incorporating a laboratory evaluation, for the selection and use of personal sampling pumps. This Guide includes consideration of low flow rate pumps (up to 500 cm^3 min^{-1}) and high flow rate, flow-controlled pumps (0.5-4.0 litres min^{-1}), to provide potential users with comprehensive information which will enable them to select the unit most suitable for their purpose and to adopt appropriate procedures for their use, maintenance and calibration.

The working group selected seven pumps in the low flow range and eight in the high flow range for evaluation purposes. These were considered to be representative of pumps commercially available in the United Kingdom. The objectives of the evaluation were:

(a) to assess the flow stability over 8 hours at near maximum, near minimum and mid range flow rates;

(b) to assess flow stability at three temperatures, approximately 0°, 20° and 40°C;

(c) to determine how flow rate varies with changes in back pressure (resistance to flow) and orientation;

(d) to determine battery lifetime at near maximum, near minimum and mid range flow rates:

(e) to investigate pulsation characteristics of each of the high flow rate pumps.

The evaluation was not intended as a direct comparison between pumps as user requirements can differ widely and the pumps are built to perform to differing specifications. The tests were designed to assess performance characteristcs so that potential users could determine the pump best suited to their needs. Details of characteristics should be checked with manufacturers and agents, because of the problems of generalizing from tests made on single units, and changes in manufacturers' specifications.

The discussion of desirable features represents the consensus opinion of the working group members arising from their experience with pumps in field use. Similarly the pump users' guide contains experience of operational practices.

2 DESIRABLE PERFORMANCE FEATURES

2.1. Flow stability

Any pump should be able to draw a sample of air through the collection medium at a constant preset flow rate over a full workshift.

The value of a preset flow rate should be maintained with a reasonable accuracy . (± 5% has been suggested by the Health and Safety Executive (HSE)) over the working shift. This flow rate should be unaffected by any changes in resistance across the collection medium that are likely to occur in use. These changes are typically in the range of 1-50 cm of water gauge when collecting particulates on filters due to the gradual blocking of the filter pores. (The SI unit of pressure is the Pascal (Pa). 10 cm water gauge = 0.98 kPa.) On the other hand when sampling for gases and vapours on solid adsorbents the resistance to flow does not change significantly. Thus many pumps for particulate sampling have flow control systems which compensate for changes in flow resistance, whereas pumps intended for sampling gases and vapours generally do not.

The sampling flow rate should be readily adjustable. If a control mechanism is fitted the warm up period for stabilized flow conditions should be less than 1 minute.

The pump should be capable of maintaining its performance over the extremes of temperature that can occur and be unaffected by variations in relative humidity. Changes in ambient pressure should have no effect on the pump's mechanical efficiency. The Gas Laws may need to be applied to correct the sampled volume to standard temperature and pressure.

2.2 Flow pulsation

When collecting particulate matter the air flow should ideally be free from pulsation.

Pulsation damping is essential in high flow reciprocating pumps when sampling for "respirable dust" (Hamilton and Walton (1961)) with cyclone size selective devices. In double diaphragm or piston pumps, pulsations can be balanced out to a large extent by running the diaphragm or pistons out of phase, but with single diaphragm or pistons a flexible buffer damper needs to be incorporated. How efficient such a damper needs to be is difficult to specify. The design of cyclones for sampling respirable dust is still an empirical exercise unlike the design of larger cyclone air cleaners whose performance is relatively predictable.

The empirical evidence on the effects of air flow pulsation on cyclone performance indicates that the greater the amplitude of the pulsations the less efficient a cyclone sampler becomes at collecting fine "respirable dust", i.e. less dust penetrates a cyclone when the air flow pulsates above a certain amount when compared with penetration using pulsation free air at the same mean flow rate (Blachman and Lippmann (1974)), Lamonica and Treaftis (1972)).

$$\text{Pulsation Ratio (PR)} = \frac{Vmax - Vmin}{Vmean}$$

$$\text{Peak to Peak (PPR)} = \frac{Vmax}{Vmin}$$

Vmax = maximum air velocity or volume

Vmin = minimum air velocity or volume

Vmean = mean air velocity or volume

A PR of 0.3 is recommended by the HSE (1978) whereas Lamonica and Treaftis (1972) recommend the more stringent limit of a PPR of less than or equal to 1.2.

As the relationship between the various pulsation criteria and the effect on cyclone penetration are not well defined, the working party propose that under the conditions of use a cyclone operated by means of a high flow personal sampling pump should provide a respirable dust result $\pm 5\%$ of that of a cyclone powered by a pulsation free air flow. Further research is required to relate this criterion to pulsation ratio.

The work of Lamonica and Treaftis (1972) indicates that a PPR of less than or equal to 1.2 would probably meet this requirement. However the PPR only takes into account the amplitude of the pulsation and not the frequency. Recent work reported by Bartley et al. (1984) indicates that both magnitude and frequency may need to be considered when predicting the effect of pulsation.

Agreed test procedures to measure the magnitude and frequency of pulsations will need to be developed as the geometry of the apparatus and the response time of the instrumentation will have an effect on the results. Unless the response time is fast enough for the instrument to follow the flow changes perfectly, the response time will affect the recorded amplitudes and hence the measured pulsation ratios.

2.3 Other factors

The battery capacity should be sufficient to run the pump at the maximum flow recommended by the manufacturer, for a full working shift, against the pressure drop of the sampling head and sample.

The performance of the pump should be unaffected by its orientation.

The pump should be unaffected by rough handling, for example by being dropped on to a hard surface. The case should remain intact and the pump should maintain its preset flow rate and retain electrical safety.

3 DESIRABLE DESIGN FEATURES

This Chapter deals with the design criteria needed not only to meet the main performance requirements but also to achieve a practical and convenient instrument which is acceptable to the wearer.

3.1 Safety and convenience

Where flammable hazards may occur the need for intrinsic safety of the pump may dictate limits on the size of battery pack and motor. (It is most unlikely that a wearer would accept the use of a pump designed with a heavy flame proof case). Secondary factors contributing to the size of the pump are the space needed to fit any control system and the requirements for a robust case.

The size and weight of the pump are largely dependent upon its performance characteristics and in particular the flow rate required.

In order that the inconvenience to the wearer is minimized, the size and weight of the pump should be kept to the minimum that is compatible with the required performance. Most low flow rate pumps are small enough to fit into a pocket. This means that they are less obtrusive and better protected against knocks than larger pumps and there is also the possibility of body warmth giving enhanced battery performance. Most pumps used for sampling particulates are too large to fit into pockets and need to be attached to a belt or a harness.

The pump must be securely attached to the person and not be dislodged by the wearer's movements or orientation.

The design of the outer casing of the pump should avoid sharp corners or other uncomfortable protruding parts. Switches and controls should be recessed to avoid accidental operation or damage but should be readily accessible.

If pumps are to be used in classified areas/hazardous atmospheres they should have a certificate of intrinsic safety (see Chapter 5 on Safety Requirements).

3.2 Flow metering

The provision of visual flow, flow control and low battery charge indicators are useful features. Although float and tube flow meters are frequently used they are often too short to provide accurate readings. The values obtained will also be dependent upon orientation and flow pulsation. In order to compensate for changes in resistance to flow certain pumps incorporate a flow stabilization system in which the flow is monitored by a sensor and regulated. The sensors are usually of the type where the response is to the cooling effect of the air flow or the pressure across a restriction. Such devices can also be used as flow meters. Another important consideration is a means of assessing the total volume sampled. The integration of volume as a function of time may be achieved in reciprocating pumps by the use of a built-in digital stroke counter.

3.3 Mechanical construction

Most pumps are of the positive displacement type, incorporating a reciprocating flexible diaphragm in the interests of low friction and cost and ease of maintenance. Other types of pump use reciprocating pistons or rotating vanes. Reciprocating pumps require non-return valves which should remain effective even in the presence of some particulate matter. However, good design dictates that an internal filter should be incorporated between the air inlet and the pump to prevent the ingress of particulates. This should be easily accessible for replacement or maintenance. Sampling pumps should not be operated in a dusty atmosphere without the protection of some form of collection medium.

In order to minimize the size of battery pack needed for full shift running an efficient motor chosen to meet the pump's requirements is essential.

Careful design is needed to reduce bearing/transmission friction. Although some systems use miniature ball races, ingress of dust can easily cause seizure and plain bearings may be preferred.

Considerable power may be lost if the couplings between motor and pump parts are not designed to cope with slight chassis misalignment or case distortion.

The instrument's case should minimize entry of dirt, water or corrosive vapours. Electrical circuits should be coated/encapsulated and other parts of the pump should be protected from corrosion by suitable materials.

Standardized pump and sampling head connexion barbs would be of advantage so that a common size of flexible, non-kinking hose could be used.

A pump outlet barb is a useful feature so that gas samples may be collected in a flexible bag for future study. However, there is always a danger that trace components will be lost by absorption, permeation, or reaction within the bag or pump.

The internal pump mechanism should be tolerant of condensed water and of the liquids and the resultant vapours arising from liquids typically used as collection media. If bubblers/impingers are used then a spray trap can be incorporated in the sampling line to protect the pump.

The noise from the pump should not be obtrusive to the wearer.

A total run time indication would assist in determining service and maintenance periods. A timer to record total sample time and a programmer to start and stop the pump in a variable sequence would be a useful optional feature.

3.4 Batteries

Low flow rate personal sampling pumps which are designed to accept rechargeable secondary cells as well as disposable primary batteries have some practical advantages. However care must be taken that this does not violate intrinsic safety certification. The cost of disposable primary cells precludes their use for the heavy duty requirements of high volume dust sampling.

Battery care, maintenance and ease of replacement of battery packs are of primary importance in retaining continuous sampling capability over a full shift.

It should also be possible to charge the batteries either internally or externally.

Some pumps have an indicator light to show fully charged or discharged battery conditions. However it would be better if a continuous indication of battery charge were fitted.

3.5 Maintenance

A pump should be designed so that most parts of the mechanism and controls can be maintained by the user without the need for specialist tools.

A good maintenance manual should contain the following information:

(a) the pump performance specifications, including test procedures for all aspects of pump operation both mechanical and electrical;

(b) labelled, exploded diagrams identifying the separate parts of the pump. All parts should be separately listed with their order numbers;

(c) a detailed description of the strip down and assembly of the pump, including diagrams and photographs, where appropriate, should be included;

(d) list of part suppliers and repair services worldwide;

(e) routine maintenance procedures, including battery care, should be identified separately. Realistic maintenance schedules, based on hours of use, should be specified;

(f) repair of commonly occurring faults, such as the accidental ingress of liquids, should be separately identified;

(g) fault finding procedures should be specified.

4 USERS' GUIDE

4.1 Pump types

Diaphragm, piston, rotating vane and peristaltic pump types are used in commercially available sampling pumps.

4.1.1 Diaphragm and piston pumps

This type of pump (Figure 1) comprises a single diaphragm which is oscillated, within a sealed chamber, by means of an electric motor and crank linked to the centre of the diaphragm. Non-return valves are fitted to inlet and outlet ports in the chamber and the oscillation of the diaphragm produces alternately negative and positive pressure which results in a flow of air through the system. The single diaphragm pump produces a pulsating flow. The amplitude of the pulsations increases with decreasing pump speeds. However if a second diaphragm is operated through the same mechanical system in parallel but 180° out of phase, the pulsations are considerably reduced.

Piston pumps (Figure 2) are similar in operation to diaphragm pumps. They comprise a rigid piston which, although free to move within a cylinder, maintains a gas tight fit. The motor reciprocates the piston in the cylinder causing alternately a reduction and an increase in the pressure in the space beyond the piston. Valves incorporated in parts in the cylinder head in combination with the oscillation of the piston result in the flow of air through the system.

The ability of these pumps to create a high suction depends mainly on the ratio of the volume displaced by the diaphragm/piston stroke to the chamber volume, and partly on valve efficiency. Flow rate is a function of motor speed and diaphragm/piston displacement. Most pumps have a speed control and some pumps have an adjustable crank-throw or changeable drive gear ratio which alters the volume per stroke, allowing greater flexibility in operating conditions. Instability of flow in these pumps is usually due to: erratic motor speed, dirty or sticking valves, deterioration of the flexible diaphragm or piston seal, wear or dirt on the piston/cylinder or drive mechanism.

4.1.2 Rotating vane pumps

The rotating vane pump (Figure 3) consists of a multi-vaned rotor with the axis mounted eccentrically within a cylindrical chamber. The sliding vanes in the rotor maintain a seal with all the walls of the chamber. When the rotor revolves the air spaces sealed between the vanes are alternately expanded and compressed because of the eccentricity of the rotor axis. Inlet and outlet ports are positioned in the chamber walls at the points of maximum expansion and compression respectively and thus and air flow is induced from the inlet port to the outlet on the opposite side. No valves are necessary with this type of pump, and as the rotor is multi-vaned and revolves at fairly high speed the pulsations which occur are of very short duration and merge into each other giving a smooth flow.

Fluctuations in flow are dependent upon motor speed, stability and rotor vane wear. The seal between the rotor vanes and the chamber is critical, and particulates entering the system will cause wear and serious loss of flow reliability. It is therefore important to ensure that this type of pump is protected by an effective in-line filter. Flow rate is altered by varying the motor speed or by adjustment of a critical orifice. This type of pump does not usually create as high a suction as a diaphragm pump.

4.1.3 Peristaltic pumps

Flow within a peristaltic pump is induced by pinching a flexible tube and then causing the contraction to move along the tubing. Continuous flow is generated by means of a number of rollers, fitted to a rotating arm or drum, repeatedly moving along a length of tubing. The flow rate is a function of the cross sectional area of the tube bore and the roller speed. These pumps do not have valves and as none of the moving parts come in contact with the sampled air they are unaffected by dust and dirt. They are usually only suitable for low flow rates and require considerable power to overcome the resistance of the tubing to compression and so need powerful batteries.

The flexible tubing needs to be changed frequently as the continual compression and relaxation causes distortion and cracking.

4.2 Selection criteria

When selecting sampling pumps from those available on the market, a number of factors have to be considered. These include:

(a) the type of sampling to be undertaken;

(b) the nature of the environment where the pumps are to be used;

(c) the desirability of using disposable batteries, if possible, instead of the more usual rechargeable type;

(d) the requirement for intrinsic safety certification and

(e) the type of sampling head devices to be used with the pumps.

4.3 Ergonomics

For personal sampling, the bulk and weight of pumps is an important consideration. The method of securing the pump and sampling device assume particular importance when the freedom of movement of the wearer is a consideration. These ergonomic considerations can be the cause of much difficulty.

Pumps and sampling heads can also be used as static samplers in which case the weight and bulk are not usually important.

4.4 Flow rate

Flow rate range is an important consideration which relates to the type of sampling required.

Much of the sampling undertaken with vapour adsorption tubes is carried out at flow rates between 5 and 200 cm^3 min^{-1}, but some circumstances may dictate the use of lower or higher flow rates.

Long term detector tubes require a flow rate which is typically in the range 15-20 cm^3 min^{-1}

When sampling for airborne particulate matter flow rates in the range 0.5-4.0 l min^{-1} are normally required.

Some gases and vapours are sampled at flow rates around 0.5 l min^{-1} using trains of bubblers or macro size adsorption tubes.

Most pumps for particulates now have servo controlled systems designed to maintain a constant flow rate of air, irrespective of changes in resistance to flow across collection filters. Thus, a source of error from changes in flow rate during the sampling period has been significantly reduced.

4.5 Bag sampling

Bag sampling requires access to the exhaust side of the pump and some pumps may be unsuitable for this purpose, not having a readily accessible exhaust port connexion, or because adsorption or reaction of some vapours might occur with materials in the pump.

