

CRANFIELD INSTITUTE OF TECHNOLOGY

COLLEGE OF AERONAUTICS

PhD THESIS

Academic Year 1992

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Atomisers for the Aerial Application of Pesticides in Tsetse (*Glossina* sp) and
Armyworm (*Spodoptera exempta*) Control

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July 1992

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Abstract

Aerial application of insecticides is likely to remain an important component in realistically-costed vector and migratory pest control operations for the foreseeable future. The objective of this work was to identify or design improved atomisers for use in two such operations, tsetse (*Glossina* sp.) and African armyworm (*Spodoptera exempta*) control, the former requiring an insecticide aerosol with a VMD of 20 to 30 μ m at rates upto 0.5 litres/minute and the latter a fine spray with a VMD of 80 to 120 μ m at rates around 16 litres/minute. In both cases rotary atomisation was confirmed as the most appropriate technique.

Assessments were made of seven commercially available atomisers and two existing prototypes, on the basis of existing reports and new data generated under simulated flight conditions in a wind tunnel. Droplet sizing was carried out using an optical array probe set to give a resolution of 5 μ m over a range of 3.6 – 312.5 μ m. None of the atomisers tested met the specification for tsetse-spraying, the limiting factors being rotation speed and inability to distribute low volumes of liquid across their full atomising surface. The Micronair AU4000 and AU5000 and the Micron X-1 were found to be suitable for armyworm control, the Micron X-1 having the additional ability to produce spray with VMDs down to 40 μ m.

A review of rotary atomiser literature provided design guidelines for the design of an atomiser capable of meeting tsetse specifications. The principle effect of liquid flow within the atomiser was found to be on the uniformity of fluid distribution. Premature ligament formation and formation of cross-flow vortices were identified as factors which could adversely influence fluid distribution under some conditions. Ligament separation from disks can be aided by slender teeth, providing that these have a spacing similar to the natural spacing of ligaments predicted by Taylor instability theory. The effect of rotation speed and atomiser diameter on droplet diameter is determined by the degree of stretching of the ligament due to its acceleration relative to the atomiser, implying that a finer spray would be achieved using a smaller rotating diameter disc than a larger diameter disc with the same peripheral speed.

A series of experimental studies was carried out using high speed photography in conjunction with the droplet sizing probe. Disturbances having the form predicted for cross-flow vortices were observed in liquid on a plain spinning disc. A single-ligament generator was constructed. With increasing rotation speed this revealed a series of increasingly unstable ligament disintegration modes in which interaction with the surrounding air became a controlling factor. Complete shattering of the ligament occurred at a Weber number of between 4 and 5, similar to reported values for liquid jets in a cross flow of gas. Droplet sizing indicated that the specified performance for tsetse operations could be obtained from 50mm diameter atomisers with a total of around 30000 issuing points at a rotation speed of 26000 RPM. This suggested cylinder rather than disc-based atomisers.

A slit was found to be impractical as a means of distributing liquid uniformly at high rotation speeds but distribution was successfully achieved using a porous flow resistor. Prototype wind- and electrically-driven atomisers were constructed using

rotating porous cylinders fed internally by spray bars designed with the help of finite element methods. Ligament formation was found to occur from a film of liquid on the outer surface of the cylinder, the variation in spacing with feedrate and rotation speed suggesting Taylor instability to be the controlling factor. The prototype atomisers achieved a performance suitable for tsetse control operations. This was not enhanced by the provision of discrete issuing points

Acknowledgements

At the risk of sounding like something out of Hollywood I would like to thank the many people who helped to make this work possible, and without whose technical expertise, craftsmanship or moral support I would long ago have packed up and gone home.

In particular I am indebted to the following:

My supervisor, Steve Parkin, for his guidance, for "giving me my head", and for his reassuring knack of putting things in perspective whenever I felt panic setting in.

Professor John Spillman, originally my co-supervisor, for his enthusiastic interest in the project long after his official involvement ceased, and for staying on the right side (just) of the thin line between mentor and tormentor when it came to the Hard Sums.

The incomparable John Wyatt. Optical, mechanical or electronic, he could always make things work and always found the time to do so.

Derek Giles, for teaching me how things are made and for turning my naively optimistic drawings into finely crafted reality. Also Paul, Malcolm, Barry, Wayne and Trevor, for their help and their good-humoured tolerance.

The gentlemen of the Natural Resources Institute – Cliff Lee, Reg Allsopp, Don Johnstone, Jerry Cooper, Hans Dobson, Francesca Casci and Rob Fenn, for advice, invaluable discussions and words of encouragement. Also for some jolly evenings in Harare and for showing me how to hunt scorpions.

The staff of ICAP, particularly Ian Outram for many hours of entertainment, and my friend and colleague Neil Morgan, who taught me humility on the electronic golf course.

My current employers, for their support whilst writing this thesis, and especially Margaret Minski for preferring the carrot to the stick.

The other people, too numerous to mention, whose brains I have picked over the years.

My venerable parents. Bemused they may have been by it all but not once did they tell me it was "time I got myself a proper job".

Above all I am grateful to Joanne for her love and support over the last few years.

Notation

A_0	discharge orifice area, m^2
b	height of vane in vaned rotary atomiser (m)
C_D	discharge coefficient
d	droplet diameter, μm
d_s	mean droplet diameter based on surface area, μm
D	rotary atomiser disc diameter, m
D_0	orifice diameter, m
D_h	hydraulic mean diameter of air exit duct, m
D_p	diameter of prefilmer in airblast atomiser, m
D_{vn}	droplet diameter below which a fraction n of the total spray volume is contained, μm
E	Young's modulus, Nm^{-2}
f	empirical friction factor
f'	drag coefficient
F	measured mass, kg
g	acceleration due to gravity, ms^{-2}
I	current, amps
l	characteristic length (eg ligament or droplet diameter) for Reynolds and Weber number calculations, m
L	length, m
m	mass flow, kgs^{-1}
MPH	miles per hour
N	rotation speed, revolutions per minute
P	pressure, Pa (values in pounds per square inch (PSI) also given)
Q	volume flow rate, $m^{-3}s^{-1}$ or, where conventional, litres minute ⁻¹

r	radial position from centre of rotary atomiser, m
r_0	radial position at which liquid is fed to a rotary atomiser
R	radius of liquid jet or ligament, m
Re	Reynolds number, where $Re = \frac{\rho U l}{\mu}$
RPM	revolutions per minute
SMD	Sauter Mean Diameter, the ratio of the total volume of the spray to its total surface area, μm
t	time, s
T	torque, Nm^{-1}
U	liquid velocity, ms^{-1}
V	potential difference, volts
VMD	Volume Median Diameter, the droplet diameter below which 50% of the spray volume is contained, μm
W	power, watts
We	Weber number, where $We = \frac{\rho U^2 l}{2 \sigma}$
z	thickness of liquid film on surface of rotary atomiser
δ	liquid film thickness at point of separation from atomiser, m
θ	angle, radians
θ_c	semicone angle of spray, degrees
λ	wavelength, m
μ	dynamic viscosity, kgm^{-1}s
ν	kinematic viscosity, m^2s^{-1}
σ	surface tension, Nm^{-1}
ρ	density, kgm^{-3}
ω	angular velocity, radians sec^{-1}

subscripts:

A	air
L	liquid
r	radial

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1) Introduction

1.1 The Aerosol Technology Unit

In 1987 the Natural Resources Institute (NRI, formally the Overseas Development Natural Resources Institute) established a programme of research to investigate means by which the application of pesticide aerosols could be improved in certain vector and pest control projects. The resulting Aerosol Technology Unit links groups at Cranfield Institute of Technology, Imperial College's International Pesticide Application and Research Centre at Silwood Park, Ascot and the NRI's Department of Pesticide Application and Management. The specific areas of interest are control of the Tsetse fly (*Glossina* sp.) and the African armyworm (*Spodoptera exempta*) but the results should be applicable to many other situations with similar requirements, including mosquito and locust control operations and forest pest control.

This part of the Unit's work is concerned primarily with the development of an aircraft-mounted ultra-low volume (ULV) aerosol generator for use in tsetse control. In addition it is intended to provide information which will be applicable to the development and use of related equipment for Armyworm control.

1.2 The Need for Tsetse and Armyworm control

Tsetse flies (*Glossina* sp.) are a major public health threat and a significant economic pest over much of Africa, infesting an area from the south of the Sahara and Somali deserts to the north of the deserts of south-west Africa, the Kalahari and the north of Zimbabwe (Laird 1977). They are vectors of the organisms which cause Trypanosomiasis, a disease which is manifested as sleeping sickness in humans and Nagana in cattle. Human population pressure means that it is no longer possible simply to avoid tsetse-infested areas, and even in regions where the human health risk is minimal the effects of Nagana can be a major constraint to rural development. Vaccination is effective but expensive, dependent on infrastructure and, unless all possible reservoirs of disease are eliminated, an unending task. Considerable effort has therefore been directed towards the eradication of the tsetse fly and a variety of control measures have been developed, principally involving their destruction using chemical insecticides. Though non-chemical methods are widely advocated, and have, in some cases,

been extensively researched, they do not yet offer a viable alternative to chemical control (Allsopp 1984).

The African Armyworm (*Spodoptera exempta*) is a major economic pest which occurs throughout Africa south of the Sahara, and is also found in Asia, Australia and the Philippines. In its larval form it feeds on the leaves of staple crops and grasses, resulting in direct crop losses as well as indirect losses due to reduction in cattle forage. Severe infestations are associated with low rainfall, a combination which can result in famine conditions. To date the only effective way to control an armyworm outbreak is by the use of chemical insecticides.

In order to define appropriate performance specifications for atomisers to be used in tsetse and armyworm control it was first necessary to review the role of aerial spraying in each of these operations.

1.3 Application of Insecticides in Tsetse Control

It is generally recognised that chemical tsetse control is best achieved by large-scale operations in which an area is cleared of flies and then protected from reinvasion by artificial or natural boundaries. Four techniques are used to apply insecticide (Allsopp and Barrett 1988):

i) Ground spraying

A residual deposit of insecticide is applied to the resting sites of the flies (tree trunks and lower branches) using knapsack or vehicle-mounted sprayers. Chemical is applied in solution, sometimes to the point of run-off. The technique is very labour-intensive and requires a high degree of logistical planning so in practice it can only be used to treat relatively small areas. It has depended on the extensive use of DDT and dieldrin and so has caused much environmental concern. Alternative chemicals have been tested but are invariably more expensive and have not always proved successful (Allsopp & Barrett 1988), though semi-persistent synthetic pyrethroids have been used successfully in Somalia (Wooff 1989). The principle use of ground spraying now is to lay down barriers to prevent reinvasion of areas cleared of flies by other means.

ii) Impregnated traps or targets

Baited traps have been used for many years to sample the fly population of an area. With the development of chemical attractants they have also acquired the potential to eradicate flies in certain circumstances (reviewed in Allsopp 1984). As concern has grown over the effects of chemicals released into the environment the idea of confining them to man-made objects rather than dispersing them uniformly over an area has become increasingly attractive. Their popularity may also be due in part to their being perceived as "appropriate technology" for use in developing countries. A typical target consists simply of a pivoted frame containing a 1 metre black or blue cloth square (visually attractive to the flies) bordered by insecticide-impregnated gauze. Small vials of acetone and octanol together with various phenols act as a potent chemical attractant. Though the technology may be relatively simple, however, the institutional and infrastructural demands arising from the use of the technique may be prohibitively complex in all but linear, riverine woodland. The large-scale use of targets in rangeland situations would create tremendous logistical difficulties, largely arising from the need to provide regular, year-round access for their installation and servicing. In difficult terrain this could greatly offset the low cost of the technique compared with methods based on more complex technology. In more accessible areas theft of targets has been a significant problem despite widespread publicity of the likely benefits to be gained from their use (one operation in Somalia lost 1116 out of 1240 deployed in a target barrier). In general targets are likely to be of greatest value as a means of preventing the reinvasion of areas cleared of flies by other means. They also have a potential role in village-based self-help projects. The logistical problems associated with impregnated targets would be avoided to some extent where settlement gradually encroached on infested land, taking with it a barrier of targets.

A variation of this technique involves the direct treatment of cattle with residual insecticide, on the basis that the cattle themselves are probably the most effective fly bait. Treatment can be carried out during routine dipping against ticks by replacing the conventional acaricide by a persistent pyrethroid. Eradication could, however, be achieved only where the cattle density is sufficiently high and alternative hosts (ie. game animals) are not present.

iii) Residual aerial application

The earliest attempts to clear tsetse-infested areas using aircraft involved single applications of spray containing doses of insecticide sufficiently high to leave a persistent residue (levels of 200 to 1500 grams/hectare of endosulfan and 12.5 grams/hectare of deltamethrin are quoted in the literature). To have any chance of achieving eradication this residue would have to remain active for a full pupal period. There is doubt as to the likelihood of this occurring. Because the doses of insecticide applied are much higher than those applied in sequential spraying, residual methods are no longer considered environmentally acceptable for general use and they are rarely used except for occasional riverine treatments and placement of barriers to protect cleared areas against reinvasion.

Since the targets for residual spraying are the foliage and branches on which the flies rest, rather than the flies themselves, the droplet sizes used in these techniques are relatively large, with Volume Median Diameters of 150 to 180 micrometres typically being produced using non-volatile insecticide formulations (for example Wooff, 1989). The first two metres above ground level are generally considered to be the resting sites of Tsetse, and riverine species are thought to rest near ground level, often on the underside of leaves and twigs (reviewed in Allsopp 1984). There is doubt as to whether a useful proportion of emitted droplets reaches below 1.5 metres in wooded areas and consequently much of the target site may remain untreated.

iv) Non-residual aerial applications

Areas of several thousands of square kilometres have been successfully cleared of flies by the application of low doses* of non-persistent insecticides in aerosol form. The aerosol droplets are sufficiently small for their movement to be controlled predominantly by air turbulence rather than by sedimentation. Lane separations of 200 to 1000 metres are routinely used during application: given a suitable light breeze across the line of flight droplets drift through the treatment area. Because of their low inertia the droplets tend to be carried around larger obstacles such as leaves and branches, impinging on smaller objects such as the flies

* for example Endosulfan doses of 6-28 grams/hectare and Deltamethrin doses of 0.25 grams/hectare are quoted for various operations

themselves. Wind-tunnel work using tsetse flies fastened to artificial twigs (Hadaaway and Barlow 1965) has shown that droplets in the range 20-30 micrometres diameter are most likely to reach their target. Subsequent field work using fluorescent tracer techniques (Johnstone *et al* 1988) has shown actual deposition on flies to correspond to predicted values and also indicated that droplets at the smaller end of the size range were more likely to be collected. There is no definite evidence that a unique droplet size within this accepted range would be the most appropriate for the whole of the treatment area and there is a feeling amongst workers in the field that a range of diameters is desirable in order to maximise the chance of spray reaching all parts of the area undergoing treatment. However consideration of spray movement and the work on droplet collection already mentioned suggests that the optimum range is likely to be narrow.

A single insecticide application will kill virtually all adult flies present with a minimal impact on non-target organisms (Douthwaite *et al* 1981). Spraying must be repeated within the First Larval Period (FLP) - the time taken for a female fly emerging from a pupa immediately after the previous application to mate, incubate and deposit its first larva. This time is calculated according to a formula (Glasgow 1963) based on average daily temperature, and checked against biological results based on the dissection of sampled females. Spraying is repeated until all pupae have emerged. The time taken for this, the pupal period, is also calculated on the basis of temperature (Glasgow 1963) backed up by observations of pupa samples. Four or five cycles of spraying are usually required.

Timing is clearly of great importance in this type of operation. Spraying must be carried out as quickly as possible once the appropriate stage of development is reached. One constraint on timing is the dependence of the technique on appropriate meteorological conditions. Winds must be present to disperse the spray but they must not be so strong as to carry a large proportion of spray outside the treatment area or enhance losses by deposition on larger, non-target surfaces. Thermally- induced vertical air movements would also contribute to losses so spraying should be carried out under strong inversion conditions which prevail between dusk and dawn. The window of appropriate conditions can be small so it is essential that as much of this time as possible is given over to emitting spray rather than reloading, ferrying and turning.

Applications are mostly carried out by fixed-wing aircraft, helicopters sometimes being used in rugged terrain where low level fixed-wing flight is not feasible. Exhaust nozzle sprayers

were used in early operations (eg Lee and Miller 1966) but these failed to produce sufficiently small droplets and resulted in significant thermal decomposition of the insecticide. They were replaced initially by conventional boom-and-nozzle systems and then by rotary atomisers, the current choice being one or two Micronair* AU4000 units. Neither system produces the required 20-30 micrometre diameter droplets directly. Formulations were therefore developed which contain 70-80% volatile solvent; this evaporates rapidly on spray emission leaving droplets of the desired size. Application rates of such formulations are typically in the order of 0.06 to 0.085 litres per hectare. Some performance Figures of aircraft currently used in this type of work are given in Appendix 1.

All of the techniques described have some part to play in tsetse control. However the most appropriate technique for rapid fly clearance from large, relatively inaccessible areas of land appears to be non-residual aerial spraying of aerosol-sized droplets, with the use of barriers of targets or ground-applied residual spray to prevent reinvasion. Where access is limited but terrain is fairly open a residual barrier could be deposited by aircraft.

1.4 Application of Insecticide in African Armyworm Control

Spodoptera exempta outbreaks tend to follow seasonal migration patterns, larvae appearing suddenly in widely separated areas along the line of migration. The gaps between infestations are thought to be traversed by the adult moth and have been linked with the movements of macro-scale climatic phenomena; for example in East Africa outbreaks are associated with the passage of the Inter-Tropical Convergence Zone. Having exhausted their local food supply the later larval stages will march *en masse* to new areas, this behaviour giving rise to the name armyworm. Occasional small pockets of larvae are thought to be the result of localised weather phenomena.

The degree of damage caused by armyworm in any one area varies considerably from year to year but a severe outbreak can cover many square kilometres. In some areas forecasting systems based on meteorological information and light-trap data can predict outbreaks in defined areas a week in advance. This short period of advance warning coupled with the

* Micronair Ltd. Bembridge Fort, Sandown, Isle of Wight

moth's short larval period (for half of which larvae are inconspicuous) mean that response to a newly discovered armyworm infestation must be rapid.

Direct and indirect approaches to crop protection can be adopted. The former involves treatment of the infested crop to minimise immediate losses while the latter aims to destroy the armyworms before they reach rich agricultural land, a broader objective being to reduce their overall population and so reduce the degree of infestation further along the migratory path. The pattern of land-use in sensitive areas favours this approach: good agricultural land tends to be separated by large tracts of drier grassland or open bush which can be used by armyworm as "staging posts" *en route* to lush areas (Yeates 1973). Infestations in such areas are vulnerable to large scale control operations by government or regional organisations.

Direct crop protection is undertaken at a variety of levels. At the subsistence farmer level it may involve the application of a powder formulation of, for example, 3% fenitrothion, to individual plants through the mesh of a small sack or from a perforated tin. Where resources will allow it water-based formulations may be sprayed on the crop using knapsack sprayers. Greater areas of crop may be treated by drift-spraying using hand-held ULV devices. Ideally spray droplets should be in the range 70 to 100 micrometres diameter, allowing a reasonable amount of drift and ensuring impaction on vegetation rather than sedimentation onto the ground.

Large farms and indirect protection operations make use of drift-spraying systems mounted on four-wheel drive vehicles. Exhaust Nozzle Sprayers (ENS) use the heat and pressure from vehicle exhaust to atomise and disperse spray, giving a VMD of around 70 micrometres and a swath of 40-100 metres. They are robust, reasonably priced and do not require additional power units, though they allegedly accelerate engine wear. Alternatively, vehicles may be fitted with powered rotary atomisers. These put no extra strain on the engine, can allow tighter control over the size of droplets, and may be adjusted to perform other spraying tasks although they require additional power and are less robust and more expensive than ENSs.

Aircraft are used to treat very large infestations and offer a rapid means of responding to forecasts of an imminent invasion. Once again drift-spraying is used though a slightly larger droplet size range, 80-120 micrometres diameter, is considered necessary to compensate for

the greater height of spray release. Rotary atomisers are used, current systems consisting of either two wing-mounted spray tanks, each fitted with a Micronair AU4000 atomiser, or Micronair AU5000 atomisers mounted on the boom of a conventional agricultural aircraft.

A variety of insecticides are used in Armyworm control. Use of DDT has been widespread but for environmental reasons it is no longer favoured. Low volatility ULV formulations of organophosphates, carbamates and synthetic pyrethroids are now recommended (for example technical Malathion or Fenitrothion, 0.5% Deltamethrin ULV or 0.25% Cypermethrin ULV) and other compounds are currently under investigation. Recommended application rates are typically 1-2 litres per hectare (Page and Dewhurst 1987).

1.5 Atomiser Specifications for Aerial Application

i) Tsetse Spraying

The current aerial application system for sequential spraying is very effective but there would be major advantages in being able to produce the necessary small droplets directly rather than by evaporation:

- a) The cost of some or all of the high volatility component of the insecticide formulation would be saved and environmental contamination minimised.
- b) The useful payload of the aircraft could be increased, allowing longer sorties and reducing non-productive ferrying time. Thus maximum use could be made of appropriate spraying conditions and flying costs could be reduced.
- c) Reduced payloads could be used, giving the aircraft a greater margin of safety. This would be of particular value for helicopter operations at high altitude where aircraft are currently running at the limits of their performance. Smaller aircraft could be used in some circumstances, reducing turning time and so further increasing available spraying time.

The required total output rate depends on the ground speed of the aircraft and the swath width it can produce. With existing volatile formulations application rates of around 0.060 - 0.085

found to give effective coverage of the area undergoing treatment. Using a Cessna 401 to apply 0.060 litres/hectare at a speed during application of 300 kilometres/hour (185mph) and a swath width of 250 metres this means a total output of 7.5 litres/minute. A Bell 206 Jetranger helicopter has a speed during application of 150 kilometres/hour (90mph) and so would require an output of 3.75 l/min to give the same coverage. Reported outputs used in past operations fall in or near this range, variations being due to different dosage requirements, formulations and aircraft speeds.

Though a VMD in the range 20 - 30 micrometres at the point of emission would be ideal, any decrease from the 60 - 80 micrometres VMD currently achieved would represent a reduction in the proportion of volatile component required in a formulation. Graph 1.1 shows the rate of chemical application theoretically required at various emitted drop sizes to give the same droplet number as 7 litres/minute atomised into 80 μ m diameter droplets: it represents an idealised situation but even with multicomponent spray formulations there is the potential to reduce output considerably.

An ideal atomiser for sequential spraying would thus produce 20-30 micrometre diameter droplets at a flowrate that allowed the total required insecticide output (in the order of 0.5 to 1.0 litres/minute) to be achieved using a practical number of atomisers per aircraft. This number would depend on the physical characteristics of the atomiser, its weight, size, reliability, power requirement, cost and influence on the aircraft's performance all having some bearing.

Table 1.1 shows the operational benefits which would be gained by having a spraying system capable of giving a seven-fold reduction in output. The greatest beneficiary would be the Cessna 401, which could more than double its sortie time while decreasing its payload by 74%. The Jetranger and Turbothrush already work at their maximum sortie length so they would benefit directly by an 86% decrease in payload per sortie. This would be of particular value to helicopters which, when taking off fully loaded at the altitudes and temperatures associated with tsetse work, are operating close to their safe limits of performance.

ii) Armyworm Spraying

The target droplet size range specified by NRI for this work was 80-120 micrometres diameter. A suitable atomiser would produce as high a proportion as possible of its output volume in the target range and, as with the tsetse atomiser, it should do so at a flowrate which would allow the required total output to be achieved with a practical number of units. For a standard agricultural aircraft applying insecticide at the rates quoted above an output of around 16 litres/minute would be required. Since the need for aerial control of Armyworm is sporadic an added benefit would be the flexibility to produce sprays suitable for other control operations (for example air-to-air locust spraying and mosquito control).

1.6 Scope of this Work

Having defined the spraying requirements of tsetse and armyworm control operations, methods of atomisation were considered and the most appropriate was selected for each task. Once this had been decided the development of spraying systems was pursued in two ways:

- i) existing equipment was reviewed, the most promising being tested under simulated operating conditions using candidate insecticide formulations. Performance limits were identified and possible improvements suggested.
- ii) The basic process of atomisation was investigated theoretically and practically with the aim of designing suitable atomisers from first principles. The influence of a range of parameters was assessed in order to identify the conditions necessary to achieve the specified droplet spectra.

On the basis of information gained from these two approaches it was possible to draw conclusions as to the suitability of existing equipment for the two types of operation and, where necessary, to design new atomisers which came closer to the ideal specification. The selection and design process is summarised in Table 1.2.

2) Measuring and Describing the Performance of Atomisers

Assessment of the atomising capabilities of existing equipment and prototype atomisers required a spray measurement system which would provide reasonable resolution at the small droplet diameters required for tsetse control while being sufficiently wide-ranging to size the larger droplets produced by atomisers for armyworm control. Measurement of the full droplet spectrum could provide valuable information concerning the process of disintegration but comparison between atomisers and operating conditions was made easier by the extraction of parameters which summarised atomisation characteristics.

2.1 Droplet Sizing

Two types of optical droplet sizing probe were available for use during this project:

i) Optical Array Cloud Spectrometer Probe OAP 260-X¹

In this device a helium-neon laser provides an intense beam of coherent, monochromatic light which is collimated, reflected across a sampling area and then focused onto a linear array of 64 photodiodes (Figure 2.1). A droplet passing through the beam casts a shadow on the array, resulting in a signal which is proportional to the number of photodiodes which are occluded. The array output is scanned at a rate of 5 megahertz so that a series of "slices" are recorded as a shadow passes, the largest of these slices being representative of the droplet's diameter. Droplets are classified into 62 size classes, the two outermost photodiodes detecting and rejecting signals from shadows which do not wholly fall within the width of the photodiode array. The size-range and resolution of measurements are defined by the degree of magnification of the shadow projected onto the photodiode array. This can be adjusted using a zoom lens in the focusing optics. The probe which was available for this work had been set so that one photodiode represented 15 μ m, allowing droplets from 15 to 930 μ m in diameter to be measured.

¹ Particle Measuring Systems, Boulder, Colorado, USA

The sample cross-section of the OAP-260X is defined by depth of field and the width of the array. The effective array width increases with decreasing droplet diameter since larger droplets cannot cross the array as near to its ends as smaller ones without obscuring one of the two outermost photodiodes. Depth of field is also dependent on particle size because the shadow cast by a droplet diverges due to diffraction. The shadows of droplets passing through the laser beam in the object plane of the magnifying optics are refocused sharply onto the photodiode array but those of other droplets are increasingly out of focus the further the droplets are from the object plane when they cross the beam. Because of this their shadow images are artificially broadened and reduced in intensity towards their edges. To maintain accurate measurement the detectors associated with each photodiode are set to require a minimum level of shadowing before they register the photodiode as occluded. This threshold is selected such that, within limits, the measured part of the shadow reflects the true diameter of the droplet. A second intensity threshold is also set which must be reached by at least one photodiode in the array before accurate measurement is possible. Since the angle of diffraction increases with decreasing droplet diameter the shadow from a small droplet will reach the reject threshold at a shorter distance from the object plane than that of a larger droplet, reducing the effective depth of field. Further details of the optics and electronics in the probe are given by Knollenberg (1970, 1976). Because of this dependency of sample cross-section on droplet size the number of particles counted in each size class must subsequently be normalised to a standard sample cross-section.

Raw particle sizing data is transferred in real time to a dedicated data acquisition system, model PDS-300¹ which displays the accumulating droplet spectrum. This allows an initial assessment of droplet spectrum quality to be made. Once a sufficiently large number of droplets has been counted sampling is terminated and the data transferred to a microcomputer for storage and subsequent analysis.

ii) Forward Scattering Spectrometer Probe PMS-FSSP 1000¹

In this type of probe a collimated beam of laser light shines across an aspirated sample region onto an opaque spot. When a particle passes through the beam some light is scattered by diffraction. This forward-scattered light is focused onto a single photodiode, allowing the quantity of scattered light to be determined (Figure 2.2).

Though the angle of diffraction decreases with increasing droplet diameter the total amount of scattered light increases and so the total light energy falling on the photodiode increases with droplet diameter. The amount of scattering is also dependent on the refractive index of the liquid in the droplet and so this must be considered during calibration. Size classes are defined by a series of energy thresholds. The FSSP has 15 size classes, the available probe being switchable to cover four size ranges from 0.5–8 μm to 2–47 μm . Mie diffraction theory predicts periodic troughs in the scattered light energy–droplet diameter curve (Yates and Sidahmed, pers. comm.). With the probe as supplied there is a possibility of these troughs crossing one of the energy level thresholds, artificially lowering the measured diameters of some particles. Yates and Sidahmed (pers. comm.) avoided this problem by adjusting the energy thresholds so that troughs remained within the set energy ranges. Sample volume is determined by depth of field and the effective width of the usable part of the laser beam's cross section. As with the optical array probe sample volume is therefore dependent on droplet diameter. A beam–splitter in front of the energy–determining photodiode directs a proportion of the scattered light onto a second opaque spot. If it is out of focus or off–centre some of this light misses the opaque spot and falls onto a second photodiode. A threshold level can be set above which the measurement is rejected. The transit time of each particle crossing the beam is added to a running mean, and the measurement of any particle crossing the beam in a shorter time than this is rejected since it probably did not pass through the centre of the beam. Droplet data is transferred in real time to a dedicated data acquisition system (PDS–300¹) and down–loaded to a microcomputer.

Several research groups have attempted to merge the fine droplet detail measured using an FSSP–100 with coarser but broader–ranging measurements made using an OAP–260X (Tate 1982, vanVliet *et al* 1987, Yates and Sidahmed (pers. comm.)). The results are unconvincing, with plots of cumulative spectrum showing pronounced discontinuities between the overlapping data sets. Using both types of probe in this way would double the number of measurements required per atomiser setting and time would need to be spent customising the threshold energy levels of the FSSP and calibrating for each formulation tested. The number of operating conditions that could be investigated in the limited time available would therefore be reduced considerably. An alternative approach was therefore used. By adjusting the zoom optics of the OAP–260X to give their maximum

magnification resolution was increased to $5\mu\text{m}$ per photodiode, giving a range of $3.6\text{--}312.5\mu\text{m}$ diameter. This was considered suitable for sizing sprays appropriate for both tsetse and armyworm control without the disadvantages associated with the use of a two-probe system.

In the existing optical array probe system, data was downloaded from the data acquisition unit to a Hewlett-Packard HP85 microcomputer and stored on magnetic tape. This system was effective but very slow and so a Quickbasic programme² was obtained which allowed the transfer of raw particle sizing data from the data acquisition system to an IBM-compatible portable computer. Each spectrum was stored on disc as a single file which could be labelled with details of the atomiser type, operating conditions and spray formulation. A series of linked, menu-driven spreadsheets was constructed which imported the raw data, normalised the numbers of droplets in each size-class to a constant sampling cross-section, plotted the resulting droplet spectra and extracted a series of spectrum parameters. Sample cross-section corrections were based on data provided by the probe's manufacturer. The large correction factors necessary for the two smallest size classes meant that the corrected counts in these classes were statistically poor. However the numbers of droplets involved was low, and in practice the volume of liquid involved was minimal even for atomisers producing sprays suitable for tsetse control.

2.2 Parameters Describing Atomiser Performance

The most direct way of displaying spray-sizing data is in the form of a histogram showing the number of droplets falling in each size class. Such a droplet number spectrum is of most value in investigations of atomisation mechanism. A similar spectrum can be produced for the total volume of the droplets in each size class. Because of the large number of size classes defined by the OAP-260X the errors introduced by calculating the volumes of all droplets in a size class on the basis of the mid-point diameter of that class are small. These volume spectra are also of diagnostic value, and can highlight discontinuities in the particle size distribution which are not immediately apparent from number spectra.

² written in 1987 by John Wyatt, College of Aeronautics, Cranfield Institute of Technology

Droplet spectra cannot easily be compared quantitatively. Comparisons of atomising performance are made more easily using a characteristic spray diameter and some indication of the distribution of droplet sizes around this value. A commonly used characteristic diameter is the Sauter Mean Diameter (SMD), defined as the ratio of the total volume of the spray to its total surface area. This is favoured in situations such as spray combustion where available surface area is an important factor. For agrochemical spraying atomiser performance is usually defined in terms of the proportion of spray liquid volume broken into droplets of a particular diameter, and so the characteristic diameter most often quoted is the Volume Median Diameter (VMD), defined as the droplet diameter below which 50% of the spray volume is contained. For this project VMD also had the advantage of low sensitivity to the statistically poor measurements in the two lowest size classes. VMD was therefore chosen as the characteristic diameter. It was derived from the spectrum data by interpolation of the size class in which it fell.

The ratio of Number Median Diameter to Volume Median Diameter has often been used as a width parameter for agrochemical sprays. A value of 1 indicates a monodisperse spray, higher values indicating increasing spectrum width. However, this parameter has no immediately obvious physical meaning, and values indicating acceptable spectrum width are generally defined empirically. Relative span is defined as

$$\frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (2.1)$$

where $D_{v n}$ represents the droplet diameter below which a fraction n of the total spray volume is contained (hence $D_{v0.5}$ is the VMD). Its physical meaning is more readily apparent and values can be calculated for a chosen maximum acceptable spectrum width. $D_{v0.9}$ is generally much larger than $D_{v0.1}$ so errors in the two lowest size classes have little influence. $D_{v0.9}$ is influenced by low numbers of large diameter droplets. By removing isolated droplets – defined as single droplets in a size class with empty size classes on either side – from spectra consistent values of relative span could be obtained for a given condition and systematic variations with operating conditions became more apparent. Removal of these droplets from the spectrum had no significant influence on VMD. Specific target droplet size ranges had been defined for this project. The proportions of spray volume falling in the specified ranges (rounded to the nearest whole size class) were therefore also given as performance indicators.

The performance of an atomiser over a range of operating conditions can be summarised by a multiple linear regression equation containing the logarithmic transforms of data for the parameters of interest. The accuracy with which such an equation fits the observed data is indicated by the covariance, R^2 . Such equations allow interpolation of existing data in order to obtain droplet size predictions for conditions other than those for which tests have been carried out. Extrapolation of such equations should be treated with caution.

2.3 Conclusions

An optical array spectrometer probe on its highest magnification setting was found to have a range and resolution suitable for sizing the sprays produced by atomisers for use in tsetse and armyworm control. Analysis software was developed to process the measured droplet spectra and extract size and width parameters. The key parameters selected for comparison of droplet spectra were Volume Median Diameter, relative span and the fractions of spray volume falling in the specified droplet diameter ranges, while atomiser performance could be summarised by multiple regression equations

3) Selection of an Appropriate Atomiser Type

In chapter one the performance requirements of atomisers for use in tsetse and armyworm control operations were identified. Rotary atomisers have come to be regarded as the most suitable devices for insecticide application by virtue of their ability to produce narrow droplet spectra but it was possible that the unusual requirements of tsetse control might be met by some other means. This chapter reviews existing classes of atomiser with respect to their ability to meet the target specifications. The general behaviour and performance characteristics of these devices has been described at length elsewhere, notably by Lefebvre (1989).

Atomisation generally involves the dispersal of bulk fluid into thin sheets or ligaments which subsequently break up into droplets either by hydrodynamic instability or by interactions with the surrounding medium. The shear-stresses and the creation of new surface area involved mean that the process is innately power-consuming, though in practice this requirement represents only a fraction of the total power usage of an atomiser, a large part of the input being lost in a variety of secondary energy transfers as summarised by Yule (1988) (see Table 3.1). It has become conventional to classify atomisers according to the means by which energy is supplied.

3.1 Hydraulic Atomisers

In these devices pressure energy is converted into kinetic energy as liquid under pressure escapes through an orifice. The momentum gained by the fluid is sufficient to overcome the opposing viscous and surface tension forces and the liquid assumes an unstable configuration from which disintegration into droplets takes place. The form of the unstable configuration depends on the exit velocity and the properties of the liquid involved as well as the design of the atomiser itself.

a) Plain Orifice

This is the simplest type of hydraulic atomiser. At relatively low supply pressures a column of liquid escapes from the orifice and collapses into droplets due to capillary instability (this process will be discussed in Chapter 5). As supply pressure is increased the velocity of fluid in this column increases. Turbulence levels within the column become greater and interactions with the surrounding medium are increasingly

significant so that atomisation becomes a much less tightly controlled process. Above a critical supply pressure atomisation takes place immediately adjacent to the orifice.

The complex mixture of mechanisms involved in atomisation from these devices results in a spray which contains a broad distribution of droplet sizes, making this type of nozzle unsuitable for the application of a narrow spectrum of insecticide droplets. A purely analytical model capable of describing this behaviour has not yet been developed, but several empirical equations have been produced (reviewed in Lefebvre, 1989). These indicate that atomisation is enhanced by increasing flow velocity and decreasing orifice diameter, and hindered by increasing liquid viscosity. They also suggest that under extreme conditions spray with a volume median diameter suitable for tsetse control could be achieved. Though the relative span might be large the spread of droplet sizes might be small enough in absolute terms to justify their use in such operations. However it can be shown that even if such an extrapolation were valid the operating conditions required would not be practical for field use:—

Using the empirical expression derived by Merrington and Richardson (1947)

$$\text{SMD} = \frac{500 D_0^{1.2} v_L^{0.2}}{U_L} \quad (3.1)$$

the exit velocity required to produce droplets with a given SMD may be estimated by inserting values typical of real insecticide formulations together with the minimum orifice size not prone to frequent blockage. An approximate value for the target SMD can be taken as the target VMD/1.2, after Simmons, 1975.

Thus for $\text{SMD} = 2.5 \times 10^{-5} \text{ m}$

$$D_0 = 5 \times 10^{-4} \text{ m}$$

$$\rho_L = 8000 \text{ kgm}^{-3}$$

$$\mu_L = 2 \times 10^{-3} \text{ kgm}^{-1}\text{s}^{-1}$$

and hence $v_L = 2.5 \times 10^{-7} \text{ m}^2\text{s}^{-1}$

$$U_L = 105 \text{ ms}^{-1}$$

The pressure drop necessary to produce such an exit velocity from the chosen orifice depends on fluid density, pressure losses within the orifice and the velocity profile of the liquid as it passes through the orifice. The two latter are influenced considerably by

the geometry of the orifice and the chamber preceding it. Again, no general quantitative theory exists which describes this behaviour, but a relationship between pressure drop, orifice size, fluid density and flow rate can be stated in which reduction in flow due to pressure losses and velocity profile are accounted for in an empirically determined discharge coefficient,

$$\frac{m_L}{(\rho_L P_L)^{0.5}} = C_D A_o \quad (3.2)$$

and from this the pressure drop necessary for a given mean exit velocity may be calculated:—

$$\text{since} \quad m_L = \rho_L Q = C_D A_o (\rho_L P_L)^{0.5} \quad (3.3)$$

$$\text{and} \quad U_{L,\text{mean}} = \frac{Q}{C_D A_o} \quad (3.4)$$

$$\text{then} \quad P_L = \frac{(\rho_L U_{L,\text{mean}})^2}{\rho_L} \quad (3.5)$$

For the stated conditions a pressure drop of 8.8×10^6 Pa (1250 PSI) would be required across the orifice, giving a flowrate of

$$Q = U_{L,\text{mean}} C_D A_o = 1.44 \times 10^{-5} \text{ m}^3 \text{ sec}^{-1} = 0.87 \text{ l min}^{-1} \quad (3.6)$$

Though assumptions have been made in arriving at this figure, it is clear that high pressures would be necessary to produce droplets of the target size. The use of such pressures would be impractical on a spraying aircraft, the necessary high-pressure pipework being a liability under field operating conditions. Thus, even if a large proportion of the spray produced was below $30 \mu\text{m}$ in diameter, a plain orifice atomiser would not be acceptable as a means of spray production.

b) Swirl Nozzles

In swirl nozzles liquid is forced into an outer chamber through tangential or helical passages. It acquires both axial and tangential components of velocity and escapes as an expanding hollow cone of liquid with walls of decreasing thickness. Under the

influence of hydrodynamic and aerodynamic forces this liquid sheet develops surface instabilities which ultimately lead to its collapse into ligaments and then droplets.

As with plain orifice nozzles the complex disintegration mechanism gives rise to a broad droplet spectrum which is unsuitable for armyworm spraying and precludes the development of a simple analytical model to describe atomisation performance. Semi-empirical expressions have been determined for a number of geometries over various ranges of operating conditions, the most general being those of Lefebvre and co-workers. Wang and Lefebvre (1987) used experimental data to determine the constants and power indices for a basic equation which they derived by considering the influence of Weber and Reynolds numbers on the principle stages of the atomisation process:—

$$\text{SMD} = 4.52 \left(\frac{\sigma \mu_L^2}{\rho_A P_L^2} \right)^{0.25} (\delta \cos \theta_c)^{0.25} + 0.39 \left(\frac{\sigma \rho_L}{\rho_A P_L} \right)^{0.25} (\delta \cos \theta_c)^{0.75} \quad (3.7)$$

This expression reveals a number of trends, for example decreasing mean drop size with increasing spray cone angle and decreasing surface tension and viscosity, but because of the difficulty in predicting spray angle and film thickness the SMD (and hence VMD) cannot be predicted accurately. Spray size data was therefore sought from nozzle manufacturers. The smallest hollow cone nozzle supplied by Lechler¹ produced a VMD of around 35µm at a pressure of 2×10^{-6} Pa (290 PSI) and a feed rate of 0.025 ml/minute. This nozzle has a 0.1 mm liquid outlet and so would be prone to blocking in field use. As with plain hydraulic nozzles a powerful pump would need to be carried and the pressurised pipe-work would be a liability.

3.2 Twin Fluid Atomisers

The hydraulic devices described previously produce a high relative velocity between the liquid and ambient air by accelerating the liquid. The same net effect can be achieved by keeping the liquid at low velocity and presenting it to a fast moving airstream. This process, known as airblast or twin-fluid atomisation, is capable of producing very small droplets, albeit with a relatively broad spectrum. Like hydraulic atomisers,

¹ Hollow cone type 212.004 , Lechler Ltd, 160 Matilda Street, Sheffield S1 4QG, UK

therefore, twin fluid atomisers are unsuitable for armyworm spraying but are worth consideration for tsetse control.

Airblast atomisation is particularly suitable for fuel injection in turbine engines and consequently it has been the subject of many investigations. These have yielded a variety of atomiser designs, but their common aim is to present as thin a film of liquid as possible to a fast-moving airstream. To this end, prefilming atomisers have been developed which make use of moving air to spread liquid over as broad an area as possible before its release. As with the devices mentioned previously, no analytical model exists but several semi-empirical expressions have been developed to relate atomisation performance to fluid and atomiser parameters. In general, these show that the mean droplet size of the spray increases with increasing liquid viscosity and surface tension and with decreasing air velocity and air to liquid mass ratio. It is recommended that the latter should exceed a value of 3 but little is to be gained by increasing its value beyond 5.

General expressions for prefilming atomisers consider droplet size to be dependent on two terms, one dominated by air density and velocity and the other by liquid viscosity. By putting these into a dimensionless form, accounting for secondary factors and determining constants experimentally El-Shanawany and Lefebvre (1980) arrived at the expression

$$\frac{SMD}{D_h} = \left(1 + \frac{m_L}{m_A}\right) \left(0.33 \left(\frac{\sigma}{\rho_A U_A^2 D_P} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} + 0.068 \left(\frac{\mu_L^2}{\sigma \rho_L D_P} \right)^{0.5} \right) \quad (3.8)$$

From equation 3.8 it can be seen that production of small droplets is favoured by high air velocities. Manufacturers were approached for details of existing atomisers' performance. Standard devices were capable of producing VMDs in the desired range but required very low feed rates and high air to liquid mass ratios. Lechler produce supersonic-pneumatic atomisers which makes use of this fact. These are capable of producing VMDs in the target range at reasonable feed rates while having no orifice smaller than 4.2mm, but are more expensive than conventional twin fluid atomisers (£400–500 each in 1992) and still require large volumes of high-speed air.

3.3 Rotary Atomisers

Fluid can be accelerated by the frictional transfer of kinetic energy from a moving surface. Liquid fed onto the centre of a rotating disc will accelerate outwards, gaining sufficient momentum to throw it clear of the disc's edge in an unstable configuration that will disintegrate into droplets. Such atomisers require only a low pressure liquid feed and need have no small orifices.

Several modes of atomisation are known to be possible with rotary atomisers, the most commonly described being direct droplet formation, ligament disintegration and sheet disintegration (Walton and Prewett 1949). At low feed rates liquid breaks away from the disc edge as discrete droplets of tightly controlled size. As the feed rate is increased liquid escapes in the form of ligaments which subsequently collapse into droplets. A well-controlled size distribution is maintained. With even higher feed rates a sheet of liquid is flung clear of the disc and disintegrates in a manner similar to that of the sheets formed by swirl nozzles, giving a droplet spectrum which is unacceptably broad for insecticide application.

Though direct droplet formation gives the narrowest size distribution it does so at the cost of impractically low feed rates. Ligament mode gives a well controlled size distribution at practical feedrates and it is in this mode that rotary atomisers intended for pesticide application are operated. Droplet size decreases with decreasing feed rate and increasing rotation speed. VMDs suitable for tsetse spraying can be produced at low feed rates and high rotation speeds.

3.4 Other Classes of Energy Input

Exhaust nozzles, as described in chapter 1.3 and 1.4, make use of the heat and pressure of vehicle exhaust to atomise and disperse spray. They are incapable of producing droplets in the tsetse spraying size range, produce a broad distribution of droplet sizes and can cause thermal decomposition of active ingredients.

Electrostatic atomisers make use of the instability induced in a column of liquid by a strong electric field. This type of disintegration can produce a narrow spectrum of droplets with a VMD suitable for tsetse spraying but requires a very low feed rate per liquid emitting point. The resulting droplets carry a charge and so would tend to be

deposited on vegetation rather than drift through the bush or over rangelands. Charge neutralisation would be technically difficult to achieve under field conditions.

Ultrasonic atomisers make use of high frequency mechanical vibrations from a piezoceramic oscillator to excite a thin film of liquid, droplets breaking away from the crests of the resulting waves. Droplets suitable for tsetse spraying can be produced using an excitation frequency of 100KHz at a feed rate of 0.017 litres/minute, with a power consumption of 30W. Thirty such units would therefore be needed to produce the specified output, with a prohibitive total power requirement.

3.5 Conclusions

Hydraulic nozzles produce too broad a droplet spectrum to be efficient for armyworm spraying. Extrapolation of semi-empirical equations describing their behaviour suggests that to produce sprays with VMDs small enough for tsetse control would require very small orifices and impractically high liquid pressures, with no guarantee that the resulting range of droplet sizes would be acceptably narrow. Twin-fluid atomisers also produce too broad a range of droplet sizes for efficient armyworm control and require the added complexity of a high volume, pressurised air supply. Supersonic pneumatic atomisers can achieve VMDs in the target range for tsetse control at reasonable feed rates but like other twin-fluid atomisers the range of droplet sizes produced is broad. Of the other types of energy input exhaust nozzles, electrostatic atomisers and ultrasonic atomisers were all ruled out, confirming rotary atomisation as the most appropriate means of producing sprays for armyworm control and the most likely technique for development into an atomiser for tsetse control.

4) Tests on Existing Rotary Atomisers

Existing aircraft-mounted rotary atomisers were considered primarily with respect to their ability to produce droplets in the specified target ranges at practical flow rates. Relevant data already existed for some of the devices and where this was available it allowed some conclusions to be drawn as to an atomiser's suitability for tsetse and armyworm work. However the data did not generally cover the very low flow rates and high rotation speeds under which small droplets are most likely to be generated. Since the various studies had been carried out using several different arrangements of particle measuring equipment their comparability was also open to question. The most promising devices were therefore tested over a range of low flow rates to produce comparable sets of droplet spectrum data. Manufacturers of the equipment tested and the fluids used are given in Appendix 2.

4.1 Formulations

At the request of NRI, tests were carried out using "blank" formulations of three insecticides, Thiodan, Glossinex and Karate, which are either currently in use or being considered for use in tsetse control. These blanks contained no active ingredient but were engineered to have the same fluid characteristics as the active formulations. No active insecticides were tested during this project, all future references to Thiodan, Glossinex and Karate being to the blank formulations. All three formulations were of the high volatility type currently required for field use and so would be unsuitable for use in direct aerosol production. However a low volatility formulation with similar viscosity and surface tension is feasible (Marrs, pers. comm.), and such a direct aerosol production formulation would have similar atomisation characteristics to the liquids tested. A fourth blank formulation, JF9436, was also tested. This had a very low volatility, but was formulated to have a high viscosity in order to control its flow rate in the application for which it was originally intended. It thus provided a more severe test of the atomisers' capabilities. The formulations and their characteristics are listed in Table 4.1. Surface tension was measured using a DeNuoy surface tensiometer and viscosity using a Brookfield viscometer. Density was determined at room temperature using a 20ml volumetric flask and an electronic balance.

4.2 Method for Wind Tunnel Testing

Tests were carried out in the ICAP open jet wind tunnel (Figure 4.1). Wind speeds up to 62.6 m/s (140 mph) could be produced, simulating the conditions experienced by an atomiser mounted on an aircraft. Its four blade propeller was driven by a 5.3 litre Chevrolet petrol engine capable of generating 150kW. Air was pushed into a contraction section fitted with flow straighteners which culminated in a 0.6 by 0.6 metre outlet. Air speed was monitored by a pitot static tube and an aircraft Air Speed Indicator. The atomiser under test was mounted on a section of boom fixed across the outlet of the contraction section.

Electrically-driven atomisers were operated at their maximum rotation speed settings. Their dry speeds were measured before testing using a digital optical tachometer. Tests were carried out over a range of flow rates in a 54 m/s (120 mph) wind, this being the maximum speed which could reasonably be used for extended periods of running. Some measurements were also taken where the wind speed was varied while flow rate was kept constant.

Wind-driven devices were tested at various speeds and flow rates. Most of the tests were carried out with a wind speed of 45 m/s (100 mph), which gave a broad range of rotation speeds with the available windmill blade pitch options. Each wind-driven atomiser had a small brass tag fitted to its moving section so that as it rotated the tag passed a capacitive sensor clamped to the body of the atomiser. The resulting stream of pulses was converted electronically into a reading of rotation speed.

Test formulations were fed to the atomiser from an 18 litre steel vessel which was maintained at constant pressure by a small compressor. A ball valve provided on/off control and pressure was measured in the output line by a transducer. The flow of liquid was initially regulated by a needle valve located between the vessel and transducer but the pressure reading dropped markedly over the duration of a test run. The needle valve was replaced by a restrictor which could be fitted with a selection of orifice plates. With this arrangement the pressure reading remained constant. Flow rates were set using combinations of vessel pressure and orifice plate, and measured using a stop-watch and measuring cylinder.

The OAP-260X laser imaging probe was mounted on a platform which traversed the mouth of the tunnel horizontally at a distance of 0.5 metres from the plane of the atomiser. At a wind speed of 120 mph (54 metres/second) spray would take in the order of 0.01 seconds to cross this distance so significant evaporation was unlikely to occur between emission and measurement. The atomisers tested were all rotary devices, producing a plume of spray with a ring-shaped cross-section. Because the band of spray was thin compared to the radius of the plume the error due to variation of spray concentration with axial position was minimal. The higher resolution (5 μ m per photodiode) probe configuration was used in all tests except those of the Unirot-4 atomiser. During the Beecomist 360A trial the two configurations were compared .

To take a spray measurement the wind tunnel was first run up to speed. Once a stable speed had been reached, the atomiser was (where necessary) switched on and the feed-line valve was opened. The probe was reset and two transects of the spray plume were made. This generally sampled a sufficiently large number of droplets but at the lowest flow rates a further pair of transects were sometimes required. In the case of wind-driven devices rotation speed was noted. The resulting data was down-loaded to a portable computer, labelled and stored for subsequent analysis. Two readings were normally taken for each condition tested. These proved to be virtually identical and so mean values are used in the tables and graphs.

4.3 Atomiser Assessments

i) The Unirot-4

This is a solidly constructed unit in which a three-phase 120 volt a.c. electric motor provides a direct drive for a slotted drum (Figure 4.2). The motor gave a very constant dry speed of 11500 rpm which did not vary greatly as the drum was loaded with fluid. Liquid is fed to the inner face of the drum from a hollow annulus with lines of three holes at regular intervals around its outer wall. At the relatively low flow rates being used this annulus did not fill completely, with the result that all the fluid escaped from the lower holes and fell onto only a small part of the slotted drum. Below 2 litres/minute only the

bottom three holes were emitting fluid. Above this rate an increasing number of holes came into use and more of the drum received liquid.

The unit tested was available for only a short period of time early in the project. Because of this it was necessary to carry out the tests using the original, coarser probe configuration. However, the measured spectra suggested that little of the spray produced was likely to fall below the detectable range. Only the Thiodan blank was available at this time. Results are summarised in Table 4.2 and Graphs 4.1 and 4.2.

Droplet spectra were broad and polymodal, implying a relatively uncontrolled breakup process which probably involves both ligament disintegration and direct mechanical shattering of the fluid by the bars of the drum. The smallest VMD achieved was $93\mu\text{m}$ at 0.6 litres/minute. VMD initially increased rapidly with flow rate but above 2 litres/minute it fluctuated between 212 and $272\mu\text{m}$. This change coincided with the condition at which liquid began to escape from more than the bottom three feed holes so that with increasing flow rate more of the slotted drum became involved in the atomisation process. Relative span initially improved as flow rate increased but above 1.5 litres/minute its value became fairly constant.

If the droplet size were to continue to decrease with flow at the same rate below 0.6 litres/minute as it did between 2.0 and 0.6 litres/minute a VMD of $30\mu\text{m}$ would be predicted at 0.1 litres/minute. This could not be tested with the feed system available when this atomiser was tested. The necessary modifications were not made since the atomiser's weight and unusual power supply made it unsuitable for use in the numbers that such a low flow rate would dictate.

A maximum of 20–22% of the volume of fluid emitted fell into the range required for armyworm control. This was achieved at a flow rate of 0.6 litres/minute, giving a relative span of 1.9 – 2.0.

ii) Beecomist 360A

The Beecomist employs a d.c. electric motor as a direct drive for either a perforated steel drum or a hollow cylinder of sintered metal (figure 4.3) from which fluid escapes. A dry

rotation speed of 10200 rpm was measured with the 28 volt power supply used in these trials. At 3.4 kilogrammes it is lighter than the Unirot but is sturdily constructed. Fluid is distributed internally by a pair of slits designed to emit two flat fans of fluid onto the inside of the drum or cylinder. Uniform distribution depends on the fluid having a sufficiently high velocity as it leaves the slit. The very low fluid flow rates which are required to produce droplets small enough for use in tsetse control can result in too low a velocity so that the fan does not spread sufficiently to give a uniform distribution. This is illustrated in figures 4.4(a) and 4.4(b).

Previous droplet-sizing data is summarised in Table 4.3. The tests carried out by Picot et al (1985) suggested that nearly all of a spray of water can be produced at diameters below 55 μm using a polyethylene head. However no further details of this head were given and it does not appear in other test reports. Other published work described operational use of Beecomists, for example in application of bacterial and viral insecticides against gypsy moth (*Lymantria dispar*) (Neisess and Hubbard 1978) or mosquito (Sandoski et al 1985, 1986; Lacey et al 1986), but provided no useful indication of the droplet spectra emitted.

Testing was carried out in order to supplement the existing data with high resolution low flow rate data using the four blank formulations. The particle measuring system was used first in the original and then in the modified, high resolution configuration. Results are given in Tables 4.4 to 4.9 and Graphs 4.3 to 4.7. The two probe configurations produced similar results, though VMDs given by the higher resolution version were slightly smaller.

a) 40 μm sintered metal head

At the lowest flow rates tested spray was seen to issue from only part of the atomiser head, reinforcing doubts as to the effectiveness of the internal distribution system under these conditions. The smallest VMDs obtained with the low viscosity formulations were 68–72 μm at 0.1 litres/minute. As flow rate approached 1 litre/minute this percentage began to fall. A maximum of 29% volume was measured in the 80–120 μm range. Relative span tended to increase slightly with flow rate and this, together with the trend in VMD indicates that the proportion of volume in the 80–120 μm range would not be improved with further increase in flow rate. The high viscosity JF9436 formulation was not atomised successfully, escaping from the open end of the atomiser head.

Multiple linear regression of the data from the three low viscosity formulations showed that it was best fitted by the linear expression

$$\text{VMD} = 64.2 + 28.2 Q \quad (4.1)$$

where VMD is in micrometres and flow rate, Q , is in litres/minute. This gave an R^2 value of 79.9%. Inclusion of viscosity and surface tension terms in the correlation increased the R^2 value by only 0.1%. There was no significant correlation between relative span and flow rate, viscosity or surface tension, though it did tend to increase with flow rate in the trials using Thiodan and Karate. Overall, span values indicate tighter droplet spectra than those produced by the Unirot atomiser. Increasing wind speed from 27 m/s (60 mph) to 62.6 m/s (140 mph) gave a 10% decrease in VMD and a drop in relative span.

b) perforated metal drum

VMDs obtained using Thiodan were slightly larger than those given by the sintered metal head while relative spans were lower, resulting in similar proportions of volume in the armyworm target range. JF9436 was also atomised successfully but the resulting droplet spectra were too coarse to be of practical value in tsetse or armyworm work. In both cases VMD increased linearly with flow rate.

Increasing wind speed from 27 m/s (60 mph) to 62.6 m/s (140 mph) gave a decrease in VMD of 8% with Thiodan. However tests using JF9436 showed a 9% increase in VMD and an increase in relative span over the same range of speeds.

iii) Micron X-15

The X-15 uses a d.c. electric motor to drive an atomiser head indirectly by means of a thin rubber belt. Speed may be adjusted by selecting combinations of pulley wheel. The maximum recommended dry speed is 10000 rpm at 24 volts, giving a power consumption of 60–80 watts. The head itself is made up from a stack of fifteen 85mm diameter 360-toothed, cup-lipped discs which revolve around a hollow shaft. Atomisation occurs by

ligament disintegration. Fluid is fed through the shaft and escapes through fifteen holes, one feeding each disc.

At the lowest flow rates tested it was clear that not all the discs were emitting fluid. Examination of the feed system showed that liquid was not forming discrete jets but was coalescing and leaving the central shaft in four streams (Figure 4.5a). This problem was overcome by soldering short lengths of hypodermic tubing into the holes (Figure 4.5b). As flow rate was increased the exit velocity of the liquid became sufficient for jetting to occur directly from each hole.

Previous data is summarised in Table 4.10. Spillman's data included speeds well in excess of the maximum specified by the manufacturers but, at the flow rates tested, droplets in the target range were not produced. Harrison's data showed that increasing flow rate decreased the rotation speed of the atomiser considerably, compounding the increase in VMD normally associated with flow rate increase.

Further particle sizing was carried out using the specified formulations at lower flow rates. Results were consistent with those of previous work and are given in Tables 4.11 to 4.13 and Graphs 4.8 to 4.9. The data was best fitted by the expression

$$\text{VMD} = 242 Q^{0.270} \mu^{0.0843} \quad (4.2)$$

where VMD is in micrometres

Q = flow rate (litres/min)

μ = viscosity $\text{Kgm}^{-1}\text{s}^{-1}$

giving a value for R^2 of 77.9%. A linear model also gave a reasonable fit. The smallest VMD achieved was 76 μm with Thiodan at a flow rate of 0.1 litres/minute. Glossinex gave significantly larger VMDs despite being similar in physical properties to Thiodan. A possible explanation of this is reduced rotation speed as a result of drive belt slippage caused by the drive belt having slackened through previous contact with Thiodan (such a slackening was observed in the seals of the pressure vessel after contact with Thiodan). A maximum of 50% volume fell into the 80–120 μm range at a flow rate of 0.26 litres/minute. The smallest VMD obtained with JF9436 was 119 μm . There was no

correlation between relative span and flow rate, viscosity or surface tension. The low values obtained implied that ligament disintegration was the dominant mode of atomisation. With the modified feed system spraying Glossinex at 0.1 litres/minute VMD fell from 91 to 69 μm while span dropped from 0.931 to 0.750. Narrow droplet spectra were produced under most conditions, becoming at first slightly broader and then narrowing with increasing flow rate.

At a constant flow rate VMD increased with wind speed. This effect was slight at low speeds but at 44.7 m/s (100mph) and above the rate of increase became much greater. Span tended to decrease with increasing wind speed.

iv) Micronair

Aircraft mounted Micronair units have been in use for around thirty years in a variety of agricultural, forestry and vector control operations. The two units currently produced for use on aircraft are the AU4000 and AU5000 (Figures 4.6 and 4.7). Both are windmill driven and can be fitted with various lengths of variable pitch blade. The atomiser heads are based on rotating drums of metal gauze. Liquid is fed in through a hollow central shaft and escapes onto a rotating perforated metal drum which acts as a primary distributor. The liquid is flung from this onto the inside of the gauze drum, which rotates at the same angular velocity. A brake can be applied to prevent overspinning during descent into spraying run.

Photographs taken by Western (1971) demonstrated that liquid leaves the primary distributor in the form of ligaments which impact on only part of the outer gauze. The same work also showed that atomisation occurs by a mixture of shattering and ligament formation, the proportion depending on the angle at which the primary ligaments hit the gauze. VanVliet and Picot (1987) suggested that at higher flow rates a layer of liquid builds up over most of the gauze with ligaments arising from surface instability.

The maximum rotation speed recommended by the manufacturer is 10000 rpm for both units but in practice both have been used at higher speeds. VanVliet and Picot (1987) reported an AU4000 at 14000 rpm showing no vibration problem after 40 hours use while in tsetse operations such speeds are regularly used. Speeds up to 16000 rpm have been

recorded during the descent into tsetse spraying runs (Hursey and Allsopp 1983) but it was during this stage of the sortie that most breakages occurred. The AU5000 is smaller and lighter than the AU4000 and has less effect on the handling of the aircraft (Brunwyn, pers. comm.). It can also be fitted to conventional aircraft spray booms whereas the AU4000 requires special mountings. However the bearings of the AU4000 are more robust, making it more suitable for sustained high speed.

Performance of the AU4000 and AU5000 has been extensively reported. Data relevant to aerosol and fine spray production are listed in Tables 4.14 and 4.15. Neither atomiser is capable of producing aerosol droplets directly under the conditions reported but fine sprays are produced under a wide range of conditions. At high rotation speeds the influence of flow rate on VMD is negligible, even when it is taken up to levels in the order of 10 litres/minute. Despite the difference in cage diameter and hence peripheral speed results are similar for the two atomisers at the same rotation speed and flow rate (comparable conditions are indicated in the Tables). The results of VanVliet and Picot (1987) did not include any kind of mean droplet size so their use in a direct comparison is not possible, though the volumes of spray with diameters less than 55 micrometres suggests that VMDs would be lower than the values found in the other studies. Mierzejewski (1982) and VanVliet and Picot (1987) found that viscosity and surface tension had little influence on spectrum except at viscosities greater than $7 \times 10^{-2} \text{ Kg m}^{-1} \text{ s}^{-1}$ (70 cP). Parkin and Siddiqui (1990) report a small increase in VMD with wind speed.

Multiple linear regression of the available AU5000 data gave the relationship

$$\text{VMD} = 2528 Q^{0.087} N^{-0.379} \quad (4.3)$$

where VMD is in micrometres

Q = flow rate (litres/minute)

N = rotation speed (rpm)

An R^2 value of 82.7% indicated that this is a reasonably good model. Predicted and measured results are shown in Graph 4.10, the plot indicating more accurate prediction of VMDs above 80 micrometres. At 14000 rpm and a flow rate of 0.2 litres/minute a VMD of 59 micrometres was predicted. The small influence of flow rate was probably a

consequence of poor internal distribution of fluid, with increasing liquid volume being emitted from an increasing area of the gauze and so having a minimal effect on flow rate per unit area.

Relative spans were reasonable at lower speeds, Siddiqui (1986) finding values of 1.1 – 1.3 for the AU4000 at 8000 rpm. At higher speeds the data suggested that spectrum width increased, with unpublished ICAP data giving a span of 2.7 for an AU5000 at 12000 rpm. Flow rate had little influence on span. The broadening of the spectrum with rotation speed is commensurate with an increase in the shattering mode of atomisation.

Results of spray monitoring undertaken during sequential tsetse spraying in Zimbabwe have been used to give an indication of the extent to which droplets evaporate after emission (Johnstone et al 1987,1988). The atomisers used were AU4000s operating at 11000 and 14500 rpm with flow rates of 5.77 litres/minute. The size and number of droplets at ground level were sampled on rotating magnesium oxide slides while fluorimetry gave the amount of fluorescent tracer they contained. The resulting concentration could be compared to that of the original tank mix. The level of evaporation found using this technique was typically around 80–90%. Working back from this data emitted VMDs in the order of 43 to 60 micrometres are indicated. Sizes calculated in this way will tend to underestimate the true values; the measured VMDs will be artificially low as larger droplets are preferentially filtered out by vegetation, and the degree of evaporation could be under estimated if the level of fluorescence had decayed significantly between emission from the aircraft and collection of samples for fluorimetry. In view of this the emitted VMDs calculated from this field data were compatible with those reported in wind tunnel trials. Earlier field measurements taken with low volatility formulations (Lee, Pope and Bowles 1977) tended to reinforce this conclusion.

v) Micron X–1

The Micron X–1 is a 0.152 kg plastic unit in which a 50mm diameter, 180–toothed cupped disc is driven by a three–bladed windmill (Figure 4.8). Uniform fluid distribution is achieved by the use of a central inlet which feeds fluid onto the inside of a cone inverted over the cupped disc. The cone rotates with the disc and fluid escapes from its smooth edge onto the grooved edge of the disc, from which it is emitted as ligaments.

Existing data is shown in Table 4.16. It suggested that the use of X-1 atomisers would offer a significant improvement in emitted droplet diameter over the Micronair units currently used for tsetse work. The VMDs at higher flow rates suggested that X-1s may also be suitable for armyworm spraying. In the light of this information detailed testing was carried out.

The pitch of the blades could be adjusted to give a wide range of rotation speeds. Combinations of wind speed and blade pitch were tested in the wind tunnel (Table 4.17 and Graph 4.11). The manufacturer's recommended maximum running speed is 18000 rpm, above which structural damage can occur. During testing a particular weak spot was found to be the clamp holding the windmill blades: this consisted of a front and back plate which were forced apart by any slight imbalance at high speed, increasing the imbalance and resulting in catastrophic failure. The clamp was modified by the addition of three countersunk screws which held its two halves tightly together. With this change rotation speeds beyond 26000 rpm could be attained without damage. The blade roots were also prone to failure at high speeds but were unaffected in the speed range used for testing. A wind speed of 100 mph was chosen for particle sizing trials, giving a range of rotation speeds from 10500 to 26000 rpm under load.

Particle sizing was carried out with the four trial formulations. Results are shown in Tables 4.18 to 4.21 and Graphs 4.12 to 4.14. JF9436 gives considerably larger VMDs than the three low viscosity formulations. Of the latter, analysis of variance showed that the VMDs obtained using Thiodan and Karate were not significantly different while those given by the marginally more viscous Glossinex were significantly, albeit slightly, bigger. Regression analysis of VMD with rotation speed, flow rate, viscosity and surface tension gave as the best fitting model

$$\text{VMD} = 258374 N^{-0.747} Q^{0.215} \mu^{0.107} \quad (4.4)$$

where VMD is in micrometres, ω in rpm, Q in litres/minute and μ in $\text{Kg m}^{-1}\text{s}^{-1}$.

An R^2 value of 98.5% showed that the model fitted the data very closely, though comparison of predicted and measured values (Graph 4.15) showed that it was less exact

for the high viscosity formulation. The lack of scatter in the data indicated that atomisation was very controlled, almost certainly occurring by the disintegration of uniformly fed ligaments.

The smallest VMD measured, 43 μm , was obtained with Glossinex at 0.1 litres/min and 24500 rpm. It exactly matched the predicted value for these conditions. For a fluid of 1.0 cP viscosity at the same speed and flow rate the model predicted a VMD of 40 μm , and with Thiodan at 0.05 litres/min and 24500 rpm a VMD of 36 μm was predicted. The smallest VMD obtained with JF9436 was 56 μm at 0.11 litres/min and 23400 rpm.

At best 35–40% volume fell in the armyworm target ranges. This was achieved under various conditions from 0.1 litres/min at 11000 rpm to 0.78 litres/min at 19500 rpm.

The relative spans obtained indicate a narrow droplet spectrum, particularly at the lowest flow rates. Using data from all formulations there was a weak correlation ($R^2=66.3\%$) with rotation speed, viscosity and flow rate, span increasing with flow rate and viscosity and decreasing slightly with rotation speed.

$$\text{Relative span} = 2.871 N^{-0.046} Q^{0.113} \mu^{0.066} \quad (4.5)$$

For the three low viscosity formulations alone the influence of rotation speed was negligible but a stronger correlation ($R^2=84.7\%$) existed with flow rate and viscosity:

$$\text{Relative span} = 2.942 Q^{0.150} \mu^{0.136} \quad (4.6)$$

vi) Prototype Atomisers

Two prototype devices were made available by their producers for inclusion in the test programme.

a) Forestry Commission X-30

The U.K. Forestry Commission has developed an electrically driven atomiser which uses a stack of thirty discs of the type found in the Micron X-15. The discs are fed from holes

with short protruding pipes as in the modified X-15 described previously. The atomiser head is driven directly by a 120 volt a.c motor and can attain a dry speed of 15800 rpm which does not fall significantly with loading. However an appropriate generator must be carried to produce the correct power supply.

Wind tunnel tests were carried out on this device, though at the request of the Forestry Commission a lower wind speed was used and the test liquid was water with 20% Actipron. Results are shown in Table 4.23. The device produced considerably smaller droplets than the X-15 at equivalent flow rate per disc but the relative span was larger, most probably due to the increased rotation speed and the increased difficulty of feeding thirty discs uniformly.

The device was not able to produce aerosol size droplets at the flow rates tested and the device's weight and high power requirement make the use of lower flow rates impractical. Only 26% volume could be produced in the armyworm size range and again the low flow rate required for this makes its use impractical for this type of work.

b) Noric Sprayers "Noricaire"

The Noricaire is a novel variation on the use of a slotted drum. The prototype consisted of a 96mm diameter cage (of the type used in centrifugal blowers) mounted on a plain axle. Liquid was fed to the inside of the drum by three slit plastic tubes, the size of the slits varying with liquid pressure. When held in an air stream the cage acted as a windmill and liquid was centrifuged from its blades. Some wind tunnel tests were carried out (Table 4.22) though these were hindered by the axle's tendency to overheat and seize up. Because of the crude feed system and the internal airflow of the device liquid was seen to escape from only a small part of the available emitting surface. A similar pressure-dependent feed system had been used successfully in a Pratt and Whitney augmentor nozzle for fuel-injection in jet engine afterburners, where a wide range of flow rates can be required during running. In pesticide application, however, such variation in flow rate is unlikely to be required during a spray run. A more uniform and repeatable internal distribution of fluid could be achieved using interchangeable nozzles capable of producing a flat fan of liquid. Nevertheless with Thiodan at 0.62 litres/minute 35% volume fell into the armyworm size range. Rotation speed was adjustable only by changing the wind speed. A

flat fan of liquid. Nevertheless with Thiodan at 0.62 litres/minute 35% volume fell into the armyworm size range. Rotation speed was adjustable only by changing the wind speed. A degree of control might be achieved by applying various degrees of obstruction to the mouth of the cage.

4.4 Conclusions

All the atomisers tested followed the expected trends in droplet size with respect to operating conditions, VMD decreasing with decreasing feed rate and increasing rotation speed. The effect of wind speed on droplet size was not consistent, an increase in wind speed giving an increased VMD for some formulations with some atomisers. Relative span generally increased slightly with increased feed rate, the initial drop in relative span with increasing feed rate observed with the Unirot atomiser most probably arising from an improvement in the quality of the liquid feed distribution.

i) Aerosol Generators for Tsetse Control

None of the devices tested were capable of the direct production of aerosol-sized droplets. The only device offering a significantly smaller emitted VMD than the tried and tested Micronair AU4000 was the Micron X-1 which, with structural modification, was able to produce spray with a VMD of around 40 micrometers at a flow rate of 0.1 litres/minute. The X-1 is small and light enough for a number of units to be fitted to a single aircraft, making it practical to achieve the required total flow rate for tsetse work (see Graph 1.1). Its principle drawback would be setting the rotation speed accurately for an airspeed of 180 mph. From Tables 1.1 and 4.17 it can be seen that a blade pitch setting somewhere between positions 5 and 4 is indicated for use on a Cessna 401 (assuming that the airspeed experienced by the atomiser is not significantly different to that of the aircraft). It would be necessary either to ensure that airspeed did not exceed the speed during spraying at any point in the sortie or to reinforce the structure of the X-1s so that they could withstand rotation speeds in excess of 30000 rpm.

The AU5000 performed as well as the AU4000, with the advantage that it had less effect on aircraft handling than the AU4000. Though its bearings are less robust it has been

found to be sufficiently reliable in operation if overhauled and greased between sorties (Hursey and Allsopp 1984).

The limitations of existing equipment with respect to aerosol production are insufficient rotation speed and too high a flow rate per ligament. Even where a large number of potential issuing points exist there is an inability to distribute low volumes of fluid evenly to them all. There is a clear need for a new device which addresses these problems.

ii) Fine Spray Generators for Armyworm Control

The Unirot, Beecomist, Micron X-15 and Micron X-30 prototype were capable of producing a proportion of spray volume in the armyworm size range, but did so at flow rates suitable for ground rather than aircraft application. The Micronair AU4000 and AU5000 were capable of handling much higher flow rates than the other candidates. An output of 16 litres/minute could be achieved with just two atomisers, vindicating the system currently used for aerial treatment of armyworm. The Micron X-1 produced a reasonable proportion of appropriately sized droplets at low flow rates but unlike the other candidates the use of a number of units would be practical, an output of 16 litres/minute being possible with 16 to 30 units on a conventional aircraft spray boom. Though no better than the Micronairs for armyworm spraying this system offers the advantage that it could also be used for tasks which require the application of near aerosol sized droplets (for example mosquito control). The Noricair was also capable of producing a comparatively large proportion of spray volume in the armyworm range and, like the Micron X-1, would be suitable for use in numbers sufficient to give the required total output. Further investigation is warranted using ball rather than plain bearings, a more robust feed system, internal airflow guides and speed control on the basis mentioned above.

5) Literature Investigation of Rotary Atomisation

The tests described in the previous chapter bore out the general description of rotary atomiser behaviour given in chapter 3, but also showed the limitations of existing devices as aerosol generators. In this chapter a more detailed review is made of the processes involved in rotary atomisation with the aim of circumventing these limitations and identifying design features which might allow a practical atomiser to achieve the performance specified for tsetse control.

5.1 General Behaviour of Rotary Atomisers

A number of investigations into rotary atomiser behaviour have been carried out using a variety of atomiser systems. Though the results had features in common, allowing some qualitative understanding of the rotary atomisation process to be developed, specific performance characteristics could vary considerably from system to system.

Bar (1935) recognised two mechanisms of disintegration from spinning disc atomisers. At low flow rates he observed direct droplet formation from the rim, with droplet size showing a strong dependency on surface tension. At higher flow rates he described a process of "velocity spraying", in which liquid broke up after leaving the disc "by impact and friction with the surrounding atmosphere". Wilson *et al* (1935) also described disintegration by the friction and tearing effect of the surrounding air. Under their experimental conditions fluid left the disc as ligaments, and the authors drew an analogy between this type of atomisation and the disintegration of jets from orifices as described by Castleman (1931). They pointed out that air entrainment by the disc retarded the onset of disintegration.

In 1949 Walton and Prewett carried out a study of rotary atomisers used for the application of insecticides. They mounted the discs horizontally and observed the pattern of the spray deposit on the ground beneath, assuming that droplets of similar size would be projected a similar distance. Two distinct bands were seen, which the authors ascribed to deposition of "main" and "satellite" droplets. Tests were carried out on discs of 20 to 80mm diameter at speeds of 500–100000 rpm, using fluids with densities of 900 to 1360 kgm⁻³ and surface tensions of 3.1×10^{-4} to 4.65×10^{-3} kgm⁻¹s⁻¹. It was found that a satisfactorily homogeneous spray was only achieved at low flow rate. At constant rotation speed flow rate had virtually no effect on the position of the spray deposit but the bands became wider with increasing flow until at "high" rates

the main and satellite bands merged. The maximum flow rate for distinct bands was dependent on the size and speed of the disc.

From the data presented in the paper it can be seen that equivalent disc peripheral speeds did not result in the same droplet sizes on discs of different diameter. Within limits of 1×10^{-5} to $1.5 \times 10^{-2} \text{ kgm}^{-1}\text{s}^{-1}$ viscosity had little effect on the atomisation process but at higher viscosities the proportion of satellite droplets increased and the maximum flow giving a homogeneous spray decreased. Walton and Prewett considered the atomisation process to be direct droplet formation under all conditions and gave a semi-empirical expression based on a balance of forces

$$d\omega \left(\frac{D\rho}{\sigma} \right)^{0.5} = \text{constant} \quad (5.1)$$

They expected the constant to be a function of a characteristic length defining the sharpness of the disc edge with respect to droplet size. However in the range tested edge profile was of minor importance. They found the value of the constant to vary between 2.7 and 6.6, with a mean value of 3.8. A higher value was obtained at higher rotation speed, and this was thought to be a result of slippage.

Hinze and Milborn (1950) observed that droplet production could occur by several mechanisms from the same device, the prevailing mode being dependent on feed-rate and rotation speed. They measured droplet diameters on magnesium oxide-coated slides and quantified the width of the resulting spectra using Rosin-Rammler distribution constants. Adler and Marshall (1951), sampling droplets by immersion cell, obtained unimodal droplet distributions from various spinning discs which yielded linear cumulative volume plots on arithmetic probability paper. There was one exception to this, a disc with rearward-facing vanes which gave a straight line on log-probability coordinates. No correlation was found between average droplet size and the calculated theoretical film thickness. Boshoff (1952) observed the influence of feed rate on droplet homogeneity. Most of his observations are explained by Hinze and Milborns' three modes of atomisation but he also notes that if feed rate is taken below a critical level while in direct droplet mode droplet size becomes very variable. In the subsequent correspondence published with the paper it was suggested that this fourth mode is a consequence of incomplete wetting of the disc surface, resulting in an irregular supply of liquid to the disc edge.

Friedman, Gluckert and Marshall (1952) used dimensional analysis and experimental results from discs of 25 – 95 mm diameter to derive a semi-empirical correlation of droplet size with operating parameters

$$\text{Sauter mean diameter} \propto \omega^{-0.6}, \mu^{0.2} \text{ and } \sigma^{0.1} \quad (5.2)$$

In dimensionless terms this gave an expression

$$\frac{\text{SMD}}{D} = 0.66 \left(\frac{2\pi r^3 \omega}{Q} \right)^{-0.6} \left(\frac{2\pi \mu^2}{\rho Q} \right)^{0.2} \left(\frac{8\pi^3 r^3}{\rho Q^2} \right)^{0.1} \quad (5.3)$$

Droplets were measured on magnesium oxide slides by microscopy. Unimodal distributions were observed. Plots of cumulative percent volume against droplet diameter were linear on log probability coordinates. Droplet spectrum was quantified using a Hatch-Choate dispersion coefficient, α , defined as

$$\alpha = \frac{d_{v0.5}}{d_{v0.8413}} \quad (5.4)$$

α was found to be approximately $3.3 (\text{SMD})^{0.1}$. There was no significant variation with any operating variable.

Oyama *et al* (1953) experimented with plain discs of 60–140 mm diameter fed at 24–600 ml/min and rotated at 1000 to 10000 rpm, collecting the resulting droplets on oil-coated slides. They arrived at the relationship

$$d_{\text{mean}} \propto \omega^{-1} Q^{0.2} D^{-0.3} \quad (5.5)$$

Droplet spectra were unimodal down to 6000 rpm. Below this speed they became bimodal and then polymodal. The breakup length of the ligaments was seen to increase with feed rate and decrease as rotation speed increased.

Herring and Marshall (1955) used vaned discs of 50 – 200 mm diameter to atomise dyed water. Droplets were collected by sedimentation into immersion cells and sorted by photomicroscopy into 30 μm size classes. The resulting spectra were linear on

square-root – normal probability coordinates, giving distinct curves on arithmetic or log– normal probability plots. They found

$$d_{\text{mean}} \propto \omega^{-0.82}, Q^{0.24}, (\text{vane height})^{-0.12} \text{ and } (\text{vane number})^{-0.15} \quad (5.6)$$

The similarity between the two vane parameters implied that wetted perimeter was the controlling factor but neither it nor vane length gave any clear correlation. The other correlations were reported to hold upto 35000 rpm with a 24 mm disc fed at 5 litres/minute on 24 straight vanes. Spray uniformity increased with rotation speed and as feed rate per unit perimeter fell. High speed cine film showed that atomisation was occurring from irregular sheets at low rotation speeds and by rapidly collapsing ligaments at higher speeds.

Frost (1981) measured the droplet sizes produced by a smooth-edged aluminium disc. He produced a set of droplet size correlations such that

$$d \propto \frac{Q^{0.44} \sigma^{0.15} \mu^{0.017}}{D^{0.80} \omega^{0.75} \rho^{0.16}} \quad (5.7)$$

Sanderson (1982) investigated the spray produced as liquid was atomised from the edge of small, high solidity windmills. He obtained the following correlation

$$d \propto \frac{Q^{0.18} \sigma^{0.19} \mu^{0.02}}{\omega^{0.58} R^{0.15} n^{0.18} \rho^{0.21}} \quad (5.8)$$

Molten metals have much higher densities than substances which are liquids at room temperature. Champagne and Angers (1984) investigated metal particle formation by the rotating electrode process, in which droplets of molten metal are flung from a rotating anode which is heated by arcing with a water-cooled tungsten cathode. Particle size distribution was assessed by sieving and high speed photography was used to observe the disintegration process. The latter showed direct droplet atomisation transforming to ligament mode as the liquid feed rate was effectively increased by raising the rate of melting. The authors found that this transition coincided with a ratio of satellite to main droplets of around 0.3 by mass. Regression of this ratio against operating parameters yielded a relationship giving the expression

$$\left(\frac{Q \omega^{0.6}}{D^{0.68}}\right) = 0.07 \left(\frac{\sigma^{0.88}}{\mu^{0.17} \rho^{0.71}}\right) \quad (5.9)$$

operating
parameters
material
parameters

which varies considerably from Hinze and Milborns' findings when set out in this form

$$\left(\frac{Q \omega^{0.6}}{D^{0.68}}\right) = 1.33 \left(\frac{\sigma^{0.88}}{\mu^{0.17} \rho^{0.71}}\right) \quad (5.10)$$

The sets of observations described in this section showed considerable variation in the dependence of mean droplet diameter and size distribution on operating parameters, the latter in particular showing no simple correlations. The droplet spectrum produced by a rotary atomiser is the end product of a process involving several stages, each of which might be influenced independently by atomiser design, and in order to arrive at a more generally applicable understanding of rotary atomiser behaviour it is necessary to consider each step of the process separately.

Rotary atomiser behaviour can be divided conveniently into two main stages – movement of fluid within or on the atomiser, and the disintegration of the fluid into droplets once it has left the atomiser. The first of these can be further divided into the steps of fluid feed onto the atomiser, its transport to the point of separation from the atomiser, and the process of separation (Figure 5.1) but since these are strongly interdependent they will be considered together.

5.2 Flow on a Rotating Disc or Cup

i) Flow to the disc edge

The influence of a rotary atomiser's flow regime on its performance has long been recognised. Matsumoto (1985) and others have used various methods to solve the Navier–Stokes equations for liquid flow on a disc and their predicted values for radial velocity and film thickness show good agreement with experimental data for the simplest case of a plain disc, the results suggesting a velocity lag of around 20%

between liquid and disc. However this represents only the simplest case and such a result gives little indication of the influence of design features on overall performance. In this respect earlier attempts at modelling flow can be enlightening and the experimental work associated with such models can show up complex, system-dependent phenomena.

In 1935 Wilson *et al* noted the influence of the roughness, regularity, groovedness and scratchedness of disc surfaces on the size of droplets produced. They also pointed out that slippage, described as "the undercutting of the thick mass of liquid", increased with feedrate and so prevented the liquid from acquiring the full rotary speed of the disc. The rotary atomisers available at that time reflect an understanding of the need for uniform distribution of liquid. Designs included single and double discs, cups and rotating vertical plates. Liquid was generally fed in from a central nozzle, though in one novel design fluid fed to the top of a disc was distributed over both faces via a section of permeable material. Another used a series of "descending" steps which effectively acted as a set of concentric rotary atomisers, the process of emission from stage to stage helping to improve the uniformity of fluid distribution.

By the time of Seltzer and Settlemeyer's 1949 review designs incorporated obstructing devices such as spokes, walls, blades and steps specifically to reduce slippage while allowing radial acceleration. Liquid was fed in either by vertical feed-pipes or via hollow shafts which emptied onto moving or stationary distributors above the main atomising surface. Internally-fed perforated cylinders were also in use, some using internal "flingers" as distributors. It was recognised that rotary atomisers actively pump both liquid and air, the latter being seen as undesirable with respect to efficiency. Attempts to prevent internal air pumping mostly involved running the atomiser as full as was commensurate with good atomisation, Seltzer and Settlemeyer pointing out that in full, rotating ducts hydrostatic pressure can be considerable. Shielding was used to reduce induced air pumping by external surfaces. In the same year Walton and Prewett (1949) commented on the need for the surface of ductless atomisers to be completely wetted to ensure a uniform fluid distribution.

Marshall and Seltzer (1950) attempted to balance the centrifugal and frictional forces acting upon a film of liquid on a plain rotating disc. For the case of laminar flow on the surface of a plain disc, with slippage and friction losses, they stated a pair of simultaneous non-linear differential equations for the radial and tangential components of flow respectively:

$$\frac{d^2r}{dt^2} + \left(\frac{2\pi\mu fr}{Q\rho_L} \right) \left(\frac{dr}{dt} \right)^2 - r \left(\frac{d\theta}{dt} \right)^2 = 0 \quad (5.11)$$

actual radial friction losses ideal (frictionless)
acceleration acceleration

$$\frac{d}{dt} \left(r \frac{d\theta}{dt} \right) - \frac{2\pi\mu fr^2}{Q\rho_L} \left(\omega - \frac{d\theta}{dt} \right) \frac{dr}{dt} = 0 \quad (5.12)$$

ideal angular friction losses due to velocity
acceleration difference between liquid and disc

The pair is soluble only by approximate or numerical methods, and depends on empirical factors to calculate friction loss. It can be seen that decreasing viscosity or increasing flowrate would reduce radial friction losses but would have an adverse effect on radial velocity through increased slippage. In the same paper Marshal and Seltzer also considered the case of laminar flow on vanes perpendicular to the plane of the disc. Ignoring the influence of gravity, assuming flow to be retarded by a viscous resistance, $t = f_m \left(\frac{dr}{dt} \right)_{\text{average}}$ and letting $a = \frac{\mu f b}{Q\rho_L}$ then an expression is obtained which is similar in form to Equation 5.1

$$\frac{d^2r}{dt^2} + a \left(\frac{dr}{dt} \right)^2 - \omega^2 r = 0 \quad (5.13)$$

From this the authors derived a further expression giving radial velocity at any radial distance:

$$u_r = \frac{\omega}{a\sqrt{2}} (2ar - 1 - C e^{-2ar})^{0.5} \quad (5.14)$$

where $C = (2ar_0 - 1) e^{2ar_0}$

Knowing the flowrate onto the disc, Equation 5.13 could be used to calculate a value for the thickness of the liquid film at any radius. The authors also derived a more

rigorous equation which took into account the relationship between viscous effects and liquid depth:

$$\frac{d^2r}{dt^2} + a' \left(\frac{dr}{dt}\right)^3 - \omega^2 r = 0 \quad (5.15)$$

where $a' = \frac{3\mu b}{Q^2 \rho_L}$

The constant 3 arises from the assumption of a parabolic velocity profile. An approximate solution for this was found, in which it was assumed that the ratio of radial to tangential velocity is constant for a given set of discs

$$u_r = \left(\frac{\omega Q^2 \rho_L}{3\mu b d'}\right)^{0.5} \tanh \left(\frac{3\omega \mu b}{d' Q^2 \rho_L}\right)^{0.5} (r-r_0) \quad (5.16)$$

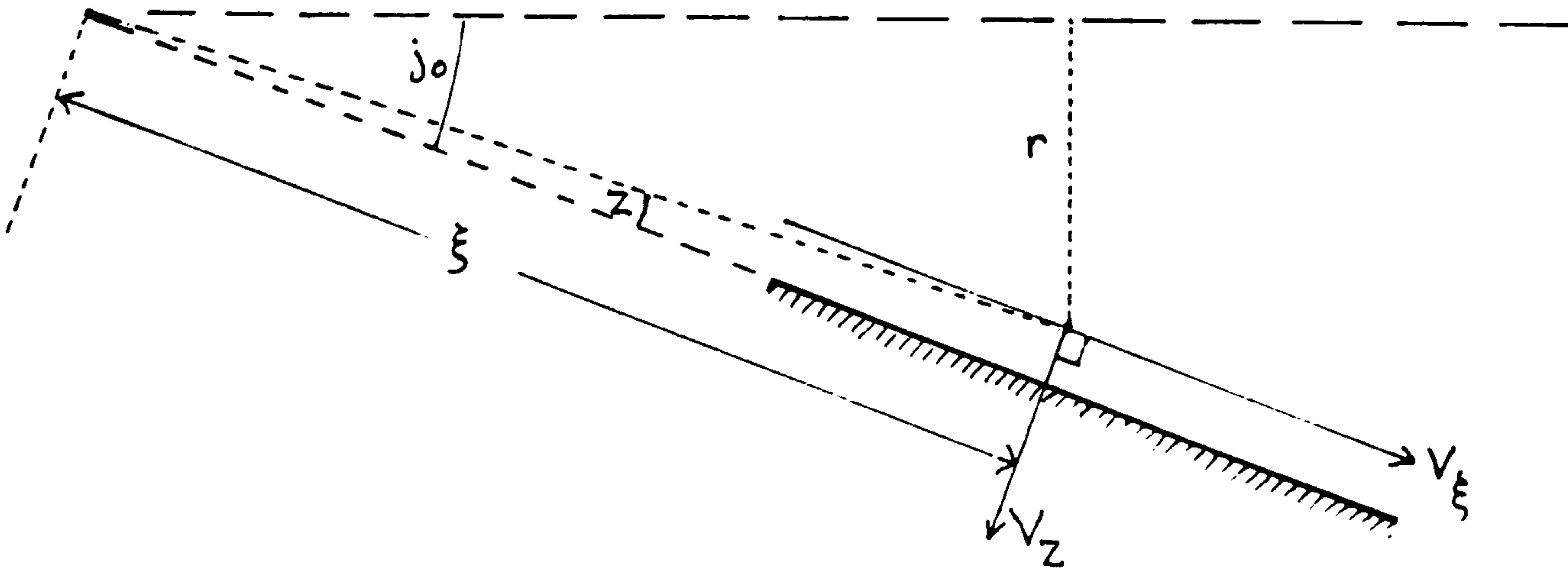
where $d' =$ ratio of radial to peripheral speed.

Turbulent flow was also considered, the parabolic flow friction term being replaced with a turbulent friction factor, $f/2$, giving

$$v_r = \left(\frac{2\omega Q}{f b d'}\right)^{0.5} \tanh \left(\frac{\omega f b}{2 d' Q}\right)^{0.5} (r-r_0) \quad (5.17)$$

In the same year Hinze and Milbourn (1950) considered the flow of a uniform layer of liquid within a plain rotating cup. They assumed the thickness of the liquid layer to be very small compared with the diameter of the cup and the flow to be completely viscous and rotationally symmetric. They deduced that the static pressure across the liquid layer would be practically constant, the velocity component normal to the cup axis would be very small relative to that parallel to the cup wall and that slippage and gravitational effects would be negligible. The dynamic pressure force was then assumed to balance the component of force due to rotation which acted parallel to the cup wall, giving the expression

$$\frac{\mu}{\rho_L} \frac{\delta^2 v_\xi}{\delta z^2} + \omega^2 \xi \sin^2 j_0 = 0 \quad (5.18)$$



Taking the boundary conditions $v_{\xi} = 0$ at the cup wall ($z = 0$) and $\frac{\delta^2 v_{\xi}}{\delta z^2} = 0$ at the free surface ($z = z_1$) this solved to give the expression

$$v_{\xi} = \frac{\rho \omega^2}{\mu} \sin^2 j_0 \left(\xi^3 z_1 z - \frac{\xi^3 z_2}{2} \right) \quad (5.19)$$

Since the total quantity of liquid flowing through the layer must equal the quantity supplied to the cup

$$Q = 2\pi r \int_0^{z_1} \xi v_{\xi} dz = \frac{2\pi \rho \omega^2 \xi^5 \sin^3 j z_1^3}{3\mu} \quad (5.20)$$

and so

$$z_1 = \left(\frac{3\mu Q}{2\pi \rho \omega^2 r^2 \sin j} \right)^{0.33} \quad (5.21)$$

$$v_{\xi} \text{ at surface} = \left(\frac{9\rho \omega^2 r \sin j Q^2}{32\pi^2 \mu r} \right)^{0.33} \quad (5.22)$$

$$v_{\xi \text{ mean}} = \left(\frac{\rho \omega^2 \sin j Q^2}{12 \pi^2 \mu r} \right)^{0.33} \quad (5.23)$$

This has the advantage over Marshal and Seltzers' approach in that it does not depend on empirical friction factors.

The authors attempted to verify these relationships experimentally by injecting dye within the liquid layer. The dye moved almost radially relative to the disc, forming a spiral track relative to a stationary observer. The spacings of the tracks formed must be a function of v_x at the depth of injection, $kv_{x\max}$, so that

$$\text{spiral spacing, } \Delta_{\xi} = k^3 \left(\frac{16 \pi \rho Q^2}{3 \mu \omega} \right)^{0.25} \quad (5.24)$$

if $v_{\xi} = v_{\xi}(\text{mean})$ then $k = 0.67$

The experimentally determined curve gave a qualitatively similar expression but yielded a value for k of 0.39.

Dixon, Russell and Swallow (1952) also investigated the path followed by fluid on a disc, using feed rates which were sufficiently high for sheet formation to occur. Their first experiments involved single droplets and so were of little relevance to the behaviour of continuous films of liquid. They went on to inject dyed glycol into a film of undyed glycol on a disc under sheet disintegration conditions. Slippage was apparent as deviation from a radial path. The authors attempted to reduce slippage by roughening the disc surface and adding radial grooves. The diameter of liquid sheet produced by the disc decreased, implying an increase in its velocity.

Freidman, Gluckert and Marshall (1952) predicted that slippage would be a function of Reynolds number. Experimental data showed an apparent drop in power requirement, implying greater slippage, when Reynolds number was increased from 2400 to 3200. They considered this to be the range over which transition from viscous to turbulent flow would occur.

In the same year Boshoff (1952) noted a marked influence of disc smoothness on the size of droplet produced. He observed irregular sizes of droplets formed with water at very low feedrates and suggested that this might be due to incomplete wetting of the disc surface. Subsequently Lake, Frost and Green (1976) observed a mixture of ligament and direct droplet atomisation occurring from a plastic disc under a range of conditions. After the disc surface had been roughened by sandblasting direct droplet formation was seen throughout that same range of conditions. This was presumed to be due to more even wetting of the disc.

Emslie *et al* (1958) applied the balance between pressure and centrifugal forces used by Hinze and Milborn for flow on a cup to the simpler case of flow on a plain disc. From an expression similar to 5.19,

$$Q = 2\pi r \int_0^{z_1} v \, dz = \frac{\rho\omega^2 r z_1^3}{3\mu} \quad (5.25)$$

and using the continuity equation in its polar cylindrical form

$$r \frac{\delta z}{\delta t} = - \frac{\delta(rQ)}{\delta r}$$

they arrived at a differential equation describing the change in fluid depth with time, and hence with distance from the centre of the disc:

$$\frac{\delta z}{\delta t} = \frac{\rho\omega^2}{3\mu r} \frac{\delta}{\delta r} (r^2 z^3) \quad (5.26)$$

which for an initially uniform distribution of liquid solves to give

$$z_1 = \frac{(z_1)_0}{\left(1 + \frac{4\rho\omega^2}{3\mu} (z_1)_0^2 t\right)^{0.5}} \quad (5.27)$$

Thus the fluid layer would be expected to decrease in thickness by a factor $1/\sqrt{2}$ in a time

$$t = \frac{3\mu}{4\rho\omega^2 (z_1)_0^2} \quad (5.28)$$

It can be seen from this relationship that a thick layer would be expected to "thin out" more rapidly than a thin layer. This was investigated further by finding a more general solution to (5.25) and applying to it a variety of non-uniform starting conditions. The model irregularities evened out with time, suggesting that initial irregularities in liquid feed would tend to even out on a sufficiently wide disc.

Maskey and Marsh (1962) considered flow within a perforated drum atomiser. They described a centrifugal fuel injector for use in jet turbine engines with annular combustion chambers in which fuel was fed along the inner surface of a hollow central shaft onto an end wall with a perforated rim, being flung off the periphery at a velocity which the authors calculated to be equivalent to an injection pressure in excess of $1.38 \times 10^{-7} \text{ Nm}^{-2}$ (2000 PSI). Though the inner face of the rim was flooded the holes did not run full. Liquid coated the walls of the exit tubes and escaped as hollow cylinders. Norster (1964) studied a similar system. He used drums of 0.041 to 0.144 metres diameter with one or more "nozzles" of 0.75 to 2 mm diameter and length to diameter ratios of 3.2 to 34. The drums were rotated at speeds in excess of 40000 rpm and fed at between 0.76 and 5.31 litres per minute. At lower feed rates the flow up the hollow central shaft was a simple vortex flow and was independent of rotation speed. At higher feed rates vortex flow occurred at low speeds but at a feed rate-dependent critical rotation speed the flow became a "fountain" of liquid surrounded by an annulus of air. Norster estimated the discharge velocity from the nozzles using photographs which showed the instantaneous path of the resulting jet. On the basis that with no radial velocity component a perfect involute would be formed he estimated a maximum radial velocity of 7% tangential velocity at his highest feed rate. However he appears to make no allowance for deformation of the jet by aerodynamic drag.

Schmidt (1967) considered atomisation from rotating cylinders of sintered metal and porous ceramic. He described how liquid from a film on the inside surface of the cylinder would pass through its wall under centrifugal pressure and, depending on flow rate, escape from the outside surface as droplets or ligaments. He observed these to form over several beads of the porous material. The size of the resulting droplets was found to be independent from the grain size of the porous material. As he increased flow rate further he observed atomisation by a "pressure dispersal" process which he compared to the complete atomisation of a jet leaving a tube. At high rotation speeds and low flow rates Schmidt observed liquid escaping as droplets without the formation of a surface film. When the flow rate was increased slightly ligaments were

seen to form from between the pores of the cylinder material. The size of the resulting droplets in these cases was dependent on the grain size in the outer layer of the cylinder.

Spillman and Sanderson (1983) measured the benefit of inducing a high radial velocity component in the layer of air above a disc designed specifically for the aerial application of pesticides. The disc was divided into segments, each of which was twisted to form a windmill blade so that it would rotate in an aircraft's slipstream. Liquid was fed onto its "upstream" face. The designers found that it was possible to increase the maximum feed rate giving ligament formation by almost an order of magnitude in a 45 metre per second wind, putting down the improvement to increased radial velocity of the fluid film on the disc. Blows and Balachandran (1991) operated the disc at considerably lower wind speeds and, predictably, failed to achieve maximum feed rates as high as those achieved under the operating conditions for which it was designed.

Reed and Saric (1989) reviewed work on the instability of three-dimensional fluid boundary layers. They described flow phenomena which under some conditions could lead to an increasingly uneven distribution of fluid on the surface of a rotating disc. These effects could occur directly in the liquid layer itself, or could possibly be induced by pressure fluctuations in the boundary layer of air above the fluid disc arising from the same type of instabilities. The types of instability depend on curvature, sweep and roughness of the surface involved and on the Reynolds number and initial conditions of the flow. A common feature is streamwise vorticity within the shear layer, where a velocity component can develop within the boundary layer perpendicular to the direction of the local inviscid flow velocity. This cross flow is unstable and can give rise to cross-flow vortices. Critical Reynolds numbers for transition to this type of flow have been determined, though they are strongly dependent on the experimental system under study. In the case of a rotating disc immersed in a fluid – such as air – the fluid is drawn axially towards the disc. A boundary layer of constant thickness develops and fluid is flung from the disc edge. Cross flow instability exists and co-rotating vortices form, spiralling outwards along logarithmic spirals at an angle of $(90 + \epsilon)^0$ with respect to the disc radius. Reed and Saric cited various work giving critical Reynolds numbers, defined in this situation as

$$Re = \left(\frac{r^2 \omega}{\nu} \right)$$

below which disturbances damp out in this type of flow. The values obtained range from 280 to 530, with $\epsilon = 11^\circ$ to 14° . In some cases vortices with $Re_{crit} = 182$ and $\epsilon = 20^\circ$ are also reported. Using linear instability analysis Malik (1986b, cited by Reed and Saric) predicted a minimum Re_{crit} of 285.36 with a vortex angle ϵ of 11.4° at the critical point. He also predicted a second possible vortex angle of 19.45° . Differences in surface roughness and detection technique were believed to be responsible for the variations in observed values. Roughness is considered to be a strong driving agent for streamwise vorticity and so would encourage crossflow. This might account in part for the observations of improved disc wetting with roughness described previously.

ii) Formation of ligaments from the liquid film

The behaviour of the liquid once it reaches the edge of the atomiser is influenced greatly by operating parameters. As mentioned previously Hinze and Milborn (1950), studying atomisation from rotating cups, observed that three distinct regimes of atomisation could occur from the same device as its rotation speed and feed rate were varied. In direct droplet disintegration they proposed that a torus of liquid collected at the cup lip, its diameter being governed by the balance between its weight and surface tension forces. The torus was unstable and became varicously deformed, the deformities developing under centrifugal acceleration and breaking away as droplets. With increased feed rate the single droplets merged into ligaments, which were stretched as the disc effectively accelerated away from them. The number of ligaments was seen to increase with feed rate until a maximum was reached beyond which it became constant, extra liquid being accommodated by fattening of the ligaments. The ligaments themselves are unstable and collapse into droplets. As feed rate was increased still further the torus of liquid became detached from the edge of the disc and sheet disintegration occurred.

Hinze and Milborn used dimensional analysis to predict the number of ligaments that would form by dimensional analysis. Taking cup angle, disc diameter and rotation speed, feed rate and liquid density, surface tension and viscosity as controlling variables they produced four dimensionless groups

$$\text{Ligament number} = f \left(\frac{\rho Q^2}{\sigma D^3}, \frac{\rho \omega^2 D^3}{\sigma}, \frac{\mu^2}{\rho \sigma D}, j_0 \right) \quad (5.29)$$

They showed experimentally that when ligament number is independent of feed rate it varies as $\omega^{0.833}$. Increasing any of the three main dimensionless groups enhanced the transition. Their theoretical analysis assumed the number of ligaments to be determined by the instability of the "column" of liquid making up the liquid torus at the rim of the cup. By calculating the optimum wavelength for growth on a column of this size, dividing this into the circumference and determining constants empirically they arrived at the expression

$$\text{ligament number} = 0.215 \left(\frac{\rho \omega^2 D}{\sigma} \right)^{0.417} \left(\frac{\sigma \rho D}{\mu^2} \right)^{0.17} \quad (5.30)$$

The first group is dimensionally incorrect. For ligament number to be dimensionless the expression should be amended to

$$\text{ligament number} = 0.215 \left(\frac{\rho \omega^2 D^3}{\sigma} \right)^{0.417} \left(\frac{\sigma \rho D}{\mu^2} \right)^{0.17} \quad (5.30a)$$

Their experimental results gave a broad spread of ligament number about the predicted value.

Peskin and Lawler (1962) re-examined the problem of predicting ligament spacing around the periphery of a disc. They considered that Taylor (rather than Rayleigh) instability would be dominant at the disc edge due to the high normal acceleration. The edge would therefore be unstable to all initial wavelengths of disturbance such that

$$\lambda > 2\pi \left(\frac{\sigma}{\omega^2 D \rho} \right)^{0.5} \quad (5.31)$$

Thus this expression describes the minimum spacing of the bulges at the disc edge from which ligaments form. It is interesting to note the predicted independence of ligament number on feed rate and the inverse relationship with angular velocity.