4.6 Intrinsic safety

Intrinsic safety certification appropriate to the conditions where pumps are to be used is a frequent requirement. (See Chapter 5 on Safety Requirements). The user must be satisfied that the pump is certified to the appropriate standard.

5 SAFETY REQUIREMENTS

For obvious reasons any equipment worn by a person must be safe and not add to any hazards in the workplace. While clearly the pump should not have sharp edges or protrusions that could injure the wearer in the event of a fall or blow, the most important requirement is that of electrical safety.

5.1 Electrical safety

In plants where flammable materials (BS 5345) are handled or stored, there is a possibility of the formation of a potentially explosive atmosphere (BS 5501). Although such a possibility is minimized in the design of the plant and process operations, it is not possible to eliminate it completely.

Where the possibility of a potentially explosive atmosphere cannot be precluded, it is necessary to minimize the possibility of the introduction of a source of ignition. Electrical apparatus is one possible source and where such apparatus is introduced into a hazardous area (BS 5345) it has to be constructed and protected so as to minimize the risk of its becoming such an ignition source.

5.2 Legislation in the UK

The main statutory requirements governing the installation and use of electrical apparatus in industries to which the Factories Act 1961 applies are given in the Electricity Regulations 1908 (SR & O No 1312) as amended by the Electricity (Factories Act) Special Regulations 1944 (SR & O No 739). Amplification of and comment on these regulations are given in the Memorandum on the Electricity Regulations published by HMSO (Form SHW 928).

Specific regulations are the Highly Flammable Liquids and Liquefied Petroleum Gases Regulations of 1972, and installations where petroleum spirit and certain other materials are stored are subject to special regulations administered by the local Petroleum Licensing Authority under the provisions of the Petroleum (Consolidation) Act 1928.

More general statutory safety requirements are contained in the Health and Safety at Work etc. Act of 1974.

5.3 UK classification of hazardous areas

This is described in BS 5345, Part 1, 1976 "Code of Practice for the Selection, Installation and Maintenance of Electrical Apparatus for Use in Potentially Explosive Atmospheres", which defines three zones (0, 1 and 2) and the type of protection required for electrical apparatus in each zone.

5.4 Type of protection

Possible types of protection for electrical apparatus in hazardous areas include flameproof enclosures and pressurized enclosures, but the most usual type applied to sampling pumps is intrinsic safety.

Intrinsic safety is defined (BS 5345) as "A protection technique based upon the restriction of electrical energy within apparatus and of interconnecting wiring, exposed to the potentially explosive atmosphere, to a level below that which can cause ignition by either sparking or heating effects".

While the techniques of designing for intrinsic safety are many, the basic aim is to eliminate the possibilities of generating a spark of sufficient energy or a surface temperature hot enough to cause ignition of flammable vapour.

5.5 Certification

Under the UK Health and Safety at Work etc. Act 1974, there is an obligation on equipment manufacturers, suppliers and installers to ensure - so far as it is under their control - that the equipment is safe when used in accordance with information supplied by them.

It is also an obligation of employers that they should provide safe equipment.

The British Standard for electrical apparatus intended for use in hazardous areas is BS 5501, Parts 1 to 7, and equipment can be certified to this standard by the national test house, the British Approvals Service for Electrical Equipment in Flammable Atmospheres (BASEEFA). BS 5501 is the same as the European Standard EN 50 014 to 020 which was written by the Comité Européen des Normes Electriques (CENELEC).

An EEC Flammable Atmospheres directive, in force since August 1980, requires EEC member states to accept each other's national certification to the European Standard.

It also appears that the American Standard for intrinsic safety is now similar to the European one, but not the same.

Equipment certified by a national test house will bear a certificate plate displaying three markings:

The first marking contains four parts:

1. The EEC community mark, of the National Certifying Authority.

2. Protection type symbol: e.g. flameproof enclosure is "d", purged enclosures is "p". Intrinsic safety is "i" followed by a or b, "a" designating a greater safety factor than "b".

3. Apparatus subgroup code: Group I is for mining use; Group II is all other industrial applications. This is followed by A, B or C which are gas groups classified according to the flame quenching distance (limiting the safe gap in a flame proof enclosure) and the minimum ignition spark energy for the gas.

The most severe conditions are for gas Group C, which for intrinsic safety comprises hydrogen, acetylene, carbon disulphide and some industrial gas mixtures.

4. Ignition temperatures: The lowest temperature at which ignition of a gas occurs under particular test conditions. These are designated T1 to T6, with T1 a maximum temperature of 450°C and T6 85°C.

The second mark is the certification authority's certificate number; this certificate will define the conditions of use for the equipment and its restrictions and should be consulted before using the equipment.

The third marking is the certification standard to which the equipment was tested.

With these regulations in mind the construction of the pump should be such that if it is dropped from a height of 1 metre onto a hard floor it will not break in such a way that an incendive electrical spark can be generated (and the circuitry must remain intrinsically safe). Furthermore the material of the casing should not be capable of generating an incendive mechanical spark when dropped. The material of construction of the case should not be capable of generating sufficient static electricity to cause an incendive spark otherwise a label must be added to warn of this potential hazard.

6 THE USE AND CARE OF BATTERIES AND CELLS

Electrochemical cells can be divided into two groups, primary or consumable, and secondary or rechargeable. There are several types in each group but only the most commonly used will be discussed here. Examples of primary cells are the zinc-carbon or Leclanché dry cell, the alkaline-manganese cell and the mercury cell. Common secondary cells are the nickel-cadmium and the lead-acid types.

6.1 Primary cells

All primary cells are available in a wide range of sizes or capacities which are often interchangeable as far as dimensions are concerned. For higher voltages many standard packs of interconnected cells or batteries are available.

The most common and inexpensive primary cells are the zinc-carbon type. Alkaline-manganese cells are a direct replacement for these and although they are more expensive they can last up to ten times as long, if the current usage is high, or about three times as long with low current drainage. Alkaline-manganese cells also do not leak corrosive substances when left discharged for long periods as do zinc-carbon cells, which should always be removed and never stored inside equipment for any prolonged period.

Mercury cells are used for special applications and unlike alkaline-manganese or zinc-carbon cells they do not have their output limited by electrode polarization and can deliver power intermittently or continuously with equal efficiency.

The capacity and discharge characteristics of each type and size of cell are dependent on storage conditions, temperature and the usage rate, whether continuous or intermittent. Some approximate performance comparisons for equal sized cells are made in Table 1.

6.2 Secondary cells

6.2.1 Nickel-cadmium cells

For portable equipment the nickel-cadmium (NiCd) cells are most commonly used. These are available in standard sizes, similar to primary cells, in button form and in battery packs.

The discharge characteristic of nickel-cadmium cells is reasonably flat varying between 1.35 volts fully charged and 1.1 volts discharged.

Recharging nickel-cadmium cells poses some problems. The small sealed cells used in portable equipment should not normally be charged faster than the Ah*/10 rate (10 hour rate) in order to avoid excessive temperature or gas pressures, as cells can explode if charged at a grossly high rate. It is desirable to use a constant current rather than a constant voltage supply, to avoid thermal runaway due to an increasing charge current with increasing cell temperature. Unless special precautions are taken to avoid exceeding the Ah/10 rate, cells should always be charged in series, never in parallel.

Nickel-cadmium cells have an ampere hour efficiency of around 75%, so about 1.4 times more charge has to be put into the cell than can be withdrawn. A fully discharged cell will then be fully charged in about 14 hours at the Ah/10 rate. Since there is little change in voltage when the cell has been fully charged it may be difficult to assess this end point other than by a time x current basis.

While moderate overcharging, at the Ah/10 rate, should not damage or reduce the life of the cell, it is not desirable. When the initial state of cellcharge is unknown or where the current x time relationship cannot be controlled, then more moderate charging rates should be used. For example, cylindrical nickel-cadmium cells may be charged indefinitely at Ah/50 while the figure for button cells is Ah/100. Alternatively the Ah/10 rate may be used for a reduced time, for example for 12 hours.

Provided the cells are fully discharged to 1.1 volts and provided they are not overcharged, faster rates than Ah/10 may be employed. Cell manufacturers may be able to supply details of special pulse charge circuits safely operating at high currents.

Ideally cells should be discharged after each use, then recharged at the normal rate to maintain best cell performance and life.

If nickel-cadmium cells have been over-discharged, e.g. to below 1 volt, it may be possible to recover them by using an extended charge of 24 hours at the Ah/10 rate.

It is not necessary to provide maintenance charging of nickel-cadmium cells during storage but up to three charge/discharge cycles may be required to achieve a cell's rated capacity after prolonged inactivity. It is recommended that the first charge following extended storage should be for 24 hours at the Ah/10 rate.

At least 300 charge/discharge cycles can be expected from a properly maintained nickel-cadmium cell.

6.2.2 Lead-acid cells

Conventional lead-sulphuric acid cells are less likely to be used in personal gas sampling equipment than the NiCd systems because of their greater weight and size. Another difficulty is the potential hazard of acid spillage, and there are problems of gas evolution and acid spray during, and particularly on the completion of, charging.

However, sealed "dry" lead-acid cells are available in the larger sizes and, unlike conventional lead-acid batteries, they do not require topping up with distilled water.

*The capacity of a secondary cell may be expressed in Ampere hours (Ah) when it is fully charged.

Their discharge characteristics are substantially flat, varying between 2.1 volts fully charged to 1.8 volts discharged.

Lead-acid cells may be charged with a constant potential, constant current or taper charging unit, using no voltage regulation.

A constant potential of around 2.4 volts per cell will give a full charge in 16 hours. Increasing the potential will speed the charge rate at some detriment to the cell life. Alternatively, continuous "trickle" charging at around 2.3 volts (current Ah/100 or below) will give longest useful performance.

They may be recharged in 14-16 hours using a constant current at the Ah/10 rate. Only at very high charge rates, above Ah/3, is there likely to be danger from gas evolution.

Uncontrolled "taper chargers" are amongst the least expensive types of charger, but the lack of voltage regulation may be detrimental to the life of any cell.

Lead-acid cells should never be left for any length of time in a discharged state or irreversible damage may occur. It is important that lead-acid cells are given a periodic maintenance charge to compensate for the self discharging which takes place within any type of secondary cell.

6.3 General notes

The designer will have given consideration to the cells most suited to his equipment. If no instructions are given to the contrary it may be unwise, even if the physical dimensions are suitable, to exchange one general type of battery pack for another. For example, as mentioned earlier, intrinsic safety considerations may require batteries to contain a concealed current limiting fuse or resistor chain.

Individual cells within a power pack should not be mixed either by age or by type. In order to avoid corrosion or short circuiting, battery compartments should be kept clean and dry.

While individual requirements vary, primary and secondary cells should be stored at between 10-25°C in an atmosphere whose relative humidity is below 65%. At the end of their life, cells must never be destroyed by fire because of the danger of explosion.

7 FLOW: MEASUREMENT, CALIBRATION AND SETTING

The basic parameter to be measured when using a sampling pump is the volume of air it has sampled over the measurement period.

Unfortunately no pumps are available which provide a direct read out of the volume sampled. However some have flowmeters fitted (float/tube type) and some have stroke counters which, if precalibrated for the volume of air sampled per stroke, can give an indirect measure of sample volume. Otherwise the air flow rate must be measured using an external meter before and after sampling, and the air volume sampled calculated from the average flow rate and the sampling duration.

Stroke counters are mainly used in low flow rate pumps. They are seldom used in high flow rate sampling pumps when collecting particulates as the collection medium usually becomes obstructed with particles, resulting in an increase in pressure drop which alters the stroke calibration factor.

Flow rate can be measured in many ways. It is easiest to use a direct reading meter so that the flow can be quickly adjusted to the desired rate. The most common type of direct reading flow meter is the float/tube (variable area) type, but direct reading electronic devices are also available. Unfortunately float/tube meters are not well suited to pulsating flows from undamped single diaphragm pumps and so it may be necessary to measure flow volumetrically using a timed displacement technique or by means of a laboratory gas meter. If a specific flow rate setting is required then the flow rate must be measured, the pump flow control adjusted, the flow rate re-measured and so on until the desired rate is obtained. This can be a lengthy process.

Whatever technique is used, the flow measurement must be made on the free air side of the sampler to avoid inaccuracies from reduced pressure.

7.1 Flow measurement

There are two basic ways to measure flow: directly with a flow meter and indirectly by timed volume displacement.

7.1.1 Direct flow measurement

Float/tube (variable area) flow meters. These are commercially available in many forms. In general, the longer the scale the greater the precision with which the flow can be measured; flow meters with scales less than about 15 cm should not be relied on for accurate measurement. The flow meter calibration scale should also be checked against a calibrated, certified flow meter for best accuracy. It is important to have a dry, clean gas flow and to mount the float/tube meter absolutely vertical. Readings should be corrected for temperature and pressure according to the manufacturer's instructions.

Differential pressure flow meters. Du Pont supply a direct reading flow meter incorporated in a pump-kit carrying-case lid. This is a differential pressure type flow meter which responds to pressure drop across a restriction and requires primary calibration.

Electronic flow meters. These use a temperature compensated, hot wire sensor or a thermistor in a flow through cell. Flow rate is read out directly on a calibrated meter. They may be unsuitable for pulsed flows, depending on the degree of meter damping; their calibration should be checked regularly, and they must only be used under the specified conditions of temperature and pressure.

7.1.2 Indirect flow measurement

This involves timing the displacement of a measured volume of air and must be used for pumps with a pulsating flow which are unsuited to direct reading flow meters. There are several types of instrument which can be used.

Wet test gas meters. These comprise a rotating drum like a vaned waterwheel working in reverse, which is partly submerged in water contained in an air-tight housing. The air flow to be measured enters under the drum and is trapped in the vanes causing it to rotate.

They can be very precise ($\pm$ 1%) if set up and used correctly but are rather too large and awkward for routine field use.

Soap bubble flow meters. Flow rate can be calculated by timing the passage of a bubble of a detergent/water mixture along a glass tube between calibrated volume graduation marks.

This method can give accurate results as the resistance to airflow is negligible, but can be troublesome in use as the solution dries out and needs frequent cleaning and replacing. The tube inner surface must be completely wetted before the bubble will move along without bursting. In use the pump is started and several bubbles are generated until the inside of the tube is completely wetted. A single bubble is then started and timed. The bubble should move slowly at the required flow rate to avoid distortion and allow accurate timing.

Glass gas syringes. This method requires an all glass syringe of 50 or 100 cm^3 capacity, calibrated in 5 or 10 cm^3 graduations, having a free-moving ground glass plunger.

In use it is opened fully, connected to the pump and the plunger timed between 10 or 20 cm^3 calibration points with the plunger held at an angle of no more than 30° above horizontal, to balance the weight of the plunger, so that its weight does not distort the reading.

Providing the plunger moves freely and does not stick in the bore, this method gives results of a similar accuracy to those obtained with soap bubble meters. It is usually only used for low flow rates ($<$1 l min^{-1}) as the maximum size of suitable syringes available is 100 cm^3.

Collapsible balloon systems. In these, a thin rubber balloon is mounted inside a rigid transparent tube. The balloon is connected to a 3-way stopcock, with the other two connexions going to a pump and to a large gas syringe.

In operation the balloon is thoroughly collapsed using the syringe, then a measured volume (20-30 cm^3) is injected from the syringe. The pump is then started and the time taken to empty the balloon measured. The technique gives reasonably accurate results and needs little maintenance but is somewhat cumbersome to use. It is mostly used for flow rates less than 1 l min^{-1}.

7.2 Calibration

7.2.1 Pump stroke counter calibration

Certain low flow pumps have counters which can be calibrated to give the volume of air sampled per stroke. Thus the number of strokes during the sampling period multiplied by the appropriate factor gives the total volume sampled.