Eisenklam (1964) also applied Taylor instability theory to fluid at a disc edge. Assuming the initial disturbance to be of smaller amplitude than the thickness of the liquid torus he arrived at expressions identical in form to 5.31 which were applicable for two conditions

$$\lambda > \pi \left(\frac{24\sigma}{\omega^2 D \rho} \right)^{0.5} \quad \{ h \geq \lambda/\pi \} \quad (5.32)$$

$$\lambda > \pi \left(\frac{16\sigma}{\omega^2 D \rho} \right)^{0.5} \quad \{ h \leq 0.2 \lambda/\pi \} \quad (5.33)$$

so that

$$\lambda \propto D^{-0.5}, \sigma^{0.5}, \rho^{-0.5}, \omega^{-1} \text{ and } \mu^0 \quad (5.34)$$

This compares well with Hinze and Milborns' semi-empirical analysis in which

$$\lambda \propto D^{-0.42}, \sigma^{0.25}, \rho^{-0.58}, \omega^{-0.83} \text{ and } \mu^{0.33}$$

Using data from Frazer Dombrowski and Routley (1963) Eisenklam predicted a ligament spacing of 2.8 mm against observed spacings of 2.9 to 3.1 mm.

Kamiya and Kayano (1970), using stainless steel discs of 60 – 100 mm diameter rotated at 2500 – 6000 rpm to atomise water, observed that at very low feed rates the liquid rim from which ligaments develop can form on the surface of the disc some distance from its edge. For the 100 mm disc fluid this occurred at feed rates below 48 ml/min. Kamiya and Kayano described the flow of liquid on the disc in terms of velocity potential and arrived at a solution which implies that the film of liquid will grow out from the disc centre only until the number of ligaments formed at its edge is sufficient to remove liquid as rapidly as it is being supplied. They derived an expression for ligament number

$$\text{ligament number} = 0.233 \left(\frac{\rho \omega^2 r^3}{\sigma} \right)^{0.5} \quad (5.35)$$

$$= 0.233 (We)^{0.5} \quad (5.36)$$

which closely resembles the first term of Hinze and Milborns' empirically determined expression (Equation 5.26a). It fitted the experimental data well for flow on the disc surface, though when the same theory was applied to the disc edge only moderate agreement was seen with experimental results.

Frost (1981) investigated ligament number and the transition between modes of atomisation, using measurements from his toothless aluminium discs to provide the indices for a dimensionally derived model

$$\text{ligament number} = 0.29 \left(\frac{\omega \rho D^2}{\mu} \right)^{0.93} \left(\frac{\sigma \delta \rho}{\mu^2} \right)^{-0.44} \quad (5.37)$$

and observed ligament formation where

$$0.46 < \left(\frac{Q\rho}{\mu D} \right) \left(\frac{\omega \rho D^2}{\mu} \right)^{0.63} \left(\frac{\sigma D \rho}{\mu^2} \right)^{0.90} \quad (5.38)$$

He suggested that discrepancies between his work and that of Dombrowski and Lloyd (1973) and Kamiya and Kayano (1970) might be due to "differences in disc geometry".

Ligament spacing can be influenced to some degree by serrating the edge of the atomiser to give teeth, or "zero-issuing points". Such teeth effectively impose a large-amplitude disturbance on the torus of fluid at the edge of the atomiser so that the natural wavelength of disturbance is over-ridden and ligament number may be maintained despite fluctuations in rotation speed. Teeth also increase the disc feed-rate at which the transition from ligament to sheet disintegration occurs. Christensen and Steely (1980, cited in Lefebvre, 1989) give the dimensionally correct version of Hinze and Milborn's formula for ligament spacing (Equation 5.30a) as an expression for the optimum number of teeth on a disc, implying that the number of teeth should ideally match the number of ligaments which would occur from a smooth edge.

5.3 Disintegration of Ligaments

The processes bringing about the disintegration of a jet of liquid have been studied for well over a hundred years without being fully resolved. Parkin (1973) and Lefebvre (1989) have provided comprehensive reviews of the subject but a summary is given here, together with some recent developments.

Like other forms of atomisation the collapse of a cylindrical jet of fluid into droplets involves competing disruptive and cohesive forces. The key to its analysis lies in

determining which disruptive force (if any) will be dominant under given conditions. Four categories of jet disintegration are generally recognised.

i) Rayleigh instability breakup

At low jet speeds axisymmetric surface waves are present due to the effect of surface tension on initial disturbances of the ligament surface. These waves are stationary with respect to the jet and grow in amplitude until they "pinch off" a volume of liquid, forming a droplet. The thin column of liquid connecting adjacent bulges in the jet collapses to form a smaller, satellite droplet.

Rayleigh (1878) considered the idealised case of an inviscid, laminar, liquid jet unaffected by the surrounding medium. He compared the effect of a small disturbance on the surface energy of the jet.

$$E_s = \frac{\pi\sigma}{2d} (\gamma^2 + n^2 - 1) b_n^2 \quad (5.39)$$

where E_s = surface potential energy

d = jet diameter

b_n = constant in Fourier series expansion

γ = dimensionless wavenumber $= 2\pi/\lambda$

n = any positive integer

$n = 0$ for axisymmetric disturbances

$n = 1$ for sinusoidal disturbances

The jet is unstable to any disturbance resulting in a decrease in surface energy (E_s is negative) relative to the undisturbed jet. Rayleigh found this to be the case for any axisymmetric disturbance with wavelength greater than πd . His analysis also showed that the rate of growth of such disturbances varied with their wavelength, the maximum growth rate occurring at a wavelength corresponding to $4.51 \times$ jet diameter. Thus a jet subjected to a broad spectrum of periodic disturbances will preferentially amplify this particular wavelength. If all the fluid under one wavelength of this fastest-growing disturbance were to form a single spherical droplet a droplet diameter of $1.89 \times$ jet diameter would be expected.

Weber (1931) extended Rayleigh's analysis to include the damping effect of viscosity, finding an optimum wavelength for growth of

$$\lambda = \sqrt{2} \pi d \left(1 + \frac{3\mu}{\sqrt{\rho\sigma}} \right)^{0.5} \quad (5.40)$$

This relationship implies that increasing viscosity would result in a longer optimum wavelength, which would be expected to give rise to larger droplets.

Rayleigh's analysis was only a first order approximation of the collapse of a liquid jet. Subsequent non-linear analysis (reviewed in Parkin, 1973) showed that ligaments collapsing under capillary instability could give rise to more than one droplet size, providing a possible explanation for the observed phenomena of alternating main and satellite droplets and bi- or polymodal droplet spectra. Data from plain jet breakup reported by Parkin (1973) showed that at the optimum wavelength for growth the diameter of satellite droplets is in the order of 25% that of the main droplets. Satellites would therefore account for around 1.5% of the atomised liquid.

ii) First wind-induced breakup mode

As jet velocity is increased the relative motion of the jet and the surrounding air begins to be significant. Air moves more rapidly over the peaks than the troughs of the disturbances resulting in a variation in static pressure which augments their growth. Weber showed that this would decrease the wavelength of maximum growth rate. With further increase in velocity sinusoidal disturbances develop, suggesting that $n = 1$ rather than $n = 0$ modes of instability are now the most rapidly growing. Reitz (1978, cited by Lefebvre, 1989) describes droplet diameters of around one jet diameter for this condition. Higher values of n are theoretically possible but would result in an increase in surface energy and so do not contribute to the collapse of the liquid cylinder.

iii) Second wind-induced breakup mode

At even higher velocities the surface of the jet becomes unstable to axisymmetric disturbances which have wavelengths much smaller than the jet diameter. These arise purely from the relative motion of the jet and surrounding air, and are

opposed by surface tension. The disturbances are dragged out into thin ligaments which collapse into a range of sizes of droplet, all of which are much smaller in diameter than the parent jet.

iv) Complete atomisation

As jet velocity is increased still further atomisation occurs almost immediately after emission producing a broad range of droplet sizes, again much smaller in diameter than the jet. Though the mechanism for this must be a consequence of gas pressure fluctuations it has not yet been fully described.

Lin and Creighton (1990) used numerical methods to compute the contributions of surface tension and pressure forces to jet instability. Their calculations confirmed that surface tension forces dominated under Rayleigh instability conditions whilst gas pressure fluctuations dominated under complete atomisation conditions.

The disintegration of a jet can be complicated by changes in the flow regime within the jet as its initial velocity is increased. Above a critical Reynolds number the flow will be turbulent rather than laminar and the resulting radial component of the liquid's velocity will aid disruption of the jet. An associated factor is velocity profile relaxation which occurs once the jet is clear of the duct in which it was formed. The redistribution of forces involved can be disruptive, particularly in laminar jets, where the initial velocity profile is parabolic. The contribution is likely to be less in turbulent jets since their initial velocity profiles will be closer to "plug" flow.

An additional level of complexity is introduced when a jet is subjected to an airstream flowing normally to the jet axis. Several attempts have been made to quantify the effect of such a cross-flow.

Ingebo and Foster (1957) investigated the transition from first to second wind-induced breakup for jets in a cross-flow of air. They showed that droplet size decreased with increasing cross-flow velocity and correlated the decrease with a function of the ratio of Weber and Reynolds number. Ingebo subsequently predicted (Ingebo 1981) that the rate of decrease in droplet size as the product of the Weber and Reynolds numbers increased would be greater during second wind-induced breakup than during first wind-induced breakup, and found experimentally that such a change in rate occurred at a value for $We \times Re$ of 10^6 .

Kitamura and Takahashi (1976) found that increasing the air velocity increased destabilising effects at the jet surface, accelerating jet breakup and resulting in a shorter breakup length. Their high speed photographs showed disintegration by liquid disturbances at low air velocities and by sinuous wave formation at high jet velocities.

Gooderum and Bushnell (1972) observed water jets in gas cross-flows with velocities upto Mach 8. At low dynamic pressures breakup occurred by the two wind-induced methods described above but above a critical value aerodynamic shattering occurred. This critical value was associated with a Weber number of 4 to 6.

Ligaments produced from rotary atomisers have a lateral velocity component relative to the bulk of the surrounding air and so are in effect always subjected to a cross-flow. Dombrowski and Lloyd (1973) considered the effect of the consequent aerodynamic drag on ligaments produced by spinning cups. Atomising a liquid with a viscosity of $7.3 \times 10^{-3} \text{ Kgm}^{-1}\text{s}^{-1}$ from 0.05 and 0.10 m diameter cups they assumed that the radial velocity component of the escaping fluid would be negligible so that if it was unaffected by drag the liquid would form an involute relative to the lip of the cup. The spacing of ligaments along a tangent to the cup's edge was measured from photographs and a ratio of ligament velocity to peripheral velocity was calculated. They found that the initial velocity was maintained for a short distance from the lip before it fell by 13 to 19 percent and suggested that for a short distance after its escape the ligament is within a co-current of moving air induced by the rotating cup, citing Ryley (1959) as demonstrating the existence of such currents. Calculations were carried out to test the feasibility of the observed velocity decrease being accounted for using standard drag relations. Considering each element of fluid as part of a straight, infinitely long cylinder of radius R metres, normal to the direction of motion, a drag coefficient, f , of 1.5 could be assumed over the range of Reynolds numbers encountered during the experimental work. A force balance predicted the velocity of the cylinder at any distance, x , from its root:

$$U_x = U_0 e^{-(0.82 f x / \rho l 2R)} \quad (5.41)$$

Good agreement was seen between observed and predicted velocity ratios, despite the differences between the normal cylinder used in this model and the conic, swept ligament occurring in reality.

Crowther (1986) used high speed photography to observe the behaviour of fluid ligaments produced from 60 mm diameter, toothed, perspex discs at rotation speed from 1000 to 3000 rpm. The ligaments were well ordered at feed rates upto 260 ml/min but at higher feed rates, irrespective of rotation speed, they showed sinusoidal disturbances in the plane of the disc and liquid was seen to accumulate in the lee of the teeth. At flows above 350 ml/min Crowther described "premature break up" with an associated broadening of the droplet spectrum as measured by a laser imaging probe. Like Dombrowski and Lloyd he compared a ligament to a cylinder in a cross-flow of air. The flow around such a cylinder is well known to be smooth at low Reynolds numbers but as Reynolds number increases a point is reached where vortices are shed from alternate sides of the cylinder, inducing an oscillation in the cylinder itself. The Reynolds number for the onset of oscillation, based on free-stream velocity and cylinder diameter, is around 30 to 40. It would be difficult to obtain a Reynolds number for a swept, contracting and, as Dombrowski and Lloyd showed, decelerating liquid cylinder but on the basis of disc peripheral speed and taking an approximate final ligament diameter as twice the VMD, values of Reynolds number at the onset of the rapid rise in spectrum width were found to be 38, 50 and 55 at rotation speeds of 1000, 2000 and 3000 rpm respectively.

An additional factor in the disintegration of ligaments produced from rotary atomisers is mechanical stretching. Sanderson (1982), assuming an inviscid ligament with no initial radial velocity, showed that as a result of the rim of the atomiser moving away from the emitted liquid the ligament experiences an acceleration of $\omega^2 r$. Continuity dictates that the accelerating ligament must become thinner, but as its radius decreases its surface tension gives rise to a greater internal pressure and so the force arising from the atomiser's acceleration is opposed by a force due to this pressure gradient. The net acceleration, and hence the rate of contraction of the ligament, is determined by the balance of these forces. Since the diameter of the ligament is decreasing Sanderson argued that the optimum wavelength for growth of a disturbance would change along its length. He suggested a model in which the amplitudes of disturbances were followed incrementally over time, adjusting the rate of growth at each step until one amplitude was greater than the jet diameter. This model predicted that

$$d \propto \frac{Q^{0.25} \sigma^{0.09}}{\omega^{0.56} R^{0.19}} \quad (5.42)$$

An inviscid liquid was assumed and Rayleigh's first order approximation was used to calculate the rates of disturbance growth under circumstances where the disturbance amplitude is not negligible, but despite this the model agreed well with his experimental results (Equation 5.7).

Martien *et al* (1985) took the understanding of the dynamics of droplet formation a significant step forward by considering how the release of one droplet can influence the formation of the next. They used the time interval, T_n , between successive droplets falling from a dripping tap to indicate the repeatability (used in this context as a measure of stability) of the process of droplet formation over a range of liquid flow rates. The results were plotted as T_{n+1} versus T_n . At low flow rates a single cluster of points was obtained. With increasing flow rate a point was reached where two clusters were seen, indicating alternating longer and shorter time intervals. Further increasing the flow rate gave rise to four clusters. With still further increase the discrete clusters were replaced by a curve or "attractor" indicating the onset of chaotic behaviour, the intervals between successive droplets varying apparently at random but within the limits defined by the attractor. The complexity of the attractor increased with flow rate. Such "period doubling" followed by chaotic behaviour is a common pattern in dynamic systems in which small changes in initial conditions may result in large variations in outcome. The authors developed a model system in which a mass of fluid suspended from an orifice oscillated at a frequency which decreased as the mass grew. The mass of fluid broke away at a time which was sensitively dependent on drop size and position, setting the remaining mass of fluid into oscillation. The T_{n+1} versus T_n plots of data produced by this model showed qualitatively similar features to those produced by the real dripping tap, with period doubling and low dimensional chaotic motion. Though this work considered the process of direct droplet formation, it is reasonable to suppose that similar behaviour could arise in a jet of liquid from which droplets were breaking away, implying that under some operating conditions the shape and width of the resulting droplet spectrum could be determined by a similar sequence of behaviour.

5.4 Discussion

The descriptions of rotary atomiser behaviour in section 5.1 showed the same general trends in droplet size as operating conditions were varied but the magnitude of dependency on each parameter varied considerably. Some of the discrepancies might be accounted for by the different particle sizing methods used but it is reasonable to

conclude that differences in the experimental systems themselves were having a significant influence on atomiser performance.

One obvious difference between experimental systems is the presence or absence of discrete issuing points. For a smooth-edged disc increasing rotation speed will not only decrease droplet size directly but will also increase the number of ligaments and so reduce the feed rate per ligament so that a toothless disc might be expected to show a greater dependency on rotation speed than a toothed disc. This is supported by comparison of Sanderson's toothed disc with Frost's plain disc but contradicted by the performance of the toothed Micron X-1 atomiser tested in Chapter 4 and the low indices of other toothless discs. The lowest indices for rotation speed were around 0.58 to 0.6, suggesting that this is the limit reached when droplet size is influenced only directly by rotation speed. Sanderson's theory predicts a similar value. Clearly it is important that models for ligament disintegration (though not necessarily models of atomiser behaviour) give the flowrate per ligament. In some cases the spread of operating conditions is such that several modes of atomisation may have occurred in the course of an experiment. The relative occurrence of each mode would have an influence on any single empirical expression used to describe droplet production under all conditions.

Each of the stages of atomisation in Figure 5.1 can contribute to the overall performance of a rotary atomiser and must be considered in atomiser design or assessment. At the low feed rates and high rotation speeds required for ligament formation the liquid film formed on cups and discs is thin enough for much of its momentum to be lost through shear stress. It is probable that the radial velocity of the fluid would be small compared to the tangential component of its velocity as it left the disc (the close spacing of Hinze and Milborn's (1950) dye tracks and Norster's (1964) observations of ligament trajectory tend to support this) and only becomes significant for feed rates resulting in sheet disintegration, as seen by Dixon *et al* (1951). A more positive aspect of this high friction force is its role in reducing slip between the fluid and the disc, ensuring that the liquid acquires almost the same tangential velocity as the disc itself.

Since radial velocity is relatively small the main influence of feeder design and transport across the surface on performance will be through the distribution of liquid to the atomiser's edge. The work of Emslie *et al* (1958) showed that initial irregularities in the fluid feed will tend to level out with radial distance, but Kamiya and Kayano

(1970) and Reed and Saric (1989) have shown that at least two mechanisms exist by which new irregularities can arise. Conditions on the discs of the Micron X-15 and Forestry Commission X-30 atomisers tested in chapter 4 were similar to those under which Kamiya and Kamayo observed ligament formation on the disc surface (at an operating feed rate of 500 ml min^{-1} the flow per disc was 33 ml min^{-1} for the X-15 and 17 ml min^{-1} for the X-30, with rotation speeds higher than those used by Kamiya and Kayano) and so this effect could account for the failure of these devices to produce useful volumes of droplets with diameters below $30 \mu\text{m}$. Roughening the disc surface can delay the onset of ligament formation, possibly by encouraging cross-flow vortices. However, the vortices themselves would lead to a deterioration in the uniformity of feed. Spreading a fixed volume of fluid over a greater number of discs does not therefore automatically guarantee an improvement in atomisation; for a given disc and rotation speed there is a limit to the benefit gained.

One solution to fluid distribution problems of this type would be to guide the liquid into radial channels before irregularities can develop. For a disc this would mean a reduction in the number of *potential* issuing points on the rim of the atomiser but if premature ligament formation was avoided the *actual* number of issuing points would be increased. On a rotating vane atomiser grooves would not affect the number of potential issuing points per unit length of vane. However in both cases there would be little opportunity for initial disturbances to even out so the uniformity of the liquid feed system would be of particular importance.

Descriptions of the transition from direct droplet formation to ligament disintegration with increasing rotation speed of a toothed disc often refer to a stage in which both types of break-up occur together, suggesting a variation in liquid feed rate to the teeth. Even with perfectly uniform distribution to the disc edge such a variation could arise if the scale of the natural disturbance wavelength at the edge of the disc was sufficient to cover several teeth, since the tooth-induced disturbances would be superimposed onto a non-uniform distribution of fluid around the disc. In designing a rotary atomiser with a plain surface the expected natural ligament number should be calculated from the expressions of Peskin and Lawler (Equation 5.30) or Eisenklam (Equations 5.31 and 5.32) and the tooth number matched to this. Again the problem would be avoided by using channels to pre-divide the liquid.

Though the initial velocity of fluid ligaments (relative to a fixed point) is dominated by the peripheral speed of the atomiser Walton and Prewett's (1949) data suggested that

for a given peripheral speed, ωr , droplet size increased with the diameter of the atomiser. This influence would be accounted for by ligament stretching, which Sanderson (1982) showed to occur at a rate of $\omega^2 r$. Thus small droplets will be produced with the least difficulty from small diameter atomisers.

Turbulent flow has been mentioned as a disruptive influence within ligaments. The onset of turbulence in plain jets is typically discouraged by the use of long, gently tapering approaches to the exit orifice. Though the flow of liquid from the surface of a rotary atomiser into a ligament is complex it is possible that the observed benefits of long, gently tapering teeth might arise from a similar stabilising influence.

Disintegration of liquid jets produced by rotary atomisers operating in ligament mode has generally been considered to occur by simple capillary instability. However such jets are as susceptible as any others to the other three types of jet disintegration described and it seems likely that these would contribute to the performance of an atomiser, particularly at high rotation speeds. The onset of $n = 1$ mode, the first-wind-induced breakup mode, could provide an alternative explanation to vortex shedding for the sinusoidal disturbances seen by Crowther, though either mechanism might be possible given appropriate conditions. Predicting the operating conditions at which each type of atomisation will occur is made difficult by the shape of ligaments and the problem of determining the relative velocity of the air flow. Changes in the prevailing type of disintegration should be discernible in the droplet spectrum produced and by changes in the dependency of droplet size on operating parameters.

The success of Sanderson's theoretical model suggests that the principle disturbance wavelength determined by Rayleigh's first order analysis gives a good indication of VMD arising from disintegration by capillary instability. This is reasonable since the largest droplets produced contain the bulk of the liquid from the ligament. However the smaller satellite droplets will be extremely mobile and could result in the transport of spray over large distances outside the target area. Whether or not the small volumes of chemical involved would cause any actual harm the perceived risk might be sufficient to prejudice opinion against spraying operations.

6) Experimental Study

The previous chapter provided some insight into the processes involved in rotary atomisation and demonstrated the influence of a range of design parameters on rotary atomiser performance. However it also showed the difficulty of predicting behaviour quantitatively in any but the simplest cases and so an experimental programme was set up with the aim of determining operating conditions under which the optimum droplet spectrum for tsetse control by non-residual insecticide application could be achieved.

6.1 Methods for Observing the Atomisation Process

i) Disc drive systems

With the exception of the large disc used for the shear-stress experiment atomiser discs were mounted on an air motor driven from a compressor. This system was capable of speeds far in excess of those that could be achieved using electric motors without the need for the additional complexity of gearing. Speed was adjusted using a needle valve in the air-line and was easily controlled to within two percent of the chosen value. The disc used in the shear-stress experiment was considerably heavier than the other experimental discs and had to be driven by an electric motor, the speed of which was controlled from a variable power supply.

ii) Stroboscopic Observation

A stroboscopic light was used to freeze the apparent motion of the disc, allowing direct observation of the atomisation process. In order to cope with minor variations in rotation speed the discs themselves were used to trigger the strobe. A capacitive sensor produced a signal each time it was passed by a copper tag or brass screw fastened to the disc base. This provided the input for a digital frequency counter which processed the sensor signal into a TTL logic-level pulse and gave a measurement of rotation speed in cycles per second, the processed pulse also triggering the strobe. At high rotation speeds the pulse rate exceeded the maximum operating speed of the strobe and so an additional logic circuit was added which divided the number of pulses by a selectable power of two (Figures 6.1(a) and (b)). In this way the pulse rate could always be kept within the optimum range for the stroboscope.

iii) Spark Photography

An extremely short exposure time was required to capture the process of atomisation. This was achieved using an argon jet spark source as the means of illumination. The spark, generated by the discharge of low inductance capacitors arranged symmetrically around a gap flooded with argon, is bright, compact and lasts only 300 nanoseconds. Light from the spark source was focused onto a pinhole located at the focal point of a Schlieren mirror. The mirror collimated the light, reflecting it into a 35mm SLR camera fitted with extension tubes and a 50mm lens which was opened up to its maximum aperture. Atomiser discs were mounted between the mirror and the camera, resulting in a shadowgraph image of the fluid leaving a section of the atomiser rim (Figure 6.2). A photograph was taken by blacking out the room, opening the camera shutter and firing the spark source. The film used was Ilford HP5, a monochrome film which gave good contrast and acceptable grain together with the necessary speed.

Most of the atomisers investigated in this section of work issued liquid from only one or very few points around their rims. To ensure that these points always appeared in the photographs it was necessary to discharge the spark source at a fixed point in the atomisers' rotation. This was achieved electronically (Figure 6.1(b)) using the pulses from the strobe control circuit; once the firing switch was pressed the next pulse would trigger the spark source. Further pulses were blocked until the switch was released, preventing multiple exposure.

iv) Droplet Sizing

Droplet sizing was carried out using the PMS imaging probe described in chapter 2. Because of the delay in achieving the fine resolution optical system measurements on the first experimental ligament generator, TR1, were made using the coarser configuration.

As a result of their drag characteristics the velocities of different sized droplets begin to vary once they leave an atomiser. Because the PMS probe samples temporally rather than spatially its measurements are independent of the droplets' horizontal velocities. However sedimentation rates also vary with droplet size and, since the sampling plane is of limited depth, the probe was positioned as closely as possible to the region of droplet formation so

that measurements were taken before larger droplets had fallen out of range. The angle between the probe and the disc was such that most of the spray passing through the sample area did so in a direction normal to the diode array. The distance between the probe and the disc was short enough for evaporation to be insignificant during transit.

6.2 Use of Shear-stress Sensitive Paint in an Attempt to Visualise Flow on a Rotating Disc

The literature indicated that shear-stress has a profound influence on the flow over the surface of a rotating disc. An attempt was made to visualise shear-stress patterns on the surface of a PVC disc using a shear-stress sensitive paint (BDH Thermochromics TM622 (R49C)).

i) Experimental procedure and observations

The disc was 91mm diameter with a sharp edge and a central well 0.8mm deep and 34mm in diameter. Its surface was polished, cleaned with 1,1,2-trichloro, trifluoroethane and painted with a thin layer of the sensitive material which was then activated by radial brushing with a soft paintbrush. The result was a copper-coloured surface layer which should turn green when subjected to shear stress.

The disc was spun up to 14000 rpm to see whether the forces imposed would be sufficient to induce a colour change. The colour changed from copper to green as the disc was accelerated. This change appeared uniform across the disc except for a small area in the centre which remained copper-coloured. In less than a minute the paint had been centrifuged off the disc. Roughening the surface of the disc with fine glasspaper did not improve the paint's adhesion.

The disc surface was repolished then cleaned and painted as before. A feed pipe was positioned over the centre of the disc and tapwater applied at a rate of around 200 ml/min while the disc was spun up to 3000 rpm. The colour change from copper to green occurred at lower rotation speeds than on the dry disc and some variation with radial position was apparent in the form of a distinct band about 10mm wide stretching outward from the edge of the well. The paint quickly washed off the outer part but the inner band remained coated even after the outer part was completely clean. On stopping the disc streak lines were visible in the surface of the paint, suggesting that the adjacent fluid had been moving radially while lagging behind the disc in angular velocity.

A 100 ml long rectangular aluminium rod with a 45^0 groove cut along one face was also tested. It was mounted symmetrically on the electric motor so that the grooved face was orthogonal to the plane of rotation. Initially the surface was cleaned and painted in the same way as the disc but the copper colour was not visible on the aluminium surface. The rod was cleaned, painted with matt black paint, polished smooth with glass-paper, cleaned again and painted with the sensitive material. This time the copper colour was visible. The groove was spun and viewed under stobe-light but no colour change was apparent. Some paint remained on the rod even after prolonged spinning. The PVC disc was given the same matt black treatment, painted and spun with water. As previously paint was lost rapidly from the outer edge while being retained closer to the centre. This time, however, no colour change was seen, implying that the paint treatment was rendering the paint ineffective. With this combination of surface and lighting spiral disturbances could be seen in the film of liquid on the disc.

ii) Discussion

The shear-stress paint was affected by the stress levels experienced on a spinning disc but the type of paint tested was of limited use for two reasons: it was not sufficiently viscous to remain on the disc when subjected to high acceleration forces and the colour change was an all-or-nothing process giving no indication of continuous variation in shear stress. In fact the behaviour of the paint layer during the wet trials resembled that of the oil-films conventionally used for flow visualisation. Though no information was gained concerning shear-stress distributions this analogy suggested that the distinct region showing complete loss of paint during these trials may have arisen through a change in flow regime on the disc surface, perhaps from a laminar, two-dimensional flow to a more disruptive three-dimensional flow with crossflow vortices as described by Reed and Saric (1989). Photographs of the spiral disturbances seen when using the matt-black disc suggested that these disturbances originated at the radius where paint loss began (Figure 6.3). Tracings were taken from the photographs, tangents were drawn to each clearly defined spiral at several points and the angles of these tangents to the disc radius were measured. The results are shown in Table 6.1, the mean angle being $110^0 \pm 8\%$. This is very close to the value of 109.45^0 predicted by Malik (1986b, cited by Reed and Saric (1989)) as a possible angle for crossflow vortices. Malik predicts the onset of such vortices at a Reynolds number of 285. Disturbances on the

experimental disc began at a radius of around 0.027m, giving a Reynolds number at 3000 rpm of 230. The similarities between Malik's predictions and the experimental values suggest that such vortices are a likely explanation for the observed flow disturbance.

A consequence of such a flow would be uneven distribution of fluid to emitting points at the disc edge, resulting in an increase in droplet size and spectrum width. Such flows would not occur in the grooved rod, and the retention of paint along its full length suggests that a smooth flow persists.

6.3 Use of a Small Diameter V-Channeled disc

It was concluded in chapter 5 that small droplets could best be produced using small-diameter atomiser discs rotated at high speeds and by confining the fluid in channels, avoiding lateral expansion, premature ligament formation and cross flow vortices.

In order to investigate such systems a disc, designated TR1, was constructed (Figure 6.4). Diameter was kept small and the design was intended to constrain the fluid in forty-five V-shaped channels. It was assumed that the Coriolis force would be sufficient to force the fluid against the trailing edge of the channel, giving a flow regime which might allow radial acceleration to contribute to the final ligament velocity. Teeth were cut into the disc's edge to provide each channel with a sharp issuing point.

i) Experimental procedure and observations

Fluid was supplied from above using a hypodermic tube fed from a pressurised container via a Rotameter flowmeter. The test liquid was tapwater with a surfactant (0.1% Agral). Rotation speeds of around 26000 rpm were attained with feed rates from 16 to 111 ml/min (0.35-2.47 ml/min per tooth).

The system's behaviour was observed using the coupled strobe-light. At lower speeds the familiar pattern was recognised, with direct droplet mode changing to ligament mode as speed was increased. The ligaments originated from the base of the teeth rather than from the trailing edge of the V-shaped channels. The system of closed channels prevented the transition to sheet disintegration at higher feed rates but as rotation speed was increased the

ligaments became increasingly unstable. Initially a sinusoidal disturbance appeared but at the highest speeds the atomisation mechanism became a shattering process which occurred adjacent to the edge of the disc.

Particle sizing was carried out using the PMS probe in its coarser configuration. Table 6.2 and 6.3, and Graphs 6.1 and 6.2 show the variation in VMD and span with rotation speed at the three flowrates tested. The initial drop in VMD followed by a slower decrease is commensurate with the observed transition from direct droplet formation to controlled ligament disintegration. The speed at which the transition occurred increased with decreasing flowrate. At higher speeds first the 2.47 ml/min/tooth curve and then the 1.22 ml/min/tooth curve showed a sudden drop in VMD. The lowest flowrate showed no such drop. Instead VMD became constant and then began to rise slightly with increasing speed. For the two higher flowrates trends in the variation of relative span were the same as those seen in VMD. The lowest flowrate showed an inverse relationship between span and VMD.

ii) Discussion

Direct observation under the strobe light was made difficult by the small size of the ligaments formed. It is possible that the discontinuities in the particle sizing plots were associated with the transition from controlled ligament disintegration to the more random process observed at higher speeds. However no firm conclusions could be drawn because of the erratic way in which fluid was emitted. There is no obvious reason why the lowest flowrate should behave differently than the two higher rates.

Several explanations for the breakdown of controlled ligament disintegration seemed possible. These included factors reviewed in the previous chapter - disturbances produced by the axial and lateral movement of a cylinder of liquid through air, the development of turbulent flows within the ligament, and the possibility of chaotic behaviour during the production of droplets. However the behaviour of this first experimental disc could also have been complicated by the lack of good issuing points, the possibility of mechanical disturbances due to imperfect balancing of the disc and the difficulty of feeding 45 channels uniformly. In order to carry out a more detailed investigation over a range of conditions a simpler system was required from which as many extraneous factors as possible could be eliminated.

6.4 Development of an Experimental Ligament Generator

A device with only six channels, designated TR3, was constructed (Figure 6.5). As with the first device the channels were triangular in section and were fed from a deep central well. Diameter was increased from 20 to 30mm in order to allow greater rim velocities to be achieved. Liquid (water with 0.1% Agral) was supplied via a hypodermic needle fed from a syringe pump (Sage Instruments 341A) at 6.48 to 25.3 ml/min (1.08 to 4.21 ml/min/tooth).

The value of discrete "zero" issuing points in establishing a stable pattern of ligaments has been discussed previously. This device presented an opportunity to test their importance in a situation where fluid was already divided into ligament-forming streams. Accordingly the edge of the disc was initially left without teeth. The disc was operated over the range of flowrates at speeds from 3000 to 24000 rpm, giving rim velocities of 4.7 to 37.7 m/sec. Photographs were taken using the spark-tube as a direct light source rather than in the shadowgraph arrangement. From these pictures it could be seen that fluid was being emitted unevenly from all three corners of the triangular channel (Figure 6.6). At all but the highest speed fluid did not leave the disc at the mouth of the channel but adhered to the disc edge for some distance before finally separating to form ligaments.

The three-way emission of fluid at most rotation speeds suggested that liquid in the central well spread up the inner wall and entered the channels from all sides before collecting in the three corners, Coriolis force being insufficient to drive it into the trailing corner of the channel. A single ligament was achieved by partially blocking the entrance of each channel with plastocene so that only the trailing corner was fed directly.

Teeth were cut into the disc edge to give disc TR4 (Figure 6.7). This was tested as before. Fluid was seen to escape from almost any angular part of the disc edge unless the channel mouth was partially blocked with plastocene as above. Once this was done, however, the teeth ensured immediate separation of the ligaments.

By collecting in the corners of channels, the free surface of the liquid, and hence its surface energy, is minimised. The reduction in pressure due to the concave surface of liquid in a corner must encourage more liquid to flow towards corners. The tendency to cling to the

outside wall of the disc is a manifestation of the Coanda effect, shown by Keller (1957) to be a result of vortex flow (rather than a surface tension phenomenon). Another consequence must be the complete loss of any radial velocity gained by the fluid during its acceleration down the channel. The resultant velocity of the escaping ligament is thus decreased, giving rise to bigger droplets than would be produced at the same speed and flowrate if the fluid had escaped directly from the channel. On a multi-issuing point device the resulting unchannelled flows might merge or divide unevenly, leading to further deterioration of the droplet spectrum. It can be concluded that even when fluid is divided into discrete ligament-forming streams sharp issuing points are of value on spinning disc atomisers except at very high peripheral speeds. Because of the complex edge behaviour seen and the possibility of an uneven distribution of liquid between the six channels disc TR4 was considered unsuitable for a detailed study of ligament disintegration.

The behaviour of the devices tested upto this point had shown that fluid does not readily slip from the corners of an enclosed V-shaped channel. A simple disc, TR5, was constructed with a central well and a single, open V-shaped groove terminating in a tooth (Figure 6.8). A diameter of 0.05m was chosen as a compromise between the weight, power requirements and atomisation advantages of a small disc and the need for a high peripheral speed. This disc was found to be unsuitable as a ligament generator since liquid was seen to escape from the groove at all but the lowest speeds and flowrates (Figure 6.9). It is possible that this was encouraged by aerodynamic factors.

It was now apparent that a disc for the study of ligament behaviour would require an enclosed channel, free of internal corners and terminating in a single sharp tooth. Three versions of an appropriate device, designated TR6, TR7 and TR8, were produced (Figures 6.10, 6.11 and 6.12). Fluid could enter the circular channel from any point of its mouth but the lack of angles within the channel encouraged most of the fluid to form a single stream, as demonstrated by the behaviour of TR7 (Figure 6.13). The "zero issuing point" of TR6 produced a single ligament but the exposed tooth face was thought to be susceptible to aerodynamic interference. TR8 produced a single ligament under a wide range of operating conditions and was used in the subsequent investigation.

6.5 Investigation of the Mechanisms of Ligament Disintegration from Disc TR8

A brass screw was inserted into the disc's base to trigger the capacitative sensor. The disc was fitted onto the air motor, which was held horizontally so that the disc was free to rotate in the vertical plane. In this position the disc rotated until the heaviest point was lowest. Another brass screw was inserted opposite to this point and its head was filed away until the disc showed no preferred resting position when it came to rest after being spun. The balanced disc could reach rotation speeds in excess of 42000 rpm without severe vibration. The air motor was turned so that the disc was horizontal and a feed system arranged so that liquid could be fed from above using the syringe pump and a hypodermic needle with its tip ground flat.

i) Photographic study

Photographs were taken using the arrangement in Figure 6.2. The disc was fed water with surfactant (0.1% v/v Agral) at flowrates of 0.37 to 5.12 ml/min. Rotation speeds of 6000 to 33000 rpm were attained, giving peripheral speeds of 15.8 to 86.4 metres/second. Six photographs were taken at each condition. Typical pictures for each condition are given in Figures 6.14 to 6. 33.

The pattern of behaviour shown in the photographs followed the general trends seen with disc TR1 but considerably more detail was apparent. At low flow rates the ligament curved smoothly and disintegrated by axisymmetrical wave growth. Main and satellite droplets could be seen to follow diverging tracks, reflecting their differing drag characteristics. With increasing rotation speed and flow rate the ligament became more irregular in shape and under some conditions sinusoidal disturbances could be seen. As speed or flow rate were raised further, the ligament became increasingly unstable. The sinusoidal disturbance became more pronounced and sections several axisymmetrical disturbance wavelengths long sometimes broke free before collapsing into droplets. At the highest speeds and flow rate the ligament shattered, yielding a broad cone of irregular-sized droplets. Where shattering occurred it did not begin immediately adjacent to the tooth but after a short length of stable ligament. The behaviour of each combination of speed and flow rate is summarised in Table 6.4.

Two other phenomena were noted. At 12000 rpm and a flow of 5.045 ml/min distinct protruberences occurred on alternating sides of the ligament, while under most conditions the

root of the ligament exhibited waves of the type described by Bohr (1919). The latter occur because the newly-formed ligament is not initially circular in cross-section. Surface tension pulls the liquid into a circular cross-section but the kinetic energy gained by the liquid is sufficient for it to "overshoot", returning to an oblate cross-section with the major axis orthogonal to that of the initial state. This in turn collapses, resulting in oscillations which, though stationary relative to the disc rather than to the ligament, resemble the $n = 2$ mode of vibration (Peskin and Lawler 1962) and so damp out (see chapter 5.2.i.(b)).

The lengths of the ligaments were measured from the photographs. Mean lengths for each condition are given in Table 6.4 together with a coefficient of variation (defined as standard deviation of the measured lengths divided by the mean). The latter was similar in all cases; it tended to increase slightly with rotation speed but this was most probably a consequence of the increased difficulty in measuring the smaller and less regular ligaments obtained.

The ligament length data was best described by the expression

$$L = 276 \times Q^{0.517} \times N^{-0.424} \quad (6.1)$$

where L = breakup length (mm)

Q = flowrate (ml/min)

N = rotation speed (rpm)

This gave a value for R^2 of 78.6%. The lengths predicted by the model are given in Table 6.5 and compared with the measured values in Graph 6.3.

ii) Droplet size study

Particle sizing was carried out as described previously using disc TR8 with water containing surfactant (0.1% v/v Agral) and with the Thiodan and JF9436 blank insecticide formulations, at flowrates of 0.37 to 4.93 ml/min and rotation speeds of 6000 to 42000 rpm. Results are given in Tables 6.6 to 6.8.

The variation of VMD with rotation speed followed a similar pattern for all three liquids, with logarithmic plots showing two distinct regions (Graphs 6.4 to 6.6). In both regions VMD

declined with increasing rotation speed but the rate of decline was greater at speeds above 20000 rpm than below this value. The most viscous formulation, JF9436, showed a distinct plateau between these two regions which persisted over a change in rotation speed of several hundred RPM at all four flow rates. The less viscous Thiodan formulation showed some sign of a plateau at the two lowest flow rates while water with surfactant showed the least sign of this behaviour. The results for water with surfactant were compared with the observed ligament behaviour (Table 6.3) and the appropriate mode-indicating letters were appended to the points on the graph. The more steeply sloping region of the graph was associated with rotation speeds and flow rates at which the fluid ligament was becoming disturbed.

Graphs 6.7 to 6.9 show the variation of relative span with flow rate and rotation speed. The relationship cannot be described by a simple equation and at first sight the behaviour of the three formulations seems to differ, but there are discernable trends which occur throughout the data and from which only single data values tend to deviate. The generic shape of the curves shows relative span first increasing and then declining with increasing rotation speed. In most cases relative span increased with flow rate. The disintegration mode letters were again added to the plot for water with surfactant (Graph 6.7). Transition from axisymmetric wave growth (mode A) to a sinusoidally disturbed ligament (mode B) was always accompanied by a decrease in relative span while transition from this mode to the more erratic mode C was accompanied by a relative span increase. This increase levelled off with the onset of the shattering mode, D.

iii) Regression analysis

The effects of flowrate, rotation speed, surface tension and viscosity, on droplet size were investigated by multiple linear regression, using the statistical software package Minitab. A regression based on all the VMD data for disc TR8 gave the equation

$$\text{VMD} = k_1 N^{-0.68} Q^{0.19} \mu^{-0.22} \sigma^{0.70} \quad (6.2)$$

which fitted the data with a value for R^2 of 90.7%. With VMD in micrometres, N in rpm, Q in ml min^{-1} , μ in $\text{kgm}^{-1}\text{s}^{-1}$ and σ in Nm^{-1} the value of k_1 was 1×10^5 .

The two stage relationship between VMD and rotation speed suggested that a more accurate model might be achieved by considering the two regions individually. VMDs measured at rotation speeds above and below 20000 rpm were treated separately to yield two regression equations

$$\text{VMD} = k_2 N^{-0.54} Q^{0.27} \mu^{-0.07} \sigma^{0.94} \quad \{ N \leq 20000 \quad (6.3)$$

$$R^2 = 92.9\%$$

$$\text{VMD} = k_3 N^{-1.11} Q^{0.14} \mu^{+0.02} \sigma^{0.51} \quad \{ N > 20000 \quad (6.4)$$

$$R^2 = 88.9\%$$

With units as for equation 6.2 $k_2 = 186209$ and $k_3 = 25118864$. A comparison of measured and predicted VMD using equations 6.3 and 6.4 is given in Graph 6.10.

iv) Droplet spectra

The distribution of droplet sizes produced by disc TR8 varied considerably with operating conditions and formulation, resulting in spectra which were often complex and polymodal. Detailed structure was most apparent in plots of volume spectra.

The behaviour of water + 0.1% Agral was the simplest, with a bimodal volume spectrum at lower rotation speeds generally collapsing to a single peak as rotation speed was increased. Conditions associated with the onset of breakup mode B were accompanied by a slight narrowing of the spectrum while with the onset of mode C the spectrum appeared to broaden. Under conditions at which mode D was observed there was a marked broadening of the volume spectrum and a reduction in the height of distinct peaks.

The two oil-based formulations showed more complex behaviour. For the two lower feed rates their volume spectra were unimodal at the lowest rotation speeds. As rotation speed increased they became first polymodal and then unimodal again. At the two higher feed rates the Thiodan volume spectra were polymodal at all but the two highest rotation speeds while the JF9436 volume spectra were polymodal under all conditions, though their complexity

decreased at the highest speed. At their most complex the JF9436 volume spectra comprised several main peaks, each of which was divided into two distinct summits.

In order to compare the structure of volume spectra produced by the three formulations bar charts were plotted showing the droplet diameter size-classes in which the summits of the main volume peaks (defined as those which spread over more than one size-class) occurred at each rotation speed and feed rate (Graphs 6.11 to 6.14). This approach revealed underlying similarities between the spectra that were not obvious from direct comparison, with peaks tending to occur in or near to the same size classes for each formulation under the same operating conditions. Under conditions giving polymodal spectra the peaks tended to occur in distinct bands. Spectra from each formulation had peaks which fell into these bands at several rotation speeds, though no formulation had a peak at every rotation speed in each band.

v) Discussion

The combination of the OAP-260X particle measuring system, a coupled strobe-light and spark photography provided a comprehensive system by which ligament disintegration from disc TR8 could be studied.

The design of disc TR8 eliminated fluid distribution problems so that atomising performance was due solely to ligament behaviour. It was suggested in Chapter 5.3 that ligament disintegration from a rotary atomiser might occur by means other than pure capillary instability. The photographic study shows this to be the case, with capillary instability, first and second wind-induced disintegration and shattering all occurring in a manner analogous to the disintegration of a plain jet from a fixed nozzle. The analogy did not extend to breakup length, the ligament becoming shorter with increasing rotation speed regardless of disintegration mechanism. This could reflect the greater importance of aerodynamic factors and ligament stretching in the breakup of ligaments from rotating discs.

Transition from capillary instability to wind-induced instability was reflected in the dependency of droplet size on operating parameters. The regression equation for the lower rotation speed region (equation 6.3) showed a dependency on rotation speed and feed rate which was very close to that of Sanderson's model (equation 5.42), suggesting that VMD is

dominated by the largest droplets produced by capillary instability in the stretching ligament. The dependency on fluid characteristics does not agree well with Sanderson, probably because of the limited data available using only three fluids. The sharp drop in VMD at higher rotation speeds is consistent with the change in ratio of droplet diameter to ligament diameter associated with a transition from capillary instability to wind-induced breakup. Droplet diameter in this higher speed regime is predominantly influenced by rotation speed, reflecting the importance of relative air speed to disintegration under these conditions. Prediction of the transition between the two regimes on the basis of a critical value of some dimensionless number describing flow (the analogy with plain jet disintegration would suggest Ohnesorge number) would require a good model of air flow relative to the swept ligament.

The short stable region of ligament before the onset of shattering suggested that shattering was a result of the crosswise movement of the ligament through the surrounding air (the stable region being within the layer of air entrained by the disc) rather than an example of the type of complete disintegration seen when a high velocity jet is injected into stationary air (chapter 5.3 (d)). The experiments of Gooderum and Bushnell (1972) found that critical Weber numbers for the onset of shattering were between 4 and 6 for a plain jet in a cross-flow of gas. An accurate calculation of Weber number for the ligaments formed from water with surfactant using disc TR8 was not possible because of uncertainties in the direction and magnitude of air flow with respect to the ligament and in the surface tension of the ageing ligament surface. However an estimate could be made (see appendix 3). The onset of shattering was observed at the highest feed rate between the rotation speeds of 18000 and 24000 rpm. The estimated Weber numbers at these two rotation speeds, 3.61 and 5.55 respectively, were sufficiently similar to Gooderum and Bushnell's critical Weber numbers to suggest that shattering was occurring by a similar mechanism.

The significance of relative span as an indicator of performance can be seen from the particle sizing data in Tables 6.6 to 6.8. Two sets of conditions producing a spray with the same VMD can differ greatly in the proportion of output volume which falls into a given droplet size range because of differences in the width of their volume spectra. Such differences were accurately reflected in values of relative span. The relative span values obtained using disc TR8 could be considered to be the lowest values that an atomiser might achieve under ideal conditions, where the nature of ligament disintegration and consequently the shape of the droplet spectrum is the limiting factor. In practice higher relative spans would be expected

from practical atomisers because of additional factors such as mechanical vibration and irregularities in liquid feed.

The single stage regression model for TR8 (equation 6.2) was similar to the regression model produced for the Micron X-1 atomiser (equation 4.4) tested in chapter 4.3.vi. Since the Micron X-1 has a 50mm diameter toothed atomiser disc a comparison of performance can be made, though it should be noted that the Micron X-1 was tested in a wind tunnel. Graph 6.15 and Table 6.9 show the measured values of VMD obtained in the Micron X-1 trial together with the values predicted by the Micron X-1 regression model and the two stage TR8 regression model. Each model is a good fit for the data set from which it was derived and so it can be concluded that, despite the additional component of air velocity provided by the wind tunnel, the Micron X-1 produces a spray with a larger VMD than disc TR8 for a given set of conditions. As expected (see above) relative spans are greater for the Micron X-1 than for disc TR8, and this would account for the greater VMD. The difference in relative span is also reflected in the proportions of spray volume falling into the target droplet size ranges.

6.6 Conclusions

Data obtained from the large disc used in the shear stress-sensitive paint trial showed that cross-flow vortices in the film of liquid on a rotating disc are a potential source of uneven liquid distribution. The various devices tested during the development of a prototype ligament generator showed that channels used to avoid such cross-flows are most effective if they are enclosed and lack sharp corners. The presence of teeth ensures that all the liquid in a channel escapes from a single point. In the absence of a sharp issuing point liquid may flow along the outer rim of the atomiser. On perforated drum-type atomisers this could lead to merging of ligaments, resulting in a deterioration in droplet spectrum.

The series of experiments with disc TR8 supported the assertion made at the end of the previous chapter that ligaments produced by spinning discs are susceptible to the same modes of disintegration as plain jets injected into still air. It was shown that the effective cross-flow of air due to the rotation of the disc had a significant influence and could lead to premature shattering of the ligament. Under ideal conditions the performance of a rotary atomiser is limited by the mechanism of ligament disintegration.

The problem of modeling air flow around ligaments produced by rotary atomisers, and hence in determining the exact manner of their disintegration under given conditions, makes accurate, universal predictions of atomiser performance difficult. This difficulty is compounded when the atomiser is mounted in the slipstream of an aircraft, particularly when atomisation is occurring by a wind-induced mechanism. Until more detailed knowledge of such air flows is achieved predictive models can at best provide guidelines for prototype design and act as tools to help explain behaviour seen during prototype testing.

In absolute terms the results obtained using disc TR8 showed conditions under which a 50mm diameter rotary atomiser could produce droplets in the two target size ranges specified in chapter 1. At a feed rate of 0.37ml/min and a rotation speed of 36000 rpm 95% of the total volume of water + surfactant applied was broken into droplets of less than 33.2 μ m diameter, with a VMD of 27 μ m and a relative span of 0.463. Thiodan gave the same VMD but because of its broader, more complex spectrum (relative span 0.661) only 87% of total volume formed droplets less than 33.2 μ m in diameter. Under the same conditions JF9436 gave a VMD of 39 μ m with a relative span of 1.097. Analysis of the volume spectra showed that JF9436 spectra tended to have peaks at the same droplet diameters as the other two formulations but had additional peaks at larger sizes. These would account for the greater VMD and relative span. At 6000 rpm and a feed rate of 0.93 ml/min the fractions of volume falling in the 82.5 - 122.5 μ m diameter size range were 66% for Thiodan and for Water with surfactant, and 69% for JF9436.

Comparison with data from the Micron X-1 atomiser showed that the ideal performance of disc TR8 would be difficult to achieve with a practical atomiser. However given a suitable atomiser design and operating conditions it should be possible to emit a large proportion of liquid volume as droplets with diameters in the target ranges.

7) Development of a Prototype Atomiser I: Feed System

It was concluded in Chapter 4 that no existing atomiser offered a practical solution to the problem of producing fine aerosol droplets in the quantities required for tsetse control by non-residual aerial spraying. A programme of work was therefore begun to design more suitable atomisers on the basis of the conclusions reached in Chapters 5 and 6. This chapter describes the development of a liquid feed system capable of distributing the small amounts of liquid required to a large number of issuing points at high rotation speeds.

7.1 Requirements

The target droplet size-range was defined previously (Chapter 1.5.(i)) as 20 to 30 μm diameter. For the application of an involatile insecticide formulation from fixed wing aircraft a total volume output in the order of 0.5 litres per minute is required.

From the conclusions reached in the previous chapters it had become apparent that an atomiser designed to meet this droplet size specification should be of small diameter, maximising the acceleration of liquid ligaments produced at a given peripheral speed and minimising the problem of obtaining a uniform fluid distribution. A small diameter would also minimise centrifugal loading, allow the atomiser to be of relatively light weight construction (compared, for example, to the Micronair AU5000 or Beecomist 360) and reduce drag on the aircraft. A diameter of 50mm was considered as meeting these criteria. The design should be such that any irregularities arising from the liquid feed or which develop as liquid flows towards the issuing points are levelled out.

Disc TR8 (Chapter 6) demonstrated conditions under which a large proportion of droplets could be produced in the target size range using a 50mm diameter spinning disc. An atomiser rotating at 36000 rpm and performing as efficiently as disc TR8 would require 1350 issuing points to meet the specified throughput. At 30000 rpm this would increase to 6600 while at 26000 rpm 20000 issuing points would be required. A practical atomiser would almost certainly be less efficient: extrapolation of the Micron X-1 regression equation suggests that at 30000 rpm 17000 issuing points might be required, rising to 30000 at 26000 rpm. With 180 issuing points per disc a total of 167 units would be required to meet the required throughput at the lower speed. However, lower rotation

speeds would reduce the difficulty of driving the atomiser and minimise its structural requirements, for example allowing the use of simple ball-bearings rather than more complex fluid bearings. A design was therefore needed which allows large numbers of issuing points, indicating a rotating cylinder rather than a disc-based design.

7.2 The Liquid Feed System

The work on existing atomisers (Chapter 4) pointed to uneven distribution of fluid as a major constraint on atomiser performance. Achieving uniformity becomes increasingly difficult at the high rotation speeds and low flowrates per issuing point necessary for very small droplet production; the atomisers themselves often have a strong pumping action and can eject fluid at a rate exceeding the rate of supply per unit length. As a result of this much of the fluid tends to be emitted from a small part of the total area available for atomisation, giving high feed rates per issuing point.

One way of reducing this problem is to ensure that fluid is introduced into the atomiser over as large an area as possible. Several feedpoints inside the atomiser will generally give a better distribution of fluid than a single point. An exception to this is where a single feed is itself capable of dispersing the fluid, for example as seen in the Beecomist or modified Micronair atomisers, but for low flowrates such a system would depend on small holes and high supply pressures. A system of slotted weirs has proven useful under certain conditions as a means of distributing fluid to each issuing point individually (Kinnersley 1987) but this system was ruled out for the current device because of the complexity necessary to feed the large number of issuing points involved. An alternative approach is to add a resistance to the flow to each issuing point. This would help to ensure that each issuing point is supplied equally by causing a uniform layer of liquid to build up within the device.

i) Use of a Slot to Restrict Flow

Small drilled holes were ruled out as restrictors because of their tendency to block (diameters less than 0.5mm are considered unsuitable for field use), their lack of adjustability, and the difficulty of providing them in large numbers. Instead a simple slot was investigated: this would be quicker and easier to manufacture, could be adjusted to

various widths for different flowrates and would be less susceptible to the effects of blockage. It would be compatible with an atomiser head design based on a series of segments (Figure 7.1).

A test device was designed and manufactured (Figure 7.2). The width of the slot could be adjusted using four screws: various thicknesses of plastic shim were inserted into the gap and the screws were tightened to clamp it lightly. The shim was then pulled out and the gap maintained by adjusting four more screws to act as spacers. The device was mounted on the Desoutter air-motor used previously (Chapter 6), which was held horizontally in a clamp beneath a shield of thick, clear perspex. The fluid used for the tests was water with 0.1% Agral. It was fed from a pressurised container via a rotameter flowmeter to a hypodermic needle inserted in the device's top-plate. The stroboscopic light system described previously was used to observe the effects of varying rotation speed, flowrate and test fluid.

For a given flowrate at high rotation speed ligaments of fluid were seen to be emitted from just a short length of each set of teeth. As speed was decreased the emitting length increased until the full length was emitting. When speed was further reduced fluid flooded out from the feed hole in the top plate (Figure 7.3). The range of speed giving full length flow without flooding (ie. where input matches the pumping rate of the total length of slit) was small, so to quantify the performance of the slot as a flow distributor the rotation speed just prior to flooding was taken for various flowrates. The results are shown in table 7.1 and Graph 7.1.

The pumping rate of the slot varied linearly with rotation speed. Since the force on the liquid, $\rho Q \omega^2 r$, varied as the square of the rotation speed the flowrate through the slit must vary as the square root of the applied force. The same result is found for flow of liquid through an orifice, suggesting that the equilibrium rotation speed occurred when the entrance to the slit was running full. Since the liquid is incompressible and accelerates along the slit its depth must decrease, and so beyond its entrance the slit will no longer run full. A rectangular orifice might therefore be expected to be as effective as a slit at distributing fluid over a length of atomiser.

Regression analysis of the data from the 0.08mm slot gave the relationship

$$N = 0.31Q + 10.84 \quad (7.1)$$

When extrapolated to a speed of 24000 rpm this gave a pumping rate of 1255 ml/min or 31.4 ml per millimetre of periphery. Halving the slot width to 0.04mm gave the relationship

$$N = 0.49Q + 24.32 \quad (7.2)$$

giving a pump rate of 767ml/min or 19.17 ml per millimetre periphery at 24000 rpm.

Graph 7.2 compares the flowrate per cross-sectional area for the two widths of slot. The lines for the two slots now appear approximately parallel, regression giving equations of

$$N = 0.961Q + 10.84 \quad (7.3)$$

for the 0.08mm slot and

$$N = 0.781Q + 24.27 \quad (7.4)$$

for the 0.04mm slot. For the same rotation speed, then, the flow per unit area is greater for the larger slot. This is probably due to lower energy losses due to shear stress for a given flow velocity in the larger slot.

The pumping action of a rotating slot is such that uniform distribution of fluid at the required flowrate per tooth can only be achieved at low rotation speeds. To achieve uniformity at high speeds would require an impractically small slot. In the light of this attention was transferred to other potential restrictors in which use is made of friction by maximising the area in contact with the fluid.

ii) Use of Porous Materials to Restrict Flow

The slots in the test rig were blocked by various porous materials and the rotation speeds for uniform emission determined for a range of flowrates. Strips of the materials were cut to the width of the test device's slot and sandwiched between its two halves. The tests were carried out with water + 0.1% Agral as before, and also with the viscous JF9436 blank formulation. Again five replicate measurements were taken. The materials used were:

- a) Nylon monofilament gauze (ASTM 100–149 micrometres, 0.09mm diameter threads, mesh count 41.84 per cm) 0.17mm thick, 10mm wide.
- b) "80 NC" reticulated metal foam 0.82mm thick, 13mm wide
- c) Sintered metal from an air–line filter, 3.5mm thick.
- d) Whatmans No.1 qualitative filter paper, 3mm wide.
- e) Sintered bronze "60 grade" 9–12 micrometre filter

Cutting tended to destroy the open structure at the edges of the sintered materials but an open edge could be achieved by snapping. The filter paper and sintered bronze were impervious to liquid at the rotation speeds attained but the other three materials acted as effective flow restrictors and distributors. Graphs 7.3 and 7.4 show the rotation speeds required for uniform distribution at a range of flowrates. The trend was roughly linear but the results were more scattered than for the plain slots. The most effective restrictor in the tests was the edge–on nylon mesh, followed by the sintered air–line filter material and then the reticulated metal foam with its relatively open structure. However in terms of flowrate per unit cross–sectional area (Graphs 7.5 and 7.6) the sintered metal performed best, regression giving the relationship

$$N = 43.4Q + 33.8 \quad (7.5)$$

which extrapolated to give a flowrate per unit area of 8.45 ml/min/mm^2 . To feed teeth 1mm apart fed at a rate of 0.5 ml/min would require a feed–slot width of 0.059mm with the same degree of blockage.

The JF9436 formulation was distributed uniformly at higher rotation speeds than the less viscous water with 0.1% Agral. The regression line for sintered metal with JF9436 gave a

poor correlation but it was clear that a larger area of the material would give an even distribution than was possible using water with Agral. This, taken with the results from the plain slits and the relative efficiencies of the various porous materials, indicated that distribution was influenced by friction at the slit entrance.

iii) Behaviour of Spray Bars

The condition represented in these trials was a severe test in that liquid was being introduced from a single, small point. As mentioned previously a better performance might be expected at low flowrates if the liquid were to be introduced at several points. The simplest means of achieving this is the spray bar, a feedpipe blocked at one end with a series of holes in the pipe wall. Several such spray bars were constructed. It was observed that uniform jets of liquid were only produced when the volume of fluid contained in the spray bar was large compared with the rate at which fluid escaped from the holes. If the internal diameter of the spray bar was too small the output of the jets varied, outflow being greatest near the blocked end of the spray bar and declining with each hole further away from this end. A similar observation was made by Morgan (pers. comm.) for the velocity of air escaping from holes along a cylindrical tube fed from one end by a centrifugal fan, and the same phenomenon is predicted by computational fluid dynamic simulations (Figure 7.4) A possible cause of such variation might be the increase in static pressure as the dynamic pressure of the fluid decreases along the tube. Where a large diameter pipe was used for the same size and number of outlets the static pressure would be higher for all the holes since the velocity, and hence dynamic pressure, of fluid moving into the spray bar would be reduced.

7.3 The Atomiser Head

Porous materials appeared to be a suitable way to obtain a uniform low-flowrate fluid supply in an atomiser. However to use porous strips in the manner described above would add considerably to the manufacturing complexity and cost of an atomiser. The strips of material would also be awkward to remove for cleaning or replacement during operational use. A simpler alternative would be to insert a complete cylinder of material in the centre of the atomiser head. This could be removed or inserted just by removing an end-plate, simplifying assembly and maintenance in the field.

i) Tests on Sintered Plastic as a Distributor

Sources of sintered material were investigated. It was found that sintered plastic cylinders were available ready-made from manufacturers of filtration systems; they were produced in a range of diameters appropriate for the intended device and were considerably lighter than their metal equivalents. Samples of 40, 60, 100 and 200 grade materials in the form of 25mm diameter cups and 50mm diameter tubes were obtained for comparison (Accumatic Filtration Ltd.). The 40 grade material (capable of retaining 5–10 micrometre diameter particles) was fragile, crumbling under light pressure. Tests were therefore carried out using the more resilient 60, 100 and 200 grade cylinders (designed to retain 10–15, 20–30 and 40–50 micrometre diameter particles respectively).

a) Laboratory tests

An initial visual assessment of the ability of the cylinders to distribute flow was made using the 25mm diameter samples. Lengths of the two coarsest grades were glued onto aluminium plugs with central steel shafts and mounted on the Desoutter air-motor, leaving 30mm of length free to emit fluid. A small copper tag was glued on to activate the synchronised strobe. The cylinder was spun up and liquid (water with 0.1% Agral) was fed in from one end via a rotameter flowmeter and hypodermic tube at a rate of 250 ml/min. A band of fluid was seen to be emitted from a short length of the cylinder coinciding with the position of the top of the aluminium plug. This suggested that the jet of liquid from the feed-pipe was hitting the plug and being centrifuged off it, a small area of the sintered material emitting all the fluid due to a high local head of fluid.

The hypodermic tube was replaced by a spray bar consisting of a 4.45mm diameter stainless steel pipe sealed at one end, with five 1mm diameter holes spaced uniformly over the first 30mm. This was fed from a pressurised container at a rate of around 1–2 litres per minute giving five equal jets of liquid. Liquid was seen to issue uniformly from the open length of the cylinder in the form of regularly spaced ligaments. The combination of sintered drum and spray bar was thus shown to be a feasible way of distributing fluid within an atomiser at the rates being considered.

b) Wind tunnel tests

The laboratory spraying rig was not suitable for testing large devices at high rotation speeds and large liquid throughputs, and the airmotor was unable to reach high speeds under these conditions. The next step was therefore to produce a device for use in the wind tunnel which would confirm the effectiveness of the spray bar/sintered plastic distributor and possibly form the basis of a working atomiser head. The simplest approach to this was to make use of an existing bearing assembly and windmill drive-system. Accordingly the plastic disc was removed from a Micron X-1 atomiser and the end of the device modified to accommodate an aluminium plug. A 30mm length of 25mm diameter 100 grade sintered plastic cup was glued onto this plug. A 3.3mm outside diameter stainless steel feed-tube passed from the base of the device through the bearing and windmill assemblies and out into the sintered plastic head. Five 1mm diameter holes, evenly spaced along the exposed length of the tube, emitted liquid onto the inside of the cup (Figure 7.5). The tube was wide enough to give uniform jets but the clearance between it and the steel tube on which the head assembly was mounted was small. A small brass tag was fastened to the base of the blade assembly so as to trigger a capacitive sensor fastened to the bearing housing.

The device was mounted in the wind tunnel with the blades on their finest setting. Wind was applied and Glossinex blank formulation fed in at 100 ml/min. With a low windspeed fluid could be seen issuing from the sintered plastic but as the speed was increased the plastic flew off. The feed-pipe was subsequently found to be broken at the point where it entered the plastic cup. It seemed probable that the glue had been weakened by the solvents in the blank formulation and in being thrown off the cup had hit and bent the feed-pipe so that it rubbed against the rotating aluminium plug surrounding it. Marks left by the rubbing were visible on the remains of the pipe. The pipe was replaced and the plastic cup fastened in place with a pressed-on steel ring but again the cup became detached at speed and the feed-pipe was found to be broken. The cup was now a considerably looser fit than it had been previously and comparison with an unused cup showed it to have distorted.

The plastic bearing-housing was showing signs of fatigue. This was thought to be a consequence of repeated excess loading due to imbalances arising after each mechanical

failure. The plastic parts were therefore replaced by replica parts machined from aluminium. The 25mm diameter cup was replaced by an equal length of the 50mm diameter 100 grade sintered tube fitted with an aluminium cap, the base plug being replaced accordingly. This had considerably thicker walls and so might have been less prone to mechanical failure, but again the tube flew off and was found to have become a loose fit. The plug-like base and cap were replaced with cupped versions held a fixed distance apart by three tie rods (Figure 7.6). This proved satisfactory at speeds beyond 24000 rpm. However the feed-pipe still snapped at the higher speeds, the damage being visible through holes in the cap.

Vibration seemed the most likely explanation for its continued rubbing on the surrounding metal. Any slight imbalance in the device would give rise to a vibration corresponding in frequency to its rotation speed. The frequency of the first harmonic of a tube clamped at one end can be calculated from the expression (Langley, pers. comm.)

$$\omega_1 = \left[\frac{1.875}{L} \right]^2 \left[\frac{E I}{d_L} \right]^{1/2} \quad (7.6)$$

where ω_1 = first harmonic (radians s^{-1})

E = Young's modulus

L = length (m)

d_L = mass/unit length (kgm^{-1})

I = second moment of area of section, $\frac{\pi}{4 (r_o^4 - r_i^4)}$

r_o = outside radius, m , r_i = inside radius, m

Assuming a Young's modulus of 2×10^{11} Newtons/ m^2 and a density of $7800 \text{ kg}/m^3$ a value of $\omega_1 = 3242 \text{ radians } s^{-1}$, equivalent to 516 Hz, was obtained. The actual feed tube had a brass plug in the free end. Such a system cannot be described analytically but can be modelled numerically by finite element analysis. This analysis was carried out using a commercially available computer programme (Offshore Structure Analysis Suite, KCK Engineering). The programme was first run with no end weight for comparison with the analytical result and gave a value of 516.5 Hz for ω_1 . A weight equivalent to the brass

plug was then incorporated into the model. This brought the ω_1 value down to 476.5 Hz. Increasing the weight further decreased ω_1 . Results are summarised in Table 7.2.

To compare this result with the real situation, a replica feed-tube was fastened firmly in a clamp which was held in a vice. The tube was bent slightly and then released, producing an audible note which was assumed to correspond in pitch to the first harmonic of the vibrating system. A signal generator was used to produce an audible tone and adjusted until it was heard to be of the same pitch as the note generated by the tube. The frequency of the note could then be read from the signal generator. This was repeated three times – once by the author and twice by an independent observer. The resulting measurement of the first harmonic was 461 ± 1 Hz, about 3% lower than the computer prediction. The slight discrepancy can be accounted for by the numerical method used in the model and uncertainty over the exact values of density and Young's modulus for the steel used in the tube.

The clamp used in the devices to hold the pipe cannot be considered to be perfectly rigid but would allow a small degree of rotational as well as lateral movement. This would tend to lower the frequency of the first harmonic, bringing it within the upper end of the operating speed range of the device.

Having identified rubbing due to vibration as the probable cause of tube breakages, several methods were considered by which rubbing could be prevented or vibration reduced. The feed-tube could not be made narrower and the width of the surrounding tube was fixed by the windmill assembly. Attempts were made to stiffen the feed-tube with a piece of narrower tubing inserted in the region where internal diameter was not so crucial to flow, and to damp the vibration with an increased mass of brass in the end-plug. Both approaches were unsuccessful, the latter reducing the rotation speed at which vibration became a problem. The problem was finally overcome at the cost of increasing complexity by supporting the tube at the point where it had been rubbing. A simple P.T.F.E. bush proved insufficiently durable so a small ball race was incorporated. Adding this to the finite element model gave predictions for ω_1 of around 1200Hz assuming complete clamping by the bearing or 836Hz allowing rotation in the plane of the vibration. Both values were well above the maximum operating speed of the device, suggesting that even for the real case where clamping is not perfect wear on the tube would be reduced by

preventing rubbing and also by eliminating large vibrations from the remaining free length of tube. The modified device was able to operate at rotation speeds in excess 400 Hz.

The device was spun up and fed with liquid (Glossinex blank formulation). The full length of the plastic cylinder was seen to be emitting liquid but there was a narrow band of greater concentration at the end furthest from the windmill. This band projected further radially than the emissions from the rest of the cylinder, implying thicker ligaments and coarser droplets. A probable explanation is a locally high flowrate where a portion of the fluid layer inside the cylinder was prevented from escaping by the edge of the end cap and so added to the flow where the surface of the plastic becomes exposed. However it is not clear why this effect would not occur at the other end of the cylinder.

7.4 Conclusions

An atomiser for use in non-residual aerial tsetse spraying requires a large number of liquid issuing points, each fed at a very low rate. The most practical means of providing these would be a toothed rotating cylinder, but feeding all the issuing points uniformly at high rotation speeds is made difficult by the centrifugal pumping action of the atomiser itself. Distribution can be improved and flow per issuing point reduced by adding a resistance to liquid flow. A plain slit would have to be impractically narrow to be effective but a slit blocked with a porous material can give good fluid distribution.

Manufacturing complexity would be reduced by inserting the porous material as a cylindrical lining rather than as a number of thin slices. Sintered plastic cylinders fed by a spray bar proved to be an effective distribution system once structural problems had been resolved.

8) Development of a prototype Atomiser II: Atomising Surface

The work of Schmidt (1967 and 1974, see Chapter 5.2.(i)) and the development of a sintered metal head for the Beecomist atomiser (Chapter 4.3.(ii)a) demonstrated that atomisation can take place directly from the surface of sintered materials. This process was investigated by a short laboratory study and by wind tunnel measurements of the atomisation characteristics of the windmill-driven sintered plastic cup developed in the previous chapter. The literature review (Chapter 5) and experimental study of ligament disintegration (Chapter 6) indicated that discrete "zero-issuing points" could improve an atomiser's performance, and so two other prototype atomiser heads were designed which made use of the distributive power of sintered plastic cylinders to feed arrangements of teeth. These were also tested in the wind tunnel. An alternative to wind power was sought so that rotation speed could be made independent of an aircraft's air speed, and a fourth, electrically-driven prototype was developed and tested.

8.1 Investigation into Atomisation from Porous Surfaces

A 25mm diameter, "200" grade sintered plastic cup was mounted on the Desoutter air motor as described in Chapter 7.3.(i)a, and fed via a spray bar with water containing 0.1% Agral. Under illumination from the coupled strobe light the number of ligaments escaping from the surface of the cylinder could be seen to vary with rotation speed. The ligaments appeared to grow from a film of liquid which covered the cylinder's surface, suggesting that their spacing would be independent of pore-spacing and hence of the grade of sintered material used.

It was thought that the spacing of the ligaments might be determined by a mechanism comparable to that controlling ligament spacing at the edge of a plain spinning disc. Eisenklam (1964) successfully predicted the latter using Taylor instability theory, calculating that the spacing between ligaments would be independent of feed rate (see Chapter 5.2.(ii), equations 5.32 to 5.34). In order to quantify the influence of operating conditions on the spacing of ligaments produced by the cylinder photographs were taken at two feed rates over a range of rotation speeds, using the spark tube as a direct source of illumination (two examples are given in Figures 8.1 and 8.2). The approximate positions of ligament roots were marked onto the sharpest area of each photograph and fifteen

measurements of the distance between adjacent pairs of these points were taken at random for each set of operating conditions. The results are shown in Table 8.1. A t-test showed that there was no significant difference in ligament spacing between the two feed rates, supporting the hypothesis that spacing was determined by Taylor instability.

Eisenklam's equations predicted that for the (one-dimensional) rim of a spinning disc atomiser the number of ligaments per unit length would be inversely proportional to rotation speed. The relationship between rotation speed and ligament spacing from the two-dimensional surface of the cylinder was not linear but a plot of (ligament spacing)² against rotation speed (Graph 8.1) gave a straight line with a value for R^2 of 95.3%, implying that the number of ligaments per unit area of the cylinder's surface is proportional to rotation speed. This was verified by counting the number of ligaments occurring in the same fixed area of the cylinder on each photograph. A plot of ligament number in a fixed area against rotation speed was linear, with an R^2 value of 96.4% (Graph 8.2).

8.2 Atomisation Characteristics of a 50mm Diameter Sintered Plastic Cylinder

Though only half the diameter of the Beecomist "40 micrometer" sintered metal drum, the wind-driven 50mm diameter sintered plastic cylinder was capable of well over double the rotation speed. Both the "60" and "100" grade materials have a much finer pore-size than the "40 micrometer" drum (values were given in Chapter 7.3.(i)), Schmidt's conclusions implying that this might give rise to a smaller droplet size. Tests on this device, subsequently referred to as prototype Pro-1, were carried out in the wind tunnel in the same way as those performed on the Micron X-1 atomiser (see Chapter 4.3.(vi)), using a range of feed rates and blade settings at a constant windspeed. Blank Glossinex was used to represent the low viscosity formulations. Supplies of the higher viscosity JF9436 formulation were unavailable at the time this section of work was being carried out. Results are shown in Table 8.2.

At lower rotation speeds VMD decreased with increasing rotation speed according to a simple power law. As rotation speed was increased, however, VMD deviated from this type of relationship, decreasing more slowly than expected (Graph 8.3). Examination of the droplet spectra showed that volume distributions were unimodal at the lower rotation

speeds but that as rotation speed was increased an additional cluster of peaks began to develop at a considerably higher diameter than the main peak, resulting in the unexpectedly large VMDs. These secondary peaks were thought to be due to droplets produced from the band of locally high flow rate described in chapter 7.3(i)b. To gain some idea of the atomiser's best potential performance, the droplet size data was transformed by removing the secondary peaks and VMDs were recalculated from the remaining data. These followed a simple power law relationship (Graph 8.4). With VMD in micrometers, feed rate in litres/minute and rotation speed in rpm multiple linear regression gave the expression

$$\text{VMD} = 331131 Q^{0.216} N^{-0.865} \quad (8.1)$$

which fitted the data with a value for R^2 of 85.5%.

Further tests were carried out using a "60" grade plastic cylinder (Table 8.3) and the resulting VMDs were compared with those from the original "100" grade cylinder (Graph 8.5). As predicted above, the difference in pore spacing had no direct effect on droplet size, but the deviation from a simple power law relationship with increasing rotation speed was less for the "60" grade cylinder than for the more porous "100" grade cylinder.

The effect of rotation speed on relative span is shown in Graph 8.6. The raw data showed an increase in relative span from around 1.5 to more than three as rotation speed increased. This could be accounted for by the presence of the secondary peaks in the volume spectra. Once these were removed from the data the value of relative span remained around 1 regardless of rotation speed. Feed rate had no systematic influence on relative span. There was no significant difference between the relative spans (calculated from the raw data) of spray produced from the two grades of cylinder (Graph 8.7).

The smallest VMD measured was 38 μm , at a rotation speed of 25020 rpm and a feed rate of 0.1 litres/minute. Under these conditions 42% of the liquid volume formed droplets less than 33.3 μm in diameter. When the secondary peaks were removed from the particle size data the VMD fell to 30 μm , with 65% of liquid volume forming droplets less than 33.2 μm in diameter. At the same feed rate a rotation speed of 12060 rpm produced a VMD (based on raw data) of 77 μm , with 57% of volume forming droplets in the finer

diameter range for armyworm control. Similar VMDs were obtained at higher feed rates but relative span also increased so that the proportion of spray in this size-range decreased.

8.3 Performance of Toothed Atomisers

i) Prototype Pro-2: Toothed Bars

An aluminium cylinder was machined to fit tightly over a 50mm diameter, 50 mm long cylinder of sintered plastic. A series of 30 degree V-shaped grooves with a pitch of about 0.5mm was cut around the circumference of the aluminium cylinder, stopping several millimetres from each end. A 0.5mm wide cutter was used to make an axial slot every 4 degrees around the cylinder so that it formed a cage with ninety axial bars about 1.5mm in width, each having 90 teeth. End caps were designed so that liquid was not fed to areas of the sintered plastic cylinder from which it could not escape. The two end caps and the two cylinders were held together by three tie-rods which fastened into the modified Micron X-1 windmill/feeder assembly used for prototype Pro-1 (Figure 8.3). Testing was carried out as previously. No Glossinex was available at this time so Thiodan was used to represent the low viscosity formulations, the experimental work of chapter 6 having shown the three low-viscosity formulations to be virtually identical in behaviour during atomisation. JF9436 was now available and so additional tests were carried out using this high viscosity formulation. Results are given in Tables 8.4 and 8.5.

The VMD of spray produced by Pro-2 fell with increasing rotation speed and decreasing feed rate according to simple power laws, with no deviation at higher rotation speeds (Graphs 8.8 to 8.11). With VMD in micrometers, feed rate in litres/minute and rotation speed in rpm multiple linear regression gave the relationship

$$\text{VMD} = 125893 Q^{0.221} N^{-0.765} \quad (8.2)$$

This fitted the data with a value for R^2 of 96.3%. The droplet volume spectra showed a considerable reduction in the size and number of secondary peaks. Examples are given in Graphs 8.12 and 8.13, which show droplet spectra produced by Pro-1 and Pro-2 respectively under near-identical operating conditions. VMDs of droplets produced using

JF9436 also declined according to power laws but at a slower rate than for Thiodan, regression giving the expression

$$\text{VMD} = 17783 Q^{0.193} N^{-0.558} \quad (8.3)$$

with an R^2 value of 94.2%.

Neither rotation speed nor feed rate had any clear systematic influence on relative span (Graphs 8.14 and 8.15), though there was generally an increase with rotation speed. At the lower feed rates relative span increased with feed rate but beyond around 0.3 litres/minute increasing the feed rate ceased to have any significant influence.

The smallest VMD achieved was 32 μm , at a rotation speed of 24060 rpm with a feed rate of 0.1 litres/minute. The relative span under these conditions was 2.037, with 54% of the spray volume forming droplets less than 33.2 μm in diameter. At the same feed rate a rotation speed of 10800 rpm gave a VMD of 72 μm and a relative span of 1.086, with 42% of spray volume falling in the finer size range for armyworm spraying.

ii) Prototype Pro-3: Stacked Discs

A multiple disc atomiser head was constructed in which a 25mm diameter sintered plastic cylinder was used to distribute liquid to 15 toothed plastic cups of the type used in the Micron X-1 atomiser (figure 8.4). The centres of the discs were drilled out to accommodate the plastic cylinder and four smaller holes were added so that the discs could be threaded onto tie-rods. Adjacent discs were separated by spacers which were also threaded onto the tie-rods. The mounting plate of the Micron X-1 windmill/feeder assembly used in prototypes Pro-1 and Pro-2 was modified to allow the Pro-3 atomiser head to be fixed in place using the four tie-rods. Testing was carried out as previously, using Thiodan and JF9436. A fault in the rotation speed sensor meant that the top speed at the lowest feed rate could not be measured. The relationship between windmill blade setting and rotation speed was found to be linear and so the missing speed value was estimated by linear regression. Results are shown in Tables 8.6 and 8.7.

As with prototype Pro-2 VMD decreased with decreasing feed rate and increasing rotation speed according to simple power laws, with no significant deviation at higher speeds and a slower rate of decrease for JF9436 than for Thiodan (Graphs 8.16 and 8.17). For Thiodan, with VMD in micrometers, feed rate in litres/minute and rotation speed in rpm, multiple linear regression gave the expression

$$\text{VMD} = 69183 Q^{0.191} N^{-0.706} \quad (8.4)$$

with an R^2 value of 92.3%.

For JF9436 the expression was

$$\text{VMD} = 5623 Q^{0.228} N^{-0.414} \quad (8.5)$$

giving an R^2 value of 85.0%.

Again the dependency of relative span on rotation speed and feed rate was complex (Graphs 8.18 and 8.19). Its value increased with feed rate and, at the two highest Thiodan feed rates, with rotation speed. At the other Thiodan feed rates tested and with JF9436 relative span remained constant or fell with increasing rotation speeds. Values ranged from 0.878 to 1.857.

The smallest VMD achieved was 40 μm at a rotation speed of 21880 (estimated) and a feed rate of 0.1 litres/minute of Thiodan. This gave a relative span of 0.878, with 30.5% spray volume in droplets less than 33.2 μm in diameter. A maximum of around 30% of the spray volume fell into the two armyworm spraying size-ranges under several sets of conditions, the highest feed rate being 0.83 litres/minute at 10560 rpm. VMDs were generally larger when spraying JF9436.

8.4 Alternative Drive Systems

Rotation speed has been shown to be the principle factor influencing the size of droplets produced by a rotary atomiser. Consequently the range of droplet sizes produced by an aircraft-mounted, wind-driven rotary atomiser is strongly dependent on the carrier's air

speed. In hilly terrain air speed must vary as the aircraft climbs over hills and descends into valleys, resulting in significant variations in droplet size. Over flat terrain air speed may be constant while spraying but structural damage can occur to atomisers if higher speeds are reached during the descent into each spraying run. A drive system which is independent of air speed would therefore be advantageous. Such a system must be capable of reaching the required high rotation speeds using the power available from the aircraft. It should be simple to maintain in the field and must be economically viable.

Constant rotation speed could be maintained by a windmill with variable pitch blades but such a system was ruled out on the grounds of complexity. Rotary atomisers mounted on a helicopter have been driven successfully at around 3000 rpm using air motors powered by air bled from the aircraft's turbine engine (Parkin 1983). To assess the viability of such a drive-system for higher speed atomisers the mass of bleed air which could be taken from an Ayres Turbo Thrush fixed-wing agricultural aircraft was calculated using data supplied by the Ayres Corporation (PO Box 3090, Albany, Georgia 31706). Cruising at sea-level 0.069kg of air per second would be available at a pressure of $5.4 \times 10^5 \text{ Nm}^{-2}$ (78 psi), giving a flow rate of 11 litres/second. A small, high speed air motor such as the Desoutter motor used during this project requires around 5 litres/second, so that at most only two such motors could be driven. Small air motors of this type would be incapable of reaching high rotation speeds when loaded with an atomiser head capable of sufficient liquid throughput. The mass of bleed air available would be lower under the conditions of high altitude and warm temperatures and the need for maximum aircraft performance normally associated with tsetse spraying. Air motors were not, therefore, considered to be a viable drive system in this case.

Electric power is readily available on aircraft and gives good control over rotation speed, but the maximum rotation speeds of general-purpose direct current motors were found to be insufficient for use in an aerosol generator. Gearing could be used but would increase complexity and power losses while potentially decreasing reliability. Brushless motors are capable of higher speeds but are expensive and require a generator to provide a suitable alternating current supply. It was found that small d.c. electric motors capable of high rotation speeds are designed and built specifically to power model racing cars. These are of the permanent magnet type and are designed to run at a nominal 7.2 volts. Their armatures are divided into three segments, standard models having 27 turns of copper wire

on each segment. In higher performance models electrical resistance in the armature is reduced by using two or more lengths of wire in parallel. The brushes are carbon, and are held against the commutator by hair-pin springs. High performance models can be "tuned" to maximise torque or rotation speed by adjusting the position of the brushes relative to the magnet.

Two of these motors were obtained. One was a basic model (Parma Cyclone II, retail price £15 in 1990) which when operated at 7.2 volts without a load was found to have a rotation speed of 21240 rpm. The other was a high performance model (retail price around £45 in 1990) which had been "tuned" by an experienced model car racer. This had an unloaded rotation speed in excess of 40000 rpm at 7.2 volts.

These motors appeared to meet the criteria for a high-speed atomiser power supply and so were used as the basis of an electrically driven version of the sintered plastic atomiser head described previously.

8.5 Development of an Electrically Driven Atomiser

i) drive system

The rotation speed of a permanent magnet motor is known to vary inversely with torque. For a given motor plots of rotation speed against torque have a constant slope regardless of supply voltage. The unloaded (zero torque) rotation speed of the Parma Cyclone II motor was measured at a range of supply voltages using an optical tachometer. To measure the stall torque (zero rotation speed) a thin aluminium beam was fixed onto the shaft of the motor. A metal knife-edge was fixed vertically into a block of wood and placed on the top-pan of an electronic weighing machine. The motor was held in a clamp in such a way that when it rotated the aluminium beam hit the metal knife-edge and stalled the motor, the resulting mass-force being read directly from the weighing machine. The knife edge was positioned so that it touched the aluminium beam at a point 100mm from the axis of the motor. Twelve replicate mass-force measurements were taken at each voltage tested, the resulting average values having 95% confidence intervals of 15% or less. Between measurements the motor was rotated in its clamp, altering the position of the

stalled armature relative to the magnets. The stall torque was calculated from the average mass–force measurements as follows

$$T = \frac{F g}{r} \quad (8.6)$$

where T = torque, Nm^{-1}

F = measured mass, kg

r = distance from axis of rotation, m

g = acceleration due to gravity, $= 9.81 \text{ ms}^{-2}$

The values of stall torque and free rotation speed obtained for each voltage allowed a series of parallel rotation speed–torque curves to be constructed. Using a 10 amp power supply to drive the motor for these measurements the highest stall torque which could be measured was that at 4 volts. However the free rotation speed at 7.2 volts was known and so a parallel rotation speed–torque curve could be drawn for this voltage (Graph 8.20).

An initial prototype was constructed in which the Parma Cyclone II motor was used to drive a "100" grade, 50mm diameter sintered plastic cup. The central drive shaft was supported by a pair of ball bearings. A spray bar was incorporated into the wall of the bearing housing. Rotation speed was measured as previously using the capacitive sensor. A laboratory power supply unit was used to provide a variable d.c. supply, and a voltmeter and ammeter were used to monitor power input. The rotation speed fell rapidly soon after power was applied. The motor also became hot to the touch, and it was suspected that the resulting increase in the armature's electrical resistance was the cause of this drop in speed. It was suggested that the liquid being sprayed might be used to keep the motor cool (Wyatt, pers. comm.) and the design was modified so that liquid passed through the motor housing before passing into the spray bar (Figure 8.5). With liquid flowing the motor was kept cool and maintained a constant rotation speed.

The effect of liquid feed rate on rotation speed was measured at the recommended operating voltage of 7.2 volts using water with 0.1% surfactant. Rotation speed was found to decrease linearly with increasing feed rate (Graph 8.21), a feed rate of 0.1 litres/minute

giving a rotation speed of 20580 rpm. The input power for each feed rate was calculated using the relationship

$$W_{in} = IV \quad (8.7)$$

where W_{in} = power input, watts

I = current drawn, amps

V = supply voltage, volts

The torque at any feed rate could be determined from the 7.2 volt rotation speed–torque curve for the motor using the rotation speed measured at that feed rate, and so output power could be calculated from the expression

$$W_{out} = T \omega \quad (8.8)$$

where W_{out} = output power, watts

T = torque, Nm^{-1}

ω = angular velocity, radians s^{-1}

The input and output powers are compared in Graph 8.22. The difference between input and output power is accounted for by losses in the motor, due principally to the resistance of the wire and friction in the bearings. Under the range of feed rates tested at 7.2 volts losses remained constant and so the overall efficiency of the motor increased with increasing torque (Graph 8.23). The graph indicated that at a feed rate of 0.1 litres/minute the power requirement would be 45 watts, 37 watts of this arising from losses in the motor, giving a rotation speed of 20500 rpm.

Graph 8.24 shows the variation in input power with rotation speed under three feed conditions. With no liquid being fed to Pro-4 its power consumption increased linearly with rotation speed. When spraying water with 0.1% surfactant power consumption increased at a rate greater than the rate of increase of rotation speed. Linear regression of power input with $(\text{rotation speed})^2$ gave a value for R^2 of 94% at a feed rate of 0.94 litres/minute and 97% at 0.46 litres/minute. The ratio of excess power required at each feed rate to the no-flow requirement remained constant at all rotation speeds.

rotation speed of 20000 rpm. In this case power input increased in direct proportion to feed rate (Graph 8.25)

ii) atomisation performance

Pro-4 was mounted in the wind tunnel and tested in the same way as previous prototypes using Thiodan. Rotation speed was adjusted by changing the voltage of the power supply. For a set supply voltage rotation speed fluctuated by less than $\pm 1\%$. Results are given in Table 8.8. VMD fell with increasing rotation speed according to a power law, and increased with feed rate (Graph 8.27). With VMD in micrometres, feed rate in litres/minute and rotation speed in rpm multiple linear regression gave the expression

$$\text{VMD} = 5370318 Q^{0.131} N^{-1.15} \quad (8.9)$$

giving a value for R^2 of 94.8%, though with only two feed rates represented this expression should be treated with caution. Relative span increased slightly with rotation speed and, with the exception of one outlying measurement, was significantly higher at the higher feed rate (Graph 8.26). The lowest VMD attained was $39\mu\text{m}$ at a rotation speed of 22000 rpm and a feed rate of 0.1 litres/minute, giving a relative span of 0.973.

Under coupled strobe-light illumination in the laboratory the output of the sintered plastic cylinder was seen to be patchy, with concentrations of ligaments associated with the positions of the three tie-rods and signs of banding corresponding to the positions of the outlet holes in the spray bar. The prototype was modified so that there was a greater clearance between the tie-rods and the inside face of the cylinder.

8.6 Discussion

The laboratory investigation into ligament formation from a rotating porous cylinder revealed that at liquid feed rates of relevance to practical rotary atomiser design ligaments arose from a film of liquid on the surface of the cylinder. This would account for Schmidt's observations (Schmidt 1967) that droplet size was independent of grain size, and for the results from trials with prototype Pro-1 in which the grade of sintered plastic cylinder used had no direct influence on droplet size. The indirect influence of porosity on the size of droplets produced by Pro-1 suggested that the "60" grade cylinder's greater

and for the results from trials with prototype Pro-1 in which the grade of sintered plastic cylinder used had no direct influence on droplet size. The indirect influence of porosity on the size of droplets produced by Pro-1 suggested that the "60" grade cylinder's greater resistance to flow aided the distribution of fluid, reducing secondary peaks by spreading the excess fluid from the end-cap region over a larger surface area than the more porous "100" grade cylinder. The redesigned end-caps used in subsequent prototypes effectively eliminated secondary peaks and so a plain porous cylinder fitted with such end caps should be capable of an atomising performance close to that indicated by the modified data from Pro-1.

The improved performance of Pro-2 compared with Pro-1 can be accounted for entirely by the modified end-caps, no apparent benefit arising from the provision of teeth in this way. In retrospect it was considered that the flow of liquid to the teeth was likely to be non-uniform; liquid could move up either face of the toothed bars, there were no channels to control pre-forming of ligaments and the spacing of the teeth was not matched to the probable natural spacing of ligaments.

Prototype Pro-3 offered an alternative approach to the problem of providing teeth. For a rotation speed of 25000 rpm and a feed rate of 0.1 litres/minute using Thiodan its regression equation predicted a VMD of 35 μ m. This is coarser than the VMDs produced by Pro-1 or Pro-2 under these conditions but finer than the 41 μ m VMD produced by a single Micron X-1 atomiser. The regression equation for the Micron X-1 predicted that at a feed rate of 6.67×10^{-3} litres/minute (one fifteenth of 0.1 litre/minute) VMD would be 23 μ m. It is possible that the performance of the X-1 discs used in Pro-3 was limited by fluid distribution in a similar way to the discs in the Micron X-15 and Forestry Commission X-30 (chapter 5.3).

The behaviour of the small direct current motors suggests that they are suitable for driving high speed rotory atomisers. They are inexpensive, easy to maintain and service and showed no problems with reliability over several hours of operation. The excess power requirement during spraying could be accounted for by loss of energy from the system as kinetic energy in the spray, suggesting that the energy requirement would increase with the feed rate of liquid to the disc and with the square of rotation speed. This was generally found to be so, the exception being the 2.8 fold doubling of energy requirement with

doubling of feed rate shown in Graph 8.24. It is possible that this anomaly arose from a single incorrect flowmeter reading.

Because time was limited at this stage of the project, only a limited number of tests could be carried out on the electric prototype. However, these were sufficient to indicate that its power requirement was low enough to allow as many units as should be necessary for tsetse spraying to be driven from a single aircraft power supply of 2400–2800 watts (see appendix 1). A system comprising of an inverter, transformer and rectifier would convert the standard 24 or 28 volts to the 7.2 volts for which the motor was designed (higher voltages may be used, though these may eventually lead to loss of magnet strength). Extrapolation from the data in Graph 8.25 suggests that with a feed rate of 0.1 litres/minute and a rotation speed of 25000 rpm power consumption would be in the order of 60–70 watts.

At 7.2 volts and 0.1 litres/minute five sixths of the required 45 watts of power supplied to the prototype was lost in the motor. Power requirement could be reduced considerably with a lower resistance armature, and this would also reduce heat production. However even ten atomisers driven by the standard motor would operate well within the limits of power available. Heat dissipation is managed effectively by the circulating liquid and on an aircraft further cooling would be brought about by the aircraft's slipstream. In view of this the cheaper, and hence more expendable standard motor would be the logical choice as the drive unit.

The VMD measured at 0.1 litres/minute and 22000 rpm was 39 μ m, rather larger than the 35 μ m VMD of the wind-driven sintered plastic head Pro-1. The reason for this probably lies in the patchy distribution of liquid in the atomiser head. A modified head was constructed in which a greater clearance was allowed between the tie-bars and the inner surface of the cylinder, but wind-tunnel time was not available for further testing.

8.7 Conclusions

At operationally useful feed rates ligament formation from rotating porous cylinders takes place from a thin film of liquid which covers the cylinder's outer surface. Spacing of the ligaments is independent of feed rate and porosity but the number of ligaments per unit

area is directly proportional to the cylinder's rotation speed. Good internal fluid distribution within a porous cylinder is aided by a high resistance to flow.

A uniformly-fed, 50mm diameter sintered plastic cylinder rotated at a speed of 25000 rpm and fed at a rate of 0.1 litres/minute has the potential to atomise more than 60% liquid volume into droplets of a size appropriate for tsetse spraying. At the same feed rate and a rotation speed of 12000 rpm 57% of spray volume falls in the finer size range specification for armyworm spraying. Two attempts to add discrete issuing points to the sintered plastic surface offered no significant improvement in atomising performance.

An alternative to a windmill as power source is desirable. Electricity is the most practical option; small, relatively inexpensive d.c. motors can be used to drive a sintered plastic atomiser head at rotation speeds suitable for tsetse spray production with a power consumption well within the 2400–2800 watts available on typical spraying aircraft. The motor of a prototype electrically-driven atomiser was kept from overheating by passing the spray liquid through a duct in the motor housing.

9) Conclusions and Recommendations for Future Work

9.1 Conclusions

i) Non-residual aerial spraying will continue to be an important component in any realistic and fully costed scheme to clear tsetse flies from large areas of land. The optimum droplet diameter for this type of spraying is between 20 and 30 micrometres. The efficiency of spraying operations could be improved significantly if these droplets could be produced directly rather than relying on the reduction of larger diameter droplets by evaporation. Under such conditions total insecticide output rates of around 0.5 litres/minute would be required. The application of insecticides by aircraft also offers a means of rapid response to threats of infestation by armyworm and other migratory pests. but the larger droplet diameters required (80–120 micrometres at rates upto 16 litres/minute) are less difficult to achieve than the aerosols required for tsetse spraying.

ii) A PMS OAP–260X droplet measuring system, set to 5 micrometre resolution operates with a size range and resolution suitable for measuring droplets in both the tsetse and armyworm target ranges. Such a system is more efficient when large numbers of droplet spectra must be measured than a system involving the merger of data from an OAP–260X set to a coarse resolution and a PMS FSSP–100 probe. For this work droplet spectrum data is most appropriately summarised as a Volume Median Diameter, a relative span and the fraction of liquid volume atomised into the target droplet size ranges.

iii) Rotary atomisation is the most suitable means of producing sprays for both armyworm and tsetse control operations.

iv) None of the existing rotary atomisers tested were capable of direct production of a spray meeting the criteria for non-residual tsetse spraying. The limiting factors were insufficient rotation speed, too high a feed rate per liquid issuing point and poor internal fluid distribution. The atomiser offering the greatest potential improvement over the spraying system currently used was the Micron X–1 atomiser, though this would have to be made more durable to be of use under tsetse spraying conditions. The Micronair AU4000 and AU5000 atomisers and the Micron X–1 met the droplet spectrum and flow rate requirements for armyworm spraying, the latter probably offering a tighter droplet spectrum and greater flexibility.

v) The literature contained several semi-empirical models for the performance of rotary atomisers based on rotation speed, feed rate and liquid characteristics. These varied according to the experimental system used, suggesting that additional parameters were significant. The flow of liquid on the atomiser, its separation and its subsequent disintegration should be considered separately. The primary influence of flow on the atomiser appeared to be in the distribution of fluid to the issuing points. Premature ligament formation and cross-flow vortices were identified as mechanisms which could hinder uniform distribution, the latter occurring under conditions which would explain the poorer than expected atomising characteristics of some existing atomisers when tested at very low feed rates. There is good evidence that the spacing of fluid ligaments at the edge of a rotary atomiser is determined by Taylor instability. "Zero issuing points" can be of value in maintaining uniform ligaments if the tooth-spacing is not very different from the natural ligament spacing. The relative motion of the escaping liquid and the rim of the atomiser is the principle factor determining ligament size and shape. The disintegration of liquid ligaments produced by a rotary atomiser is analogous to the breakup of a jet from a stationary source, implying that at high rotation speeds types of instability other than Rayleigh instability might dominate the breakup process. There is evidence that droplet formation might be sensitively dependent on initial conditions, the resulting potential for chaotic behaviour fundamentally limiting the narrowness of droplet spectrum that could be achieved under some circumstances.

vi) Spiral irregularities were observed in a film of liquid flowing over a rotating disc. Their curvature and the Reynolds number at which they occurred coincided with values predicted for cross-flow vortices. Depending on operating conditions ligament disintegration was seen to be controlled by Rayleigh instability or by first wind-induced mode instability. Premature shattering was seen to occur before strong second wind-induced mode instabilities were observed. The critical Weber number for this shattering coincided with literature values for the shattering of a plain jet in a cross-flow. Droplet spectra reflected the changes in disintegration regime. There was an underlying pattern to the seemingly random distribution of peaks in the complex droplet volume spectra obtained under some conditions. Using a 50mm diameter ligament generator at a rotation speed of 36000 rpm, and a feed rate per issuing point of 0.37 ml/minute, 95% of liquid volume fell into the target range for tsetse spraying. Such a performance would be difficult to

emulate in a practical, multi-issuing point atomiser. This is illustrated by comparison of the droplet spectra obtained using TR8 with those produced by the Micron X-1 atomiser at the same rotation speed and feed rate per issuing point. The relatively broad spectra obtained from the Micron X-1 resulted in a coarser spray than that produced in the laboratory by the ideal ligament generator TR8. Nevertheless these results indicate that it should be possible to produce a droplet spectrum suitable for tsetse spraying using a rotary atomiser at a high rotation speed with a low feed rate per issuing point.

vii) A practical atomiser would require a rotation speed below 36000 rpm and consequently the feed rate per issuing point must be considerably less than 0.36 ml/minute. A slit proved inadequate as a means of distributing small volumes of liquid over a large area but the problem was surmounted using porous materials with a high resistance to liquid flow. Sintered plastic cylinders fed internally by a spray bar proved to be effective fluid distributors. To obtain a uniform flow from all the exit holes in a spray bar its bore had to be considerably greater than the diameter of the exit holes.

viii) Ligament formation at the surface of a rotating sintered plastic cylinder took place from a film of liquid which covered the cylinder's surface. The spacing of the ligaments was independent of feed rate but the number of ligaments per unit surface area was found to be proportional to rotation speed. A uniformly fed, wind-driven sintered plastic cylinder rotating at 25000 rpm and fed at 0.1 litres/minute was capable of atomising more than 60% of spray volume into droplets suitable for tsetse spraying, representing a considerable improvement over existing atomisers. Attempts to add discrete issuing points offered no significant improvement in atomiser performance. Small d.c electric motors were found to be a suitable alternative to wind power, being capable of high rotation speeds with reasonable power requirements. A prototype, electrically driven version of the sintered plastic atomiser was constructed, in which the liquid fed to the atomiser was used to cool the motor before being emitted.

9.2 Recommendations for Future Work

A detailed analysis of the benefits to be gained by the direct production of aerosol droplets by aircraft-mounted atomisers would be of value. Such a study should consider such factors as operational safety and environmental impact as well as cost-benefits. The

technique requires a low viscosity, low volatility insecticide formulation, and agrochemical companies should now be approached for samples of a suitable formulation.

The range of experiments carried out using the ligament generator TR8 in the laboratory was restricted by the requirement to move on to the development of working atomisers. There is scope for a considerably more detailed study of ligament disintegration using the techniques described in this work. Further experiments could be carried out over smaller increments of feed rate and rotation speed in order to determine the exact conditions under which Rayleigh and wind-induced modes of atomisation take place, and to determine a more exact value for the critical Weber number at which the onset of "cross-flow" shattering occurs. The influence of the ambient air on ligament behaviour could be isolated from internal jet stability factors by running disc TR8 in a sealed chamber from which air could be removed by a vacuum pump. Under such conditions it would be necessary to fit the air motor with pipework to remove the exhaust air, or else to replace it with a "tuned" electric motor of the type described in Chapter 8. An investigation into the influence of fluid properties would also be of value, using liquids with a wider range of densities, viscosities and surface tensions than were available for this project. Computational Fluid Dynamic procedures such as those used by Lin and Creighton (1990) are more likely to succeed in predicting ligament behaviour than analytical methods, and once relevant operational parameters have been identified this computational approach could be extended to the case of a ligament issuing from a rotating source. The observations of ligament formation from the surface of porous cylinders suggested that the spacing of ligaments probably arises from Taylor instability. Calculations of the type carried out by Eisenklam (1964) should be extended to two-dimensions to check for the observed relationship between ligament spacing and rotation speed.

The final design of the wind-driven sintered plastic atomiser (recommended in Chapter 8) should be constructed and its atomisation performance tested with a low viscosity, low volatility formulation under simulated aircraft conditions. The current design of the electrically-driven prototype atomiser leads to non-uniform distribution of fluid to the atomiser head and minor modifications are necessary to ensure that a uniform distribution is achieved. The most obvious such modifications to evaluate would be to increase the spacing between the integral spray bar and the inner surface of the cylinder. The unit should also be tested using the higher performance motors which are available. Both the

wind-driven and electrically-driven atomisers would then require durability testing before being fitted to an aircraft and tested under field conditions. Mast and vehicle-mounted versions of the electrically-driven version could also be tested.

Additional pesticide application roles for fine aerosol generators of the type described in this work include air-to-air spraying of migratory pests, control of mosquitoes and houseflies, forest insect pest control, and fumigation of buildings. Other uses might include greenhouse humidification, and, with a porous ceramic head replacing the sintered plastic, fuel injection. The principle restriction on the use of such atomisers is their inability to handle liquids containing particulates. Further research and development is required to develop an aerosol generator suitable for use with such materials. One possible route would be development of the segmented cylinder idea proposed in Chapter 7, using channels etched, pressed, or moulded into the faces of the segments to aid fluid distribution.