Calibration is best undertaken by measuring the volume sampled over a prolonged period so that variations between individual strokes are averaged out. The pump should be allowed to settle-down after initial switch on before calibration is carried out.

Calibration must be conducted with the sampling head in place, at the flow rate which is to be used for sampling and preferably at a similar temperature to that of the location to be sampled. The pump should also be positioned in the same orientation in which it is to be used.

Sample volume is best measured with a wet test meter but a timed displacement method can also be used for shorter periods. The calibration factor is then simply the total volume of displaced air divided by the number of pump strokes indicated by the counter.

7.2.2 Motor voltage calibration

One pump, the Casella T13298 (Sipin SP15), features a socket for reading motor voltage which when calibrated can also be used to indicate flow rate. This calibration should be carried out with the same precautions as for determining a stroke factor, using either an accurate direct-reading flow meter or a timed displacement measurement. The voltage can either be averaged by eye over the time displacement period or displayed on a chart recorder.

7.2.3 Temperature and pressure corrections

If a pump is calibrated indoors at typically 20°C but then because of the outside ambient conditions operates at 0°C, the elevation in the air density will increase the mass of air sampled by about 7%, for the same volumetric flow rate. Similarly, for an operating location temperature of 40°C when the pump has been calibrated at 20°C, a decrease of around 7% would result.

So long as the volume of contaminant vapour and the sample air volume are calculated for the same temperature, the result, if expressed in terms of volume ratio (e.g. ppm), will not be affected by temperature and so does not necessarily need to be corrected to a reference temperature.

The value expressed in units of mass per unit volume (e.g. mg m^{-3}), however, will vary with temperature, and so the air volume sampled should be corrected to a reference temperature.

Differences in atmospheric pressure will also affect the calculation for the volume of air sampled and should be corrected to a reference pressure.

For converting ppm to mg m^{-3}, HSE Control and Recommended Limits specify a temperature of 25°C and a pressure of 1 bar.

The corrected air sample volume (Vcorr) is calculated from:

$$V_{corr} = \frac{V \cdot T_r \cdot P_a}{T_a \cdot P_r}$$

where: V = sampled air volume at atmospheric temperature T_a °K and pressure P_a,

T_r = reference temperature °K,

T_a = sample air temperature °K,

P_r = reference air pressure,

P_a = sample air pressure.

7.3 Procedures for setting up pumps

1. Ensure that the pump is fitted with a filter, to prevent particulate matter entering.

2. Ensure that the pump is fitted with a fully charged battery.

3. Check that the tubing used to connect the sampling system to the pump is clean, free from kinks or restrictions and undamaged.

4. (a) For gravimetric sampling place a pre-weighed, equilibrated filter into an appropriate filter holder, label the holder for identification and attach the holder to the pump inlet using the flexible tube. For other particulate sampling (e.g. asbestos fibre counts) there is no need to weigh or condition the filter.

   OR

   (b) Select a suitable vapour adsorption tube; if sealed, break off the tips and ensure that the correct end of the tube is connected to the pump inlet by flexible tubing.

   OR

   (c) Add the required volume of reagent to a bubbler which is connected to the pump via a spray trap using flexible tubing. Ensure when connecting up that the flow through the bubbler is in the correct direction to avoid drawing the reagent into the pump.

5. Adjust the pump to the desired flow rate in a clean atmosphere.

6. Once the flow rate is set the system can be used to collect a sample. Before switching the system on, note and record the reading on the stroke counter (if fitted). After sampling for a prescribed period note and record the new reading on the counter. The difference in reading can be used to determine the volume sampled provided the pump's calibration factor is known. The flow rate of the system should again be checked and should not have changed significantly from the initial value.

7. Determine the sample volume:

(a) **Low flow pumps:**

(i) Volume in litres $= \dfrac{M.T}{1000}$

where M = flow rate, $cm^3\ min^{-1}$,

T = sampling period, min.

or (ii) Volume in litres $= \dfrac{K.N}{1000}$

where K = calibration factor, cm^3/stroke,

N = number of pump strokes.

(b) **High flow pumps:**

Volume in litres = M.T

where M = flow rate, $1\ min^{-1}$,

T = sampling period, min.

Sample volumes should then be corrected to standard temperature and pressure.

8. Pumps should be maintained and calibrated regularly on a planned basis.

9. Never open the pump casing in a hazardous area and always ensure that the casing is intact (see Chapter 5):

8 DESCRIPTION OF PUMPS TESTED

Details of the personal sampling pumps tested are given in Table 2a (low flow) and Table 2b (high flow).

The low flow pumps used in these tests were supplied by the manufacturers or their agents, and were models commercially available in 1979/80. The high flow pumps were purchased in 1981/82. Details of characteristics should be checked with manufacturers and agents, because of the problems of generalizing from tests made on single units and changes in manufacturers' specifications.

8.1. Low flow pumps

8.1.1 Casella T13298 (Sipin SP15)

The Casella T13298 is operated by a motor-driven diaphragm pump which has a flow range of nominally 2 to 200 cm^3 min^{-1}. Flow rate is selected by adjusting a potentiometer situated on the front of the case and a high/low range switch inside the pump. The on/off switch is recessed at the back of the sampler. Overload or low flow conditions activate a warning light. A digital stroke counter linked to the pump drive motor can be used to assess the total air sample volume. The pump has an air outlet connexion. Batteries and electronics are encapsulated as this pump meets the highest intrinsic safety standard. There is provision for measuring flow rate indirectly by reading the motor voltage via a socket in the pump case.

A version is now available with a stainless steel case.

8.1.2 Compur 4902

The Compur 4902 is operated by a motor-driven diaphragm pump with a flow rate of nominally 7 to 33 cm^3 min^{-1}, adjusted by a potentiometer. On this early type of pump tested an electronic readout-unit is required which, when connected to the pump, displays the number of pump strokes. Sample volume is calculated from the average stroke volume determined before and after sampling (or by flow rate measurement). Later 4902 pumps have a liquid crystal display on the outer front case which displays pump stroke counts continuously. The number of counts is retained in a memory even after the pump is switched off. The display is reset by inserting the charger jack into the pump socket for 5 seconds. (The pump tested corresponds more with the new model designation 4900). The on/off switch is recessed in the rear of the case.

8.1.3 Draeger Polymeter

The Polymeter is designed for use with long-term detector tubes. It uses an electrically driven peristaltic pump with factory calibrated silicone rubber tubes. The pump operates at a single flow setting of approximately 15 cm^3 min^{-1}. Each rotation of the rotor is recorded on a digital counter which enables the sample volume to be calculated. The motor is powered by a sealed lead-acid accumulator. The on/off switch is located under a hinged cover on top of the pump.

8.1.4 Du Pont Model P125

The Du Pont P125 sampler consists of an electrically driven single diaphragm pump with a flow range of nominally 25 to 125 cm^3 min^{-1}. The flow rate is set by adjusting a needle valve. A closed-loop control system monitors and maintains constant flow through the pump at the pre-selected rate. The same system activates a warning light if the flow becomes obstructed. A discharged battery is indicated by another light emitting diode. The air volume sampled is calculated from the sampling duration and the measured flow rate of the pump. All sampler controls including the on/off switch are located within the instrument cover; this is secured by a socket head screw which must be removed in order to switch on or off and to adjust the flow rate. The instrument has an optional air outlet. Similar pumps with different flow ranges are available.

8.1.5 MDA Accuhaler Model 808

The Accuhaler 808 operates on a constant displacement principle by reproducibly controlled aspirations through a flow limiting orifice into a bellows of fixed volume. Flow is effected by a motor, to compress the bellows, and a spring return mechanism. The pump can be operated in the range of about 0.5 to 100 cm^3 min^{-1}. The flow rate is pre-set by use of a range of removeable limiting orifices which are fitted to the inlet port. A digital meter records the number of pump strokes. An alternative model (818) which has an outlet connector for sample air collection is available.

The air volume sampled is calculated from the volumetric calibration of the diaphragm and the number of strokes on the counter. The on/off switch is recessed in the base of the pump body.

8.1.6 Rotheroe and Mitchell C500

The C500 sampling unit consists of a rotating vane pump operating in a flow range of nominally 5 to 500 cm^3 min^{-1}. Alternative interchangeable float and tube flow meters, fitted to the pump exhaust, are available with scale ranges of 5 to 100 cm^3 min^{-1} and 50 to 500 cm^3 min^{-1}. However, because these are very short and have few calibration markings, they are not suitable for accurate flow measurement and were not assessed in the tests. They are only suitable for rough flow measurement and as flow indicators. Flow rate adjustment is by means of a throttle valve in the exhaust port of the pump unit. Indication of low flow conditions is by visual observation of the flow meter. The air volume is calculated from the measured flow rate and sampling duration. The on/off switch is recessed in the back of the pump case.

A light emitting diode on the front of the sampler is activated at low battery voltage conditions.

8.1.7 SKC Model 222-4

The SKC 222-4 is operated by a motor-driven diaphragm pump and has a flow range of nominally 20 to 80 cm^3 min^{-1}. Flow rate is adjusted by the motor speed control located on the front of the case. The air volume sampled can be calculated using the digital stroke counter linked to the drive motor. Pump motor supply is voltage regulated. The pump has an air outlet connexion. The on/off switch is recessed in the back of the pump body.

8.2 High flow pumps

8.2.1 Bendix BDX60

The BDX60 is nominally for flow rates from 1 to 3 litres min^{-1}. It is intended for fixed flow rate operation as flow rate changing is rather complicated and precludes rapid resetting.

The pump has two diaphragms, operated in parallel but out of phase, followed by a pulsation damper, to give a relatively pulsation-free flow.

The on/off press button switch is situated under a rubber diaphragm and a float/tube flow-meter with arbitrary markings of 1 to 4 is in circuit, under suction, between the sampling inlet and the pump. The other controls, for flow setting (2 switches and 4 potentiometers) and the low flow indicator are inside the pump, accessed by removing the battery pack which is secured by 4 screws. The battery pack also contains much of the electronic circuitry, and, although it could be charged separately, replacement packs are somewhat expensive.

Flow is stabilized by maintaining a constant motor speed using a chopper disc monitoring system.

A low flow indication/cut off system is incorporated whereby the pump can either be switched off or an indicator lit if flow is restricted for more than 7 seconds.

8.2.2 Casella AFC 123

The AFC 123 is nominally for flow rates from 1.0 to 2.3 litres min^{-1} and is a single diaphragm pump with a pulsation damper. An intrinsically safe version with a stainless steel case and pump stroke counter is available.

All controls and features are mounted on the case: the on/off slide switch, the flow setting adjustment and also two light emitting diodes, one indicating "pump running" and the other "low battery".

Flow is stabilized using a thermistor sensor to measure flow rate and a feedback circuit which controls motor speed.

The battery pack can be removed for replacement and external charging or it can be charged in situ.

8.2.3 Du Pont P2500

The P2500 is for flow rates nominally in the range 0.5 to 2.5 litres min^{-1} and has a double diaphragm pump operated out of phase to minimize pulsations, but has no pulsation damper. It is possible to obtain an intrinsically safe version of this pump.

All controls are beneath a removable cover secured by a socket screw and Velcro pads. There is an on/off toggle switch and a fast start button to override the delay in starting due to the flow control mechanism. A light emitting diode indicates if the battery charge is sufficient for 8 hours operation and another light emitting diode (visible through a hole in the cover) indicates that flow has not been interrupted for more than 15 to 45 seconds.

The pump is stabilized using a pressure sensor across a restriction, to measure flow, and a feed back circuit which controls the motor speed.

The battery pack can be removed for replacement or separate charging or it can be charged in situ.

8.2.4 Du Pont P4000

The P4000 is nominally for flow rates from 1.0 to 4 litres min^{-1}. The pump has 4 diaphragms arranged to give a relatively pulsation-free flow, and can be set to different flow rates by changing drive pulleys, and setting a selector valve and a flow valve. It also incorporates an automatic timer option which can be used to sample over interrupted sampling periods or to shut off at a pre-set time.

Flow is stabilized using a pressure sensor across a restricton, to measure flow rate, and a feedback circuit which controls the motor speed.

All controls and indicators are under a removable plate which covers one side of the sampler and is secured by a knurled screw. The battery pack can be removed for replacement or charging separately or it can be charged in situ. A light emitting diode indicates if the batteries have sufficient charge for 8 hours running. If flow is interrupted for between 15 and 45 seconds a light emitting diode will light.

8.2.5 MSA FIXT FLO

The Fixt Flo is nominally for flow rates in the range of 1.0 to 3.5 litres min^{-1} and uses a double diaphragm pump operated out of phase with flows in parallel; a pulsation damper is incorporated before the pump to give a low pulsation level. One of the pump heads is connected to an outlet to enable gas bags to be inflated.

The on/off push switch and flow rate adjuster are located under a removable flap secured by a Dzus fastener. Three indicator light emitting diodes are set under a window; one indicates any interruption in flow (flow failure), the next indicates if flow rate was below 80% of the set point for more than 8 mins, and the other indicates full battery charge. The battery pack is removable for replacement or separate charging or it can be charged in situ.

Flow is stabilized using a hot wire filament sensor to measure flow rate and a feedback circuit which controls the motor speed.

8.2.6 Rotheroe and Mitchell L2SF MKII

The L2SFis nominally for flow rates from 1.0 to 4 litres min^{-1} and has a rotary vane pump with 4 sliding graphite vanes giving a smoother flow than that obtained with a diaphragm pump. All controls and indicators are mounted on the case and a calibrated float/tube flow meter is located under a slot in the case. The flow meter is on the pump outlet side and so operates at ambient pressure. A more sophisticated version of this pump is available which has intrinsic safety certification, a stainless steel case, a sampling duration timer, low battery charge indication and obstructed flow indication.

Flow is stabilized using a pressure sensor across a restriction to measure flow rate and a feedback circuit which controls the motor speed.

The battery pack is not readily removable for replacement or separate charging and must be charged in situ.

8.2.7 Samplet 828C

The Samplet is basically a fixed flow rate pump for use around 2.0 litres min^{-1} but some adjustment for other rates is possible.

The pump is a double piston arrangement, which is actually a double ended piston reciprocating in a single cylinder with valves at each end. The dual pump heads thus run out of phase and are connected in parallel to minimize pulsations.

Flow is claimed to be compensated for pressure changes but it is not stated how this control is achieved.

The only controls on the case are the on/off switch and a low battery charge indicator.

The battery pack is not easily removable for replacement or separate recharging and must be charged in situ.

8.2.8 Vinten Zephyr

The Vinten Zephyr is set to run at 2 litres min^{-1} against a pressure drop of 5 cm of water gauge. Some variation in flow rate is achievable by means of a potentiometer inside the pump housing.

The pump comprises a pair of pistons that run out of phase to minimize pulsations. Flow is controlled by monitoring and stabilizing the motor input voltage. The on/off switch is mounted in a recess in the base of the pump.

If the battery pack voltage falls below approximately 3.6 volts, a cut-out operates to prevent "over-discharge". The battery pack cannot be removed for recharging and must be charged in situ.

9 TESTS ON PUMPS

This Chapter describes the tests which were carried out by the University of Aston in Birmingham on the seven low flow pumps and eight high flow pumps, and presents the results obtained.

Test 1: Effect of back pressure on flow rate (Figures 4 to 18 and Tables 9 and 10).

Test 2: Battery life (Tables 3a and 3b).

Test 3: Flow stability over 8 hours (Tables 4a and 4b).

Test 4: Effect of temperature on flow rate and stability (Tables 5a and 5b).

Test 5: Effect of orientation on flow rate (Tables 6a and 6b).

Test 6: Noise emission (Tables 7a and 7b).

Test 7: Air flow pulsation (Table 8).