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Dept of Mechanical Engineering, University of Manchester Institute of Science and
Technology

Appendix 1

Aircraft currently used in tsetse spraying operations

(figures provided by the principle company engaged in this work; Agricaire, PO Box 3683, Harare, Zimbabwe)

	Bell 206 "Jetranger"	Cessna 401	S2RT "Turbo-Thrush"
Fuel consumption	25 USGal/hr (Jet A1)	28 USGal/hr (Avgas)	47 USGal/hr (Jet A1)
Fuel reserve	15 USGal	21 USGal	35 USGal
Fuel available	60 USGal	130 USGal	180 USGal
Fuel unusable	5 USGal	10 USGal	12 USGal
Payload	324 Kg	415 Kg	800 litres (=706 Kg Thiodan)
Loading time	10 mins	15 mins	15 mins
Refuelling time	10 mins	15 mins	10 mins
Maximum sortie speed	104 mph	184 mph	138 mph
Application speed	92 mph	184 mph	132 mph
Ferry speed	92 mph	190 mph	132 mph
Turn time	variable	5 mins	5 mins
Land/taxying time	1 min	5 mins	5 mins
Taxying/take-off time	1 min	8 mins	5 mins
Longest feasible sortie	1.8 hrs	2.5 hrs	2.5 hrs
Bleed air available	nil	nil	nil
Electrical power	28V 100A	24V 100A	28V 200A

Appendix 2

Equipment and Materials

Blank insecticide formulations

Thiodan Germany	Hoechst Aktiengesellschaft, 6000 Frankfurt (M) 71, Lyonestrasse,
Glossinex	Wellcome Public Health Insecticides Berkhamsted, Herts HP4 2DY
Karate JF9436	ICI Public Health Fernhurst, Haslemere, Surrey GU27 3JE

Atomisers

Micron X-1 Micron X-15	Micron Sprayers Ltd Three Mills, Bromyard, Herefordshire HR7 4HU
Micronair AU4000 AU5000	Micronair Ltd Bembridge Fort, Sandown, Isle of Wight PO36 8QS
Unirot	Aviation Service of the Ministry of Agriculture, 1502 Budapest PO Box 56 Hungary
Beecomist	Beecomist Systems 31 Meeting House Rd, Telford PA 18969
X-30	UK Forestry Commission, Edinburgh
Noricair	Noric Spraying Systems Kasteelweg 30, B-3700 Tongeren-Widooie, Belgium

Components of prototypes

Sintered plastic	Accumatic Filtration Ltd Llay Hall, Cefn-y-Bedd, Wrexham, North Wales LL12 9YH
Electric motor	Parma Cyclone II, 27 turns, 0.65mm single Parma European Sales, Unit 2, 25 Horsecroft Rd, The Pinnacles, Harlow, Essex CM19 5BH
Reticulated metal foam	Dunlop, Coventry

Appendix 3

Estimation of Weber numbers for ligaments produced by disc TR8

Since the ligament is contracting the part of the ligament just outside the layer of air entrained by the disc will have the highest Weber number so shattering will begin at this point.

Assumptions:

the cross-flow of air relative to the ligament at this point is equal to the tangential velocity of the disc, V_T .

the liquid has a jet velocity, V_J , of 0 m/s at the edge of the disc (a component of radial velocity would lead to a thinner ligament and a reduction in Weber number)

the liquid is accelerating with respect to the disc at a rate $\omega^2 r$ (ignoring the adverse pressure gradient in the contracting ligament; allowing for this would predict a fatter ligament and hence a higher Weber number)

Estimating the thickness of the entrained air layer to be 0.001 m then from the equations of motion the velocity of the jet, V_J at this point is given by

$$V_J^2 = 0 + 2 \cdot \omega^2 r \cdot 0.004$$

The ligament diameter, d_{lig} , at this point is

$$d_{lig} = \left(\frac{4 Q}{\pi V_J} \right)^{0.5}$$

where d_{lig} is in metres, Q in m^3/sec and V_J in m/s

These values can now be substituted into the expression for Weber number with respect to the airsteam

$$We = \frac{\rho_a V_T^2 d_{lig}}{2 \sigma}$$

(continued...)

Taking ρ_a as 1.16 Kg/m^3 and σ as $3.2 \times 10^{-2} \text{ N/m}$ then

rotation speed	300 Hz	400 Hz
V_J	13.3m/s	17.8 m/s
V_T	47.1 m/s	62.8 m/s
d_{lig}	89.6 μm	77.6 μm
We	3.61	5.55

Table 1.1

Benefits of a seven-fold decrease in output flow rate on sortie length and payload for aircraft currently used in tsetse control (based on figures in Appendix 1)

	Bell 206 "Jetranger"	Cessna 401	S2RT "Turbo-Thrush"
Spraying speed (mph)	92	184	132
Current output (l/min)	3.5	7.0	5.0
Maximum payload (litres Thiodan)	360	461	800
Maximum potential spraying time (mins)	103	66	160
Time available for spraying (mins) *	78	120	120
Maximum load which can be used in a sortie (litres Thiodan)	273	461	600
Maximum load which could be used with a 7-fold decrease in output	39	120	84
Increase over current sortie length	0%	227%	0%
% decrease over current payload for maximum sortie	86%	74%	86%

* taken as (longest sortie – 30 minutes), an arbitrary time chosen to illustrate that not all of a sortie is available for spraying

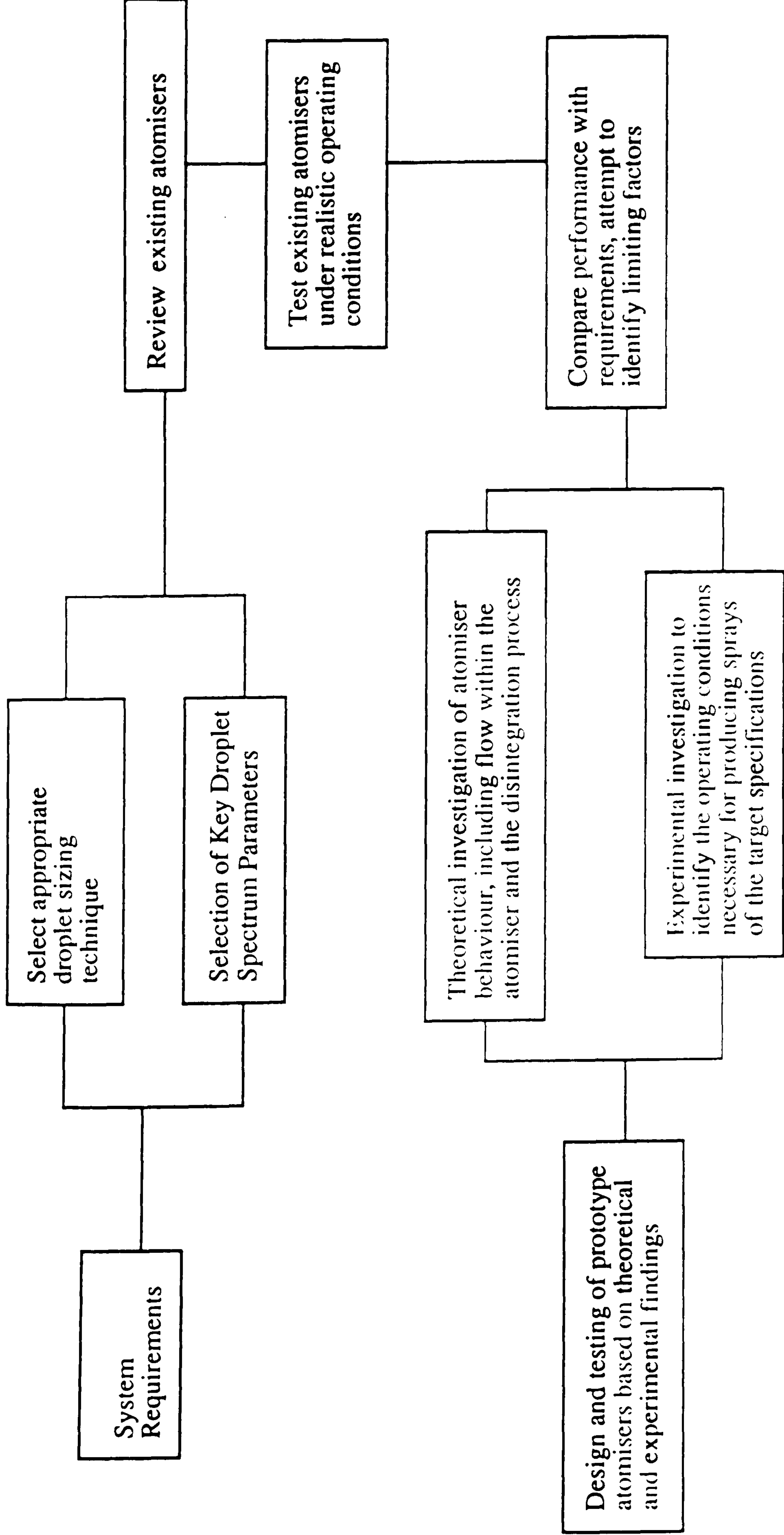


Table 1.2 Procedure for the development of atomisers to be used in tsetse and armyworm control

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Table 3.1 Power usage in atomisers

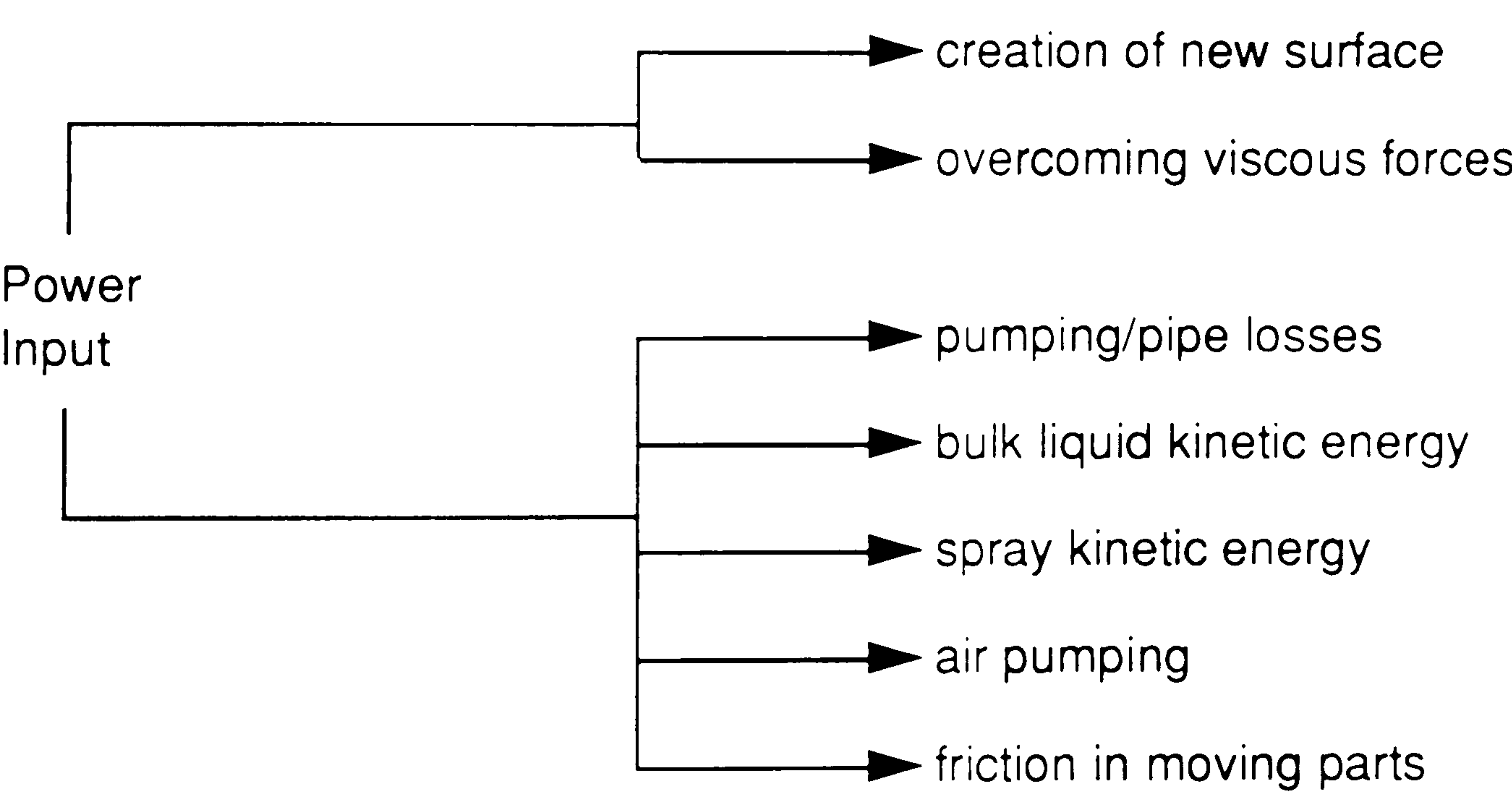


Table 4.1

Properties of fluids used in the test programme (room temperature)

Name	Supplier	Viscosity (Kg m ⁻¹ s ⁻¹)	Surface Tension (Nm ⁻¹)	Density (Kgm ⁻³)
Thiodan	Hoechst	1.5 x10 ⁻³	0.0288	0.883
Glossinex	Wellcome	2.2x10 ⁻³	0.0293	*
Karate	I.C.I.	1.3x10 ⁻³	0.0321	*
JF9436	I.C.I.	3.0 x10 ⁻²	0.0357	0.915
Water + 0.1% Agral	Cranfield tap water, Agral from I.C.I.	1.0x10 ⁻³	0.032	1.000

* data unavailable

Table 4.2

Atomisation characteristics of a Unirot atomiser with R-30 cage spraying Thiodan blank formulation, measured using coarse configuration probe

Windspeed 53.6 m/s (120 mph)
Rotation speed 11500 rpm (without load)

Flowrate (l/min)	VMD (μm)	relative span	% volume		
			<33.2	70.1- 99.8 μm	67.7- 122.5 μm
0.6	93	2.042	4.2	20.9	22.1
0.75	112	1.857	3.1	18.5	21.4
1.0	170	1.867	1.9	13.3	16.1
1.15	213	1.620	1.6	11.4	13.4
1.7	245	1.410	1.0	8.6	10.9
2.45	272	1.297	0.6	6.7	9.2
2.95	238	1.235	0.7	7.9	11.1
3.5	212	1.408	0.8	9.2	13.2
4.0	247	1.227	0.5	7.1	10.3

Table 4.3

Previous data on the use of Beecomist atomisers

	Rotation Speed (RPM)	Wind Speed (MPH)	Flowrate (l/minute)	VMD (µm)
Yates et al 1984	11700	50	2.27	125
OAP, 33µm size-class	11700	100	2.27	123
intervals, minimum 24µm	8300	50	11.36	191
water	8350	100	11.36	178
Picot et al 1985	7200	89	1.2	97% vol 15- 55µm, 10-15% vol <30µm
Polythene sleeve FSSP and photography water				
VanVliet et al 1987				
40µm sintered metal	13920	94	0.76	54% vol 15- 55µm
sleeve, FSSP and OAP deicing fluid (simulant for fenitrihion/water emulsion)				
Harrison (unpublished)	10200	100	0.2	74
40µm sintered metal	10200	100	0.5	86
sleeve, OAP, 15µm size-	10200	100	1.0	127
class intervals, minimum	10200	100	1.5	157
10µm, oil	12000	40	1.8	110

Table 4.4

Atomisation characteristics of a Beecomist 360A atomiser with 40µm sintered metal head spraying blank Thiodan formulation measured using original PMS configuration

a) effect of flowrate

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span
0.09	74	1.436
0.26	80	1.677
0.35	80	1.715
0.44	84	1.593
0.66	92	1.383

b) effect of windspeed

Flowrate 400 ml/min

Windspeed m/s (mph)	VMD (µm)	relative span
22.3 (50)	79	1.885
26.8 (60)	-	-
31.3 (70)	81	1.615
35.8 (80)	83	1.372
40.2 (90)	81	1.457
44.7 (100)	79	1.838
49.2 (110)	74	1.715
53.6 (120)	72	1.783
58.1 (130)	70	1.783
62.6 (140)	67	1.734

Flowrate 70 ml/min

Windspeed m/s (mph)	VMD (µm)	relative span
22.3 (50)	79	0.923
26.8 (60)	78	0.921
31.3 (70)	76	0.982
35.8 (80)	75	0.999
40.2 (90)	76	1.109
44.7 (100)	75	1.181
49.2 (110)	74	1.238
53.6 (120)	-	-
58.1 (130)	71	1.289
62.6 (140)	75	1.291

Table 4.5

Atomisation characteristics of a Beecomist 360A atomiser with 40µm sintered metal head spraying blank Thiodan formulation

a) effect of flowrate

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span	% Volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.10	68	1.419	3.4	34.6	14.1
0.26	70	1.468	3.3	35.2	17.5
0.37	71	1.374	3.4	65.7	19.2
0.41	73	1.496	3.1	36.0	19.5
0.60	76	1.577	3.1	34.9	21.6
0.84	86	1.571	2.8	34.3	26.6
1.20	116	1.374	1.5	25.4	27.8

b) effect of windspeed

Flowrate 0.41 l/min

Windspeed m/s	(mph)	VMD (µm)	relative span	% Volume		
				<33.2µm	67.7- 102.5µm	82.5- 122.5µm
26.8	(60)	76	1.527	6.4	41.7	22.8
31.3	(70)	76	1.603	5.4	39.7	22.4
35.8	(80)	76	1.480	3.8	42.2	23.5
40.2	(90)	74	1.552	3.8	37.5	20.8
44.7	(100)	73	1.516	3.7	35.5	19.8
49.2	(110)	72	1.536	3.5	35.2	19.1
53.6	(120)	72	1.441	3.5	35.2	19.4
58.1	(130)	70	1.551	3.8	33.0	17.8
62.6	(140)	69	1.427	4.8	30.7	18.1

Flowrate 0.10 l/min

50 68 0.795 8.0 46.3 15.6

Flowrate 0.84 l/min

60 85 1.710 4.9 34.1 26.3

Flowrate 1.200 l/min

60 103 1.428 2.8 30.0 30.5

Table 4.6

Atomisation characteristics of a Beecomist 360A atomiser with 40µm sintered metal head spraying blank Glossinex formulation

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span	% Volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.10	72	1.173	3.6	41.6	21.5
0.25	73	1.436	3.5	41.1	21.1
0.38	77	1.490	3.4	37.8	23.2
0.41	77	1.520	3.3	37.7	23.1
0.60	80	1.647	3.5	34.5	23.7
0.78	84	1.696	3.6	32.9	23.9
1.24	94	1.680	3.5	31.0	25.8

Table 4.7

Atomisation characteristics of a Beecomist 360A atomiser with 40µm sintered metal head spraying blank Karate formulation

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span	% Volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.10	69	1.477	4.4	33.2	16.7
0.27	72	1.482	4.5	36.2	19.5
0.37	75	1.497	4.0	37.6	21.4
0.41	79	1.513	3.6	39.6	25.1
0.60	81	1.425	5.8	38.9	28.7
0.84	84	1.619	5.6	36.1	28.4
1.20	96	1.667	3.2	31.7	27.4

Table 4.8

Atomisation characteristics of a Beecomist 360A atomiser with perforated metal drum head spraying blank Thiodan formulation

a) Effect of flowrate

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span	% Volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.10	66	0.903	5.7	37.3	15.2
0.26	76	1.252	4.0	42.9	26.1
0.37	75	1.395	4.7	38.0	23.5
0.40	82	1.516	5.9	37.2	28.7
0.60	86	1.530	3.8	38.3	29.7
0.88	101	1.468	2.8	31.9	32.7
1.24	111	1.492	2.5	27.4	29.7

b) effect of windspeed

Flowrate 410 ml/min

Windspeed m/s (mph)		VMD (µm)	relative span	% Volume		
				<33.2µm	67.7- 102.5µm	82.5- 122.5µm
17.9	(40)	87	1.504	6.2	33.6	31.7
26.8	(60)	89	1.383	6.8	37.7	36.5
35.8	(80)	93	1.454	4.6	36.1	34.9
44.7	(100)	86	1.326	4.3	39.9	33.5
53.6	(120)	86	1.428	3.6	41.5	32.8
62.6	(140)	82	1.384	4.1	42.5	30.9

Table 4.9

Atomisation characteristics of a Beecomist 360A atomiser with perforated metal drum head spraying blank JF9436 formulation

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (µm)	relative span	% Volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.12	87	1.384	3.7	40.4	33.2
0.25	93	1.384	3.3	36.9	33.1
0.42	106	1.465	2.6	29.5	28.8
0.82	123	1.323	2.4	23.1	26.7
1.14	136	1.269	2.0	18.7	24.0

b) effect of windspeed

Flowrate 410 ml/min

Windspeed m/s (mph)		VMD (µm)	relative span	% Volume		
				<33.2µm	67.7- 102.5µm	82.5- 122.5µm
17.9	(40)	89	1.349	6.1	34.6	34.6
26.8	(60)	97	1.323	5.6	33.5	37.5
35.8	(80)	95	1.332	5.1	32.3	34.3
44.7	(100)	100	1.433	3.6	30.5	30.2
53.6	(120)	103	1.431	2.8	30.8	29.0
62.6	(140)	106	1.445	2.6	30.3	29.5

Table 4.10

Previous particle sizing data on the Micron X-15 atomiser

	Rotation Speed (RPM)	Wind Speed (m/s)	Flowrate (l/minute)	VMD (μm)
<hr/>				
Spillman 1987	4300		1.6	120
OAP, 15μm size-class				
intervals, minimum 10μm	6000		0.6	100
water + Agral	6000		1.2	106
	6000		1.8	106
	12000		0.6	67
	12000		1.2	78
	12000		1.8	82
	14000		0.6	60
	14000		1.2	72
	14000		1.8	78
				VMD (μm)
Harrison (unpublished)	6750	25.4	0.8	132
OAP, 15μm size-class	6250	25.4	1.2	137
intervals, minimum 10μm	5400	25.4	1.6	141
Actipron + water	5050	25.4	2.0	168
24 volts	4600	25.4	2.4	169
<hr/>				

Table 4.11

Atomisation characteristics of a Micron X-15 atomiser spraying blank Thiodan formulation

a) effect of flowrate

Windspeed 53.6 m/s (120 mph)

Flowrate (l/min)	VMD (μ m)	relative span	% volume		
			<33.2 μ m	67.7- 102.5 μ m	82.5- 122.5 μ m
0.1	76	0.777	4.2	54.5	34.6
0.26	85	0.909	3.2	47.5	43.5
0.35	90	1.055	3.3	39.0	42.3
0.40	105	1.269	3.4	24.6	30.8
0.60	112	1.313	2.5	23.4	28.6
0.80	126	1.366	1.8	20.2	24.7
1.24	146	1.194	1.1	15.7	21.3

b) effect of windspeed

Flowrate 0.51 l/min

Windspeed (mph)	VMD (μ m)	relative span	% volume		
			<33.2 μ m	67.7- 102.5 μ m	82.5- 122.5 μ m
40	82	1.342	3.3	29.9	28.5
60	85	1.258	3.6	28.4	30.5
80	88	1.196	3.7	29.8	33.4
100	97	1.283	3.0	28.6	34.3
120	104	1.257	2.1	27.7	34.2
140	118	1.139	1.2	22.8	33.7

Table 4.12

Atomisation characteristics of a Micron X-15 atomiser spraying blank Glossinex formulation

Windspeed 120 mph

Flowrate (l/min)	VMD (µm)	relative span	% volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.10	91	0.931	2.0	39.5	41.1
0.27	99	0.891	2.0	39.4	50.1
0.35	104	0.988	1.9	32.2	46.9
0.40	107	0.695	1.8	29.5	43.0
0.61	132	1.119	1.1	16.6	24.9
0.80	194	0.985	0.7	8.2	11.2
1.24	190	0.965	0.6	8.3	11.5
modified feed					
0.10	69	0.750	3.7	46.1	21.3

Table 4.13

Atomisation characteristics of a Micron X-15 atomiser spraying blank JF9436 formulation

a) effect of flowrate

Windspeed 120 mph

Flowrate (l/min)	VMD (μ m)	relative span	% volume		
			<33.2 μ m	67.7- 102.5 μ m	82.5- 122.5 μ m
0.13	119	1.083	2.8	18.0	30.1
0.34	132	1.228	2.8	16.6	18.8
0.40	140	1.171	2.0	16.2	15.9
0.75	155	1.142	1.1	15.4	19.6
1.15	173	1.039	0.8	9.2	14.0

b) effect of windspeed

Flowrate 0.48 l/min

Windspeed (mph)	VMD (μ m)	relative span	% volume		
			<33.2 μ m	67.7- 102.5 μ m	82.5- 122.5 μ m
40	95	1.251	1.7	35.8	32.9
60	99	1.165	1.8	36.5	36.1
80	102	1.192	2.1	32.3	32.9
100	115	1.260	2.0	24.6	26.7
120	138	1.246	1.6	19.1	21.7
140	158	1.118	1.3	15.0	18.1

Table 4.14

Particle size data for Micronair AU4000 atomiser

	Rotation Speed (RPM)	Wind Speed (MPH)	Flowrate (l/minute)	VMD (µm)
Siddiqui 1986	6000	—	2.5	98 a
OAP, 15µm size-class	6000	—	5.0	113
intervals, minimum 10µm	6000	—	10.0	138
water	6000	—	20.0	162
	8000	—	2.5	90 b
	8000	—	5.0	105 c
	8000	—	10.0	123 d
	8000	—	20.0	142
ICAP unpublished report	11500	—	4.5	80 e
for TDRI	11480	—	7.0	77
OAP, 15µm size-class	8120	—	4.5	100
intervals, minimum 10µm	8120	—	7.0	102
Thiodan				
vanVliet + Picot 1987				% volume
in	FSSP and OAP			
range 15-55µm				
Equal mixture by volume	14000	—	0.9	83%
of IPA and deicing fluid	14000	—	2.1	86%
	14000	—	7.2	40%
60% wt sucrose	14000	—	3.4	45%
40% wt water				
68% wt sucrose	9000	—	1.8	58%
40% wt water	9000	—	4.0	37%
80% vol water	9000	—	1.9	47%
80% vol IPA	9000	—	3.8	38%

a-e conditions for which equivalent AU5000 data exists

Table 4.15

Particle size data for Micronair AU5000 atomiser

	Rotation Speed (RPM)	Wind Speed (MPH)	Flowrate (l/minute)	VMD (μ m)
Mierzejewski 1982	11200	92	2.5	66
OAP, 15 μ m size-class	9250	69	2.5	75
intervals, minimum 10 μ m	8100	92	2.5	88 b
water	5750	69	2.5	96 a
	5150	92	2.5	134
	12450	92	5.0	78
	7900	92	5.0	103 c
	5050	92	5.0	130
Yates et al 1984	11700	130	2.3	81
OAP, 33 μ m size-class	9100	110	2.3	110
intervals, minimum 24 μ m	10850	130	11.4	79
water	8000	100	11.4	118 d
Yates + Akesson 1985				
OAP, 33 μ m size-class	8900	-	2.3	110
intervals, minimum 24 μ m	5200	-	2.3	145
cotton seed oil+solvent				
Harrison (ICAP report)	12120	-	4.5	85 e
OAP, 15 μ m size-class	12030	-	7.0	85
intervals, minimum 10 μ m	10400	-	2.1	79
unspecified oil	10200	-	4.3	89
	7000	-	3.8	99
	7000	-	2.7	94
	7000	-	1.0	88
	7000	-	0.5	77
	7000	-	0.4	76
a-e conditions for which equivalent AU4000 data exists				

Table 4.16

Previous particle sizing data on the Micron X-1 atomiser

	Rotation Speed (RPM)	Wind Speed (MPH)	Flowrate (l/minute)	VMD (µm)
Yates et al 1984				
OAP, 33µm size-class				
intervals, minimum 24µm	13000	100	1.14	137
water	8150	100	1.14	159
Yates + Akesson 1985				
OAP, 33µm size-class				
intervals, minimum 24µm	18000	100	1.1	137
Cotton seed oil	8100	100	1.1	173
Spillman 1987				
	18200	112	0.05	38
OAP, 15µm size-class	18200	112	0.1	42
intervals, minimum 10µm	18200	112	0.2	51
water + Agral	18200	112	0.4	75
110 mph wind	18200	112	0.8	91
Harrison (ICAP report)				
OAP, 15µm size-class	21100	145	0.05	46
intervals, minimum 10µm	21010	145	0.1	50
Thiodan, 110 mph wind	20900	145	0.2	62
VanVliet + Picot 1987				
FSSP and OAP	top speed (unspecified) at			
	0.09 l/min gave			
water + 9% propanol	44.2% volume in 15-55µm range			

Table 4.17

Effect of windspeed on the rotation speed of a Micron X-1 atomiser running without load

		coarse	Blade	setting	fine	
Windspeed		5	4	3	2	1
m/ s	(mph)					
17.9	(40)	4800	6300	7920	7860	
22.3	(50)	5160	6600	8400	10800	11400
26.8	(60)	6300	8100	10260	13500	13920
31.3	(70)	7500	9660	12540	16800	17280
35.8	(80)	8760	11520	15060	19980	20880
40.2	(90)	10140	13440	17760	23400	23880
44.7	(100)	11400	15240	19680	26280	
49.2	(110)	12840	17100	22200	28200	
53.6	(120)	14100	19080	25140		
58.1	(130)	15480	20820	27600		
62.6	(140)	16920	22800			
by extrapolation						
71.5	(160)	19552	25756			
80.5	(180)	21519	29161			
89.4	(200)	23995	32565			

Table 4.18

Atomisation characteristics of a Micron X-1 atomiser spraying Glossinex blank formulation

Windspeed 44.7 m/s (100 mph)

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% Volume		
					<33.2 μm	67.7- 102.5 μm	82.5- 122.5 μm
0.1	5	10920	77	0.968	3.8	43.6	32.4
	4	14400	62	0.889	6.6	34.0	14.5
	3	19140	50	0.854	13.8	12.3	3.7
	2	24480	43	0.894	23.2	6.2	1.7
0.26	5	10920	93	1.136	2.7	34.1	35.5
	4	14700	77	1.091	3.9	39.3	31.8
	3	19500	64	0.999	6.6	34.4	18.3
	2	24600	55	0.968	10.5	20.4	7.8
0.36	5	10500	109	1.104	1.9	26.7	33.6
	4	14220	88	1.159	3.0	36.6	34.6
	3	19020	69	1.091	5.1	37.1	23.5
	2	23340	62	1.069	7.5	29.7	15.6
0.62	5	10800	122	1.193	1.7	22.2	26.3
	4	13800	101	1.201	2.4	29.7	32.6
	3	18300	81	1.245	3.9	37.3	31.0
	2	23460	65	1.214	6.8	31.5	18.5
0.78	5	10740	128	1.142	1.6	19.8	24.4
	4	14700	99	1.205	2.7	30.2	32.6
	3	18120	82	1.314	3.9	36.4	30.8
	2	23640	66	1.267	7.4	31.3	20.3
1.18	5	10740	135	1.203	1.5	18.4	22.4
	4	14580	106	1.243	2.6	26.8	30.8
	3	18900	84	1.350	4.3	33.6	30.2
	2	22980	71	1.332	6.7	32.7	24.3

Table 4.19

Atomisation characteristics of a Micron X-1 atomiser spraying Thiodan blank formulation
Windspeed 44.7 m/s (100 mph)

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (µm)	relative span	% Volume		
					<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.26	4	14700	73	0.980	3.8	41.7	29.0
	2	24600	53	0.898	12.1	16.90	6.6
0.62	4	13800	96	1.114	3.1	32.4	36.3
	2	23460	62	1.130	9.0	30.3	17.3
1.18	4	14580	103	1.171	3.0	27.4	32.5
	2	22980	72	1.216	7.2	34.7	26.7

Table 4.20

Atomisation characteristics of a Micron X-1 atomiser spraying Karate blank formulation
Windspeed 44.7 m/s (100 mph)

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (µm)	relative span	% Volume		
					<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.26	4	15600	73	1.037	4.0	40.7	27.5
	2	23280	54	0.913	11.2	19.5	7.4
0.62	4	14700	93	1.183	2.8	34.2	35.0
	2	22440	65	1.123	7.2	32.2	19.4
1.18	4	14400	102	1.212	3.1	27.7	31.8
	2	23280	66	1.284	8.4	30.8	20.4

Table 4.21

Atomisation characteristics of a Micron X-1 atomiser spraying JF9436 blank formulation
Windspeed 44.7 m/s (100 mph)

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% Volume		
					<33.2 μm	67.7- 102.5 μm	82.5- 122.5 μm
0.11	5	10500	79	1.285	4.1	33.5	27.5
	4	14340	69	1.225	6.3	33.0	24.0
	3	18840	62	1.244	9.4	28.5	17.8
	2	23400	56	1.258	13.3	24.3	13.5
0.22	5	11160	121	1.343	3.0	19.5	19.6
	4	15000	103	1.285	3.4	25.3	27.1
	3	19680	88	1.206	4.3	34.2	33.1
	2	24780	73	1.219	6.5	35.7	27.3
0.54	5	11100	153	1.233	2.5	14.7	13.6
	4	14280	145	1.206	3.2	12.9	13.9
	3	19080	121	1.194	4.1	17.7	23.3
	2	23280	117	1.162	4.5	19.2	26.4

Table 4.22

Atomisation characteristics of the Noric prototype windmill–driven Atomiser spraying blank Thiodan formulation

Flowrate 0.62 l/min

Windspeed		Rotation Speed	VMD	relative span	% Volume		
					<33.2µm	67.7– 102.5µm	82.5– 122.5µm
53.6	(120)	5700	113	1.244	1.8	25.9	30.2
58.1	(130)	6540	101	1.290	2.2	32.6	35.5

Flowrate 1.25 l/min

Windspeed		Rotation Speed	VMD	relative span	% Volume		
					<33.2µm	67.7– 102.5µm	82.5– 122.5µm
26.8	(60)	2400	186	1.085	0.7	10.3	13.7
35.8	(80)	3600	166	1.179	1.3	13.1	16.1
44.7	(100)	4740	140	1.202	1.5	18.1	20.8
53.6	(120)	5700	123	1.309	1.7	22.8	26.4
58.1	(130)	6300	113	1.370	1.7	26.4	30.7

Table 4.23

Atomisation characteristics of the Forestry Commission's prototype X-30 atomiser spraying a 20% (v/v) aqueous solution of Actipron

Windspeed 25.5 m/s (57mph)

Flowrate (l/min)	VMD (µm)	relative span	% volume		
			<33.2µm	67.7- 102.5µm	82.5- 122.5µm
0.66	61	1.518	12.1	24.9	18.4
1.24	82	1.844	5.5	27.6	23.5
1.90	95	1.816	4.3	26.6	24.0
2.60	108	1.694	2.9	25.7	25.3

Table 6.1

Angles subtended to radius by tangents drawn to spiral disturbances in photographs of the layer of water on a rotating disc

	Photograph 1	Photograph 2	
	90 + 24 ⁰	90 + 28 ⁰	
	90 + 23 ⁰	90 + 22 ⁰	
	90 + 20 ⁰	90 + 22 ⁰	
	90 + 26 ⁰	90 + 28 ⁰	
	90 + 20 ⁰	90 + 24 ⁰	
	90 + 18 ⁰	90 + 16 ⁰	
	90 + 20 ⁰	90 + 15 ⁰	
	90 + 18 ⁰	90 + 23 ⁰	
	90 + 18 ⁰	90 + 18 ⁰	
	90 + 16 ⁰	90 + 21 ⁰	
	90 + 20 ⁰	90 + 20 ⁰	combined data
	90 + 18 ⁰	90 + 19 ⁰	from both photographs
	90 + 12 ⁰	90 + 17 ⁰	
		90 + 13 ⁰	
mean	90 + 19.46 ⁰	90 + 20.43 ⁰	90 + 19.96 ⁰
	± 11.1%	± 12.7%	± 8.0%
(95% confidence limit)			

Table 6.2

Volume Median Diameter of spray produced by 22mm diameter 45-channelled disc, TR1, using water + 0.1% Agral

Rotation Speed (Hz)	Rim Velocity (m sec ⁻¹)	Flowrate (ml/min)		
		16	55	111
56	3.86	666	-	393
75	5.18	593	418	313
100	6.19	567	-	-
125	8.64	-	247	293
150	10.37	177	239	278
175	12.10	170	237	275
200	13.82	-	231	270
225	15.55	154	225	260
250	17.28	151	219	250
275	19.01	215	244	-
300	20.73	145	212	238
325	22.46	143	209	207
350	24.19	141	205	205
375	25.92	141	202	205
400	27.65	142	-	205
410	28.34	-	187	205
421	29.09	144	-	-

Table 6.3

Relative Span of spray produced by 22mm diameter 45-channelled disc, TR1, using water + 0.1% Agral

Rotation Speed (Hz)	Rim Velocity (m sec ⁻¹)	Flowrate (ml/min)		
		16	55	111
56	3.86	0.527	-	1.577
75	5.18	0.728	1.410	2.015
100	6.91	0.844	-	-
125	8.64	-	1.309	1.772
150	10.37	0.673	0.841	1.664
175	12.10	1.309	0.724	1.423
200	13.82	-	0.655	1.266
225	15.55	1.440	0.655	0.974
250	17.28	1.495	0.671	0.835
275	19.01	1.526	0.674	0.783
300	20.73	.556	0.677	0.755
325	22.46	1.581	0.683	0.651
350	24.19	1.621	0.689	0.655
375	25.92	1.643	0.696	0.656
400	27.65	1.641	-	0.659
410	28.34	-	0.653	0.661
421	29.09	1.648	-	-

Table 6.4

Observed behaviour of fluid ligaments produced by disc TR8 over a range of flow rates and rotation speeds

Rotation speed (RPM)	Flow rate (ml/min)			
	0.37	0.93	2.06	4.93
6000	A	A	A	A
12000	A	A	A	B*
18000	A	B	B	C
24000	B	C	C	D
30000	B	C	C	D

- A smoothly curving ligament, axisymmetrical wave growth
- B disturbed ligament, axisymmetrical wave growth, some sinusoidal disturbance
- C strongly disturbed ligaments, strong sinusoidal disturbance, fragments of ligament break off
- D shattering of ligament close to the disc edge

* distinct alternating protuberences along ligament

Table 6.5

Mean breakup lengths of ligaments produced by disc TR8 fed with water containing 0.1% Agral

Flowrate (ml/min)	Rotation Speed (RPM)	Peripheral Speed (m/sec)	Mean Breakup Length (mm)	Mean Coefficient of Variation	Predicted Value (mm)
0.363	6000	15.7	2.9	5.8%	4.1
0.921	6000	15.7	8.4	10.5%	6.6
2.053	6000	15.7	12.5	5.8%	10.0
5.045	6000	15.7	16.6	8.9%	15.9
0.363	12000	31.4	4.3	9.9%	3.0
0.921	12000	31.4	6.3	9.8%	4.9
2.053	12000	31.4	9.0	6.2%	7.5
5.045	12000	31.4	7.6	6.1%	11.9
0.363	18000	47.1	2.0	12.7%	2.6
0.921	18000	47.1	4.2	10.2%	4.2
2.053	18000	47.1	5.4	10.6%	6.3
5.045	18000	47.1	7.0	10.6%	10.0
0.363	24000	62.8	1.3	8.3%	2.3
0.921	24000	62.8	4.1	9.3%	3.7
2.053	24000	62.8	7.2	8.3%	5.6
5.045	24000	62.8	—	—	8.9
0.363	30000	78.5	2.3	11.4%	2.1
0.921	30000	78.5	4.3	10.0%	3.3
2.053	30000	78.5	6.0	8.0%	5.1
5.045	30000	78.5	—	—	8.1
0.363	33000	86.4	1.8	—	2.0
0.921	33000	86.4	3.6	12.4%	3.2
2.053	33000	86.4	8.1	8.1%	4.9
5.045	33000	86.4	—	—	7.7

Table 6.6

Atomisation characteristics of trial disc TR8 fed with water containing 0.1% Agral

flowrate (ml/min)	Rotation	Peripheral	VMD (μ m)	relative span	% volume	
	Speed (RPM)	Speed (m/sec)			<33.2 μ m	82.5– 122.5 μ m
0.37	6000	15.7	79	0.428	0.0	35.5
	12000	31.4	56	0.325	0.9	0.7
	18000	47.1	47	0.575	4.2	0.9
	24000	62.8	41	0.520	15.4	0.2
	30000	78.5	32	0.451	56.0	0.0
	36000	94.3	27	0.463	95.0	0.0
	42000	110.0	25	0.455	97.7	0.0
0.93	6000	15.7	100	0.568	0.0	65.9
	12000	31.4	71	0.641	0.9	19.3
	18000	47.1	63	0.452	0.9	2.5
	24000	62.8	48	0.687	14.2	0.9
	30000	78.5	47	0.625	11.6	1.2
	36000	94.3	28	0.631	78.9	0.0
	42000	110.0	25	0.629	93.0	0.0
2.06	6000	15.7	130	0.634	0.0	17.8
	12000	31.4	89	0.666	0.3	61.7
	18000	47.1	77	0.629	0.8	31.6
	24000	62.8	63	0.827	8.1	13.2
	30000	78.5	46	0.966	22.7	3.3
	36000	94.3	32	0.949	56.5	0.4
	42000	110.0	27	0.795	77.5	0.1
4.93	6000	15.7	175	0.719	0.0	8.3
	12000	31.4	135	0.627	0.1	20.2
	18000	47.1	121	0.811	2.1	36.2
	24000	62.8	78	1.179	8.7	32.9
	30000	78.5	54	1.148	22.3	11.4
	36000	94.3	38	1.312	38.9	3.7
	42000	110.0	32	1.414	54.6	3.6

Table 6.7

Atomisation characteristics of trial disc TR8 fed with Thiodan

flowrate (ml/min)	Rotation Speed (RPM)	Peripheral Speed (m/sec)	VMD (μm)	relative span	% volume	
					<33.2 μm	82.5– 122.5 μm
0.37	6000	15.7	69	0.401	0.1	12.3
	12000	31.4	51	0.805	3.5	6.0
	18000	47.1	46	0.873	12.6	4.1
	24000	62.8	35	0.722	43.3	0.0
	30000	78.5	28	0.677	80.7	0.0
	36000	94.3	27	0.611	87.3	0.0
	42000	110.0	26	0.562	91.6	0.0
0.93	6000	15.7	92	0.526	0.0	65.8
	12000	31.4	72	0.676	0.5	24.9
	18000	47.1	52	0.799	6.7	5.8
	24000	62.8	48	0.880	19.2	2.5
	30000	78.5	39	0.940	34.1	0.5
	36000	94.3	33	0.814	50.5	0.4
	42000	110.0	30	0.713	66.1	0.0
2.06	6000	15.7	118	0.619	0.0	45.0
	12000	31.4	83	0.780	0.3	43.6
	18000	47.1	70	0.883	3.6	28.7
	24000	62.8	61	0.971	14.6	16.5
	30000	78.5	47	1.070	28.8	4.5
	36000	94.3	34	1.071	47.2	0.4
	42000	110.0	30	0.826	67.4	0.1
4.93	6000	15.7	157	0.546	0.0	17.6
	12000	31.4	115	0.695	0.2	43.1
	18000	47.1	73	1.206	7.0	28.4
	24000	62.8	57	1.264	16.5	17.4
	30000	78.5	43	1.185	29.8	5.0
	36000	94.3	34	1.116	47.6	1.2
	42000	110.0	27	0.556	87.7	0.0

Table 6.8

Atomisation characteristics of trial disc TR8 fed with JF9436

flowrate (ml/min)	Rotation Speed (RPM)	Peripheral Speed (m/sec)	VMD (μm)	relative span	% volume	
					<33.2 μm	82.5– 122.5 μm
0.37	6000	15.7	77	0.369	0.8	29.7
	12000	31.4	56	0.628	3.4	6.3
	18000	47.1	45	1.775	18.9	23.9
	24000	62.8	45	1.230	25.4	6.4
	30000	78.5	39	1.097	35.1	0.4
	36000	94.3	31	1.070	59.7	0.3
	42000	110.0	29	0.898	69.9	0.0
0.93	6000	15.7	108	0.450	0.3	68.8
	12000	31.4	70	0.925	5.5	23.9
	18000	47.1	55	1.830	17.4	12.2
	24000	62.8	51	1.392	23.1	14.3
	30000	78.5	48	1.304	30.0	9.9
	36000	94.3	38	1.292	38.9	1.7
	42000	110.0	30	0.990	64.6	0.1
2.06	6000	15.7	128	0.858	0.5	17.4
	12000	31.4	75	1.198	7.7	33.7
	18000	47.1	59	2.075	20.9	17.3
	24000	62.8	58	1.506	24.2	16.3
	30000	78.5	50	1.315	29.2	10.6
	36000	94.3	41	1.313	36.2	4.2
	42000	110.0	34	1.171	49.1	1.0
4.93	6000	15.7	170	0.807	0.6	17.1
	12000	31.4	78	1.808	5.4	16.9
	18000	47.1	69	2.136	16.9	20.5
	24000	62.8	65	1.722	26.5	24.1
	30000	78.5	58	1.543	32.2	19.3
	36000	94.3	47	1.443	36.5	9.9
	42000	110.0	33	1.476	49.6	2.1

(table 6.8 continued)

Karate

1.44	15600	73	67	73
1.44	23280	54	51	55
3.44	14700	93	87	95
3.44	22440	65	65	65
6.56	14400	102	104	114
6.56	23280	66	75	68

JF9436

0.61	10500	79	104	63
0.61	14340	69	84	53
0.61	18840	62	69	46
0.61	23400	56	60	54
1.22	11160	121	119	74
1.22	15000	103	97	63
1.22	19680	88	80	54
1.22	24780	73	68	56
3.00	11100	153	149	94
3.00	14280	145	126	82
3.00	19080	121	103	70
3.00	23280	117	90	68

Table 6.9 Comparison of performance of the Micron X-1 atomiser with the Micron X-1 empirical model and the TR8 two-stage empirical model

Flow per tooth (ml/min)	Rotation speed (rpm)	Measured VMD (µm)	Prediction of Micron X-1 model (µm)	Prediction of TR8 model (µm)
Glossinex				
0.56	10920	77	72	61
0.56	14400	62	59	52
0.56	19140	50	49	45
0.56	24480	43	41	44
1.44	10920	93	92	78
1.44	14700	77	75	67
1.44	19500	64	61	57
1.44	24600	55	52	50
2.00	10500	109	102	87
2.00	14220	88	83	74
2.00	19020	69	68	63
2.00	23340	62	59	55
3.44	10800	122	115	99
3.44	13800	101	97	87
3.44	18300	81	80	75
3.44	23460	65	67	59
4.33	10740	128	123	106
4.33	14700	99	99	89
4.33	18120	82	85	80
4.33	23640	66	71	61
6.56	10740	135	136	118
6.56	14580	106	110	100
6.56	18900	84	92	87
6.56	22980	71	81	66
Thiodan				
1.44	14700	73	71	67
1.44	24600	53	50	49
3.44	13800	96	93	88
3.44	23460	62	64	58
6.56	14580	103	105	101
6.56	22980	72	77	65

(continued.....)

Table 7.1

Rotation speeds neccessary to emit uniformly all fluid fed into the variable slit test rig
(means of five measurements)

a) Water + 0.1% Agral

Revs per second for uniform emission					
Flowrate (ml/min)	0.04m gap	0.08mm gap	nylon mesh	retic. foam	sint. metal
16	32		83		
23	34		98		
27	38	19	101	28	41
33	42		104		
38	42	22	107	33	48
43	46		110		
49	48	26	112	33	48
54	51		115		
58	53	28	117	31	51
63	54		122		
67	57	31	125	30	55

b) JF9436

Revs per second for uniform emission			
Flowrate (ml/min)	nylon mesh	retic. foam	sint. metal
22	151	48	87
29	187	52	102
34	209	54	103
46	234	66	105

Table 7.2

Finite element analysis of atomiser feed–pipe with various end masses

Pipe length (mm)	Position of support from clamped end (mm)	End weight (g)	first harmonic (hz)
89	no support	0	516.5
"	" "	0.154	476.5
"	" "	0.500	411.9
"	" "	1.000	352.2
"	" "	1.500	312.5
"	50		
	(fully clamped)	0.154	1194.0
"	50		
	(rotation allowed)	0.154	836.3

Table 8.1

Variation in the spacing of ligaments produced from the surface of a 25mm diameter, "200" grade sintered plastic cup with rotation speed and feed rate

rotation speed (rpm)	0.2 litres/minute		0.4 litres/minute	
	mean spacing (mm)	95% confidence limit (mm (%))	mean spacing (mm)	95% confidence limit (mm (%))
6000	2.16	0.34 (16%)	1.95	0.20 (10%)
9000	1.63	0.14 (9%)	-	-
12000	1.44	0.15 (10%)	1.34	0.11 (8%)
15000	1.13	0.09 (8%)	1.28	0.11 (8%)
18000	1.06	0.11 (11%)	1.15	0.15 (13%)
21000	0.83	0.11 (13%)	0.88	0.11 (13%)

Table 8.2 Atomisation characteristics of prototype atomiser Pro-1, "100" grade cylinder

Windspeed 44.7 m/s (100 mph), spraying Glossinex blank formulation

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% volume		
					<33.2 μm	67.7– 102.5 μm	82.5– 122.5 μm
0.1	5	12060	77	0.779	2.4	57.4	31.2
	4	15540	56	0.991	5.8	13.7	6.4
	3	19140	43	3.086	21.3	4.5	1.9
	2	25020	38	4.661	42.1	1.3	1.3
smoothed	3	19140	41	0.850	24.1	5.1	2.1
	2	25020	30	0.997	65.0	1.9	0.8
0.26	5	12420	75	1.148	3.2	47.2	24.0
	4	15840	59	1.970	6.1	18.2	9.8
	3	19080	49	3.355	17.2	7.0	3.7
	2	24960	48	4.135	31.9	2.8	1.8
smoothed	3	19080	43	1.048	22.2	9.2	4.9
	2	24960	33	1.215	52.1	4.6	2.6
0.36	5	10680	89	1.289	3.2	42.5	38.3
	4	13620	67	1.393	5.2	31.8	14.9
	3	18900	52	3.229	15.2	8.3	4.7
	2	24780	52	3.720	27.7	4.2	2.8
smoothed	3	18900	45	1.066	20.2	11.0	6.3
	2	24780	36	1.280	45.0	6.8	3.6
0.62	5	10800	91	1.417	3.0	38.3	35.1
	4	13920	72	1.929	4.9	30.8	17.7
	3	18300	59	2.741	11.8	15.6	10.6
	2	22800	58	3.057	19.0	11.5	8.0
0.78	5	10980	95	1.552	2.8	33.9	32.9
	4	14700	71	2.033	5.9	24.4	17.3
	3	17580	68	2.419	8.6	19.5	14.9
	2	22440	65	2.879	14.1	14.8	11.2
1.18	5	10800	103	1.617	2.6	28.7	29.7
	4	14700	86	2.087	4.8	23.6	18.8
	3	17400	82	2.318	6.5	20.3	16.7
	2	21840	85	2.375	10.3	16.6	14.2

Table 8.3

Atomisation characteristics of prototype atomiser Pro-1, "60" grade cylinder

Windspeed 44.7 m/s (100 mph), spraying Glossinex blank formulation

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (µm)	relative span	% volume		
					<33.2µm	67.7– 102.5µm	82.5– 122.5µm
0.78	5	10680	101	1.468	4.4	27.6	31.4
	4	13800	77	1.875	6.5	32.4	21.8
	3	18600	61	2.559	11.7	18.8	13.1
	2	22500	52	2.749	20.3	14.9	10.3
1.18	5	11040	107	1.679	3.9	25.8	27.0
	4	14400	82	2.115	5.9	27.1	20.0
	3	18540	73	2.469	9.4	19.8	15.3
	2	24180	73	2.657	15.1	15.6	13.1

Table 8.4

Atomisation characteristics of prototype atomiser Pro-2
Windspeed 44.7 m/s (100 mph), spraying blank Thiodan formulation

Flowrate (l/min)	Blade Setting	Rotation	VMD (μm)	relative span	% volume		
		Speed (RPM)			<33.2 μm	67.7– 102.5 μm	82.5– 122.5 μm
0.10	5	10800	72	1.086	5.4	41.9	24.1
	4	15480	48	1.183	16.9	12.9	6.1
	3	17580	42	1.355	25.5	8.4	3.9
	2	24060	32	2.307	53.7	4.1	1.6
0.25	5	11040	75	1.438	4.5	37.6	23.0
	4	14880	58	1.528	9.8	21.8	14.2
	3	19800	46	1.996	22.8	12.4	7.6
	2	23460	41	1.872	32.4	10.5	6.2
0.35	5	10980	78	1.541	4.4	35.8	24.0
	4	14160	61	1.590	8.3	23.2	15.1
	3	17880	52	2.246	14.9	15.5	9.3
	2	23520	42	2.500	30.3	9.6	5.6
0.63	5	11040	84	1.627	4.2	34.2	26.3
	4	14340	69	1.936	7.4	25.4	18.0
	3	19500	58	2.391	14.1	18.5	12.9
	2	23280	53	2.520	20.1	15.9	11.2
0.80	5	10800	93	1.684	3.6	30.6	26.6
	4	14700	72	2.022	7.4	24.2	18.1
	3	17580	66	2.294	10.6	20.3	15.3
	2	23340	55	2.649	18.3	16.8	12.2
1.21	5	10500	112	1.648	2.4	25.5	25.2
	4	15000	86	2.051	5.2	23.7	20.1
	3	17820	79	2.213	7.3	22.2	18.5
	2	22560	67	2.470	12.2	19.1	15.3

Table 8.5

Atomisation characteristics of prototype atomiser Pro-2

Windspeed 44.7 m/s (100 mph), spraying blank JF9436 formulation

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% volume		
					<33.2 μm	67.7– 102.5 μm	82.5– 122.5 μm
0.11	5	10800	74	1.223	7.9	39.3	26.5
	4	13380	59	1.271	12.2	24.3	12.9
	3	20280	48	2.058	23.1	14.0	7.9
	2	23820	41	1.600	31.9	10.1	5.2
0.23	5	10380	78	1.439	6.8	36.2	27.7
	4	14820	56	1.973	13.4	19.4	11.4
	3	19800	51	2.326	19.8	15.4	8.8
	2	23640	48	2.227	23.4	13.0	7.3
0.56	5	10020	87	1.770	5.4	27.7	24.1
	4	13380	73	1.888	8.3	25.9	20.2
	3	19020	66	2.077	11.6	23.5	17.5
	2	21960	61	1.820	13.7	22.2	16.4
0.86	5	10140	102	1.783	4.0	24.3	22.8
	4	14700	82	2.239	7.4	23.8	19.7
	3	17940	75	2.171	9.3	23.9	19.1
	2	21180	71	2.141	10.0	23.9	18.4

Table 8.6

Atomisation characteristics of prototype atomiser Pro-3

Windspeed 44.7 m/s (100 mph), spraying blank Thiodan formulation

Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% volume		
					<33.2 μm	67.7– 102.5 μm	82.5– 122.5 μm
0.10	5	11220	65	1.077	6.1	33.1	20.0
	4	14640	54	0.997	11.5	23.5	9.5
	3	18360	47	0.974	17.8	11.7	5.1
	2	[21880]	40	0.878	30.5	2.8	1.1
0.25	5	11760	68	1.174	6.0	32.0	25.7
	4	13680	59	1.152	10.0	28.7	14.8
	3	16560	51	1.041	14.6	14.8	6.9
	2	–	–	–	–	–	–
0.35	5	10920	73	1.292	4.9	32.7	26.6
	4	–	–	–	–	–	–
	3	17340	55	1.142	12.3	20.1	10.7
	2	19800	47	1.184	18.1	12.6	6.6
0.63	5	10560	87	1.434	3.3	31.4	29.7
	4	12420	76	1.410	4.9	33.8	26.0
	3	16920	63	1.510	8.2	25.3	17.4
	2	18600	56	1.468	10.8	21.8	14.3
0.83	5	10560	100	1.515	2.5	28.5	29.1
	4	13200	81	1.563	4.2	32.4	25.8
	3	16560	68	1.570	7.0	27.3	20.2
	2	18900	62	1.586	9.3	24.6	17.6
1.22	5	10440	117	1.523	1.9	23.8	25.8
	4	13560	98	1.735	2.8	28.0	25.4
	3	16200	83	1.807	4.5	27.2	23.4
	2	18900	73	1.857	6.5	26.1	21.0

[] denotes rotation speed estimated by linear regression

Table 8.7

Atomisation characteristics of prototype atomiser PR3

Windspeed 44.7 m/s (100 mph), spraying blank JF9436 formulation

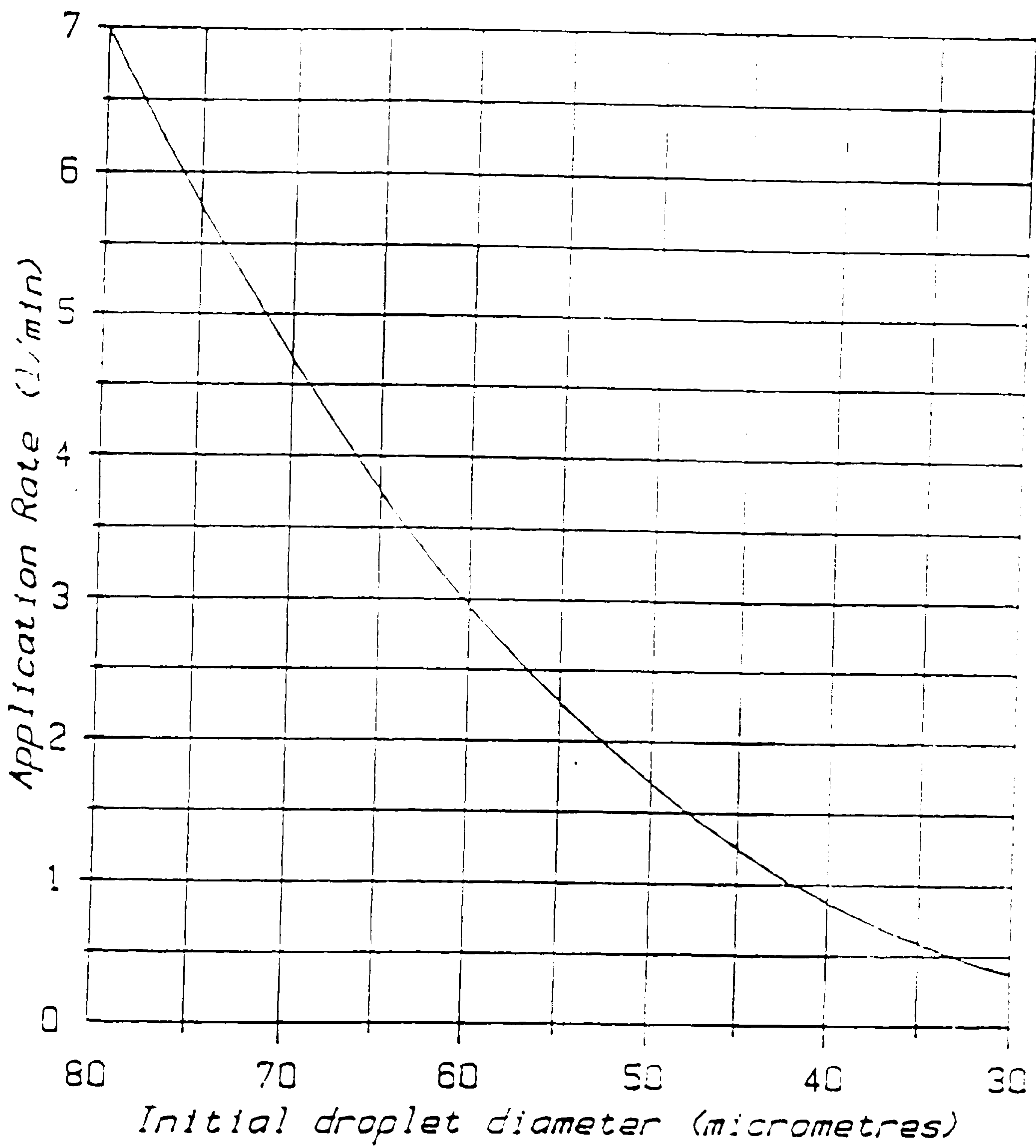
Flowrate (l/min)	Blade Setting	Rotation Speed (RPM)	VMD (μm)	relative span	% volume		
					<33.2 μm	67.7– 102.5 μm	82.5– 122.5 μm
0.11	5	10980	77	1.431	3.6	34.8	24.4
	4	14880	64	1.068	6.9	32.6	18.8
	3	17760	62	1.197	7.7	30.5	18.2
	2	20220	60	1.222	10.1	27.6	16.7
0.27	5	11100	82	1.449	3.1	34.9	28.6
	4	14940	72	1.389	5.1	33.4	23.7
	3	18000	66	1.245	7.1	31.1	20.3
	2	20520	62	1.223	8.7	29.0	18.4
0.49	5	10620	106	1.695	1.9	27.8	60.0
	4	14520	95	1.708	2.6	29.1	26.1
	3	17520	96	1.789	3.0	27.3	24.6
	2	19200	84	1.631	3.8	31.4	26.3

Table 8.8

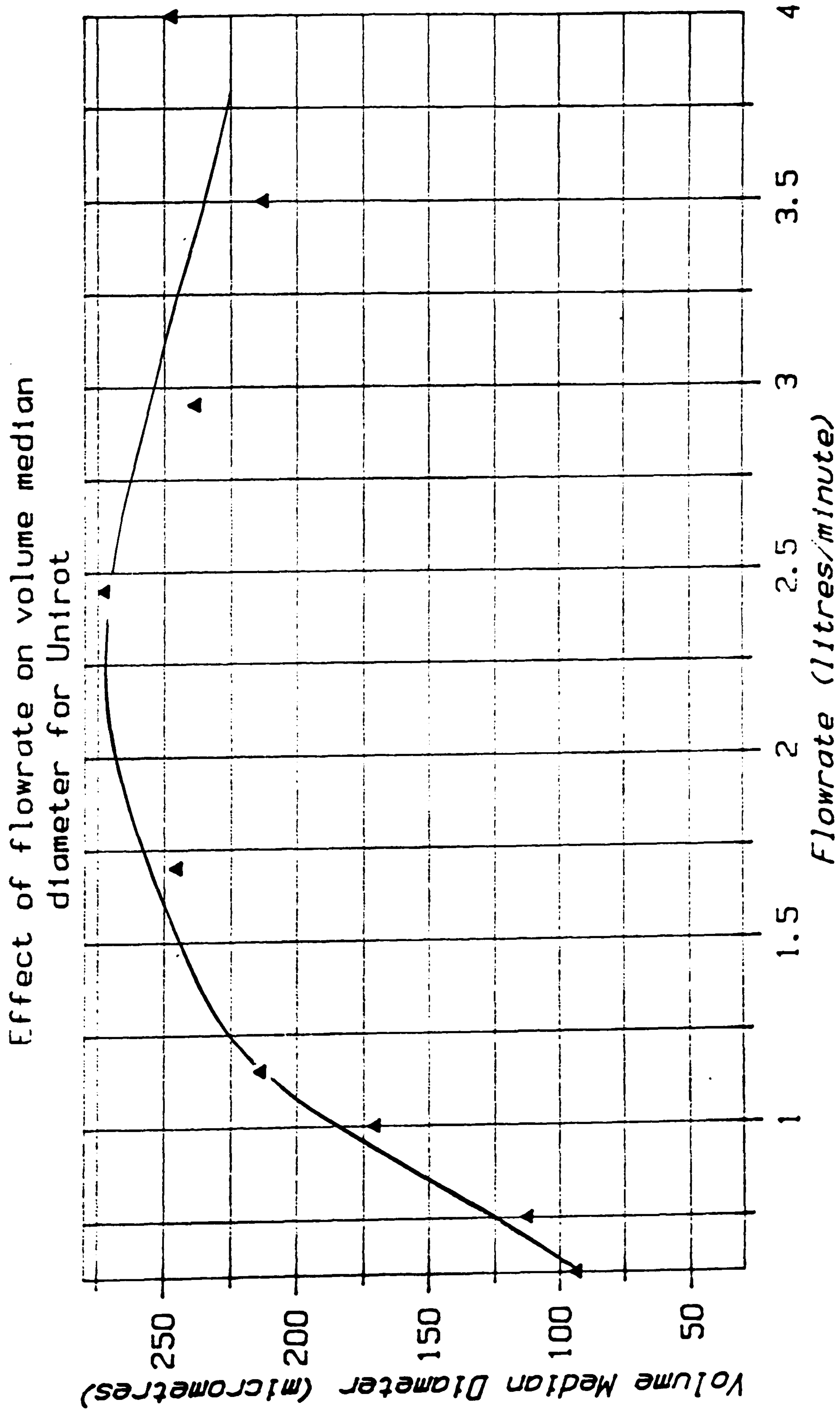
Atomisation characteristics of prototype atomiser Pro—4

Windspeed 44.7 m/s (100 mph), spraying blank Thiodan formulation

Flowrate (l/min)	Rotation Speed Range (RPM)	VMD (μ m)	relative span	% volume		
				<33.2 μ m	67.7– 102.5 μ m	82.5– 122.5 μ m
0.10	13560–13680	74	1.331	3.2	43.4	21.4
	15660–15840	59	0.942	6.1	22.7	10.4
	17400–17520	52	1.004	9.3	15.1	8.1
	19020–19440	46	0.970	13.9	10.6	5.3
	21480–22260	39	0.973	28.6	5.5	2.4
0.42	13020–13200	81	1.384	4.0	39.8	29.1
	15780–15960	68	1.493	5.3	28.9	19.2
	16500–16920	65	1.545	6.2	25.2	18.2
	19980–20640	55	1.604	11.0	19.6	13.9

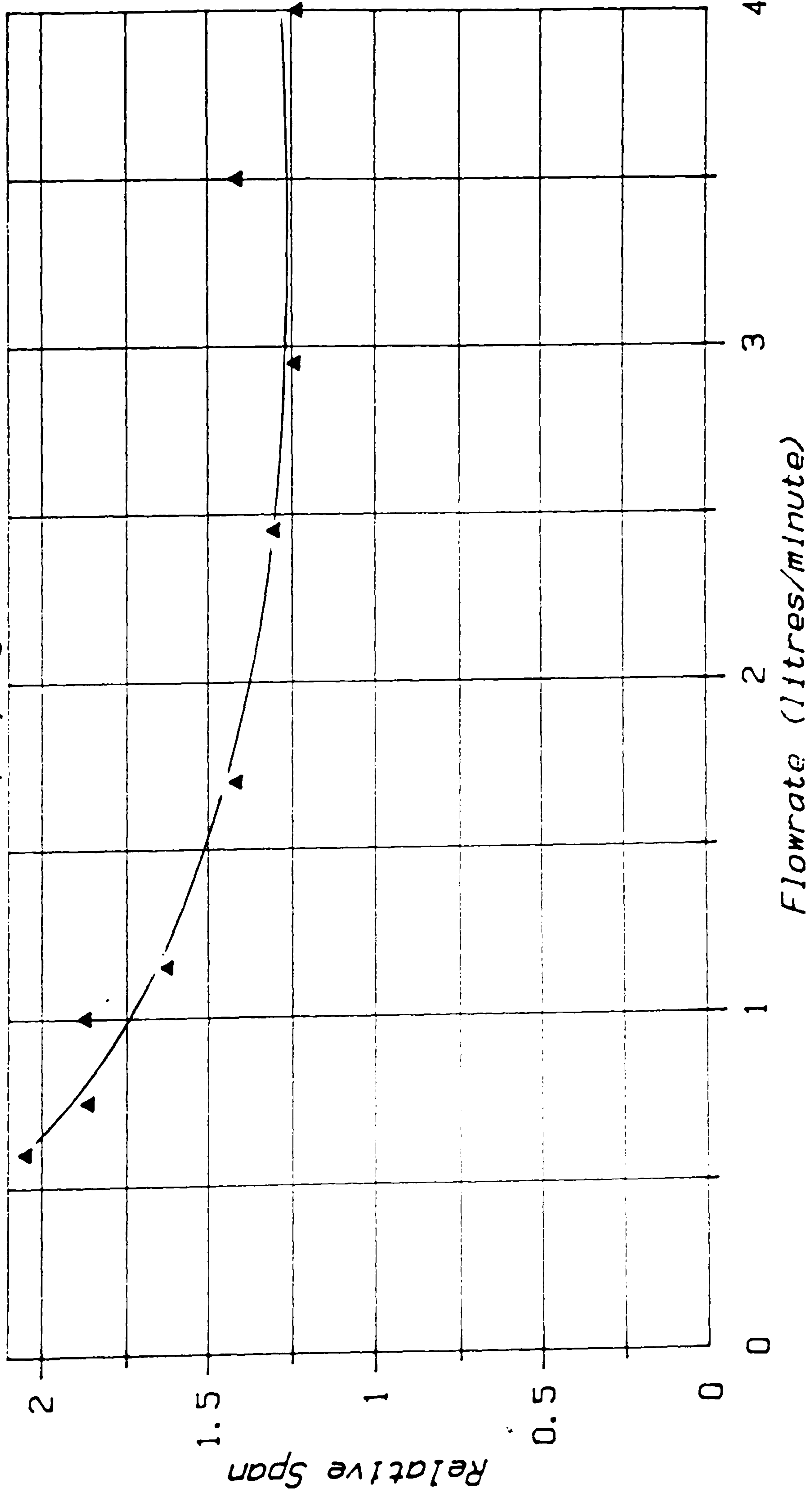


Graph 1.1 Rate of chemical application required at various droplet diameters to give the same droplet numbers as a feed rate of 7 litres/minute at 80um diameter

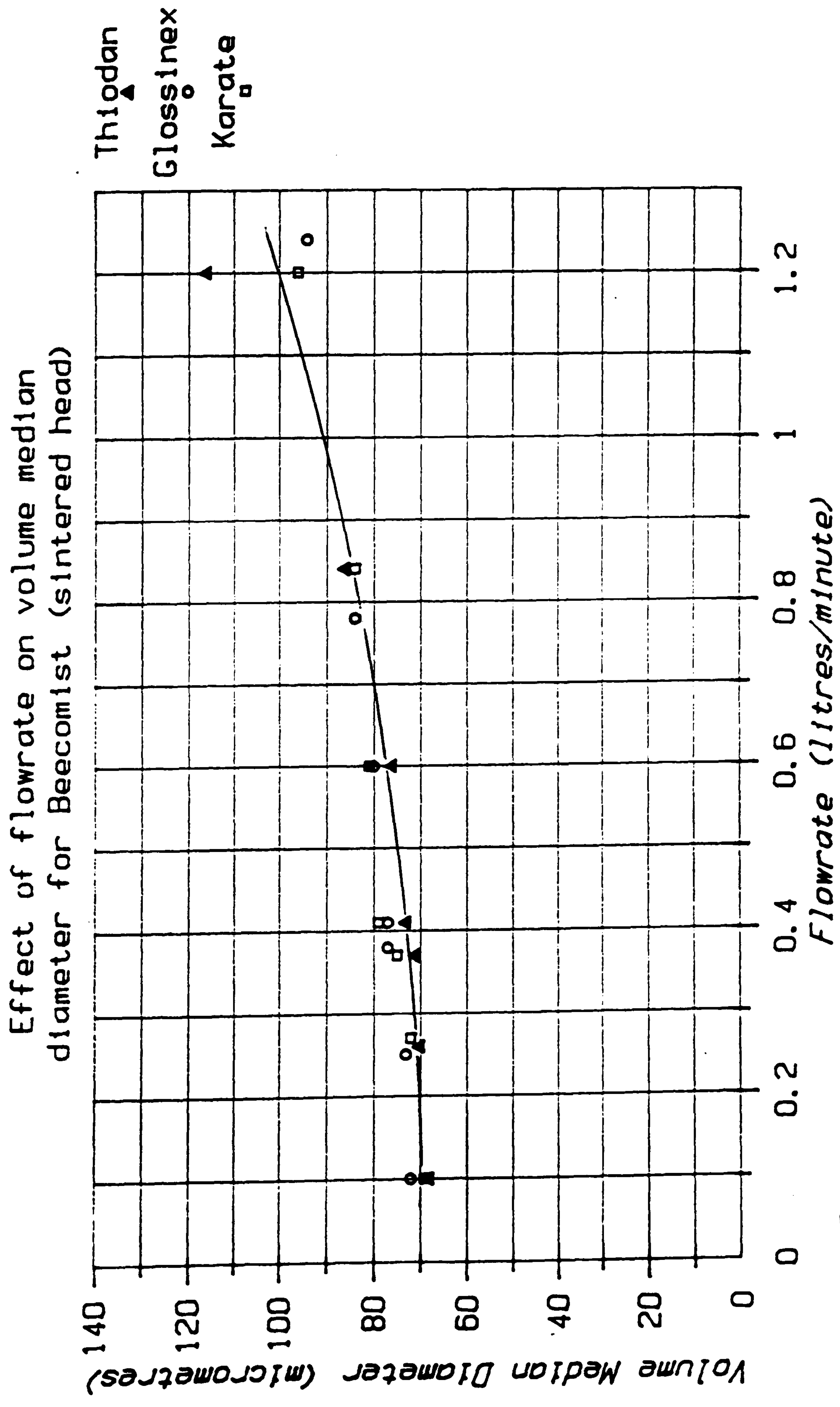


Graph 4.1

Effect of flowrate on relative span
for Unirof spraying Thiodan

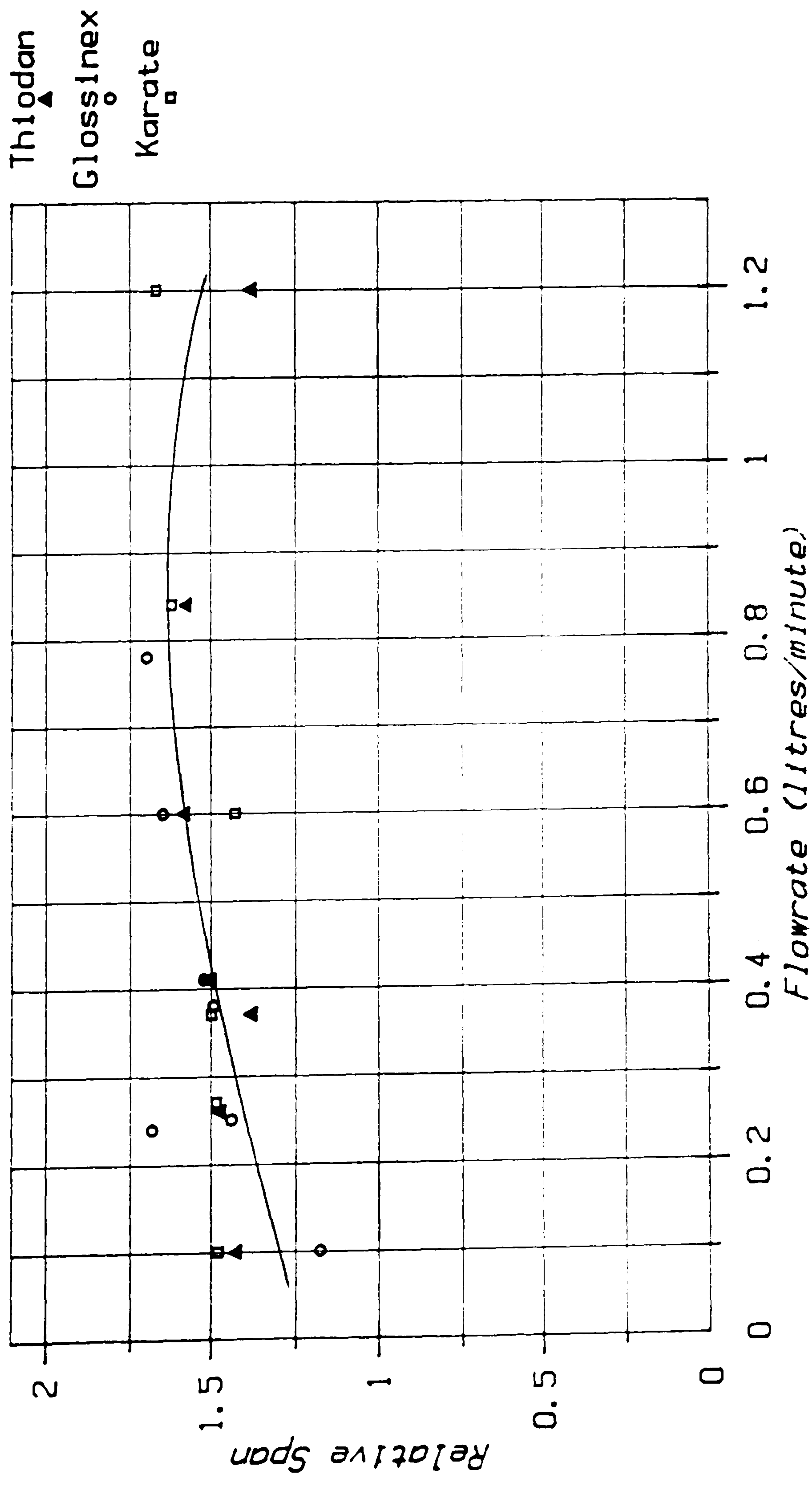


Graph 4.2



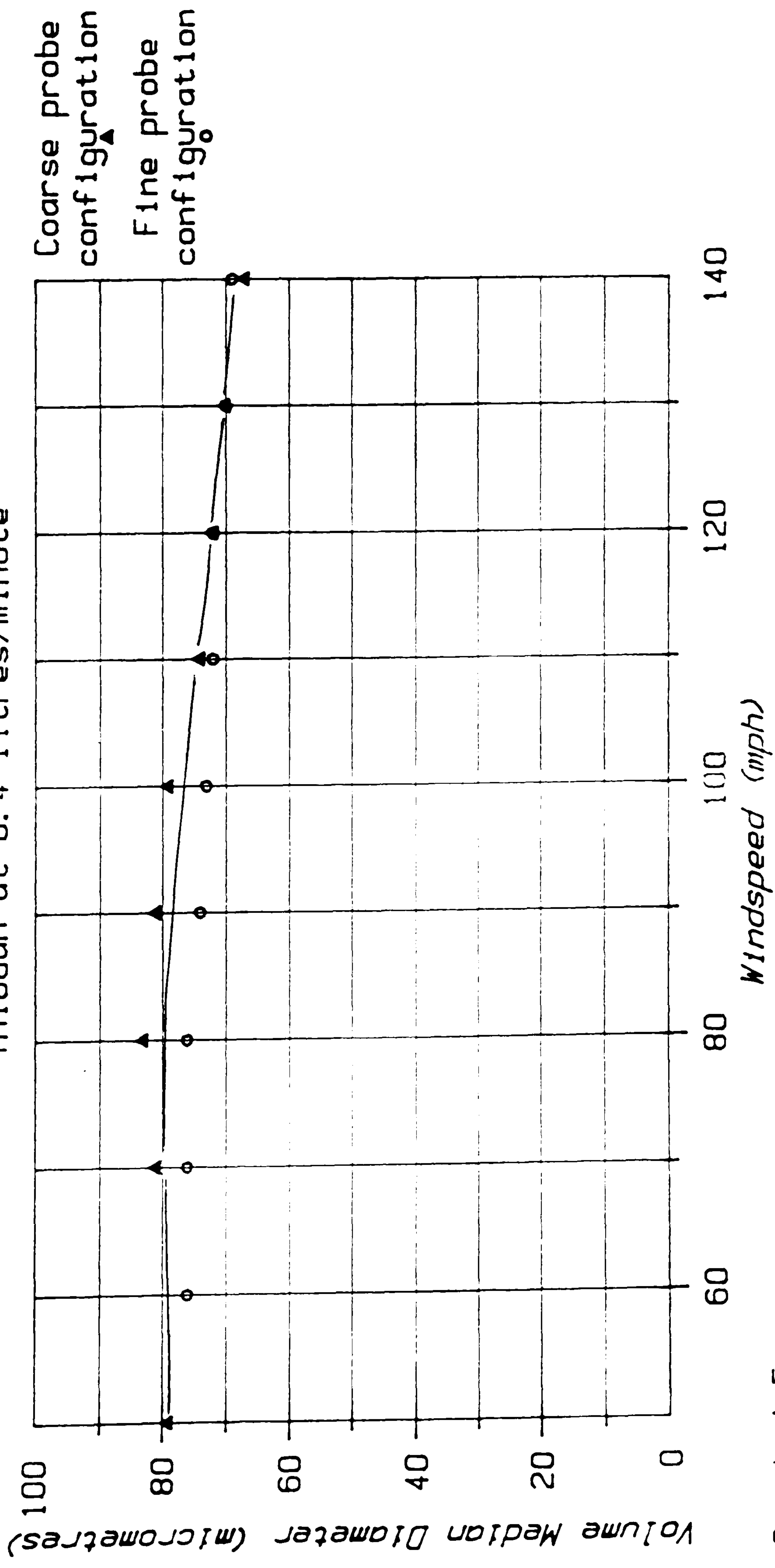
Graph 4.3

Effect of flowrate on relative span
for Beecomist (sintered head)

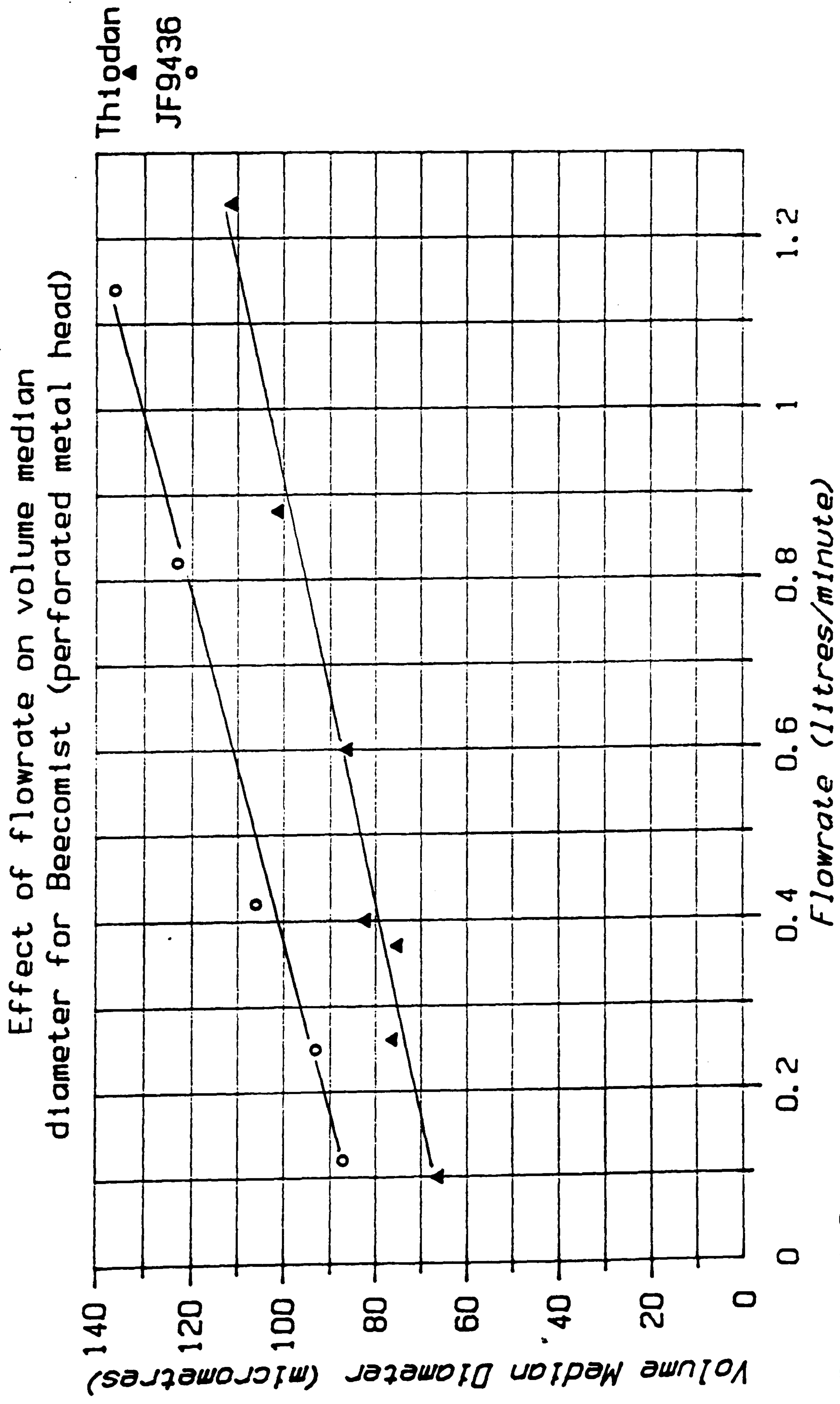


Graph 4.4

Effect of windspeed on volume median diameter
for Beecomist (sintered metal head) spraying
Thiodan at 0.4 litres/minute

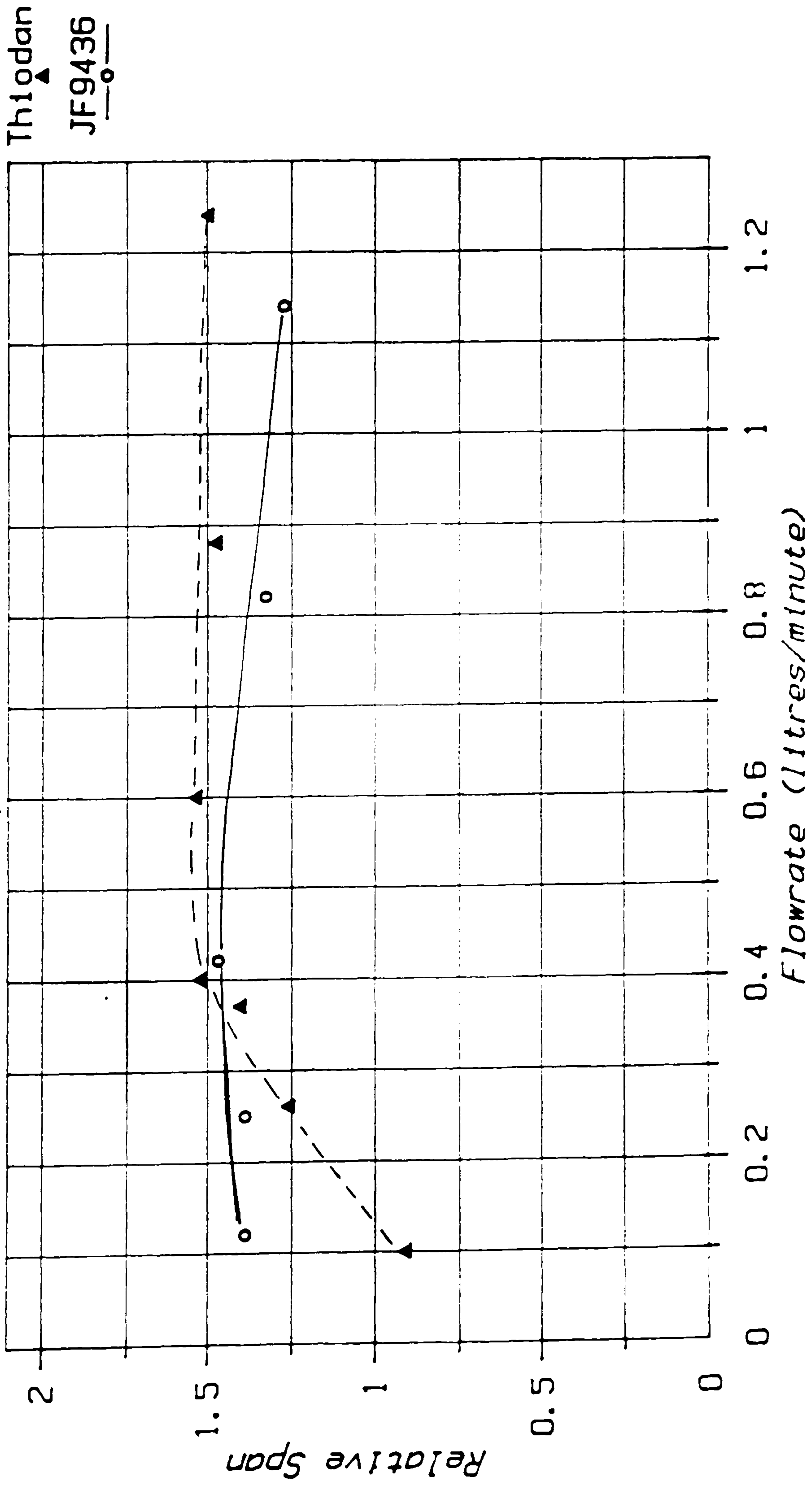


Graph 4.5



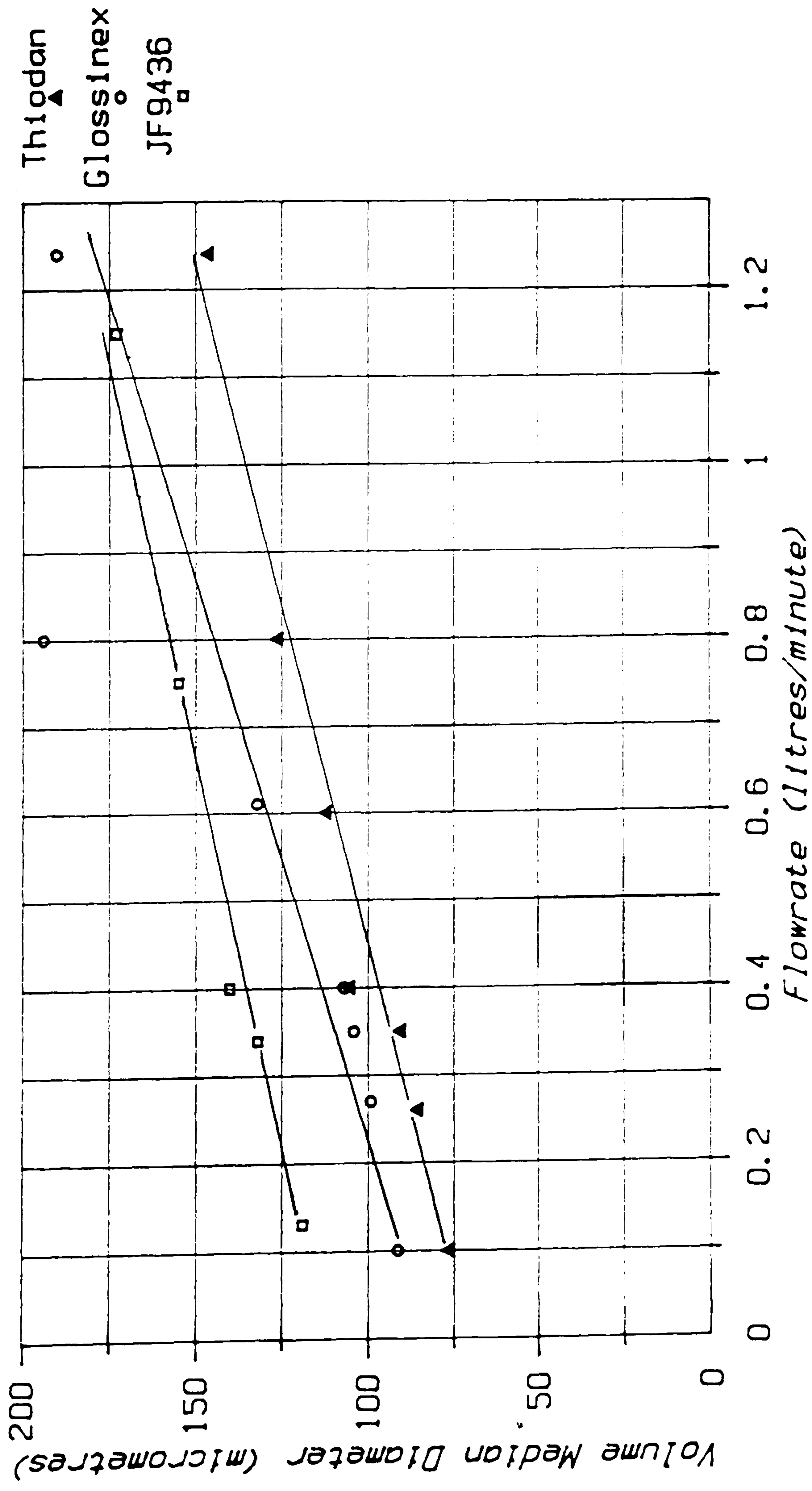
Graph 4.6

Effect of flowrate on relative span
for Beecomist (perforated metal head)



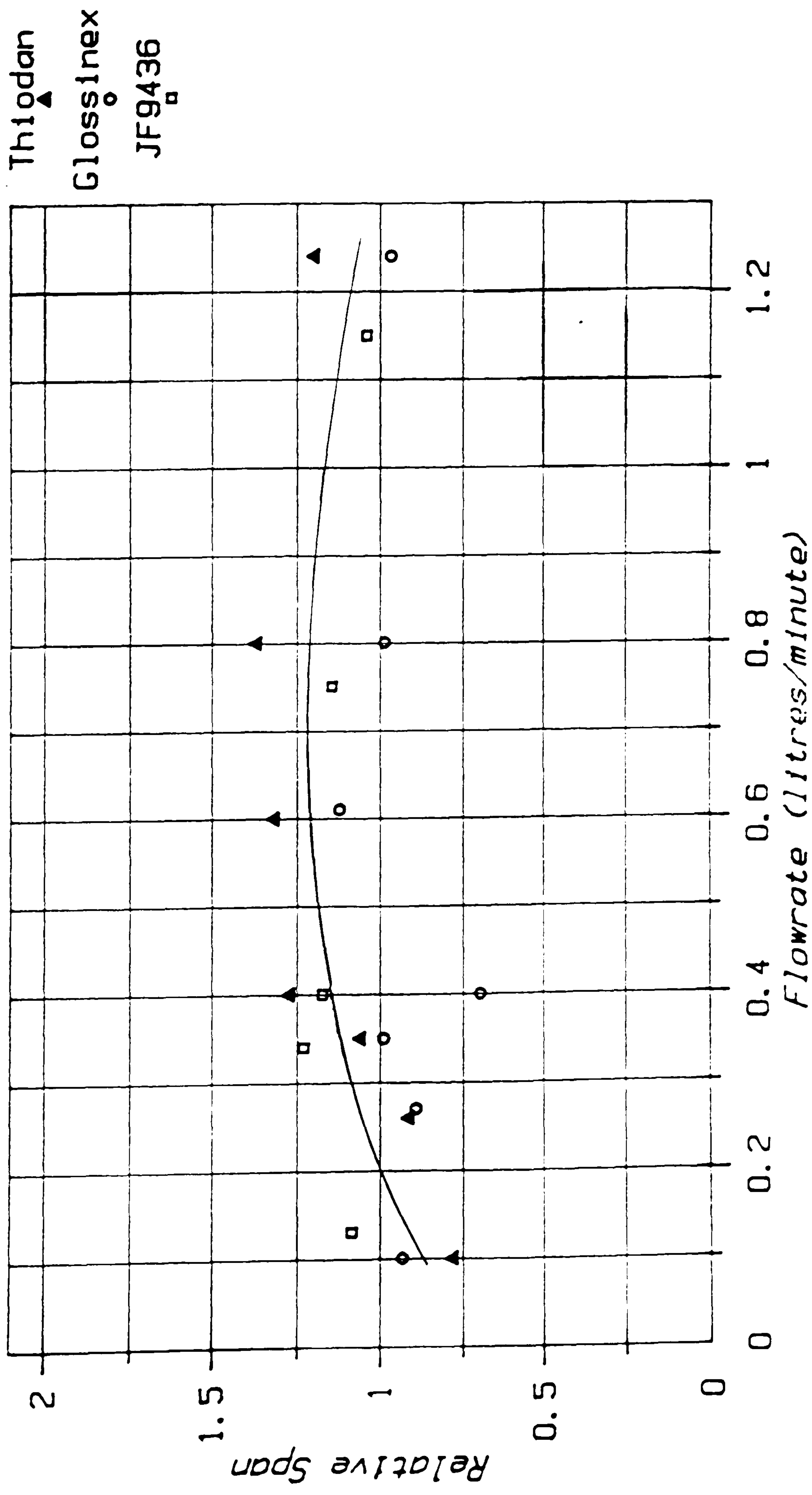
Graph 4.7

Effect of flowrate on volume median diameter for Micron X-15



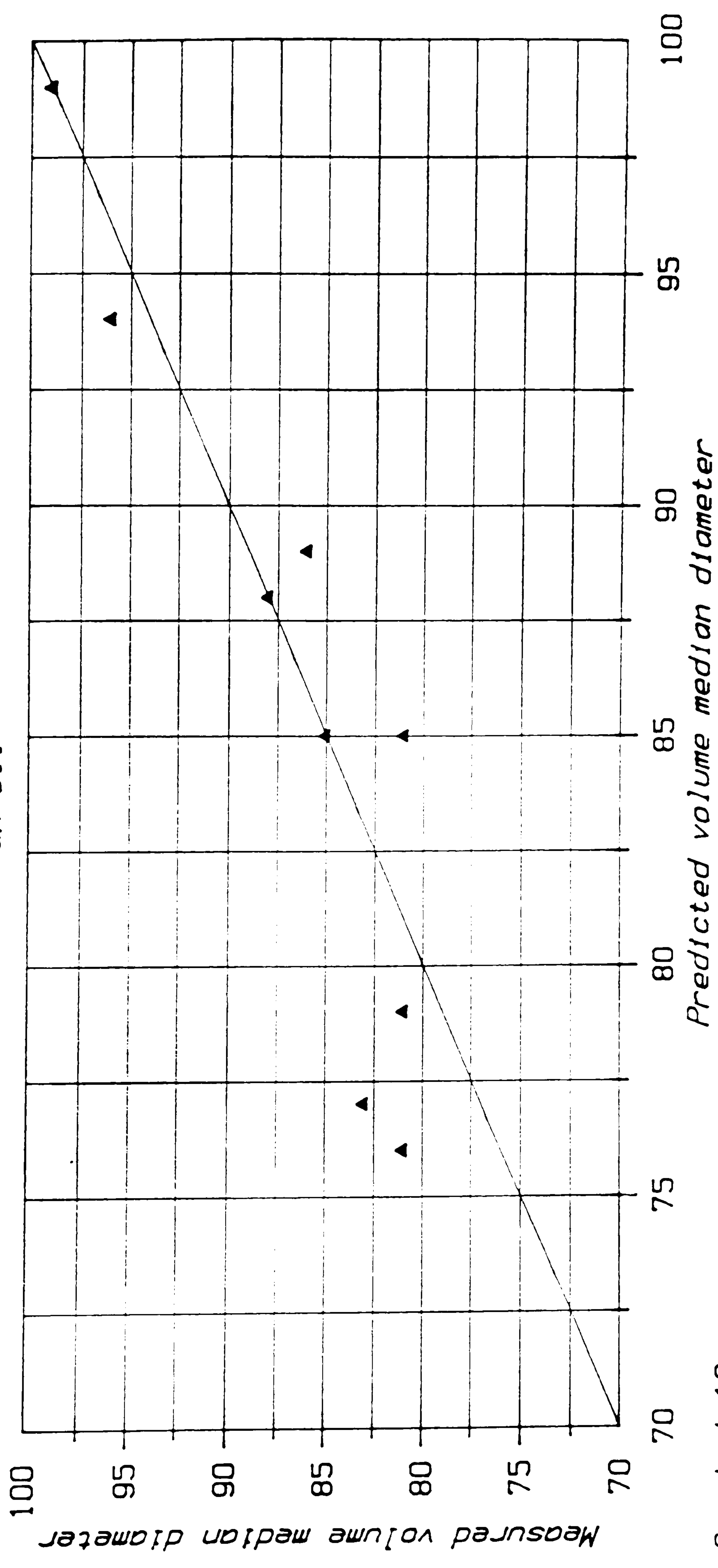
Graph 4.8

Effect of flowrate on relative span
for Micron X-15

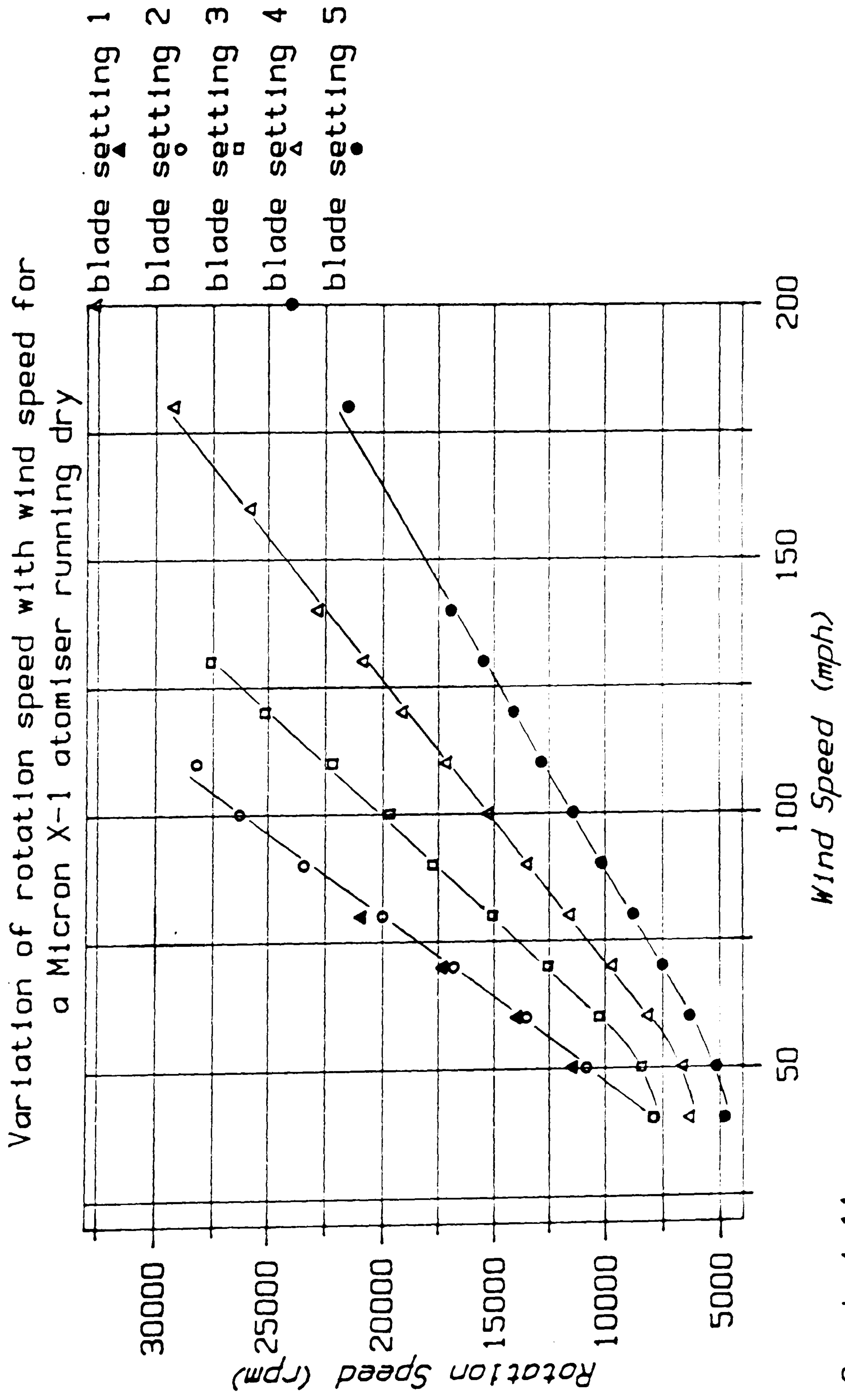


Graph 4.9

Comparison of predicted and measured volume
median diameters for a Micronair AU5000 spraying
an oil