Before testing, the new pumps were bench run-in for a total of 48 hours at about 50% of the quoted maximum flow rate (where variable) in eight hour running periods followed by recharging as recommended by the manufacturers. All tests except where stated were carried out in the laboratory at 20 ± 2°C with the pumps lying face up (orientation 6, see Table 6a). Before each test the batteries were recharged as recommended by the manufacturers.

The apparatus used in these tests was:

A Nupro stainless steel fine metering valve.

Paul Poddy perspex differential manometers, 0 to 40 cm water range filled with hydrocarbon fluid of S.G. 0.800; above 40 cm water the manometer was filled with mercury (range equivalent to 0 to 330 cm water (10 cm water = 1 kPa).

An Alexander Wright wet test gas meter of 0.25 litres per revolution.

A Smiths Servoscribe flatbed potentiometric chart recorder Type RE 542.20, set for span using an Avometer Type A.

A CEL-175 precision grade integrating sound level meter, calibrated with a CEL-177 precision acoustic calibrator.

A Prosser AVM 502 thermal anemometer.

Oscilloscope (Telequipment TG 152 DM).

TEST 1: Flow rate vs back pressure at three flow settings.

Because of the wide range of uses to which pumps may be applied, it is useful to know their limitations in terms of flow rate as a function of back pressure.

As most of the pumps have some means of varying the flow rate, tests were carried out over a range of settings.

For the low flow pumps these were: near minimum, near maximum and the midpoint of the range with a vapour adsorption tube in line.

For the high flow pumps, the lowest flow rate employed in the test was 1.0 litres min^{-1} as this is generally the minimum rate used when sampling for particulates. The mid-range flow rate was 1.9 litres min^{-1}, the flow commonly used when sampling with a cyclone. The highest flow rate was set at 90% of the maximum achievable with a 2.5 cm Whatman GF/A filter in line.

In this simple test, the pump was connected to the needle valve, used as a variable constriction, then to the wet test meter to measure the air volume. The manometer was connected across the valve to measure the pressure drop.

The results for the low flow pumps are given in Table 9 and are plotted graphically in Figures 4 to 10, and for the high flow pumps in Table 10 and Figures 9 to 18. These show flow rate as a function of back pressure (resistance to flow). (10 cm water gauge is about 1 kPa). Also given are the indicated flow rates for those pumps with counters (MDA 808, Draeger Polymeter, SKC 222-4 and Casella T13298) calculated using the calibration factor at the initial flow setting.

TEST 2: Battery life at three different flow settings.

This test demonstrated the running time for each pump at three flow rate settings, for those pumps with variable flow, and at the fixed value for the remainder. The low flow pumps were run against a back pressure of 10 cm of water (1 kPa) whilst the high flow pumps were run with a 2.5 cm Whatman GF/A filter in line at the high flow rate.

The pump was connected via a needle valve (to set the back pressure) and to the wet test meter (to measure volume and flow rate), and the recorder was connected across the pump battery to measure the change of voltage with time. The back pressure was measured by means of a differential manometer connected across the valve.

Two critical times were measured: firstly the time at which the flow rate fell to 90% of the initial setting and secondly the time taken for the battery to reach its nominal discharged voltage (V_1 in Table 3). The discharged voltages are not clearly defined for each battery type and so from experience 1.1V per cell was taken for the NiCd batteries and 1.8V per cell (under load) for the lead-acid battery in the Polymeter.

The MDA 808 pump will accept disposable batteries and this test was repeated using HP7 zinc-carbon cells type batteries which were run until the pump stopped, when they read 1.3-1.4V under load.

The test data are shown in Tables 3a and 3b.

TEST 3: Flow stability over 8 hours at the flow rate settings and back pressure conditions given in Test 2.

This test was carried out to determine the magnitude of the variation in the flow rate from the initial seting over an 8 hour run.

The same equipment was used as for Test 1, i.e. the pump was connected to the needle valve to produce the required back pressure and then to the wet test meter to measure the air volume sampled as a function of time. The back pressure was measured using the differential manometer connected across the needle valve.

In practice it is recommended that the pump flow rates are measured at the beginning and end of the sampling period and the average of these two readings taken as the flow rate. In these tests flow rate readings were taken after each hour. Tables 4a and 4b list the initial and final flow rates and their average; the average of the hourly readings, the standard deviation and their range.

TEST 4: Effect of temperature on flow rate and flow stability.

In use, pumps are often set up in a laboratory, office or control room then put on the wearer who may be working outside at extremes of cold or heat. The ability of the pumps to maintain flow rate settings and their flow stability was tested by setting the pump running with a back pressure of 10 cm water gauge (1 kPa) at room temperature (20 $\pm$ 2°C), then placing the pump in either a refrigerator at 0°C or an oven at 40°C for several hours. For comparison the pumps were also tested at 20° $\pm$ 2°C. Flow rates were measured over each hour using the same apparatus as for Tests 1 and 3 and battery current was also measured using an Avometer Type A.

The air supply to the pump was dried for the test at 0°C to prevent problems from condensation.

Test data are given in Tables 5a and 5b which show:

test temperature and duration;

initial flow rate, flow rate after the first hour, final flow rate, the average of the initial and final flow rates, the average of the hourly readings and their range;

and, in the case of the low flow rate pumps, initial, average and range of hourly battery current readings.

The flow rates quoted are at room temperature (20 $\pm$ 2°C).

TEST 5: Effect of orientation on flow rate.

Pumps are not always installed vertically and the wearer may have to work in different positions, so this test was carried out to determine the effect of orientation on pump flow rate.

The pumps were set running at their mid-range flow rate with the same back pressure settings as for Test 2 using the same equipment as for Tests 1, 3 and 4. The orientation of the pump was changed 6 times as shown in the diagram accompanying Tables 6a and 6b and the flow rate measured over 5 minutes at each orientation.

Tables 6a and 6b list the average flow rates, together with the mimimum and maximum rates and the orientations at which they occurred.

TEST 6: Noise emission.

Wearer acceptability is always a problem with personal monitoring and the noise of the pump can be a contributory factor.

The noise emissions were measured with the pumps running at nominally 95% of their maximum flow rates and suspended in space in free field conditions in an "Amplaid" silent cabin. Sound levels were measured 32 cm from the pumps, with the microphone facing the pumps, at the six orientations given in the diagram accompanying Table 6. The sound level meter was used on its slow-response setting.

The distance of 32 cm was selected as it is approximately the distance from a pump worn in an overall top pocket to the nearest ear.

Tables 7a and 7b show the minimum and maximum sound levels in dB(A) and the orientations at which they occurred. The average of the six readings calculated after conversion to pressure levels is also shown.

Sound emissions from the MDA 808 and Draeger Polymeter were not a continuous steady level and so maximum levels are reported.

TEST 7: Air flow pulsation.

In an attempt to simulate the actual pulsation likely to occur in practice the test was performed in the following manner:

The pump under test was connected to a Simquads cyclone with a 0.75 m length of tubing. The cyclone contained a 2.5 cm diameter PVC filter (5 μm pore size). The flow rate was adjusted to 1.9 litres min^{-1} and the pulsations measured by means of a hot wire anemometer positioned across the inlet of the cyclone. The output from the anemometer was displayed on an oscilloscope and the display recorded by means of a Polaroid camera. The oscilloscope screen had been calibrated previously and the results were read from the recorded output. The time constant of the hot wire anemometer was of the order of 1 millisecond.

The results of the test are summarized in Table 8.

Air flow pulsation is difficult to quantify. All air flow measuring devices have a finite response time which affects the results obtained. In addition the length of tubing used to connect the cyclone to the pump and the filter type can reduce or increase pulsation due to resonance effects at certain frequencies (Bartley et al. (1984)).

10 DISCUSSION OF RESULTS

It should be noted that there may be variations in performance between pumps of the same type. The data presented in this guide refer only to the pump tested and may not apply exactly to other pumps of the same type.

10.1 Low flow pumps

TEST 1: Effect of back pressure on flow rate.

The results of the test are summarized in Table 9 and Figures 4 to 10.

The pumps which have stroke counters* showed that the calibration factor (volume of air per stroke) generally varies with back pressure, due probably to factors such as deformation of the membrane with increasing suction and a lower than ambient air pressure in the pump chamber at the start of each stroke. This indicates that the calibration factors need to be measured under conditions as close to the sampler back pressure and the sampling flow rate as possible. The data given in Figures 4 to 10 should enable the user to make some estimate of the degree of error that may be expected at other conditions. (10 cm water gauge is about 1 kPa.)

The percentage change in flow rate with back pressure was fairly constant at all flow rate settings and back pressures.

The Du Pont P125 has a constant flow rate system which compensated very accurately for changes in back pressure.

TEST 2: Battery life.

All pumps ran for at least 10 hours on a fully charged battery as supplied, and maintained a flow rate within 10% of the set rate for over 8 hours (Table 3a).

The MDA Accuhaler can be used with any disposable batteries of suitable size and the zinc-carbon type tested also gave this performance except at the very highest flow rate when they lasted only 6 hours. Disposable alkaline-manganese cells would be expected to last longer.

These data should be taken only as a guide. There may be differences in performance between batteries and the performance of rechargeable batteries can deteriorate in use, particularly if they are used irregularly.

*MDA Accuhaler 808, Draeger Polymeter, SKC 222-4 and Casella T13298. Also later Compur models (see Chapter 8, Description of Pumps Tested).

TEST 3: Flow stability with time.

Flow rate is usually estimated by averaging the initial and final flow rates measured. This value has been included in Table 4a along with the average of the hourly flow rate readings, their standard deviation and range.

Under the test conditions all pumps maintained adequate flow stability, with five of the seven being within ± 5% of the average over 8 hours.

The mean of the initial and final flow rates gives an acceptable agreement with the mean of the hourly readings (all better than ± 5%, average agreement ± 1.5%). This is better than using only the initial flow rate which leads to errors of up to ± 7% and nearly doubles the average error at ± 2.8%.

TEST 4: Flow stability with temperature.

Temperature can affect flow rate in several ways. Firstly, changes in air density with temperature will change the mass of air contained in a fixed volume. Secondly, the battery output will be affected by temperature, which may cause a decrease in flow at lower temperatures in pumps with no compensatory system. Thirdly, electrical control circuitry may be affected and, fourthly, the mechanical resistance of the bearings, drive train and elasticity of the membrane will be affected.

The overall effect of these factors on the measured flow rate is generally to give a slightly lower flow rate at low temperature (average change -0.2%, range ±2%), and a higher flow rate at high temperature (average +2%, range +9 to -3.5%). The flow rates of four of the pumps changed by more than ±5% from the set flow at both high and low temperature but only one was affected to that extent at the mid range temperature.

One pump stopped altogether after several minutes operation at 39°C.

TEST 5: Orientation of pump.

All pumps maintained their set flow rate within ± 3% at all orientations except for one which varied by about ± 7% (Table 6a).

TEST 6: Noise emission.

All pumps were below 55 dB(A) average continuous sound level. The MDA Accuhaler 808 peak sound level was slightly above this but the sound is not continuous (Table 7a).

10.2 High flow pumps

TEST 1: Effect of back pressure on flow rate.

At the commonly used flow rates of 1.0 and 1.9 litres min^{-1}, six of the eight pumps exhibited good regulation of flow. However, at the highest flow rates the control was not as good. The approximate pressure drops required to produce a nominal 10% change from the initial set flows are summarized in Table 10 (see also Figures 11 to 18).

TEST 2: Battery life.

When set at 1.9 litres min^{-1} all pumps ran for a minimum of 10 hours on a fully charged battery as supplied (Table 3b).

TEST 3: Flow stability over 8 hours at the flow rate settings and back pressure conditions given in Test 2.

All of the pumps maintained their set flow within ± 5% over the test period (Table 4b).

TEST 4: Effect of temperature on flow rate and flow stability.

At the low temperature setting, two of the pumps varied by more than ± 10% of their set flow rate; the other pumps maintained the set flow to better than ± 5%. At the high temperature setting, all the pumps maintained the flow to better than ± 5%. At 20°C, all but one of the pumps maintained the flow better than ± 5%. However this finding was inconsistent with the results of Test 3 wherethe flow stability for this pump was better than ± 5% (Table 5b).

TEST 5: Effect of orientation on flow rate.

Some small variations in flow rate with change in orientation were observed for the majority of the pumps tested. However all but one of the pumps controlled within ±5% of the average value (Table 6b).

TEST 6: Noise emission.

The average sound level for all the pumps was generally in the range 50-60 dB(A) (Table 7b).

TEST 7: Air flow pulsation.

The pulsation of two of the pumps could not be quantified with the instrumentation employed because the time constant of the hot wire anemometer was too long.

If the results in Table 8 are compared with the PPR criteria of 1.2 recommended by Lamonica and Treaftis (1972), it can be seen that only one pump met this standard although allowances must be made for the error of the measurement procedure. Neither the Samplet 828C nor the Vinten Zephyr contains a pulsation damper (Table 8).

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TABLE 1

Characteristics of primary and secondary cells

Cells	Nominal voltage	Relative capacity for equal physical size (Ah)	Operating temperature range (°C)	Shelf life to 80% of full charge at 20°C (months)
Primary				
Zinc-Carbon (Leclanché dry cell)	1.50	1.0	- 20 to 70	6-18
Alkaline-Manganese	1.50	2.8	- 20 to 60	30
Mercury	1.35	0.8	- 20 to 70 (storage - 60 to 160)	30
Secondary				
Nickel-Cadmium	1.20	1.4	- 20 to 45 (storage - 60 to 60)	1
Lead-Acid	2.00	1.0	- 40 to 65	36 (to minimum charge)

TABLE 2a

Details of low flow pumps tested

	CASELLA T13298 (SIPIN SP15)	COMPUR 4902	DRAEGER POLYMETER	DU PONT P125	MDA ACCUHALER 808	ROTHEROE AND MITCHELL C500	SKC 222.4
Country of origin	USA	W.GERMANY	W.GERMANY	USA	USA	UK	USA
Cost £** (July 1984)	375	425	290	575	310	318	276
Intrinsic safety certification*	YES	YES	YES	YES	YES	YES	YES
Dimensions length mm	130	119	170	133	165	120	130
width	64	64	85	74	89	73	64
depth	32	41	50	38	38	45	32
Weight g	350	369	1000	400	340	425	285
Type of pump	Diaphragm	Diaphragm	Peristaltic	Diaphragm	Diaphragm	Rotating vane	Diaphragm
Battery condition Indicator	NO	NO	NO	YES	NO	YES	NO
Low flow indicator	YES	NO	NO	YES	NO	NO	NO
Rechargeable batteries	YES	YES	YES	YES	YES	YES	YES
Disposable batteries	NO	NO	NO	NO	YES	NO	NO
On/Off switch	On case	On case	Under hinged cover	Remove cover	On case	On case	On case
Gas outlet	YES	NO	YES	Optional	Optional	Can be adapted	YES
Flow setting	Front dial	Remove cover	Fixed	S'driver slot - remove cover	Change orifice	S'driver slot	Front dial
Flow control	NO	NO	NO	YES	NO	NO	NO
Flow meter fitted	NO	NO	NO	NO	NO	YES	NO
Pump stroke counter	YES	YES	YES	NO	YES	NO	YES

* The user must ensure that the level of certification is adequate for the application.
**Approximate UK cost of pump quoted or nearest current equivalent.

TABLE 2b

DETAILS OF HIGH FLOW PUMPS TESTED

	BENDIX BDX60	CASELLA AFC 123	DU PONT P2500	DU PONT P4000	MSA FIXT FLO	ROTHEROE AND MITCHELL L2SF MK II	SAMPLET 828C	VINTEN ZEPHYR
Country of Origin	USA	UK	USA	USA	USA	UK	UK	UK
Cost Intrinsic Safety Certification *	YES	YES	YES	YES	NO	YES	NO	NO
Dimensions: Length mm Width Depth	117 127 65	120 75 44	165 103 45	155 105 60	105 158 50	127 95 57	120 65 41	125 70 35
Weight g	830	440	737	1270	900	1000	480	400
Type of Pump	Double diaphragm	Single diaphragm	Double diaphragm	2 Double diaphragms	Double diaphragm	Rotary vanes	Double piston	Double piston
Battery Indicator	NO	YES	YES	YES	YES	NO	YES	NO
Low Flow Indicator	YES	NO	YES	YES	YES	NO	NO	NO
Batteries	3 Ni/Cd	5 Ah 4 Ni/Cd	4 Ni/cd	8 Ni/Cd	2 Ah 4 Ni/Cd	4 Ah 4 Ni/Cd	4 Ah 4 Ni/Cd	
Charge Rate	Not specified	100 mA 14 h		240 mA 14-16 h	200 mA 16 h	250 mA 12 h	100 mA 14 h	
On/Off Switch	Press rubber diaphragm on case	Slide switch recessed in case	Toggle under removable cover	Slide switch under removable cover	Toggle under removable cover	Toggle recessed in side of case	Slide switch on case	
Exchangeable Battery Packs	NO	YES	YES	YES	YES	NO	NO	
Air Outlet	NO	NO	NO	EXTRA	YES	NO	NO	NO
Built-in Filter	YES	YES	YES	YES	YES	NO	NO	
Flow Setting	4 potentiometers inside pump	Screwdriver slot in case	Screwdriver slot under removable cover	Change pulleys, switch and s'driver slot	Potentiometer under flap on case	Screwdriver slot in case	Fixed	
Flow Control Sensor	Chopper disc on drive motor	Thermistor	Differential pressure	Differential pressure	Hot wire filament flow sensor	Differential pressure		
Pulsation Damper	YES	YES	NO	NO	YES	NO	NO	
Pump Running Indicator	Flowmeter	LED	NO	Moving Belt Drive	NO	Flowmeter	NO	
Flow Meter	0.6 to 4.4 l min^{-1} 60 mm scale	NO	NO	NO	NO	0.5 to 5.0 l min^{-1} 75 mm scale	NO	NO
Flow Range l min^{-1}	0 to 3.0	1.0 to 2.3	0.1 to 2.5	0.2 to 4.0	0.5 to 3.5	1.0 to 4.0	2.0	
Temperature Range °C	0 to 40	Not Specified	0 to 50	-7 to 49	0 to 45	Not specified	Not specified	
Flow Control Specification cm of water gauge	$< \pm$ 5% over 0 to 38	$< \pm$ 5% over 0 to 102	$< \pm$ 5% over 0 to 38	$< \pm$ 5% over 0 to 64	18 - 89	$< \pm$ 5 % over 0 to 57	$< \pm$ 10 % over 5 to 30	

* The user must ensure that the level of certification is adequate for the application.

TABLE 3a

Battery life

PUMP	Flow rate (cm^3 min^{-1})	Running time to 90% of set flow rate (h)	Running time to Voltage V (h)	Voltage V
CASELLA T13298	11	17	17	2.2
	105	12	15	2.2
	190	11	14	2.2
COMPUR 4902	5	19	20	5.5
	18	>16	16	5.5
	38	11	14	5.5
DRAEGER POLYMETER	18	14	23	5.5
DU PONT P125	19	62	62	4.4
	105	50	59	4.4
	200	13	28	4.4
MDA ACCUHALER 808	5	>67	67	2.2
	49	18	40	2.2
	109	15	17	2.2
	20 *	51	51	1.3
	52 *	18	18	1.3
	110 *	6	6	1.4
ROTHEROE AND MITCHELL C500	25	12	19	3.3
	260	9	16	3.3
	501	11	11	3.3
SKC 222-4	7	12	>20	2.2
	37	>15	>16	2.2
	68	>17	>17	2.2

* Using zinc-carbon disposable batteries type HP7/R6HP

TABLE 3b

Battery life

PUMP	Initial flow rate at voltage V (litres min^{-1})	Final flow rate at voltage V_1 (litres min^{-1})	Initial voltage V	Final voltage V_1	Running time to voltage V_1 (h)
BENDIX BDX60	1.9	1.9	6.30	4.60	25.6
CASELLA AFC 123	1.9	1.9	5.45	4.40	27.5
DU PONT P2500	1.9	0.2	5.20	4.16	15.0
DU PONT P4000	1.9	1.9	5.30	4.40	34.0
MSA FIXT FLO	1.9	1.9	5.55	4.40	15.4
ROTHEROE AND MITCHELL L2SF Mk II					
SAMPLET 828C	1.9	1.9	4.45	3.30	12.0
VINTEN ZEPHYR	1.9	0.0	5.20	3.50	11.0

TABLE 4a

Flow stability over 8 hours at 20°C

PUMP	Flow rate (cm^3 min^{-1})						
	Initial (A)	Final (B)	$\frac{A + B}{2}$	Mean of hourly readings	Standard deviation	(%)	Range
CASELLA T13298	44	40	42	42	1.90	4.6	39 - 44
	93	107	100	97	5.10	5.2	90 - 107
	134	135	135	133	0.86	0.6	132 - 135
COMPUR 4902	35	35	35	35	0.38	1.1	34 - 35
DRAEGER POLYMETER	15	15	15	15	0.63	4.3	14 - 16
DU PONT P125	31	31	31	31	0.39	1.3	31 - 32
	59	60	60	59	0.34	0.6	59 - 60
	100	99	100	99	0.62	0.6	98 - 100
MDA ACCUHALER 808	6	6	6	6	0.22	3.6	6
	38	34	36	35	1.85	5.2	33 - 38
	76	70	73	72	2.16	3.0	70 - 76
ROTHEROE AND MITCHELL C500	28	29	29	28	1.00	3.5	26 - 30
	183	189	186	189	2.31	1.2	183 - 192
	284	296	290	292	4.66	1.6	284 - 296
SKC 222-4	25	25	25	24	0.86	3.6	22 - 25
	41	36	39	39	1.80	4.7	36 - 41
	58	57	58	58	0.70	1.2	56 - 59

TABLE 4b

Flow stability over 8 hours at 20°C

PUMP	Flow rate (litres min^{-1})						
	Initial (A)	Final (B)	$\frac{A+B}{2}$	Mean of hourly readings	Standard deviation	(%)	Range
BENDIX BDX60	1.1	1.1	1.1	1.1	-	-	1.1
	2.0	1.9	2.0	1.9	0.03	1.5	1.9 - 2.0
	3.2	3.1	3.2	3.2	0.05	1.4	3.1 - 3.2
CASELLA AFC 123	1.3	1.3	1.3	1.3	0.03	2.2	1.3
	1.9	1.9	1.9	1.9	-	-	1.9
	3.2	3.2	3.2	3.2	-	-	3.2
DU PONT P2500	1.0	1.0	1.0	1.0	-	-	1.0
	1.9	1.9	1.9	1.9	-	-	1.8 - 1.9
	3.9	3.7	3.8	3.7	0.13	3.6	3.5 - 3.8
DU PONT P4000	1.2	1.2	1.2	1.2	-	-	1.2
	2.0	2.0	2.0	2.0	-	-	2.0
	4.4	4.4	4.4	4.4	-	-	4.4
MSA FIXT FLO	1.2	1.2	1.2	1.2	-	-	1.2
	1.9	1.9	1.9	1.9	0.01	0.4	1.9
	3.6	3.6	3.6	3.6	-	-	3.6
ROTHEROE AND MITCHELL L2SF Mk II	1.2	1.1	1.2	1.1	0.03	3.1	1.1 - 1.2
	1.9	1.9	1.9	1.9	-	-	1.9
	4.6	4.2	4.4	4.3	0.10	2.3	4.2 - 4.6
SAMPLET 828C	1.1	1.1	1.1	1.1	0.02	1.8	1.1
	2.0	2.0	2.0	2.0	-	-	2.0
	2.8	2.9	2.9	2.9	0.04	1.2	2.8 - 2.9
VINTEN ZEPHYR	1.9	1.8	1.9	1.9	0.01	0.3	1.8 - 2.0

TABLE 5a

Effect of temperature on flow rate and stability

PUMP	Temperature (°C)	Duration (h)	Flow rate ($cm^3\ min^{-1}$) Initial set up 20°C(A)	After 1 hour	Final (B)	$\frac{A + B}{2}$	Mean of hourly readings	Standard deviation	(%)	Range	Battery current (mA) Initial	Mean*	Range
CASELLA T13298	0	8	113	112	119	116	119	3.20	2.7	112 - 122	38	38	38
	20	7	87	86	84	86	85	1.13	1.3	83 - 87	34	33	33 - 34
	40	8	86	79	78	82	78	0.88	1.1	77 - 86	37	38	37 - 38
COMPUR 4902	0	8	38	35	37	38	37	0.65	1.8	35 - 38	31	26	23 - 31
	20	7	34	34	34	34	34	0.22	0.6	34	16	15	13 - 16
	40	6	27	25	26	26	26	0.73	2.9	25 - 27	15	15	15
DRAEGER POLYMETER	0	8	15	15	16	15	15	0.50	3.3	15 - 17	30	30	30
	20	7	12	12	13	12	12	0.32	2.6	12 - 13	30	31	30 - 32
	40	7	12	12	10	11	11	0.88	7.7	10 - 12	33	33	33
DU PONT P125	0	8	179	179	192	186	188	4.60	2.4	179 - 195	15	15	15
	20	4	56	55	54	55	55	0.49	0.9	54 - 56	10	10	9 - 10
	40	7	53	43	45	49	45	0.81	1.8	43 - 53	10	10	10
MDA ACCUHALER 808	0	8	38	38	37	38	38	0.40	1.1	37 - 38	125	119	110 - 125
	20	6	76	71	70	73	72	0.81	1.1	70 - 76	84	84	82 - 85
	40	6	30	29	28	29	29	0.50	1.8	28 - 30	90	93	90 - 95
ROTHEROE AND MITCHELL C500	0	8	95	93	88	92	92	1.54	1.7	88 - 95	72	69	67 - 72
	20	8	69	70	69	69	70	0.43	0.6	69 - 70	73	73	73
	40	STOPPED AFTER 40 MINUTES											
SKC 222-4	0	8	50	50	50	50	50	0.47	0.9	50 - 51	34	36	34 - 37
	20	6	46	46	46	46	46	0.26	0.6	46	18	19	18 - 20
	40	5	40	39	41	41	40	0.80	2.0	39 - 41	23	17	16 - 23

*Mean of the hourly readings

TABLE 5b

Effect of temperature on flow rate and stability

PUMP	Temperature (°C)	Duration (h)	Initial set up 20°C(A)	After 1 hour	Final (B)	$\frac{A + B}{2}$	Mean of hourly readings	Standard deviation	(%)	Range
			Flow rate (litres min^{-1})							
BENDIX BDX60	0	10	1.9	1.9	1.9	1.9	1.9	-	-	1.9
	20	10	2.0	2.0	1.9	2.0	1.9	0.02	1.1	1.9 - 2.0
	40	10	2.0	2.0	2.0	2.0	2.0	-	-	2.0
CASELLA AFC 123	0	10	1.9	1.9	2.0	2.0	2.0	0.03	1.6	1.9 - 2.0
	20	10	1.9	1.9	1.9	1.9	1.9	-	0.2	1.9
	40	10	1.9	1.9	1.9	1.9	1.9	-	-	1.9
DU PONT P2500	0	10	1.9	1.9	1.8	1.9	1.9	-	0.2	1.8 - 1.9
	20	10	1.9	1.9	1.9	1.9	1.9	-	-	1.9
	40	10	1.9	1.9	1.8	1.9	1.9	-	0.1	1.9
DU PONT P4000	0	8	1.9	1.6	1.5	1.7	1.5	0.12	11.7	1.3 - 1.9
	20	8	2.0	2.0	2.0	2.0	2.0	-	-	2.0
	40	8	1.9	1.9	1.9	1.9	1.9	0.01	0.3	1.9
MSA FIXT FLO	0	10	1.9	1.9	1.8	1.9	1.9	0.03	1.5	1.8 - 2.0
	20	10	1.9	1.9	1.9	1.9	1.9	0.01	0.4	1.9
	40	10	1.9	1.9	1.9	1.9	1.9	0.01	0.3	1.9
ROTHEROE AND MITCHELL L2SF Mk II	0	10	1.9	2.0	2.0	2.0	2.0	-	0.2	1.9 - 2.0
	20	10	1.9	1.9	1.9	1.9	1.9	-	0.2	1.9
	40	10	2.0	2.0	2.0	2.0	2.0	-	-	2.0
SAMPLET 828C	0	10	1.9	1.9	1.9	1.9	1.9	0.01	0.6	1.9
	20	10	2.0	2.0	2.0	2.0	2.0	-	-	2.0
	40	10	1.9	1.9	1.9	1.9	1.9	-	-	1.9
VINTEN ZEPHYR	0	10	2.1	2.1	1.8	2.0	2.1	0.27	13.0	1.8 - 2.5
	20	10	1.9	1.9	1.6	1.8	1.8	0.14	7.9	1.6 - 1.9
	40	10	2.0	1.9	1.8	1.9	1.9	0.07	3.6	1.8 - 2.0

TABLE 6a

Flow rate variations with orientation

PUMP	Flow rate (litres min^{-1})				
	Minimum	at orientation.*	Maximum	at orientation.*	Average
CASELLA T13298	99	2	101	4	101
COMPUR 4902	24	no variation	24	no variation	24
DRAEGER POLYMETER	13	no variation	13	no variation	13
DU PONT P125	100	1,2,3,5,6	101	4	100
MDA ACCUHALER 808	77	6	79	5	78
ROTHEROE AND MITCHELL C500	310	2	355	5	335
SKC 222-4	37	2,4	38	1,3,5,6	38

*Orientation side uppermost.

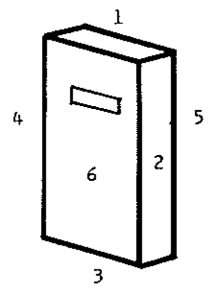

TABLE 6b

Flow rate variations with orientation

PUMP	Flow rate (litres min^{-1})				
	Minimum	at orientation.*	Maximum	at orientation.*	Average
BENDIX BDX60	1.9	6	1.9	2,3	1.9
CASELLA AFC 123	1.9	1	1.9	5	1.9
DU PONT P2500	1.9	1,2,4	2.0	5	1.9
DU PONT P4000	1.9	4	1.9	6	1.9
MSA FIXT FLO	1.9	5,6	1.9	1	1.9
ROTHEROE AND MITCHELL L2SF Mk II	1.9	1	2.0	2,5	2.0
SAMPLET 828C	1.7	4	1.9	2	1.9
VINTEN ZEPHYR	2.0	1	2.2	3,5	2.1

* See Table 6a.

TABLE 7a

Noise emission in dB(A)
(at near maximum flow rate)

PUMP	Flow rate (cm^3 min^{-1})	Minimum sound level	Orientation**	Maximum sound level	Orientation**	Average sound level
CASELLA T13298	190	51	1,5	54	2	53
COMPUR 4902	45	38	3	45	1	42
DRAEGER POLYMETER *	15	44	2	52	4	49
DU PONT P125	190	38	1,2,5,6	42	3	39
MDA ACCUHALER 808 *	100	55	1,3,4	58	6	56
ROTHEROE AND MITCHELL C500	570	41	5	45	6	43
SKC 222-4	72	40	3,4	42	6	41

* Noise levels quoted are based on maximum measured as the level varies.