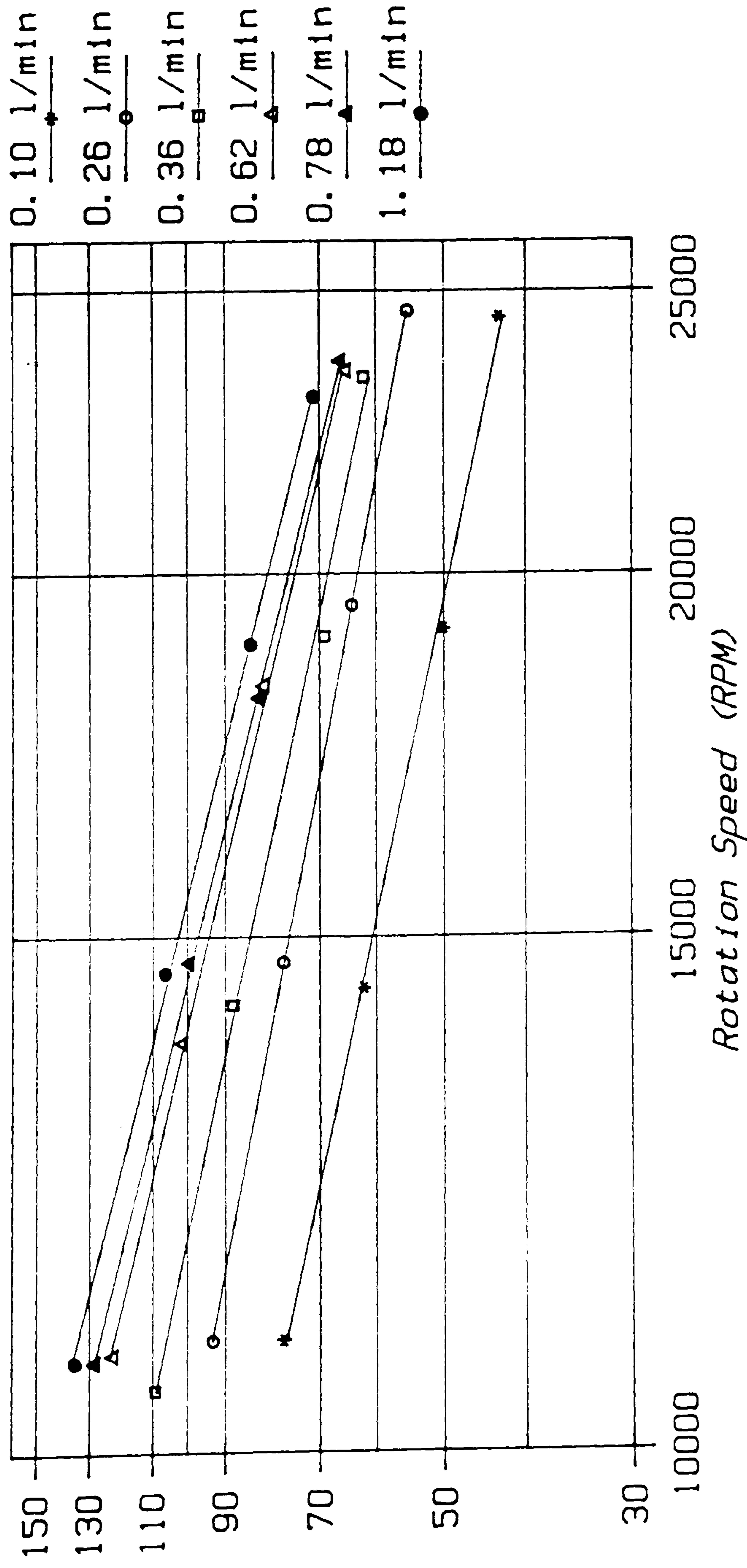


Graph 4.10



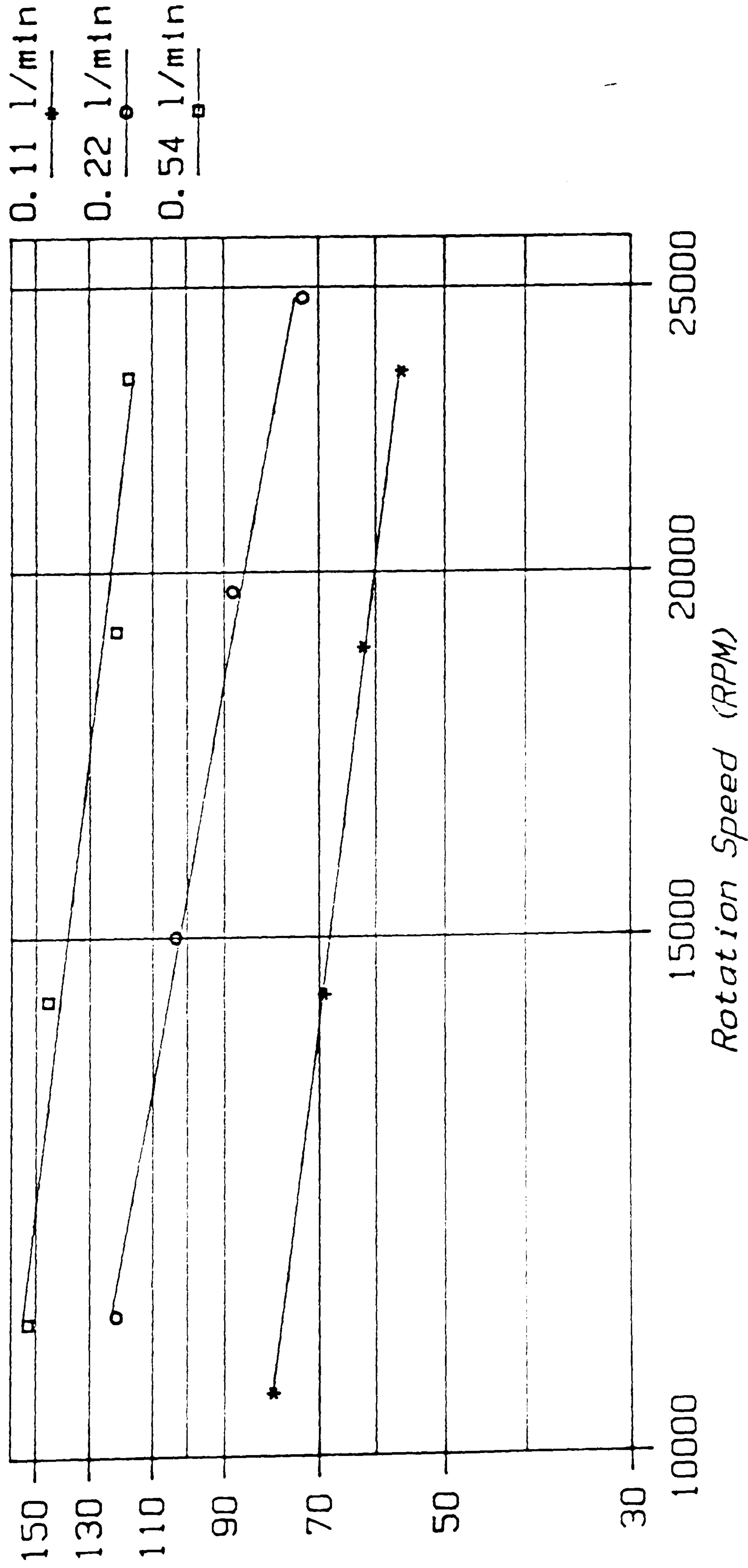
Graph 4.11

Effect of rotation speed on volume median diameter for Micron X-1 spaying Glossinex



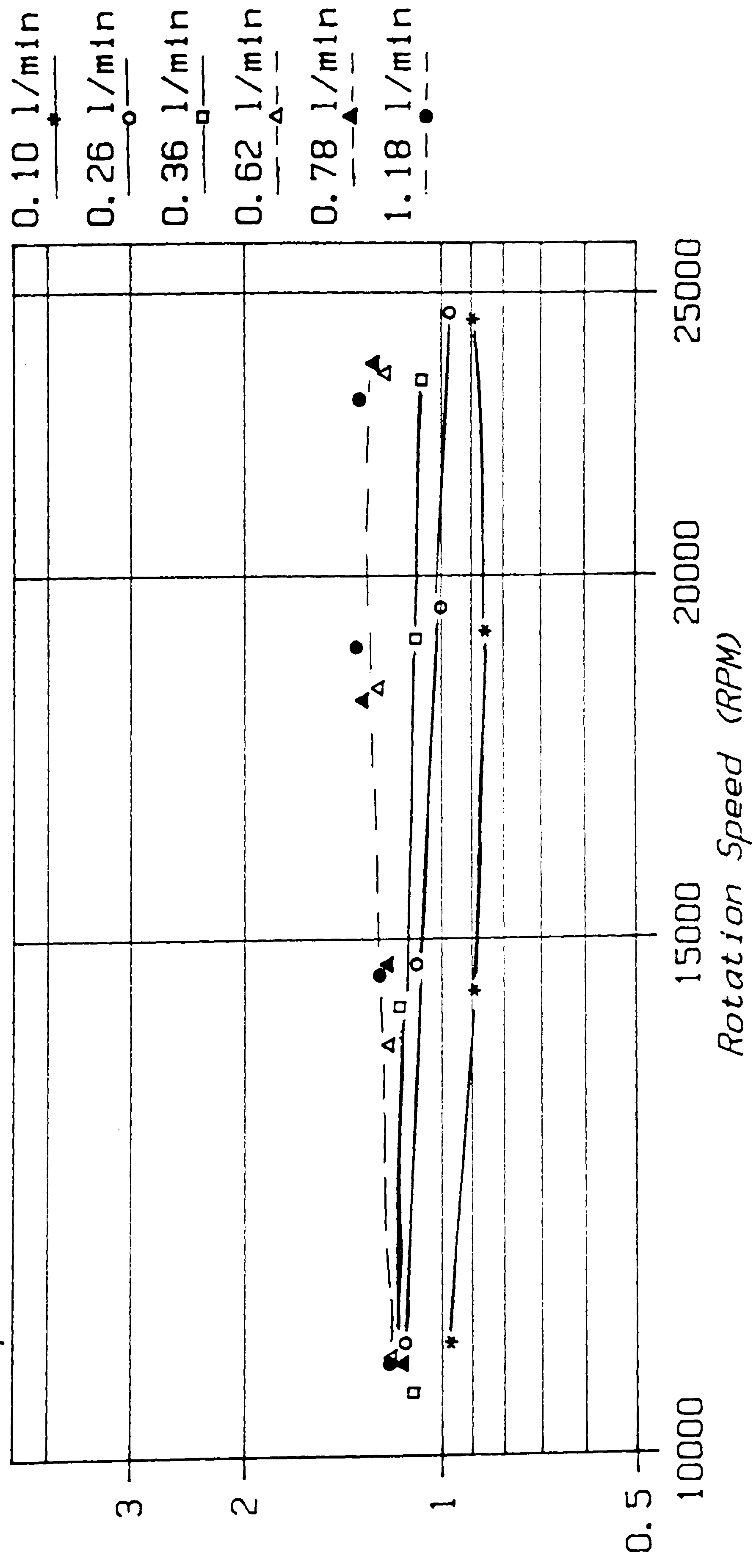
Graph 4.12

Effect of rotation speed on volume median diameter for Micron X-1 spaying JF9436



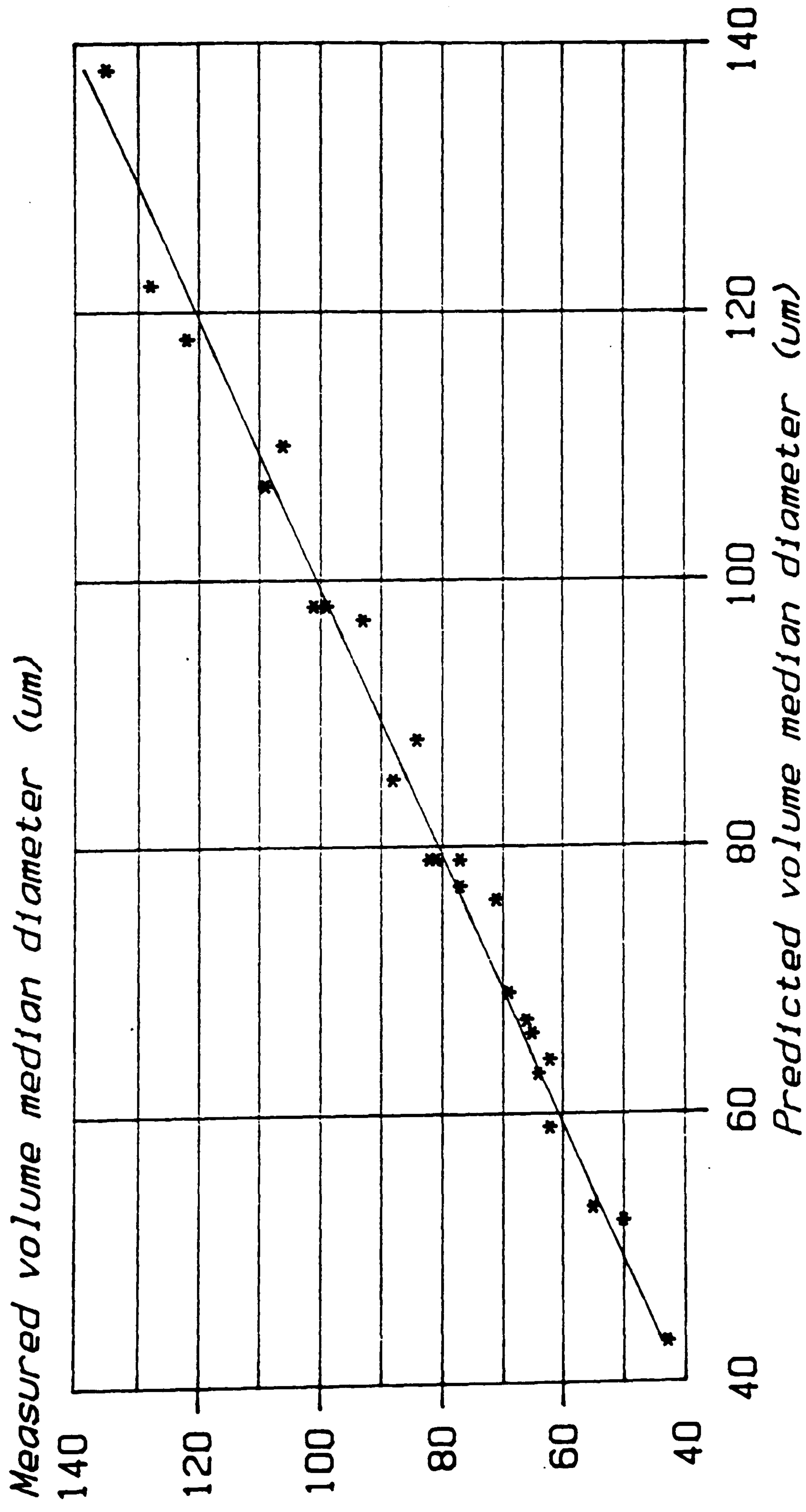
Graph 4.13

Effect of rotation speed on relative span of
 spray produced by Micron X-1 spraying Glossinex

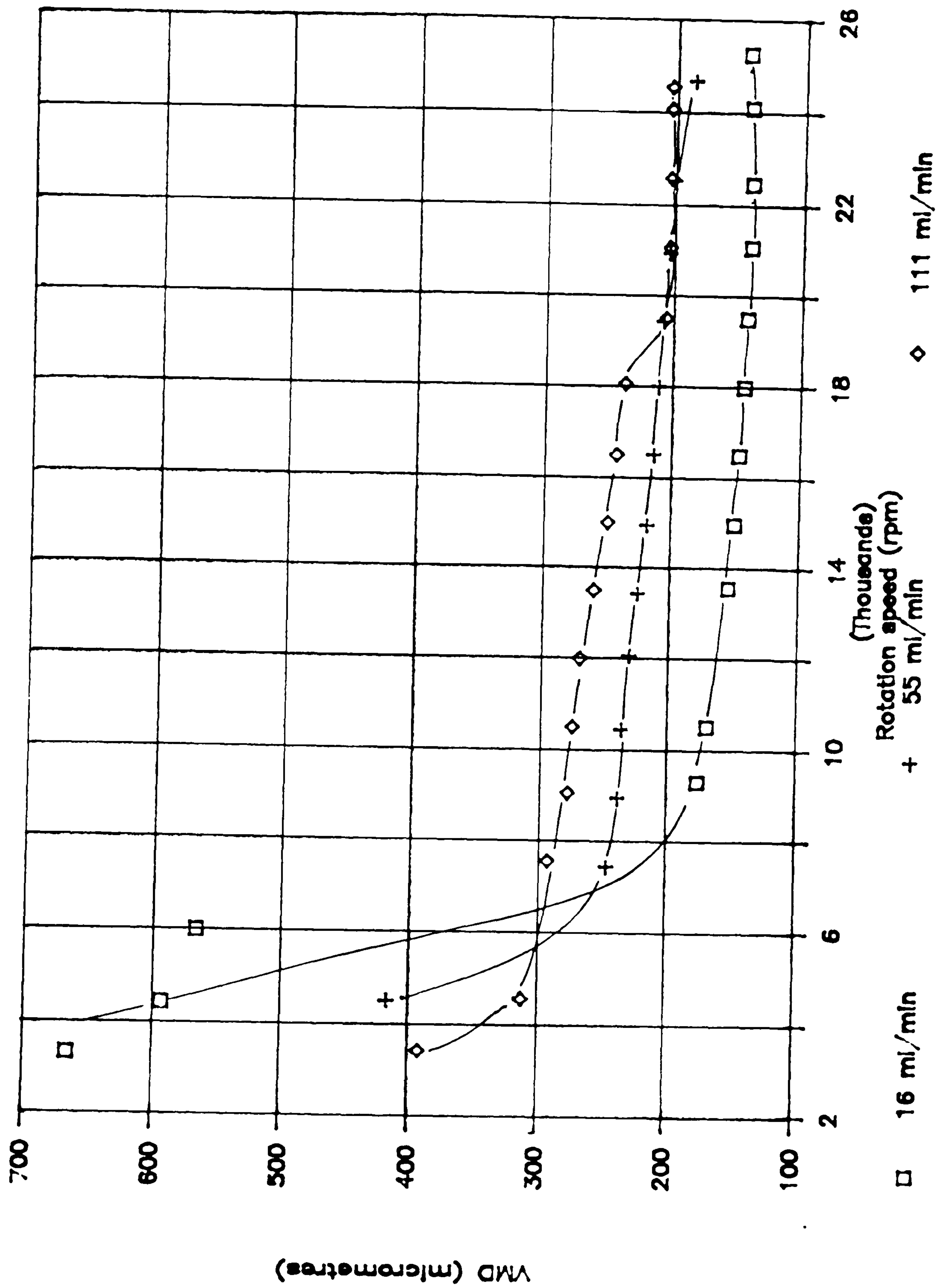


Graph 4.14

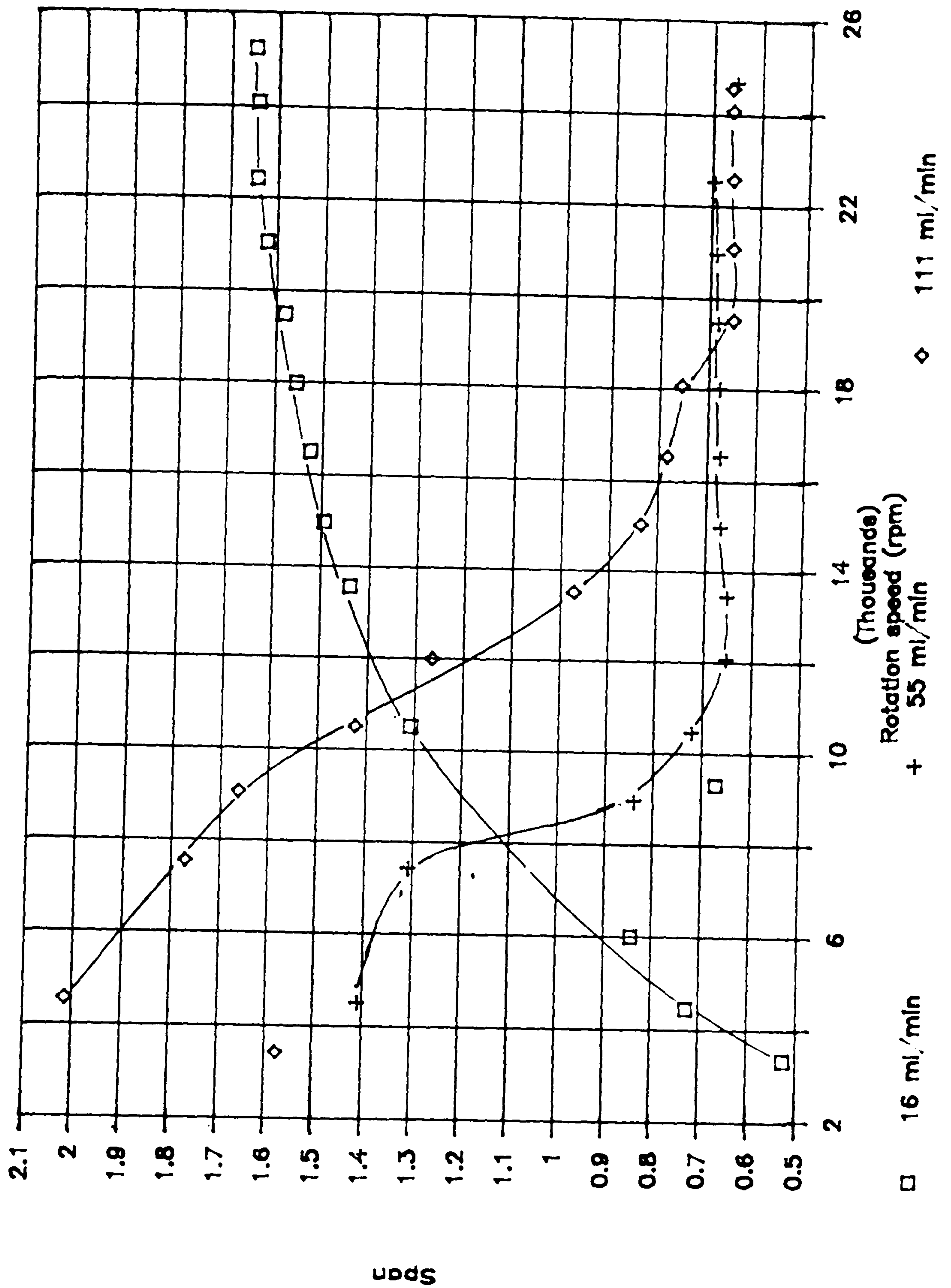
Comparison of predicted and measured volume
 median diameters for a Micron X-1 spraying
 Glossinex



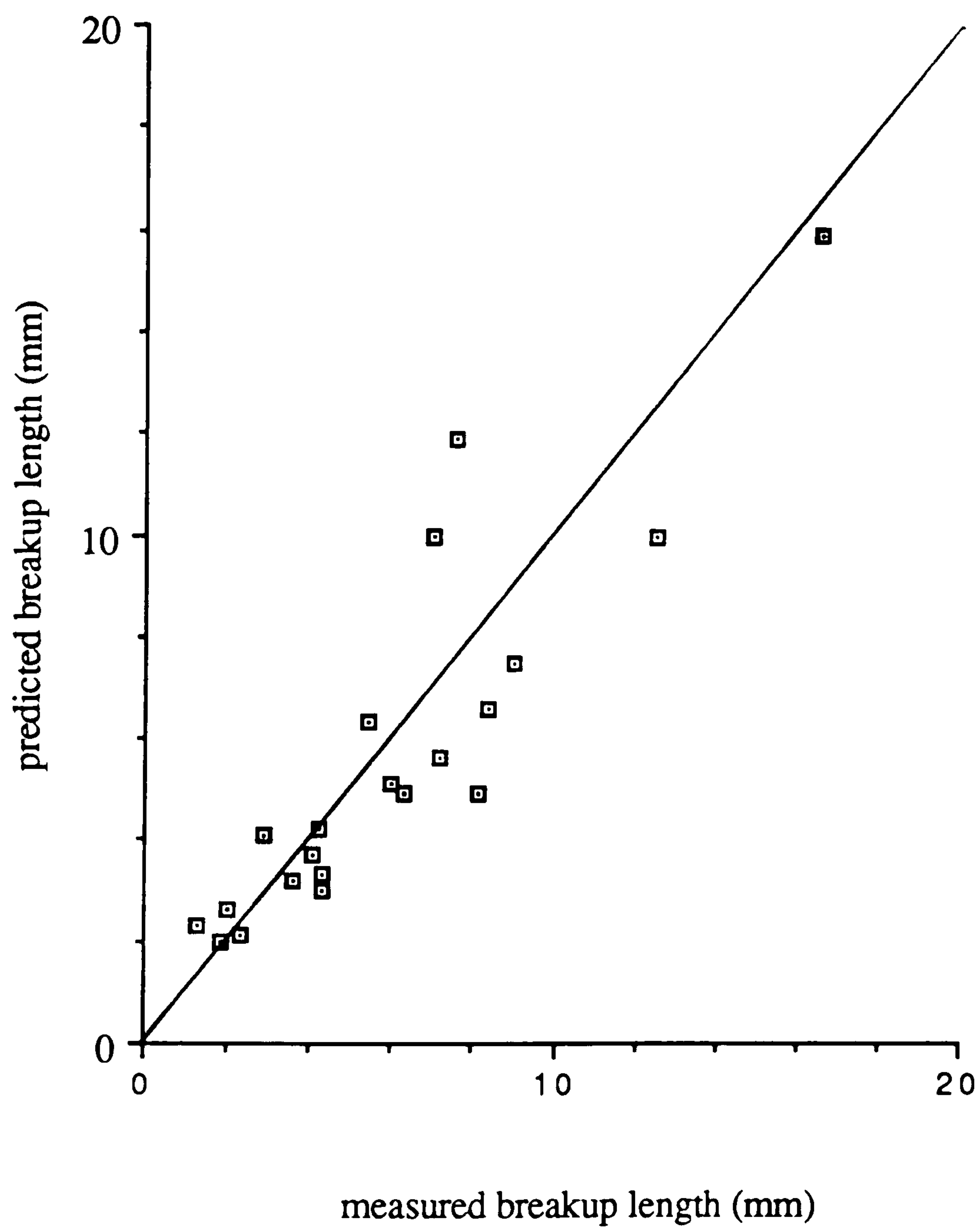
Graph 4.15



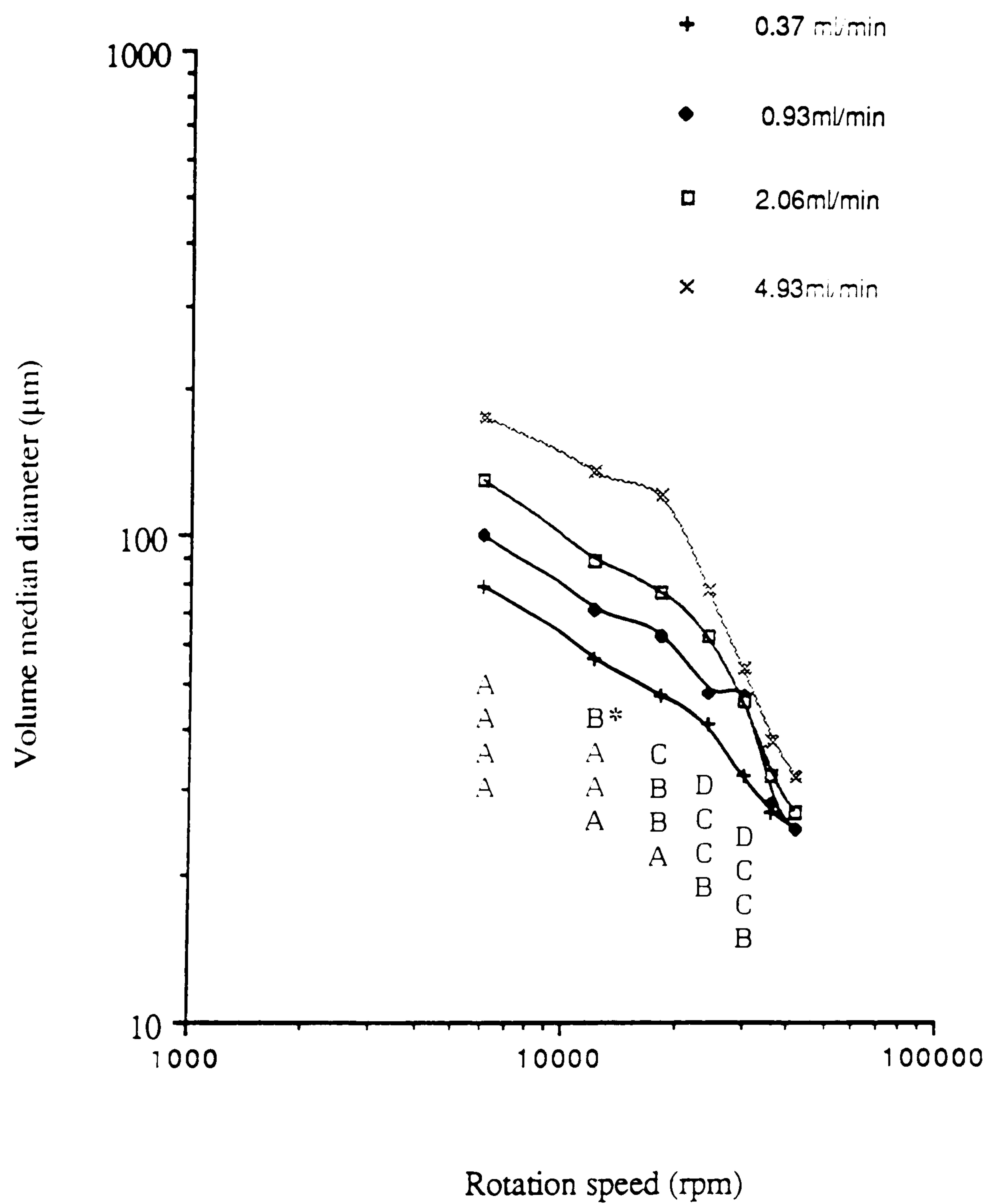
Graph 6.1 Effect of rotation speed on VMD of spray produced by trial disc TR1



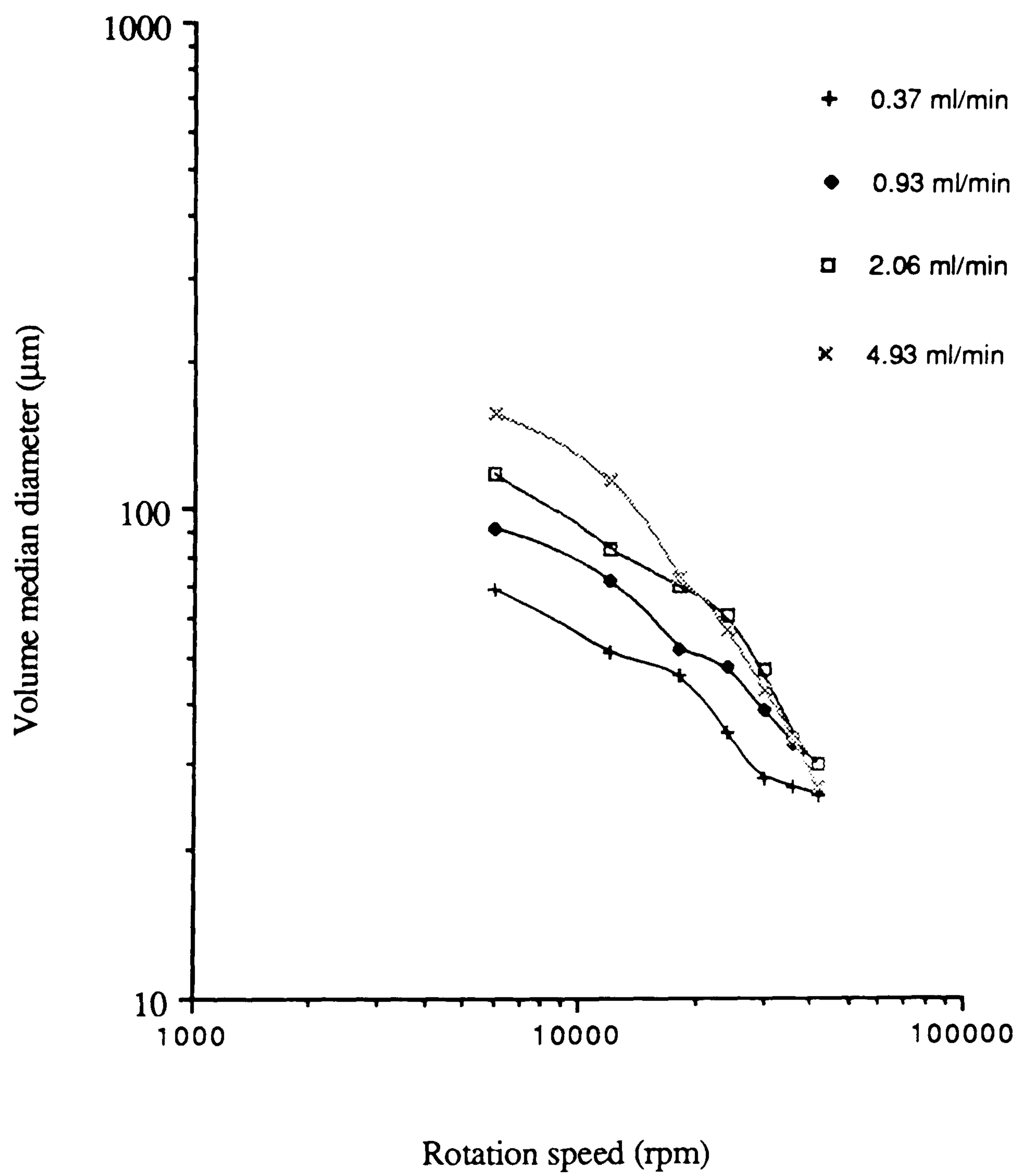
Graph 6.2 Effect of rotation speed on relative span of spray produced by trial disc TR1



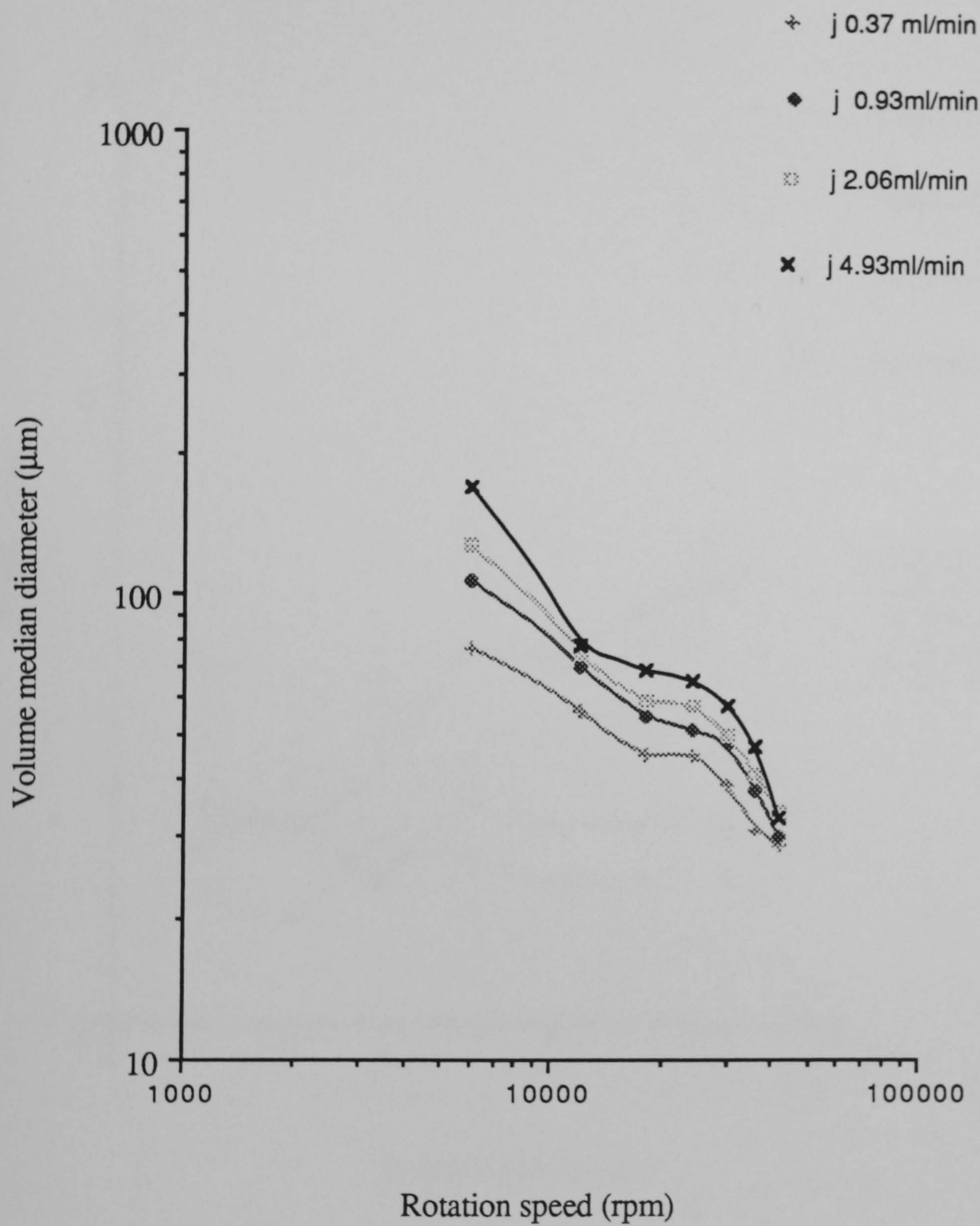
Graph 6.3 Comparison of measured and predicted values
for breakup length of liquid ligaments
produced by trial disc TR8



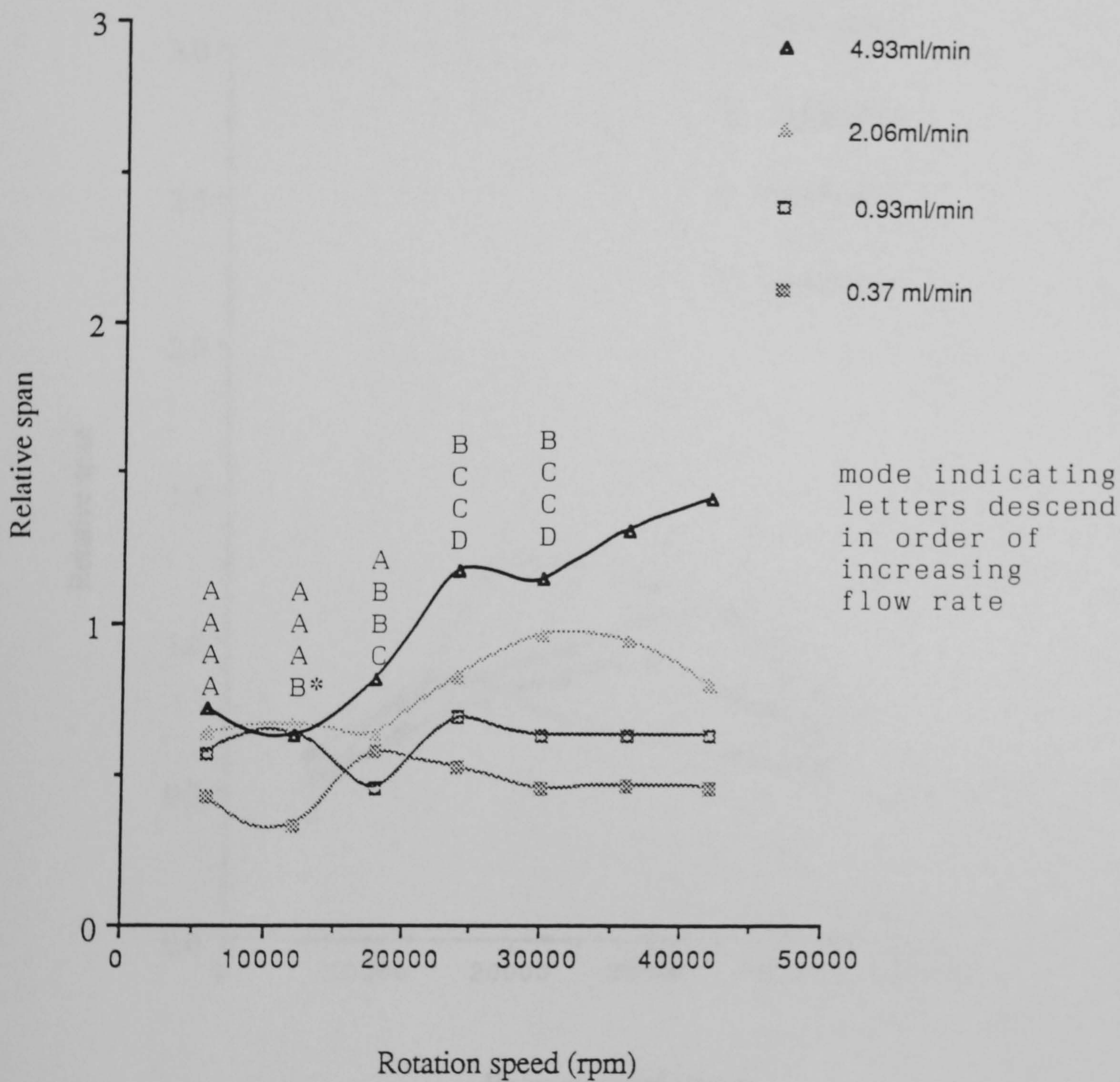
Graph 6.4 Variation of VMD with rotation speed for trial disc TR8 spraying Water + 0.1% Agral



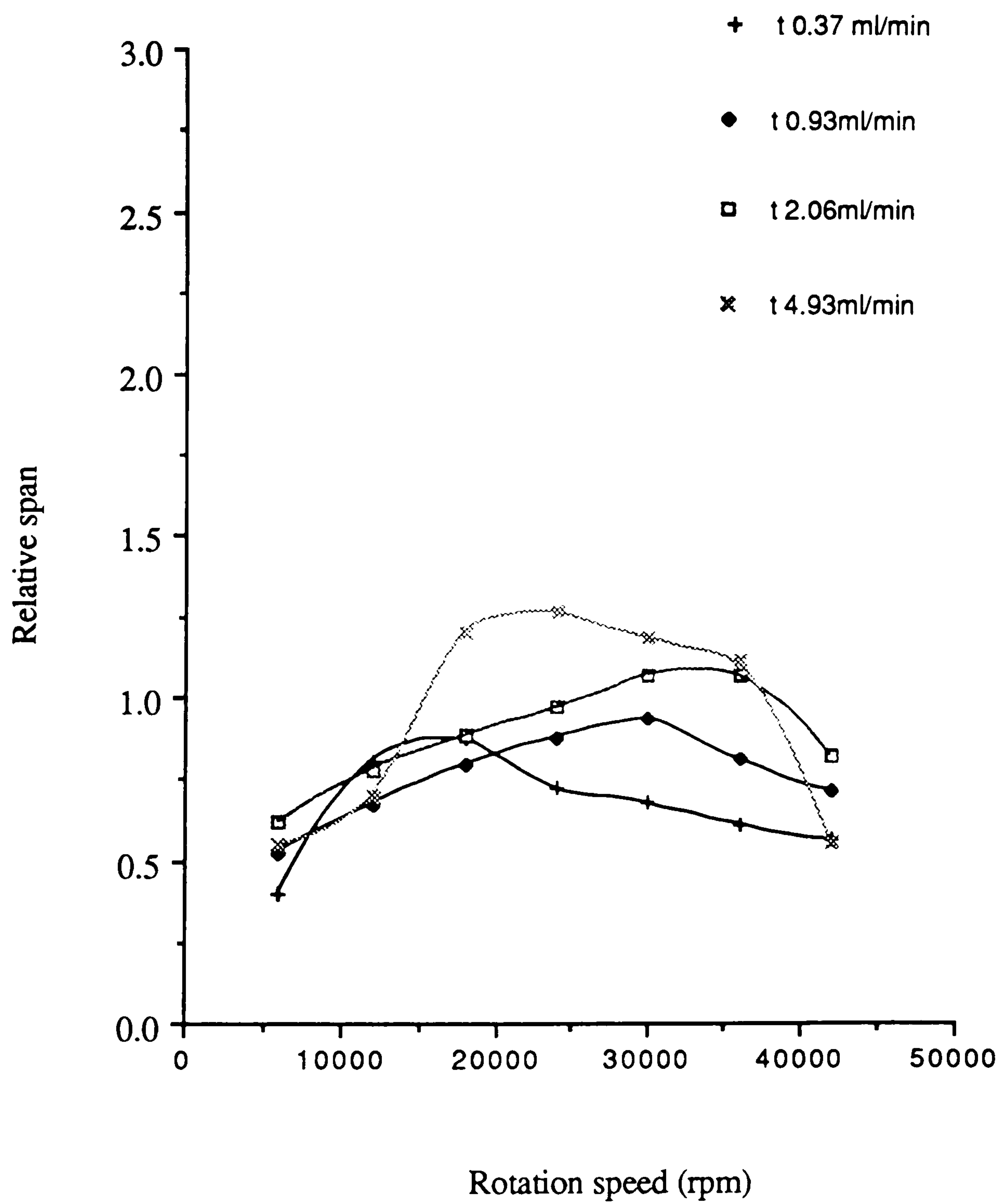
Graph 6.5 Variation of VMD with rotation speed for trial disc TR8 spraying Thiodan



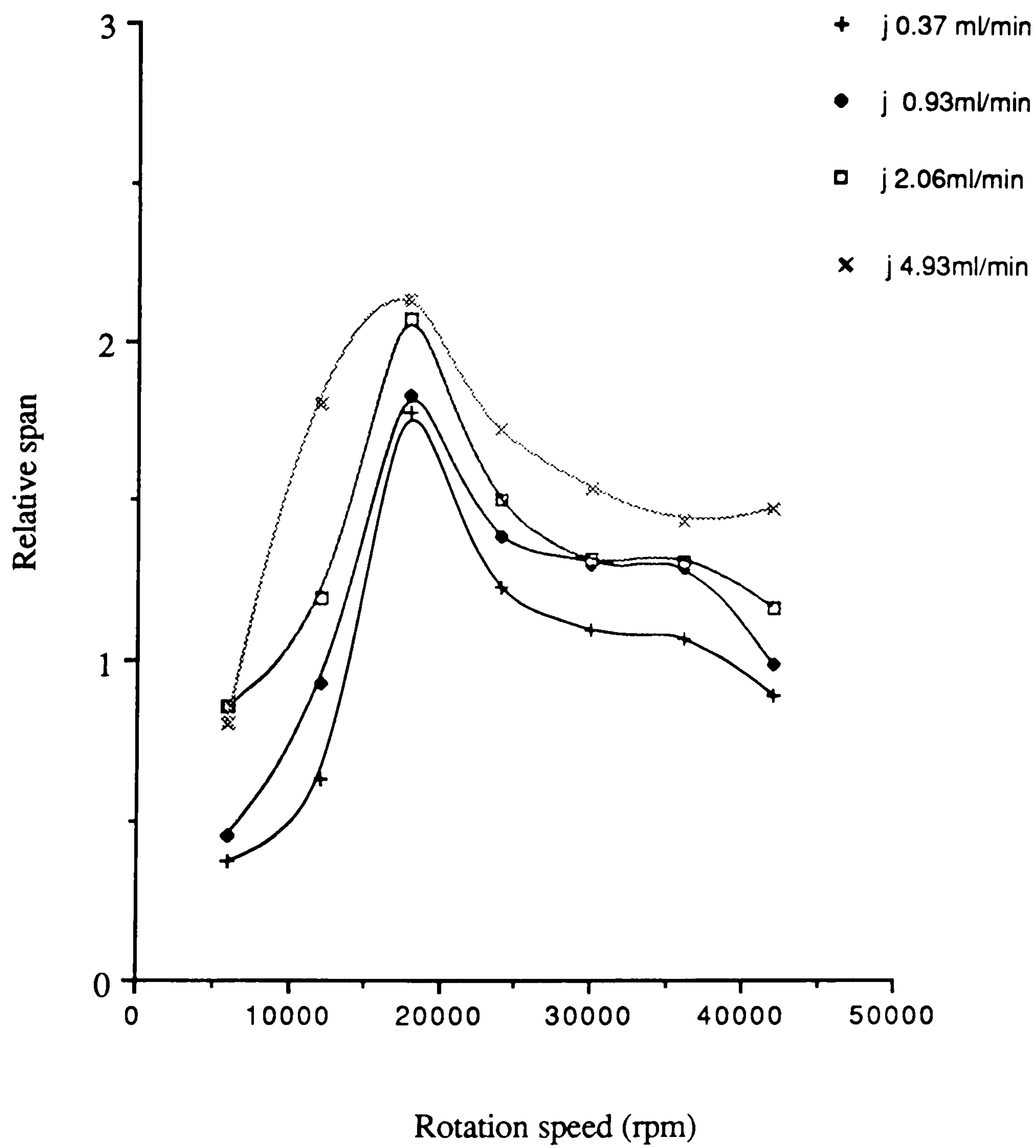
Graph 6.6 Variation of VMD with rotation speed for trial disc TR8 spraying JF9436



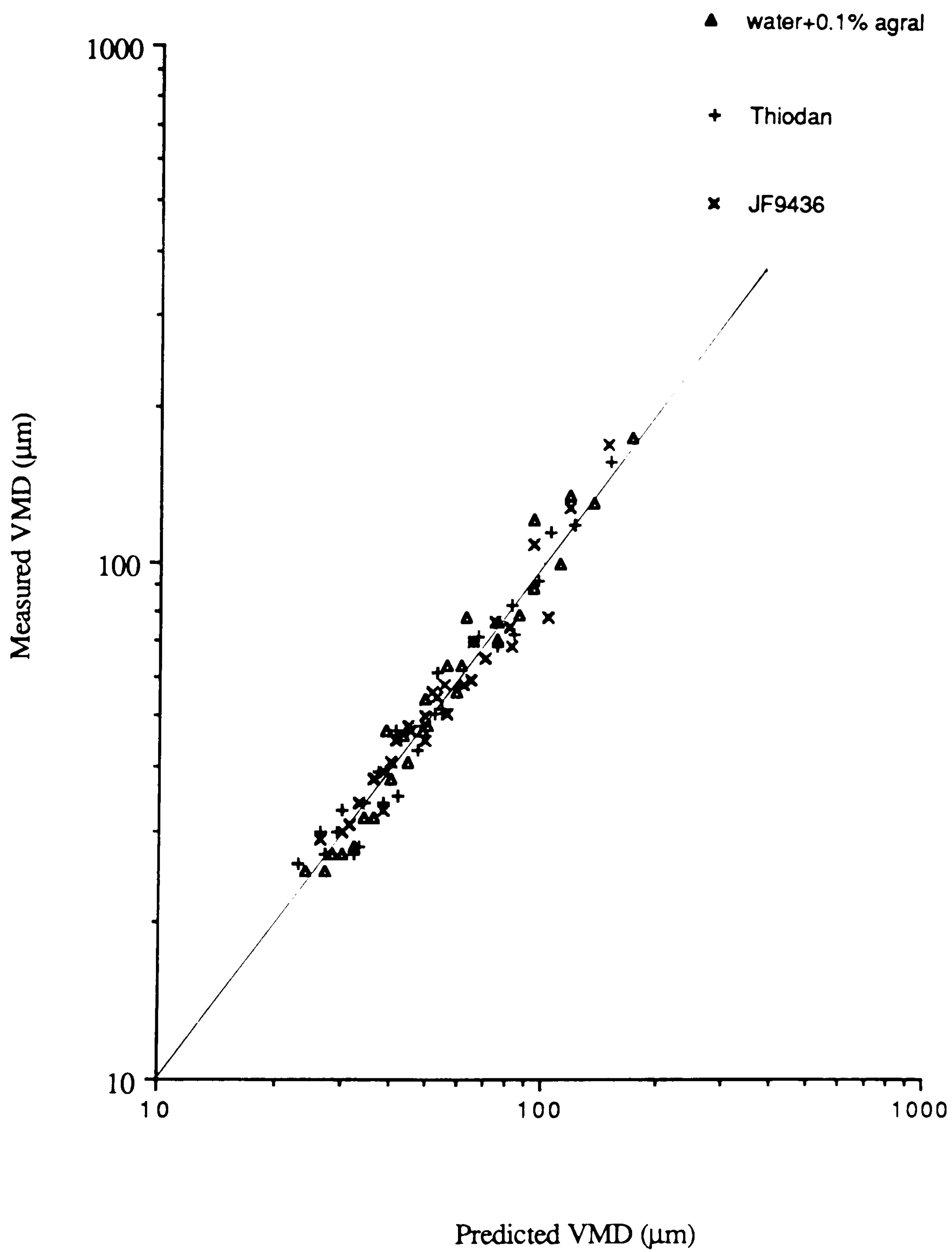
Graph 6.7 Variation of relative span with rotation speed for trial disc TR8 spraying Water + 0.1% Agral