** See Table 6a.

TABLE 7b

Noise emission in dB(A)
(at near maximum flow rate)

PUMP	Flow rate litres min^{-1})	Minimum sound level	Orientation*	Maximum sound level	Orientation*	Average sound level
BENDIX BDX60	3.3	56	3	60	5	57
CASELLA AFC 123	2.3	51	3	55	5	54
DU PONT P2500	3.2	56	2	60	3	57
DU PONT P4000	4.6	49	3	52	2,4	51
MSA FIXT FLO	3.7	50	5	53	6	52
ROTHEROE AND MITCHELL L2SF Mk II	4.6	58	3	63	1	60
SAMPLET 828C	1.9	52	1	53	3,4	52
VINTEN ZEPHYR	1.9	43	4	45	1	44

* See Table 6a.

TABLE 8

Air flow pulsation

PUMP	Maximum air velocity (V max)	Minimum air velocity (V min)	V max / V min	(V max - V min) / V mean	Frequency of pulsation (Hz)
BENDIX BDX60	2.80	1.30	2.2	0.8	50
CASELLA AFC 123	2.35	1.95	1.2	0.2	80
DU PONT P2500	**	**	**	**	**
DU PONT P4000	2.30	1.80	1.3	0.3	50
MSA FIXT FLO	*	*	*	*	*
ROTHEROE AND MITCHELL L2SF Mk II	*	*	*	*	*
SAMPLET 828C	2.50	1.25	2.0	0.7	70
VINTEN ZEPHYR	3.10	0.30	10.3	1.5	40

* Not quantifiable.

** Not available.

TABLE 9

Summary of the effects of back pressure on flow rate

PUMP	Maximum suction (cm water)	Average flow rate drop per cm water gauge increase in back pressure (%)
CASELLA T13298	50 (high setting)	0.3 - 0.6
COMPUR 4902	50	0.5
DRAEGER POLYMETER	50	0.5
DU PONT P125	50	0.1
MDA ACCUHALER 808	18	5
ROTHEROE AND MITCHELL C500	20-25	4
SKC 222-4	50	0.5 - 0.7

TABLE 10

Effects of back pressure on flow rate

PUMP	Nominal flow rate (litres min^{-1}) 1.0	1.9	90% of maximum
	Pressure drop required to produce 10% change in flow rate (cm of water gauge)		
BENDIX BDX60	100	76	50
CASELLA AFC 123	57	50	30
DU PONT P2500	180	80	40
DU PONT P4000	42	30	20
MSA FIXT FLO	124	90	45
ROTHEROE AND MITCHELL L2SF Mk II	100	80	55
SAMPLET 828C	40	6	13
VINTEN ZEPHYR	*	12	*

* Not applicable.

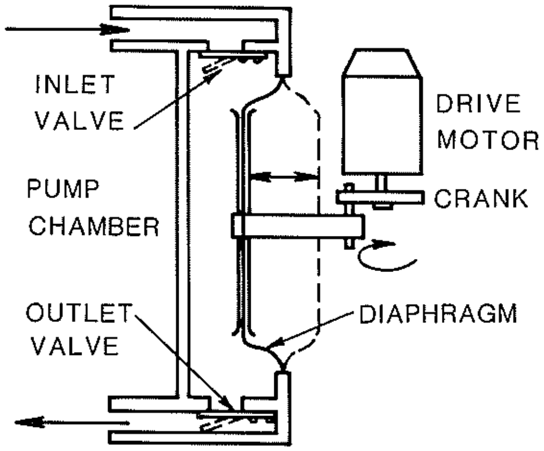

Fig. 1. Single diaphragm pump.

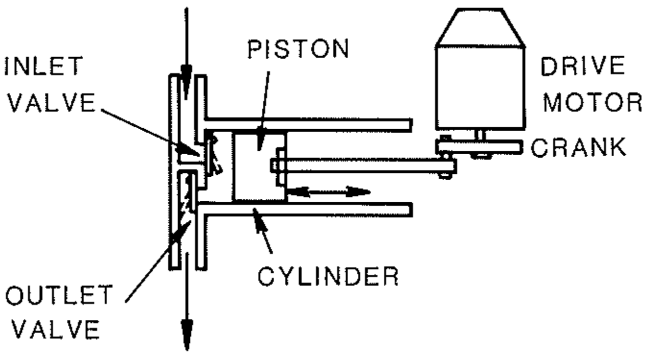

Fig. 2. Piston pump.

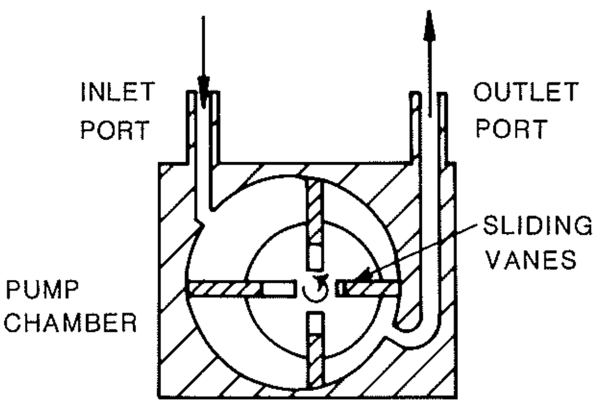

Fig. 3. Rotary vane pump.

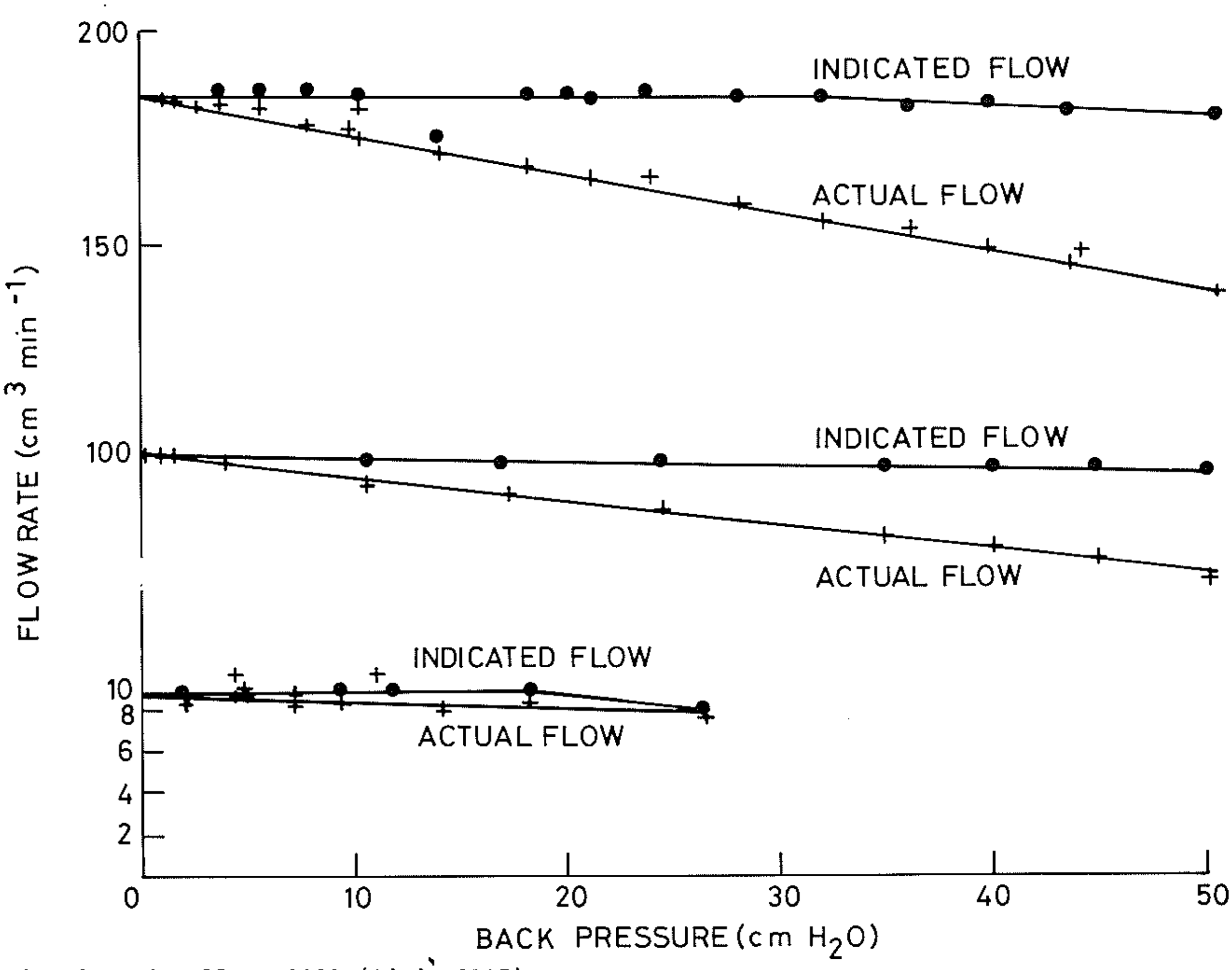

Fig. 4. Casella T13298 (Sipin SP15).

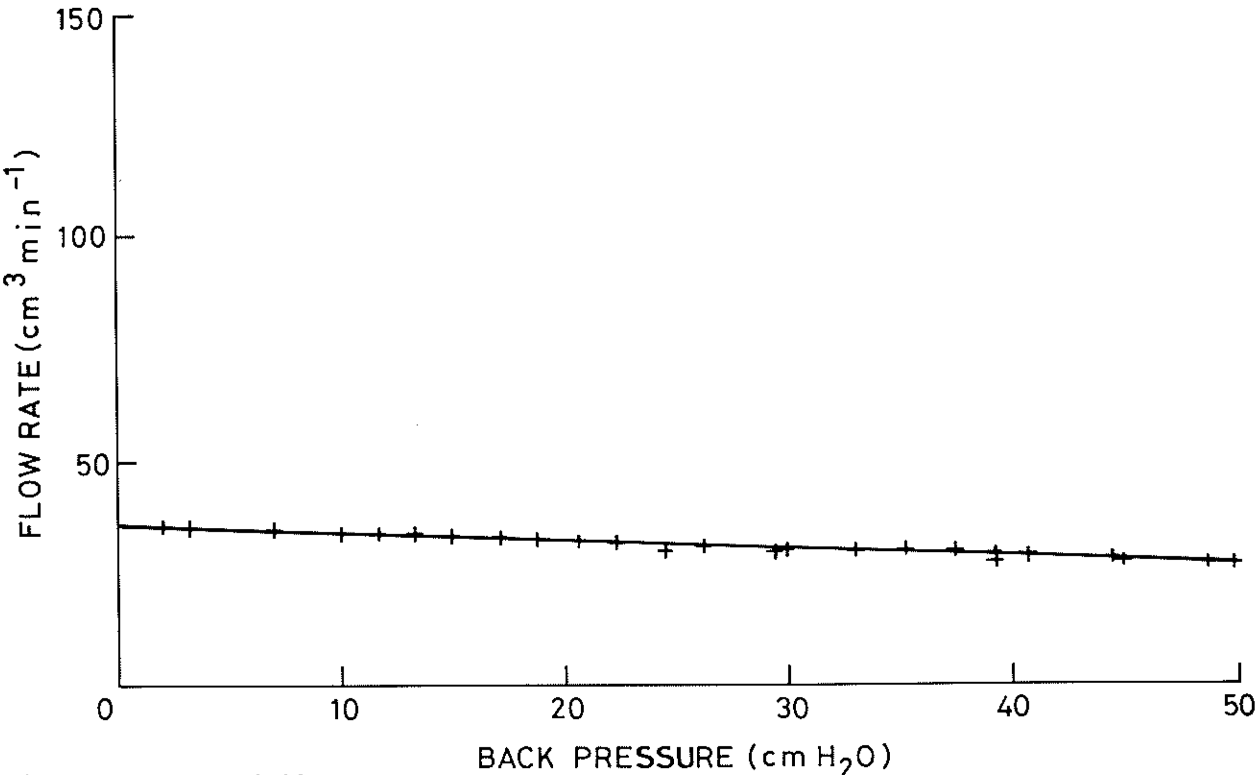

Fig. 5. Compur 4902.

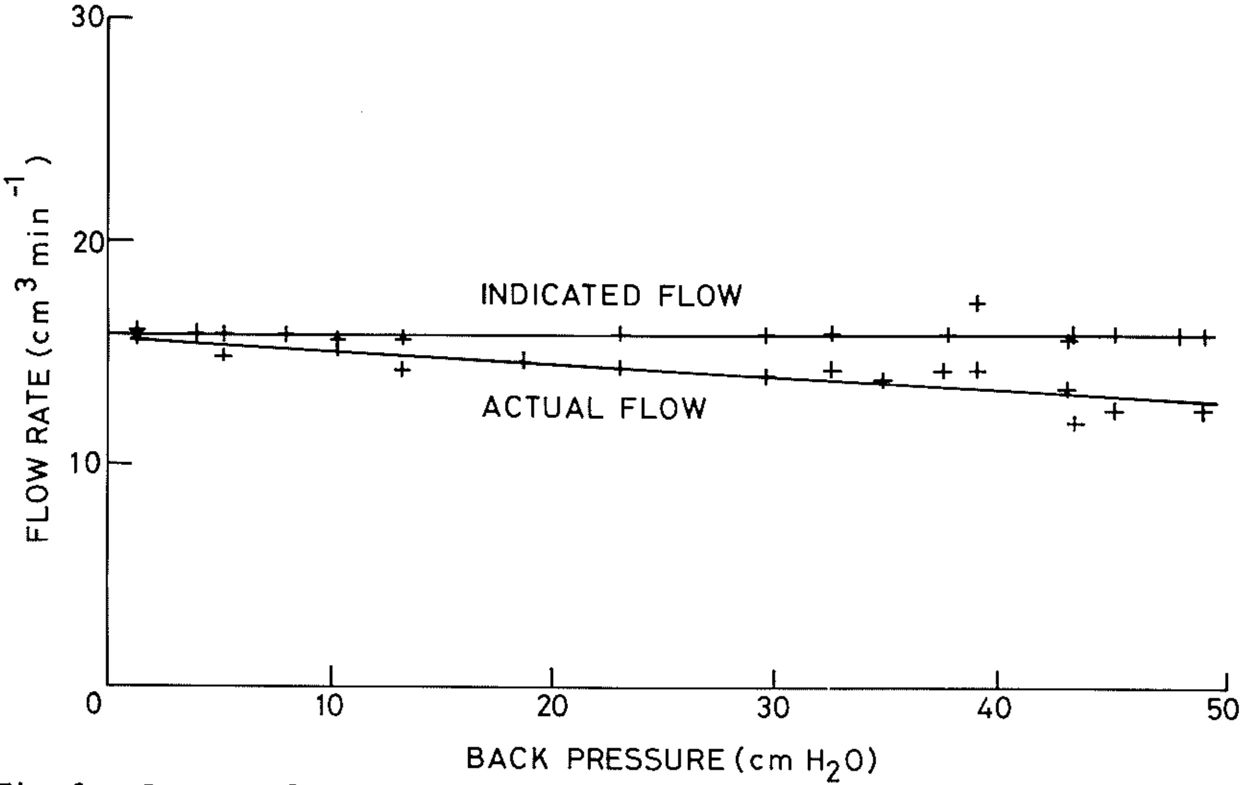

Fig. 6. Draeger Polymeter.

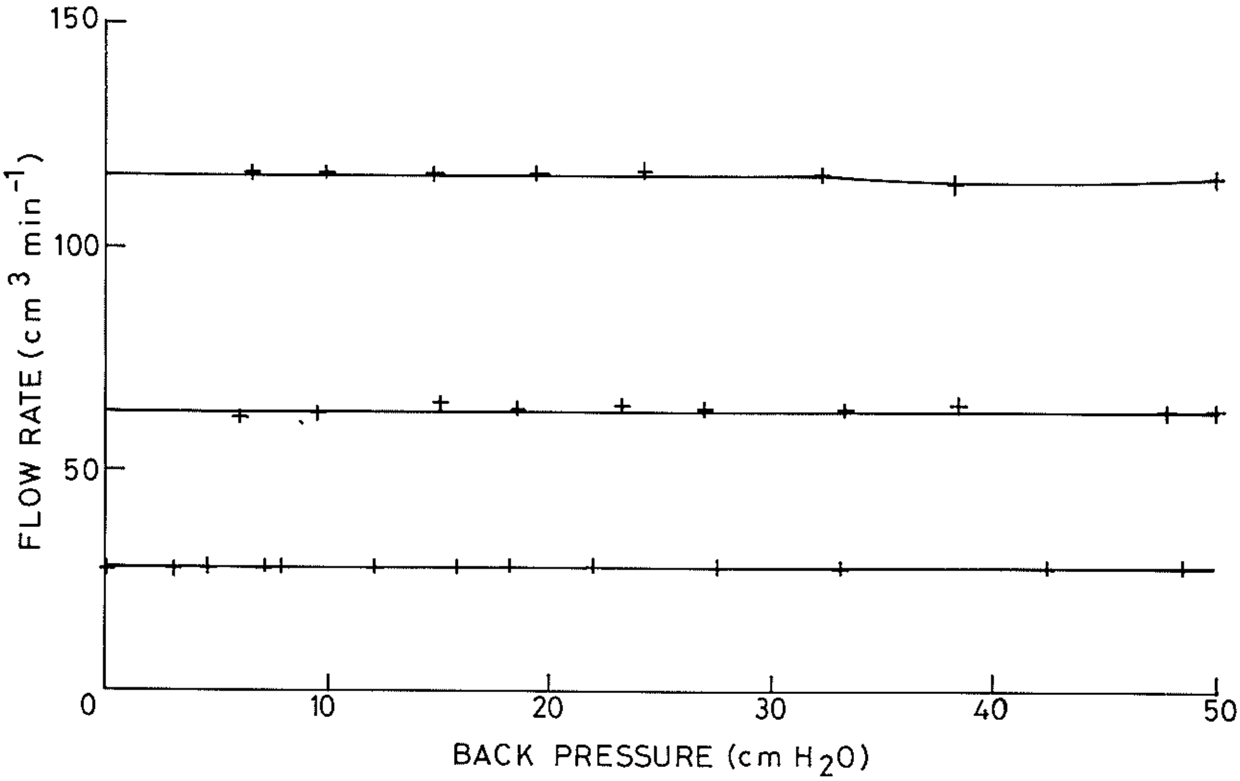

Fig. 7. Du Pont P125.

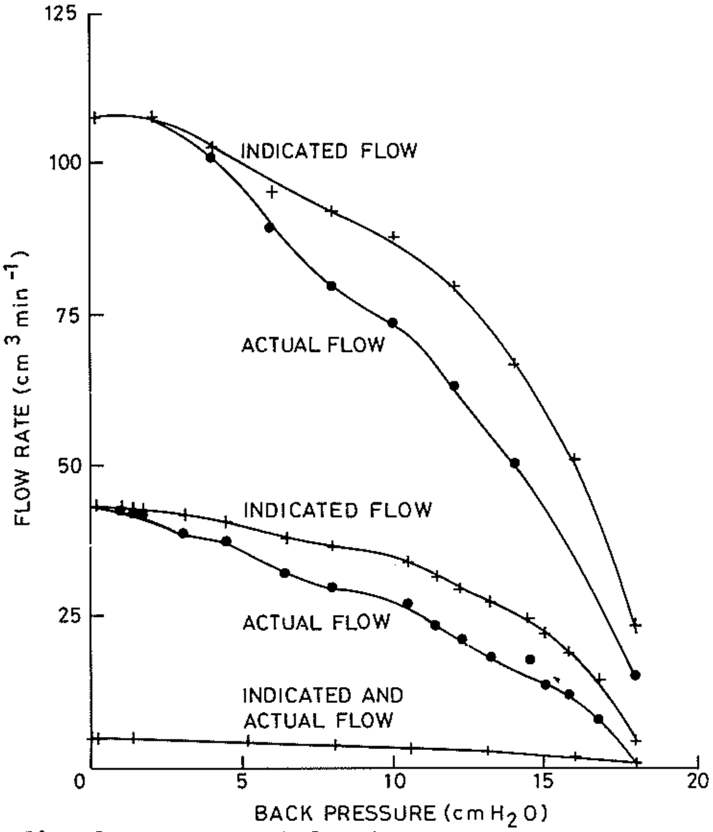

Fig. 8. MDA Accuhaler 808.

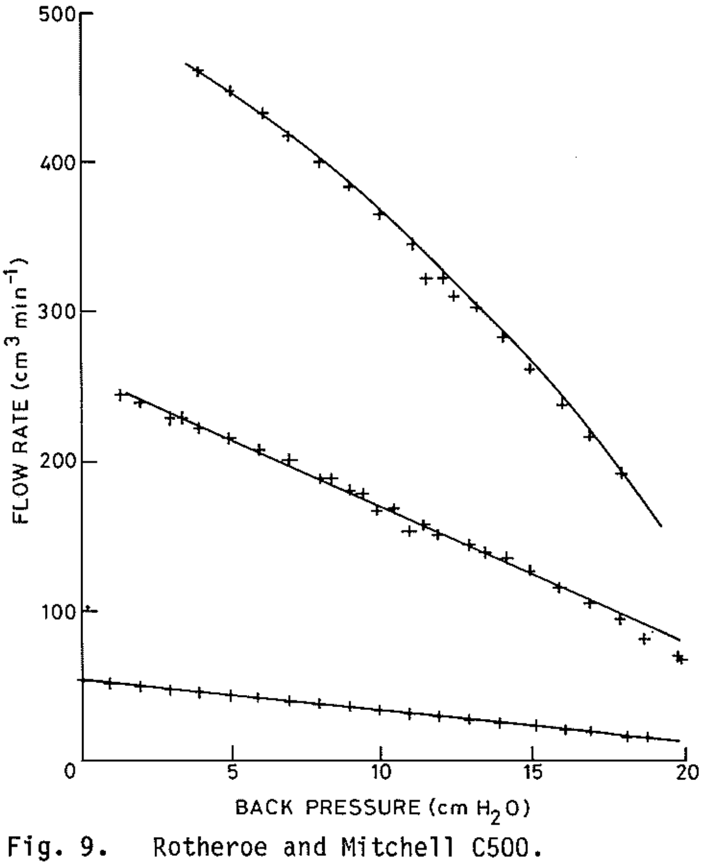

Fig. 9. Rotheroe and Mitchell C500.

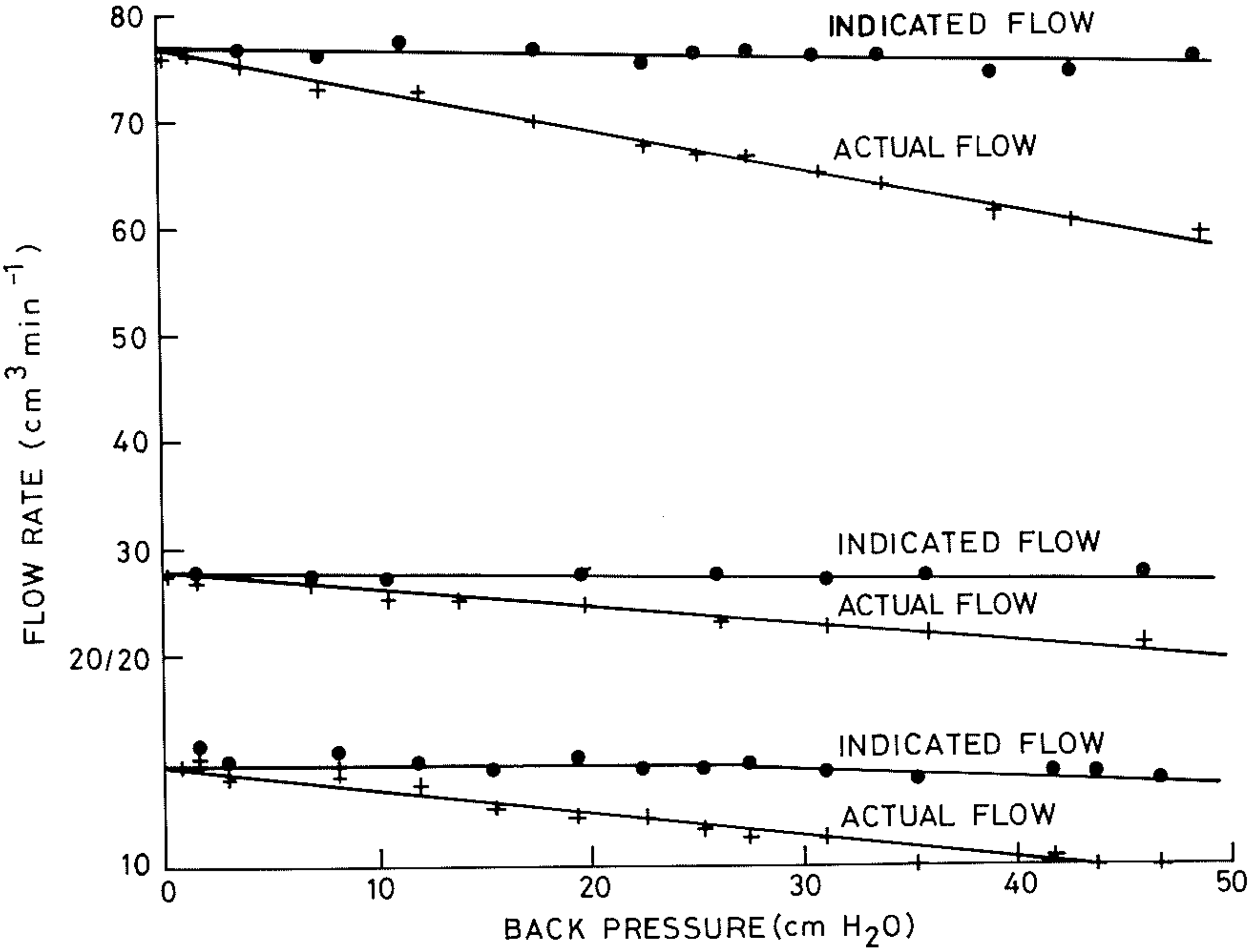

Fig. 10. SKC 222-4.

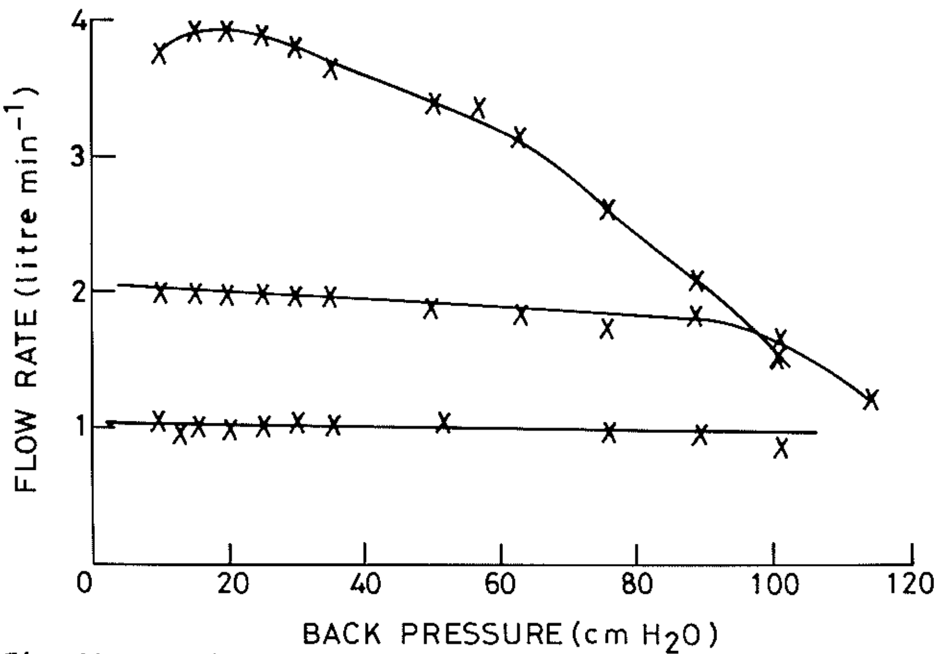

Fig. 11. Bendix BDX60.

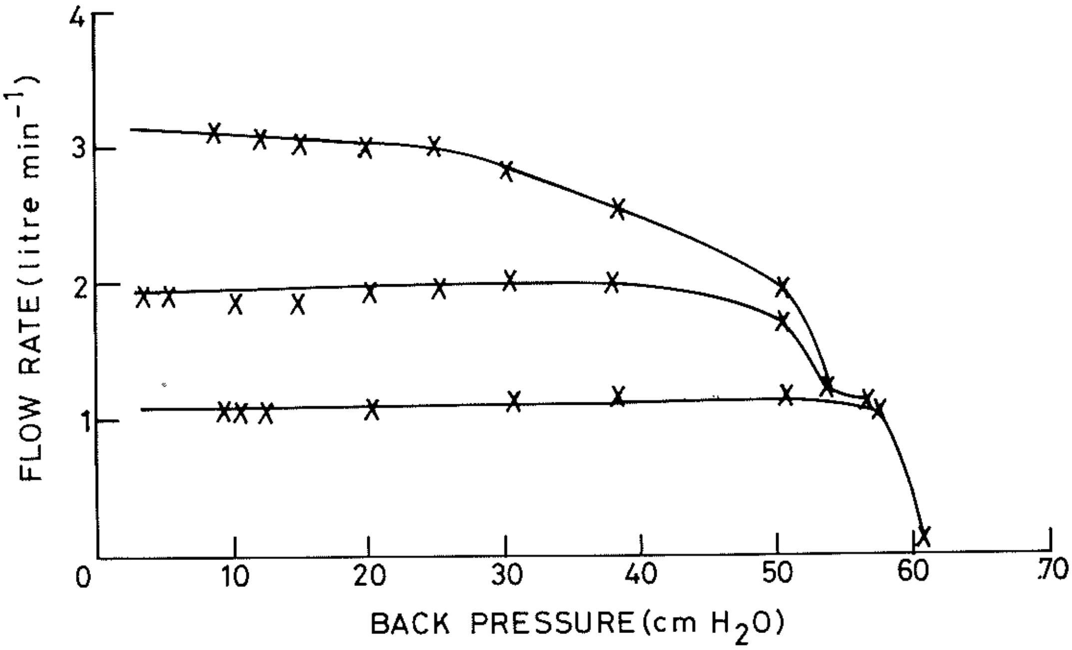

Fig. 12. Casella AFC 123.

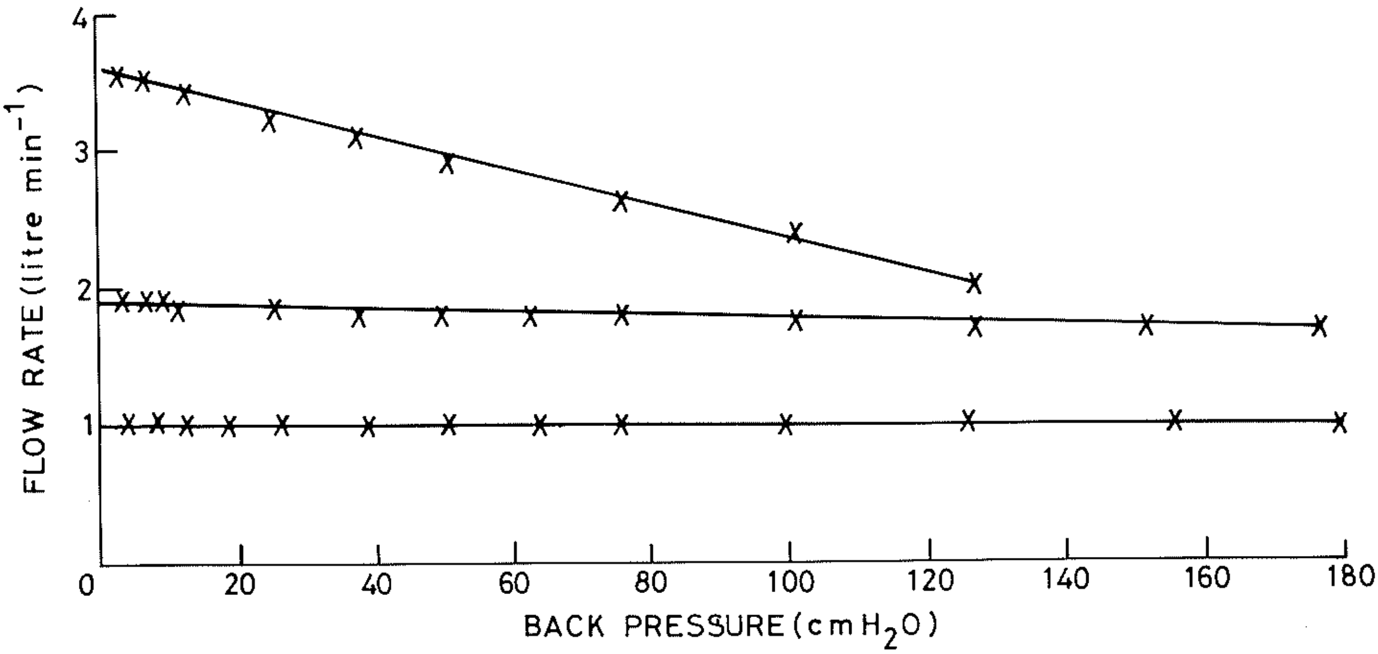

Fig. 13. Du Pont P2500.

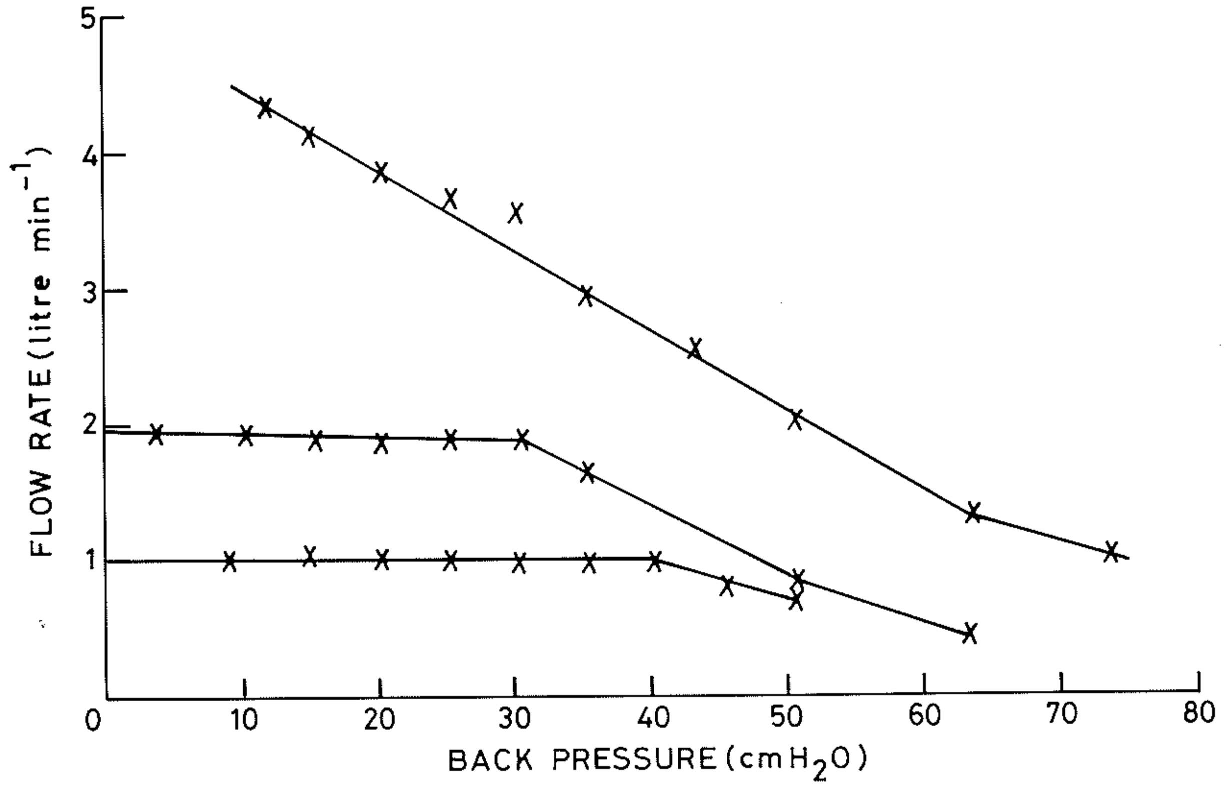

Fig. 14. Du Pont P4000.

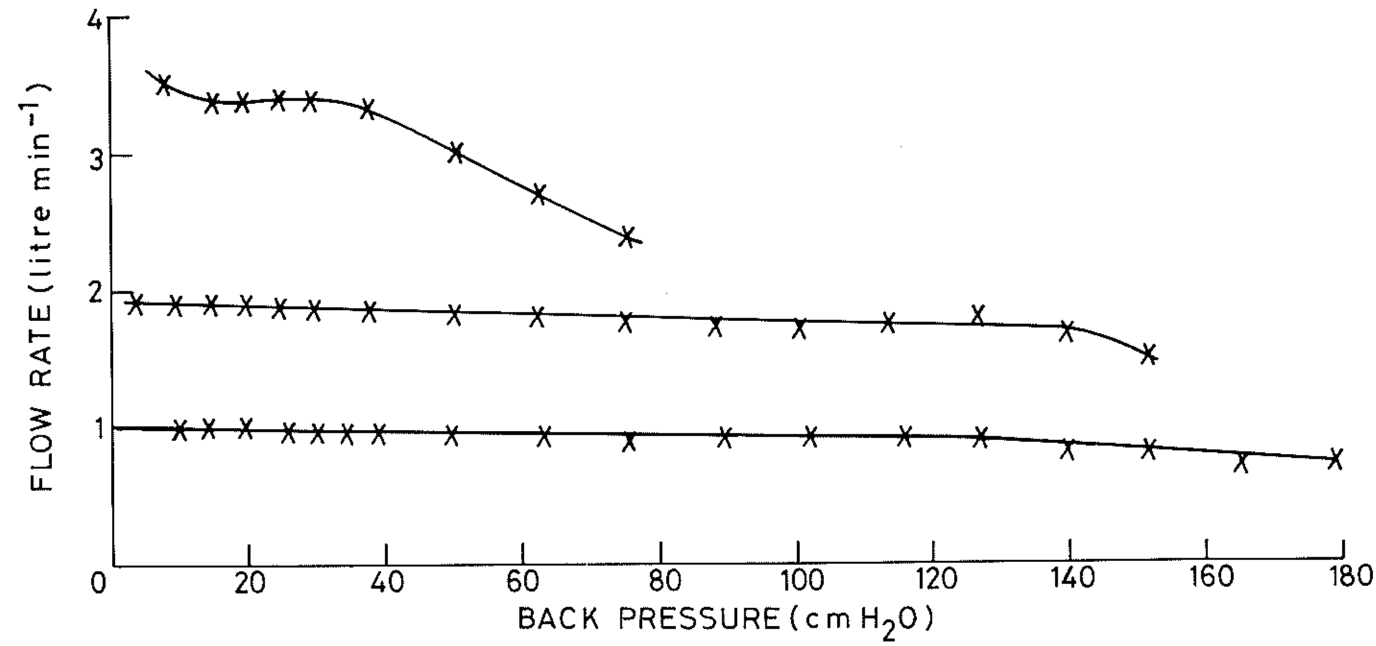

Fig. 15. MSA Fixt Flo.

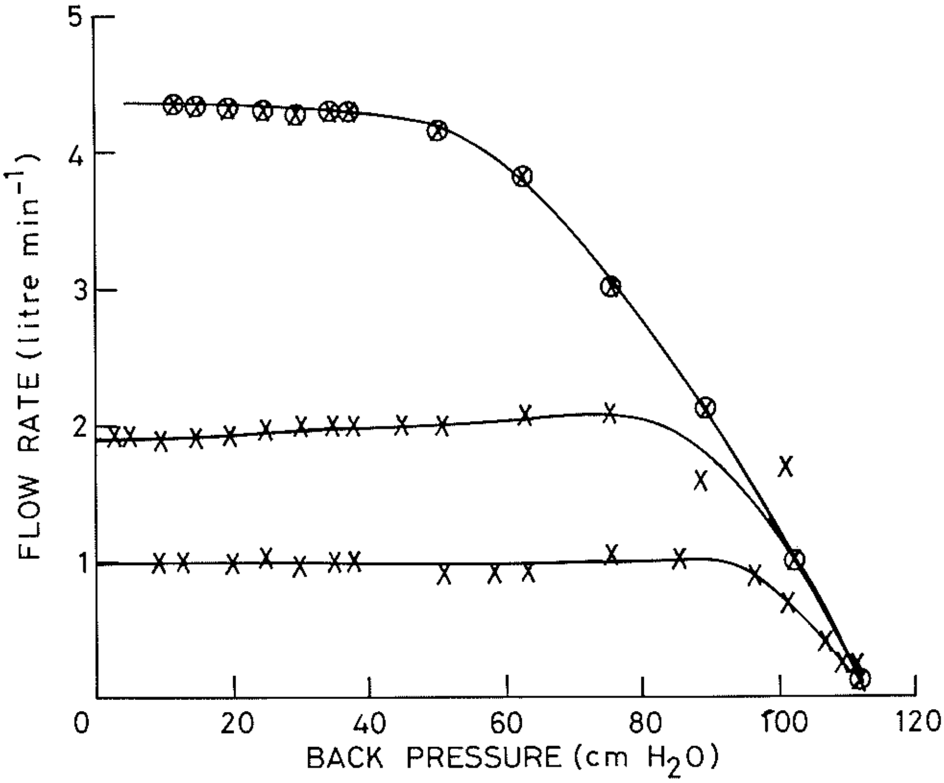

Fig. 16. Rotheroe and Mitchell L2SF Mk II.

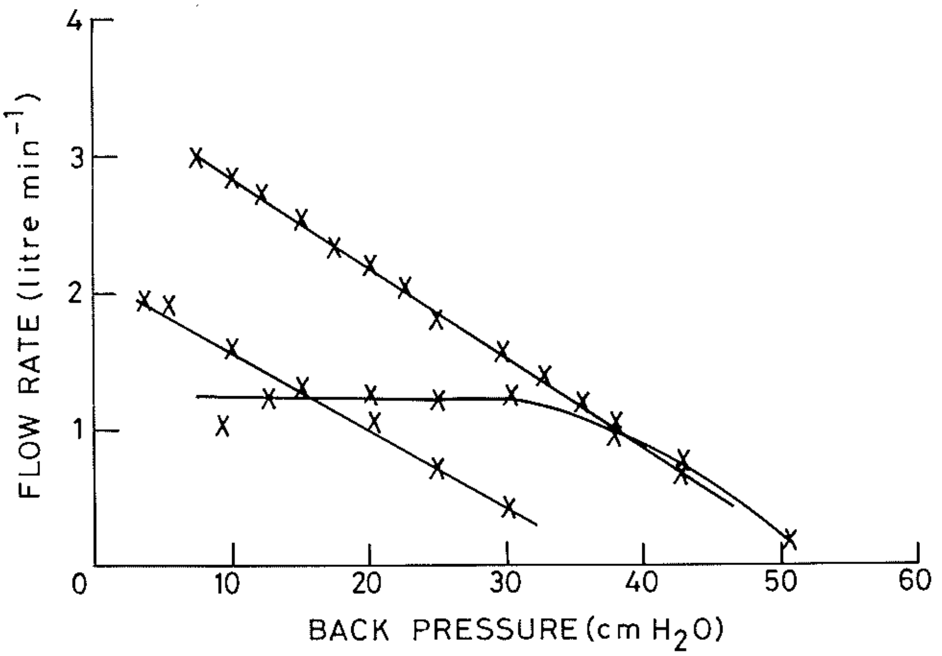

Fig. 17. Samplet 828C.

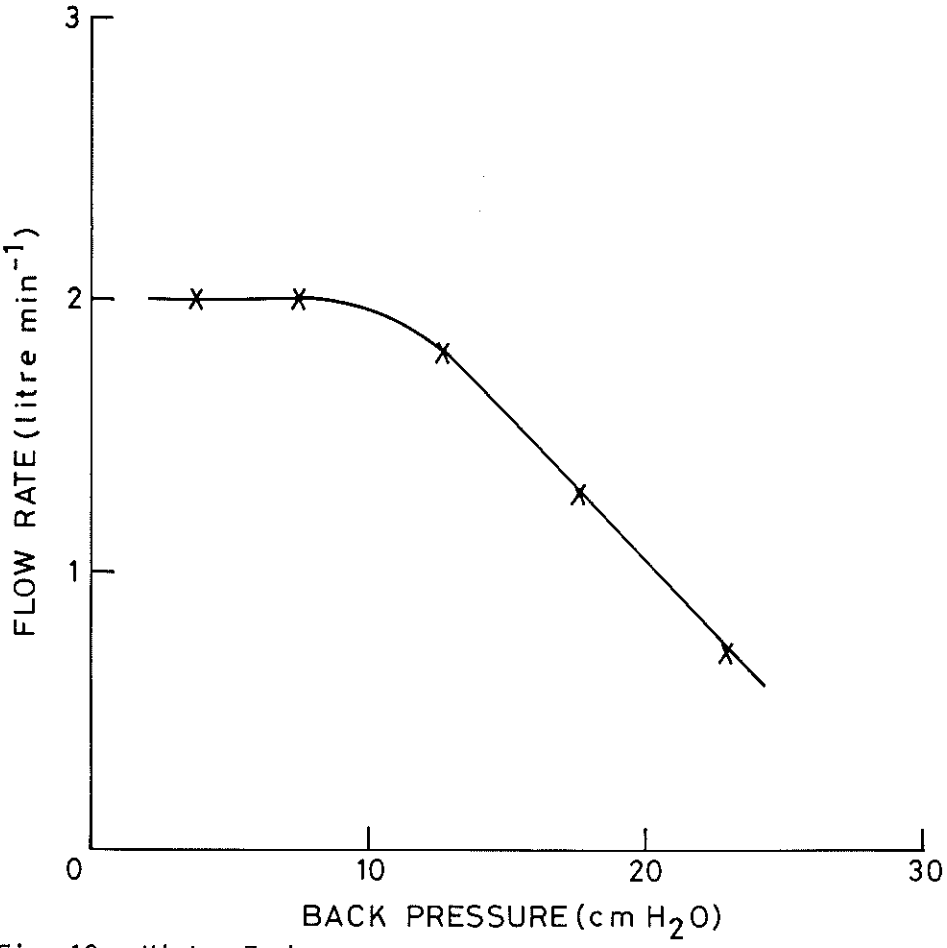

Fig. 18. Vinten Zephyr.

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