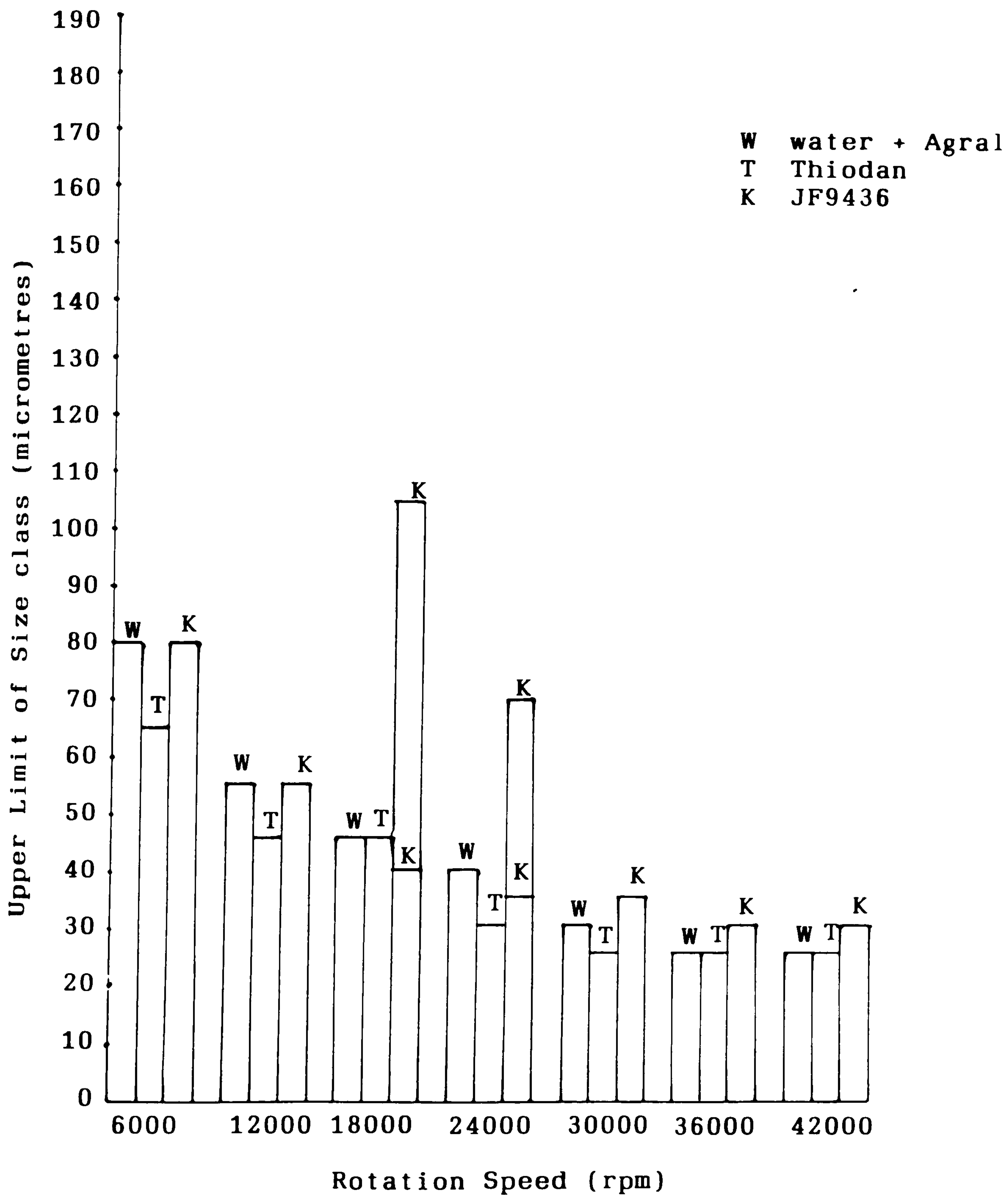
Graph 6.8 Variation of relative span with rotation speed for trial disc TR8 spraying Thiodan



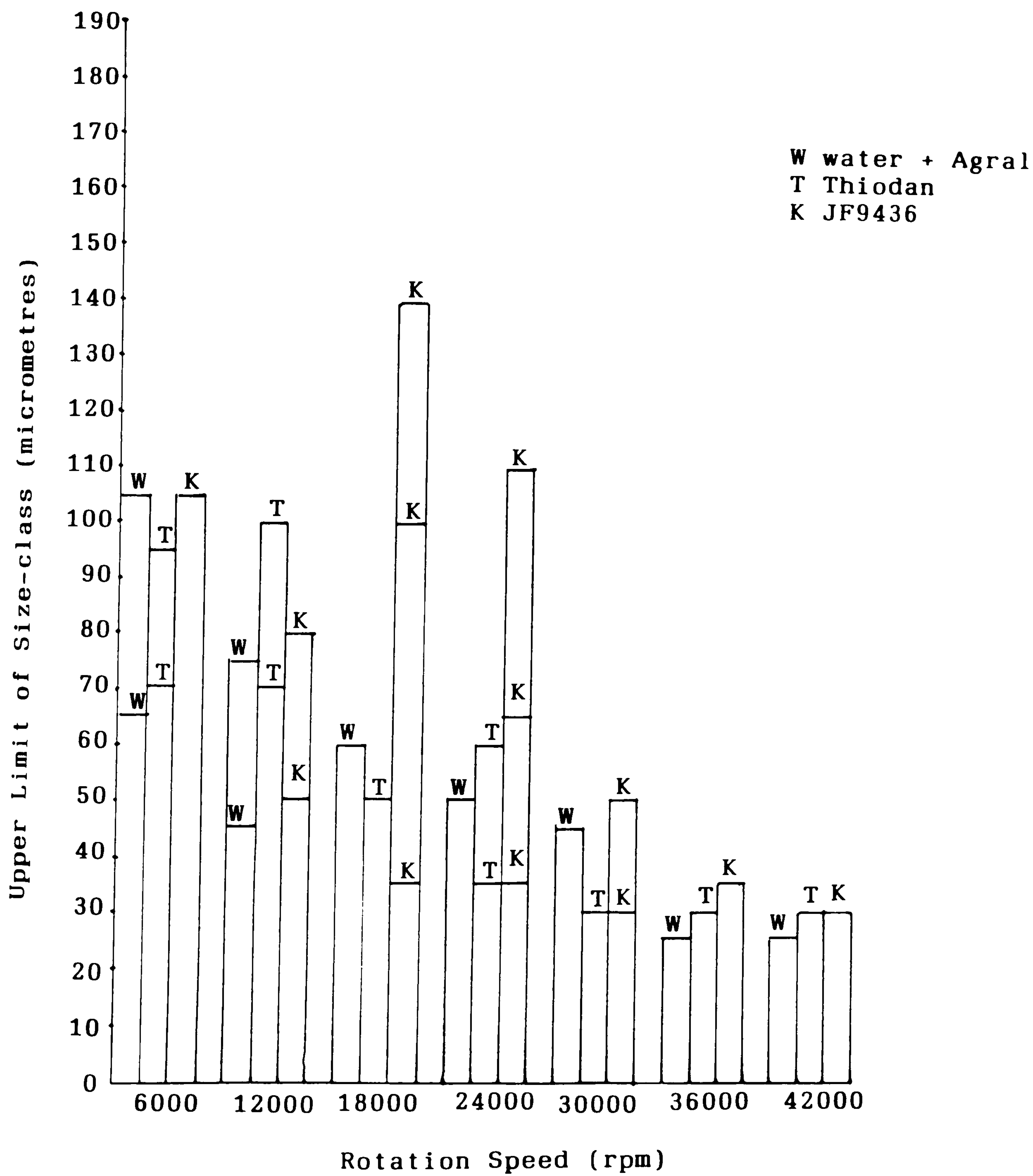
Graph 6.9 Variation of relative span with rotation speed for trial disc TR8 spraying JF9436



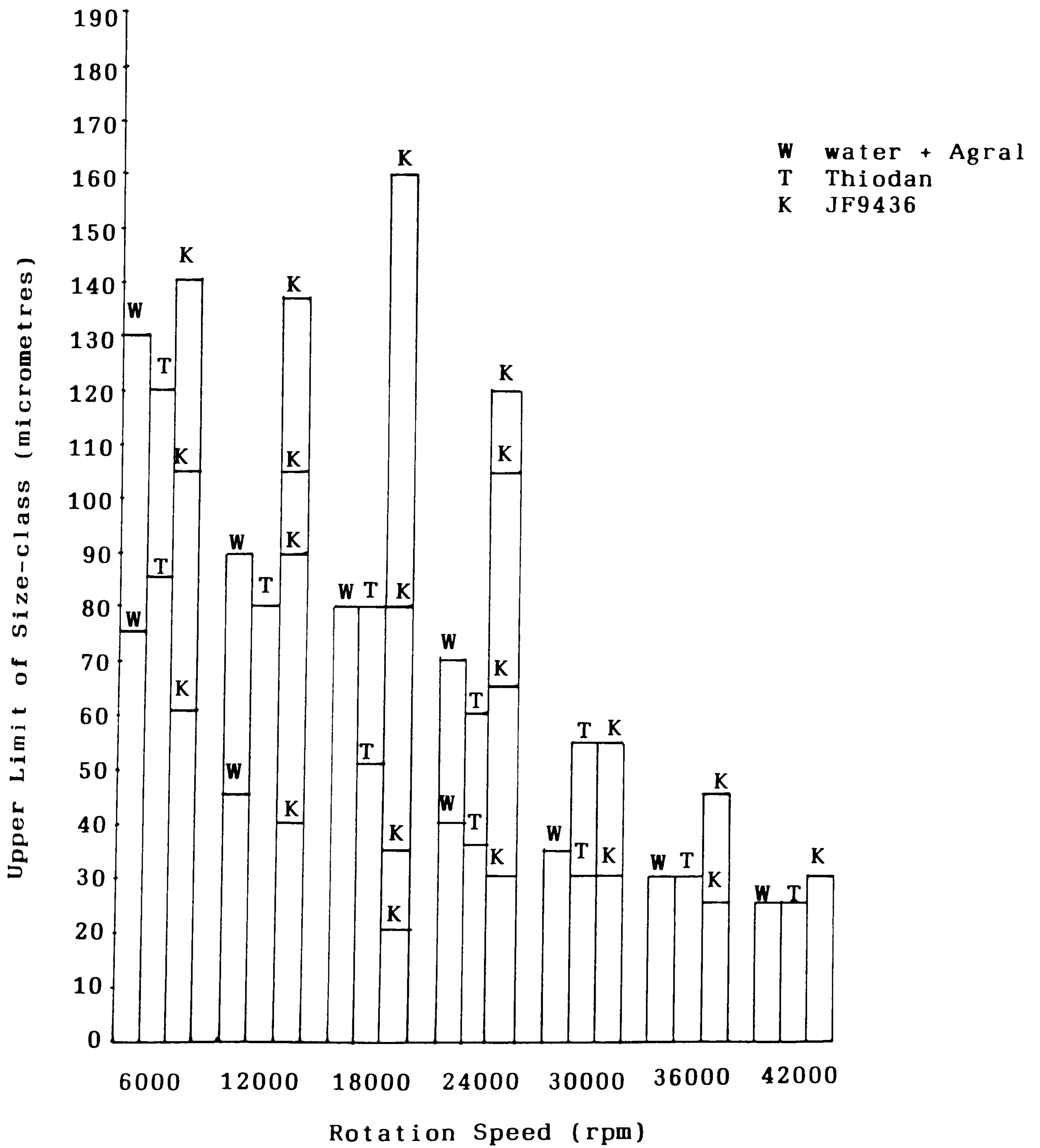
Graph 6.10 Comparison of measured values of VMD with values predicted using a two-stage empirical model



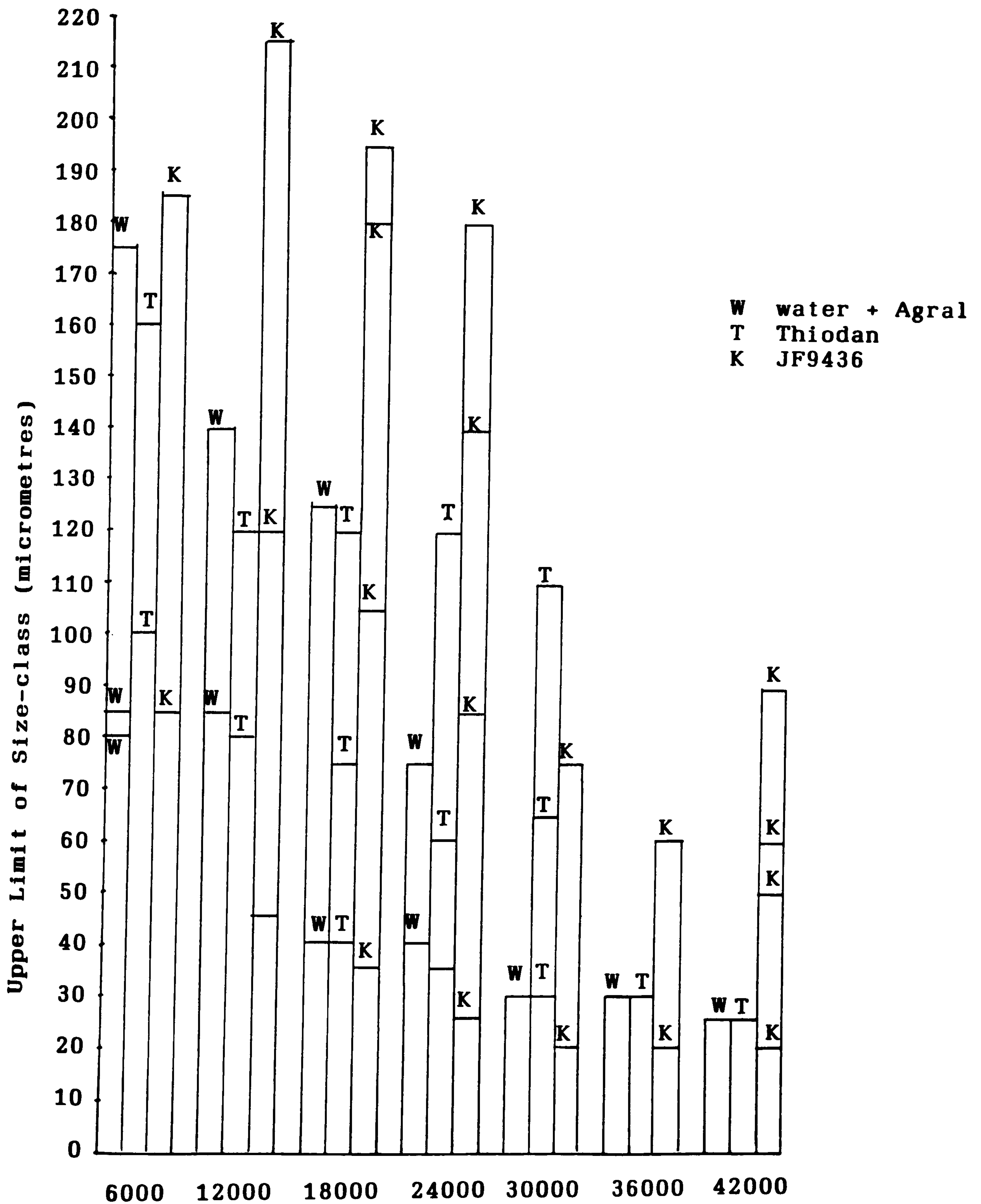
Graph 6.11 Volume peaks from spectra produced using disc TR8 at a feed rate of 0.37 ml/min



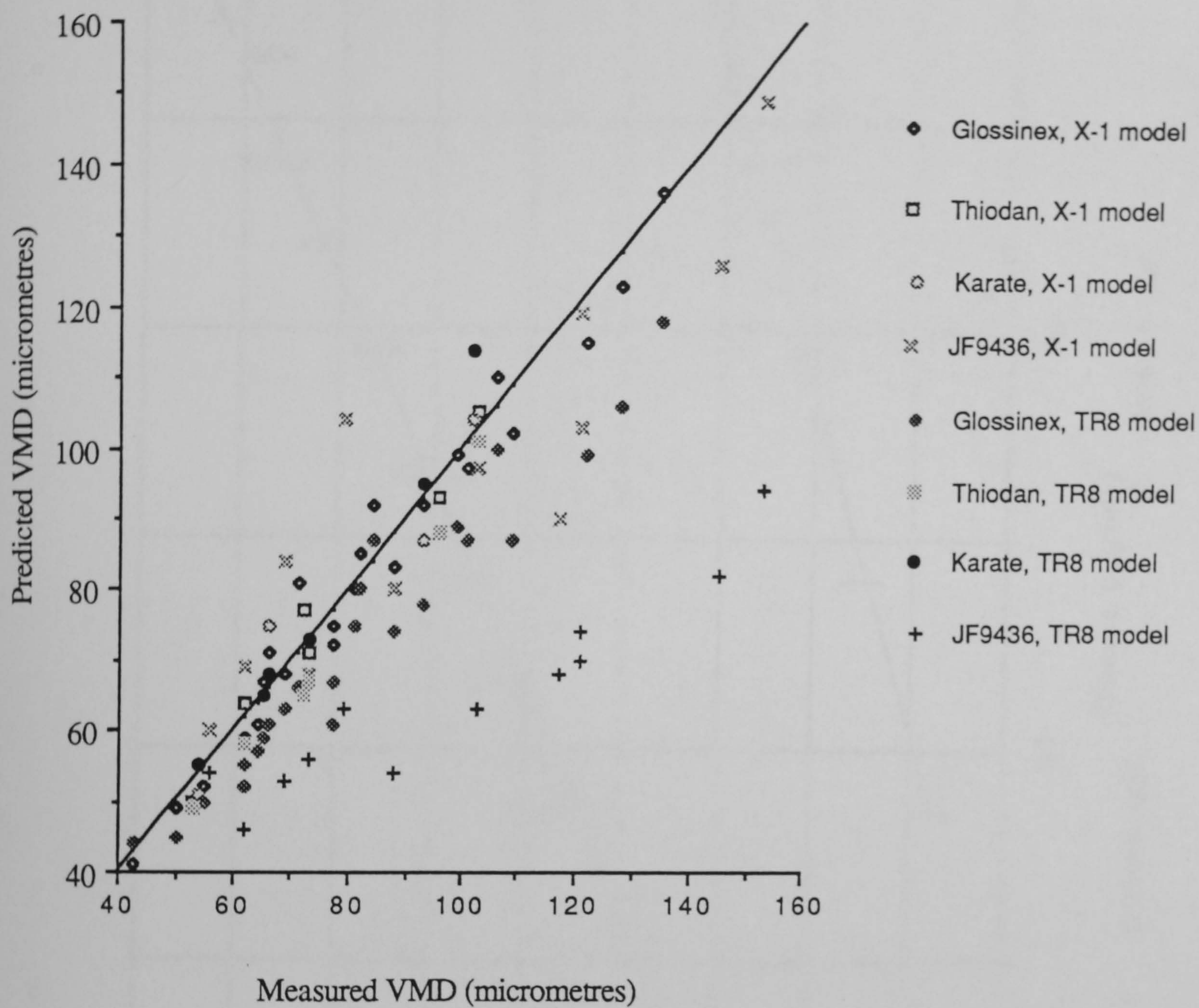
Graph 6.12 Volume peaks from spectra produced using disc TR8 at a feed rate of 0.93 ml/min



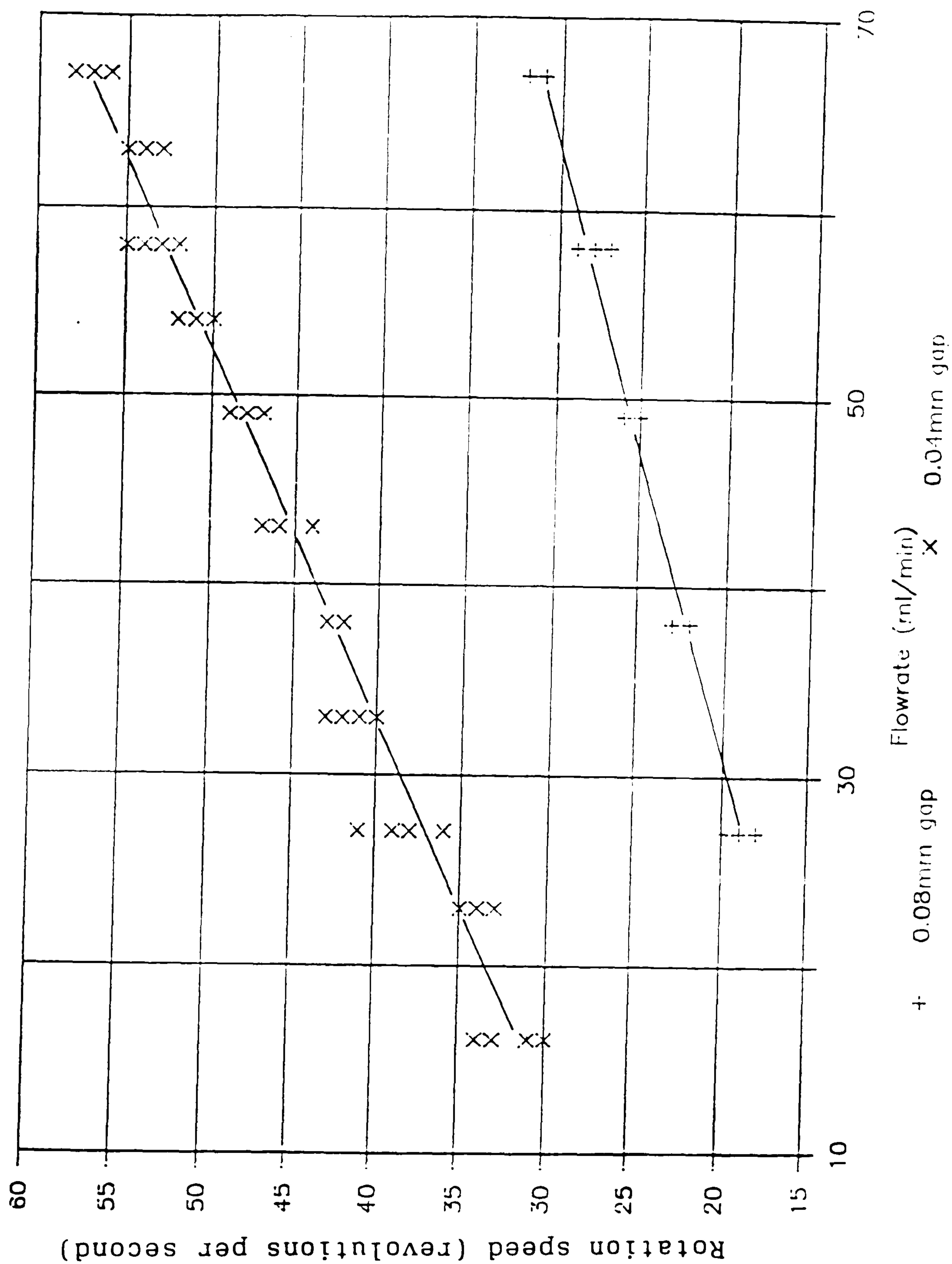
Graph 6.13 Volume peaks from spectra produced using disc TR8 at a feed rate of 2.06 ml/min



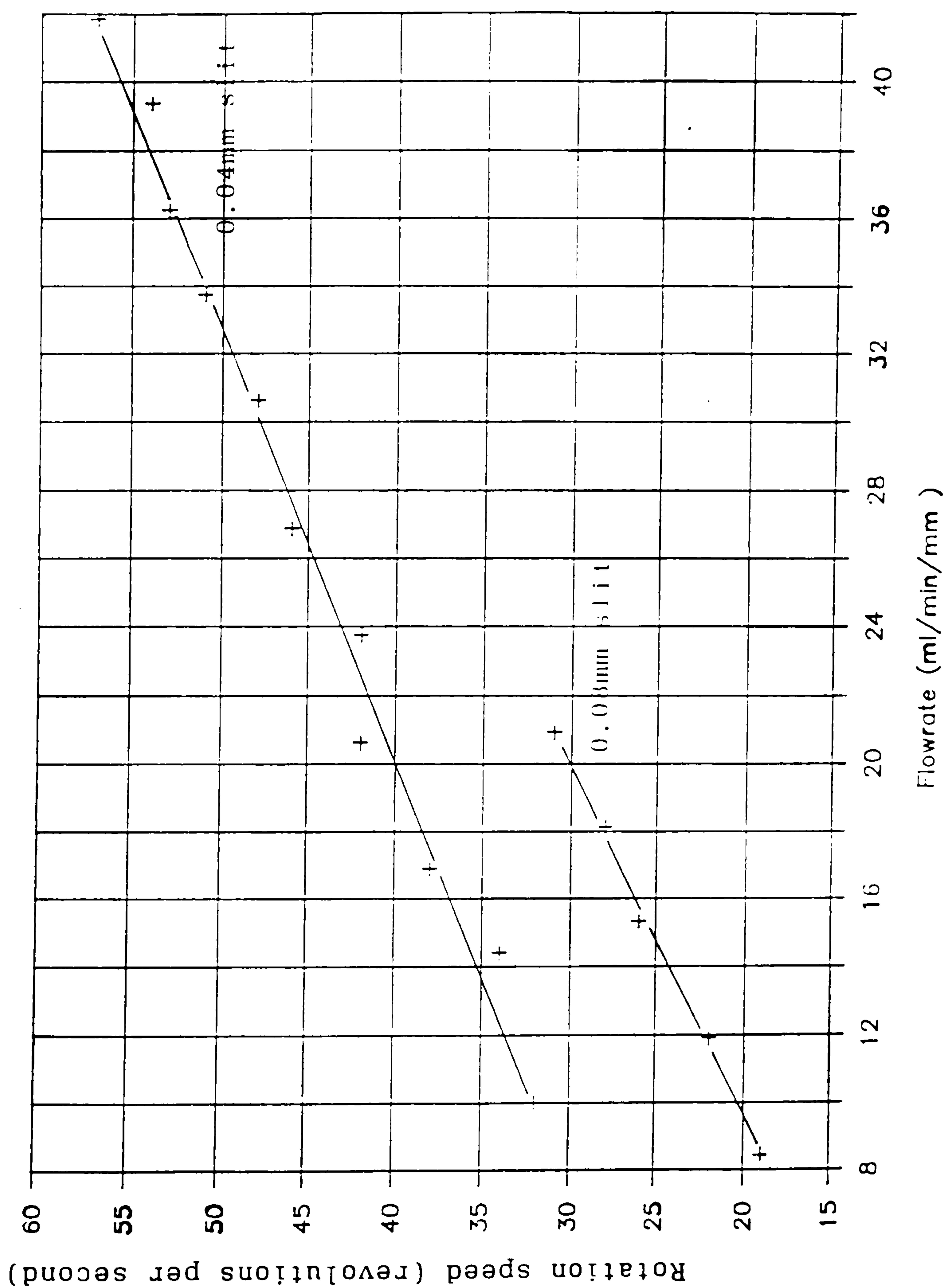
Graph 6.14 Volume peaks from spectra produces using disc TR8 at a feed rate of 4.93 ml/min



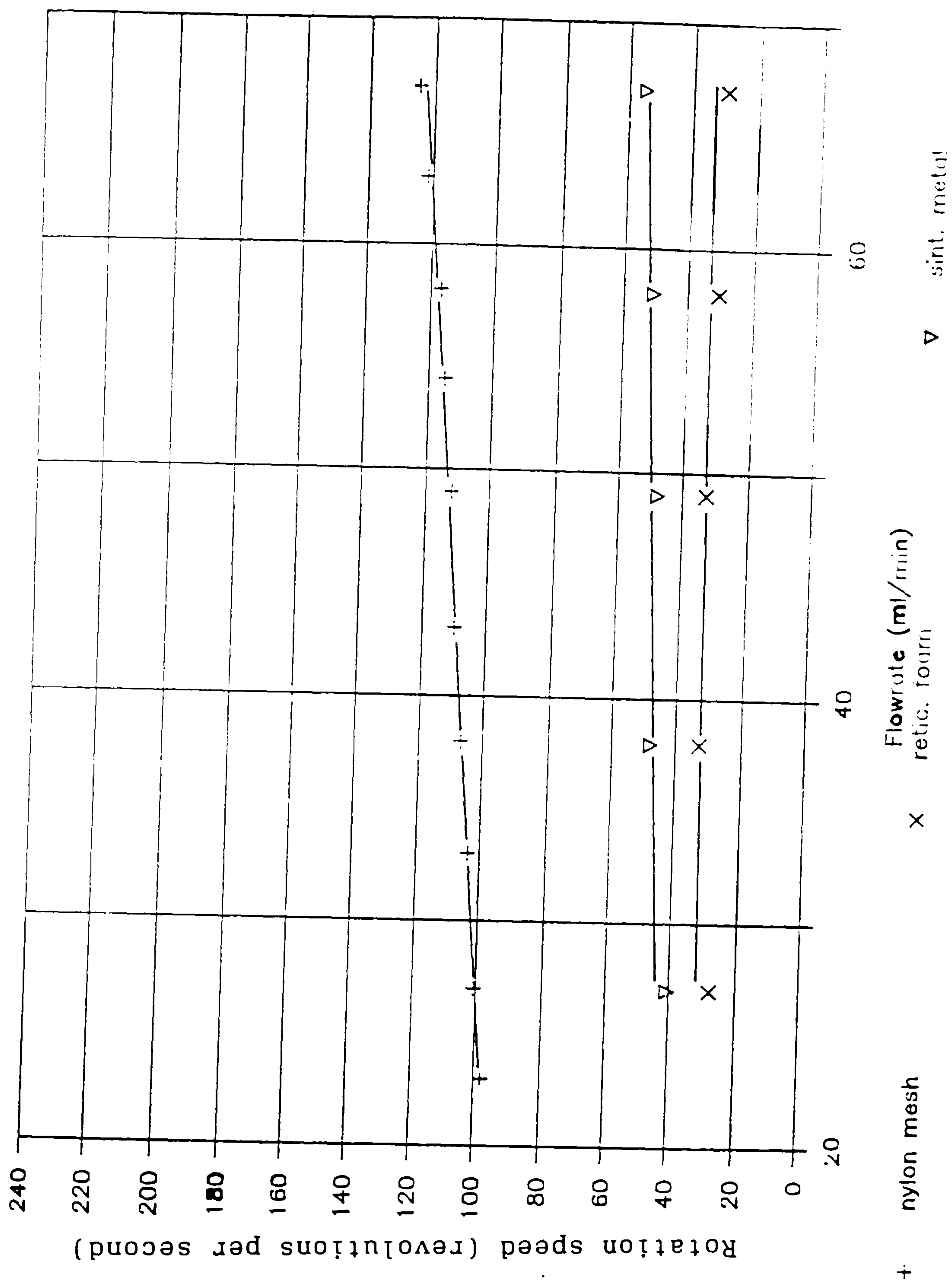
Graph 6.15 Comparison of measured VMDs obtained using the Micron X-1 atomiser with values predicted using the Micron X-1 empirical model and the two-step empirical model for trial disc TR8



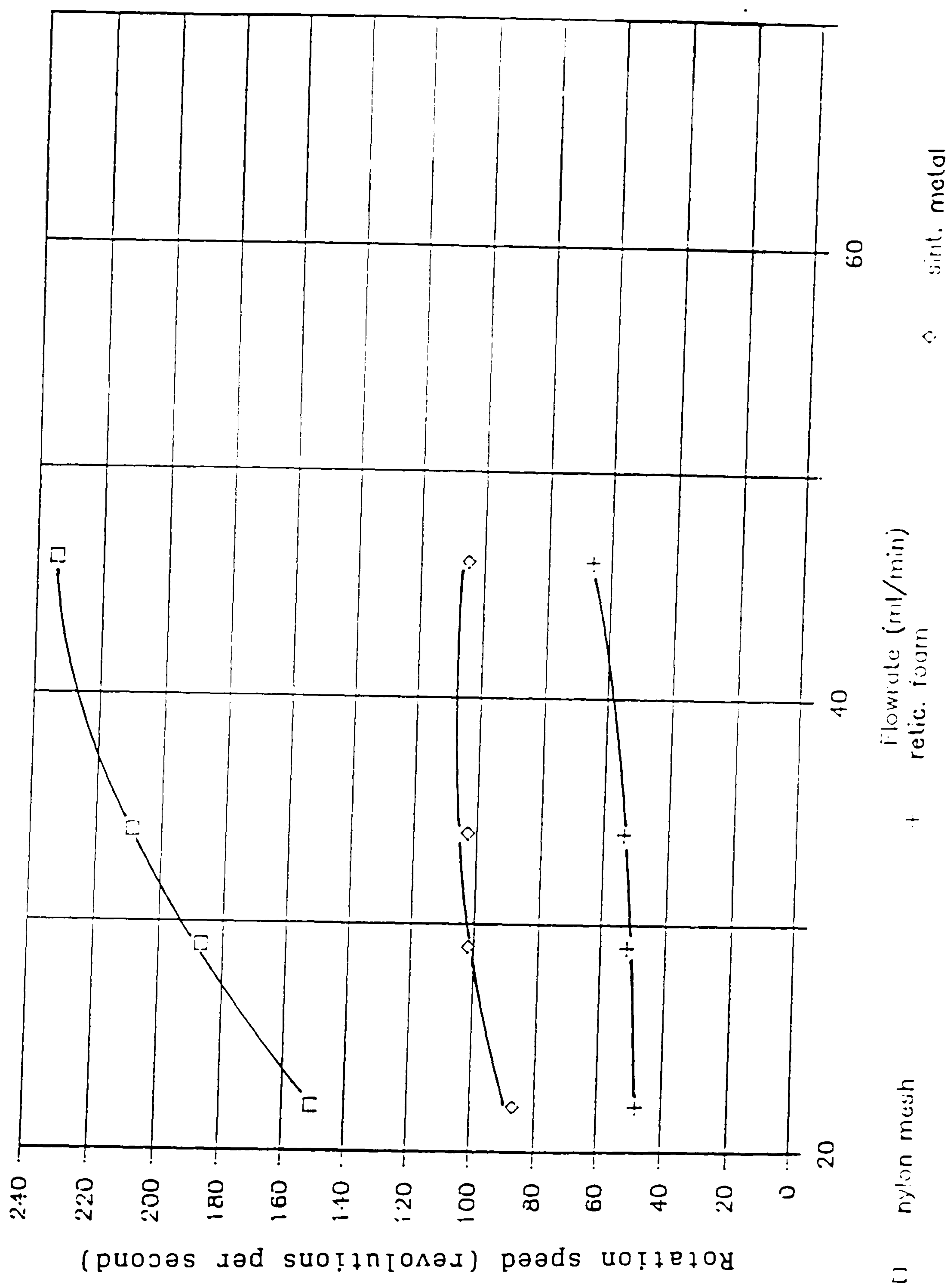
Graph 7.1 Rotation speed at which pumping rate is equal to various feed rates for two sizes of slit (liquid used : water + 0.1% Agral)



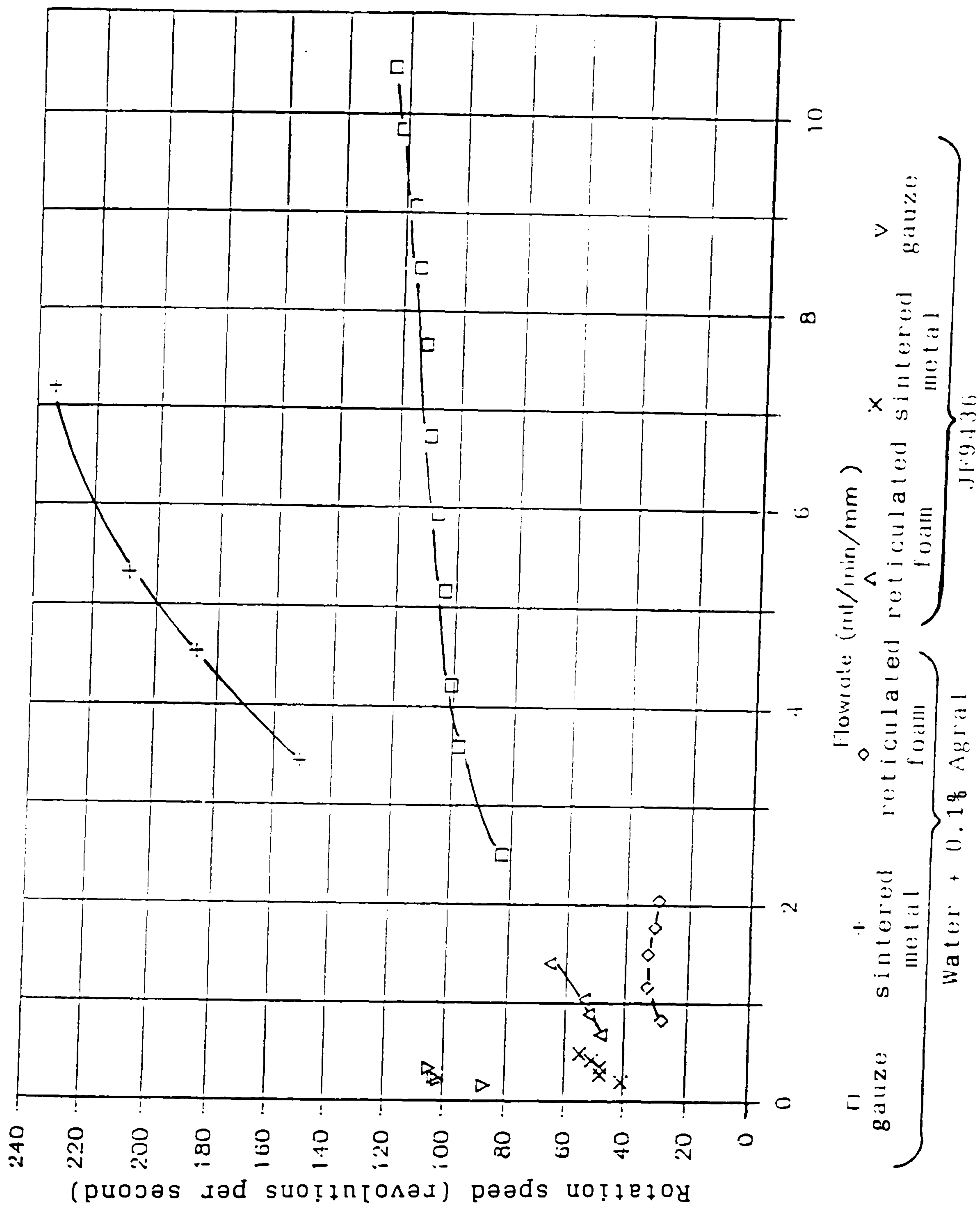
Graph 7.2 Flowrate per unit cross-sectional area for two widths of rotating slit running full at various rotation speeds
(liquid used: water + 0.1% Agral)



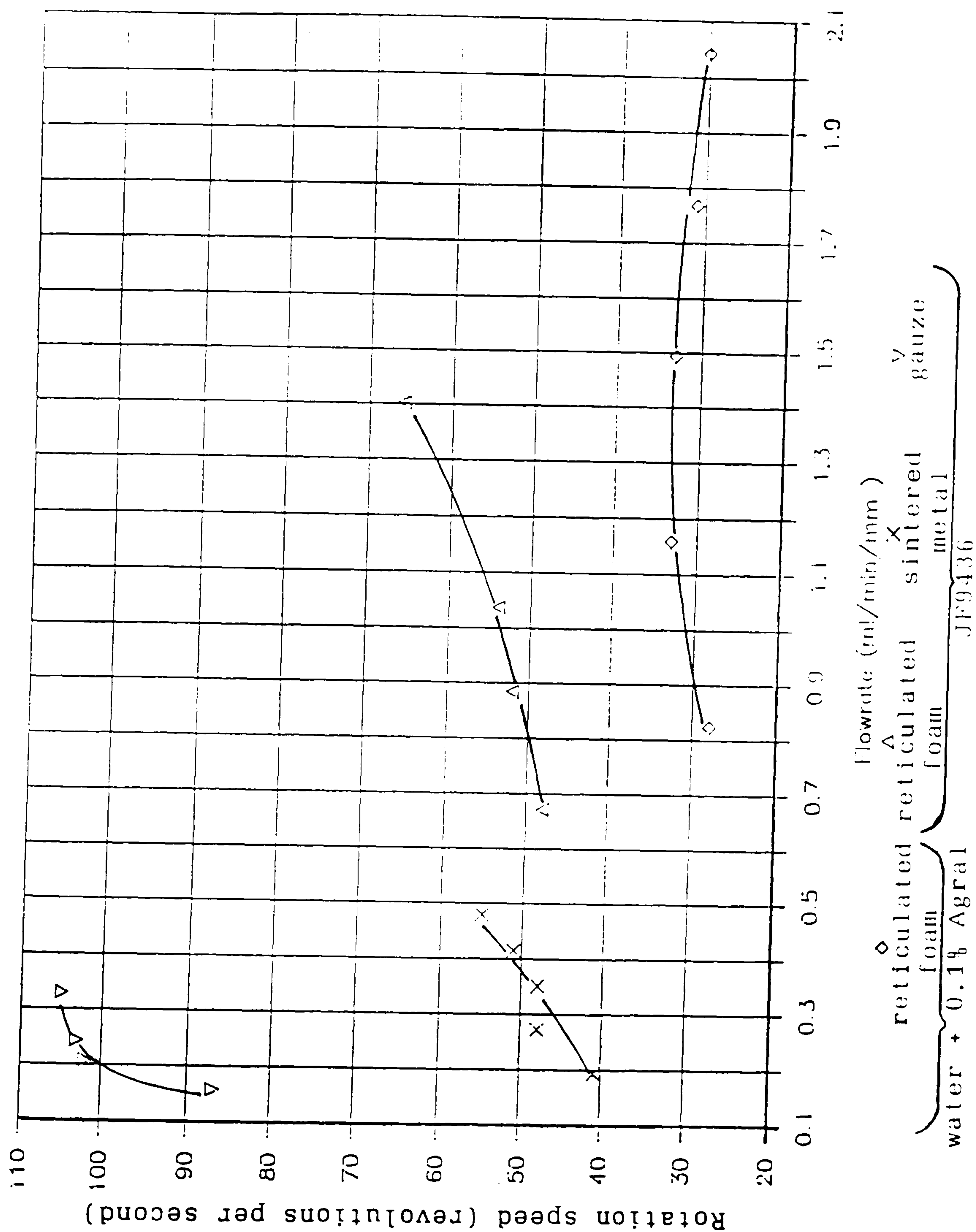
Graph 7.3 Rotation speeds at which pumping rate is equal to various feed rates for a rotating slit blocked with porous materials (liquid used: water + 0.1% Agral)



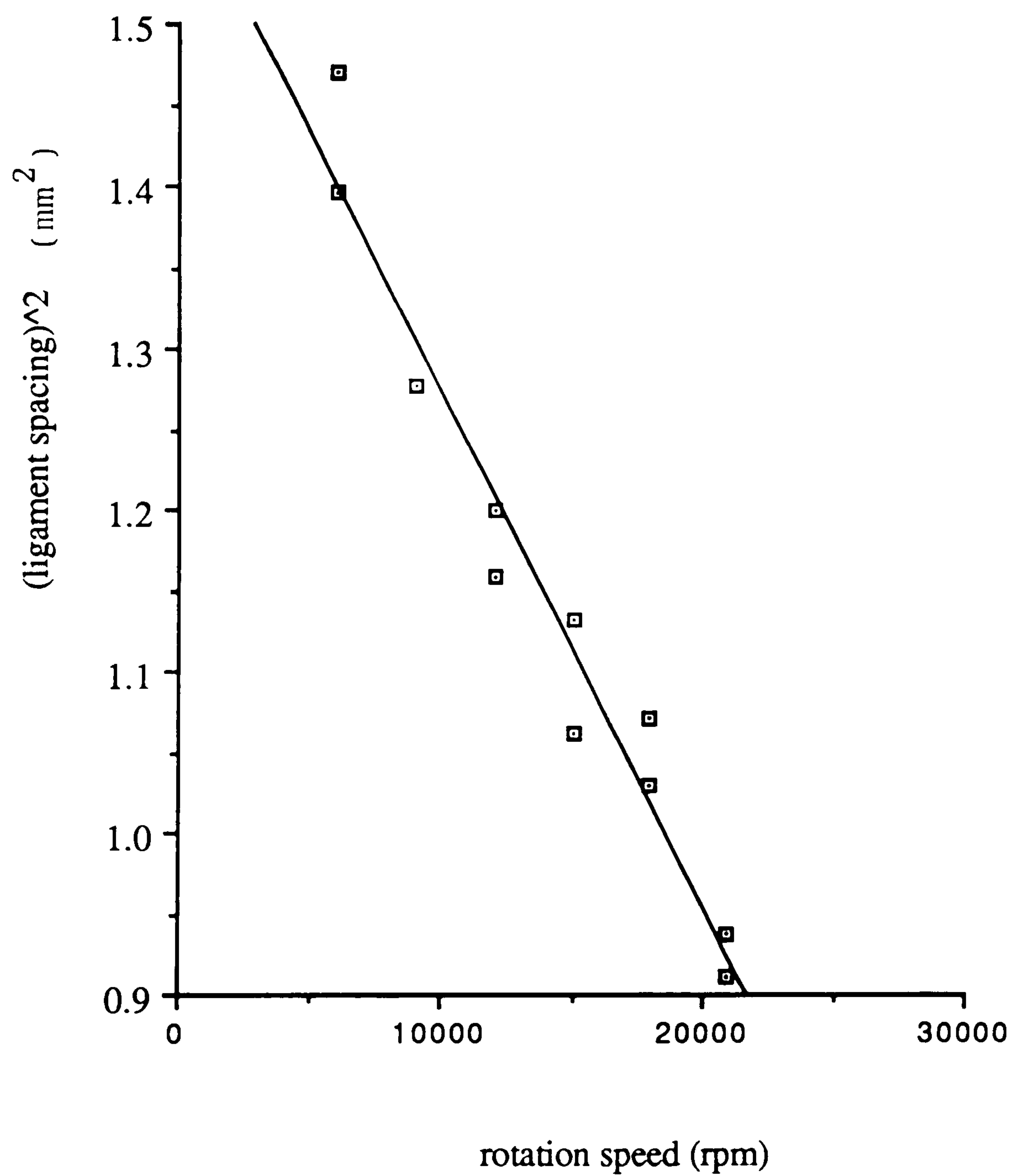
Graph 7.4 Rotation speeds at which pumping rate is equal to various feed rates for a rotating slit blocked with porous materials (liquid used: JF9436)



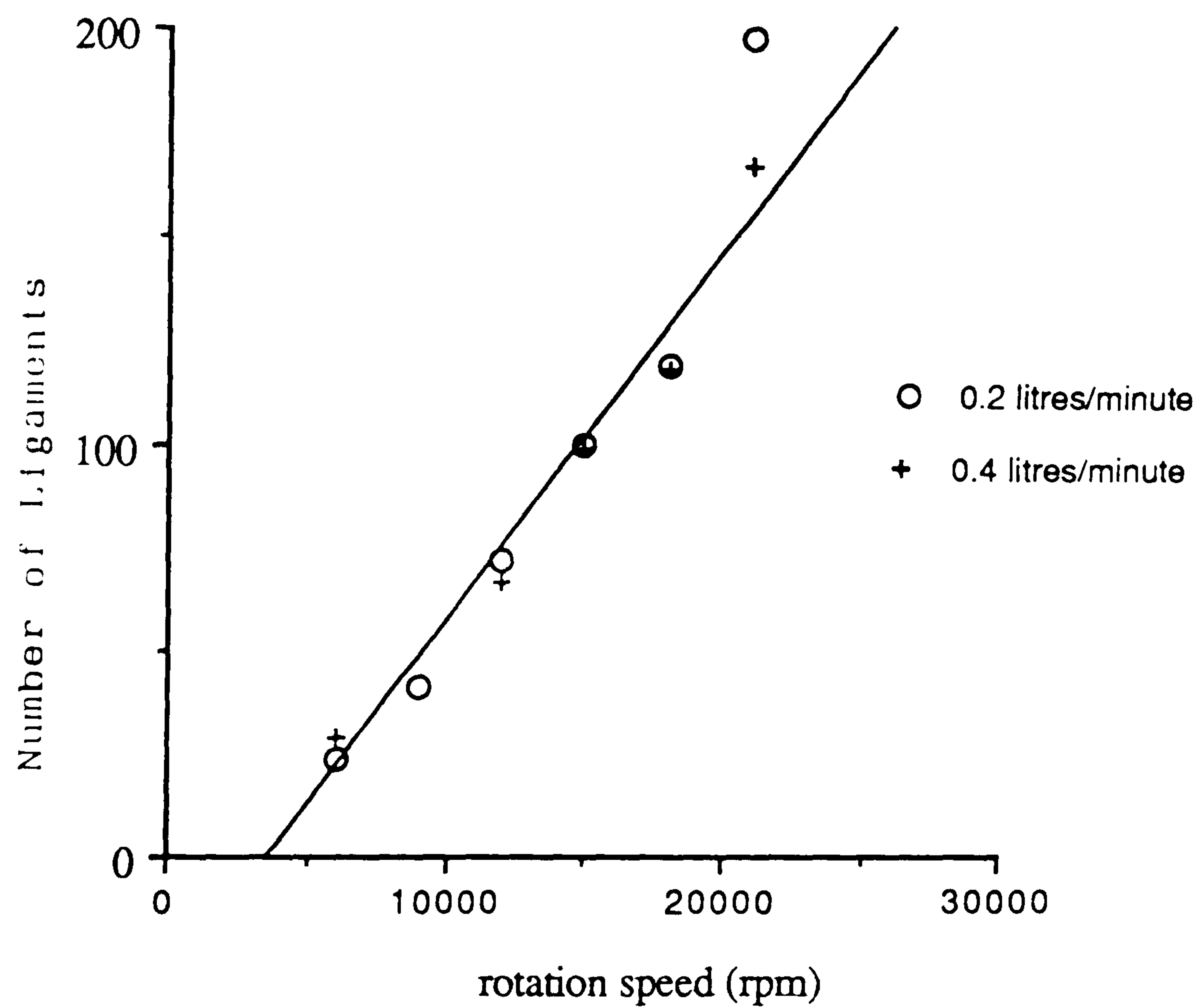
Graph 7.5 Flowrate per unit cross-sectional area for rotating slit blocked with various porous materials over a range of rotation speeds



Graph 7.6 Flowrate per unit cross-sectional area for rotating slit blocked with various porous materials - detail of lower flowrate end of graph 7.5)

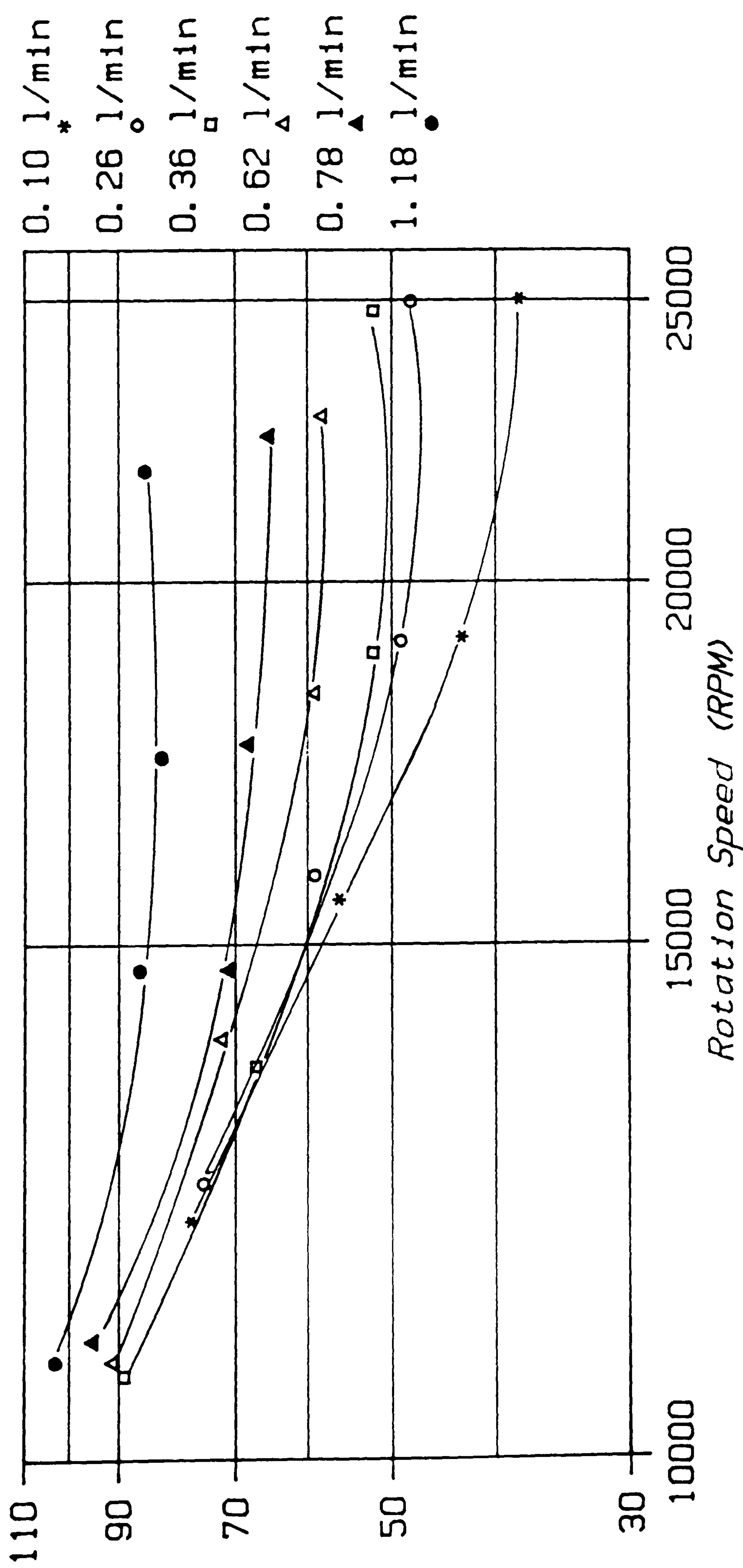


Graph 8.1 Variation of ligament spacing with rotation speed for a 25mm diameter sintered plastic cylinder fed with water + 0.1% Agral

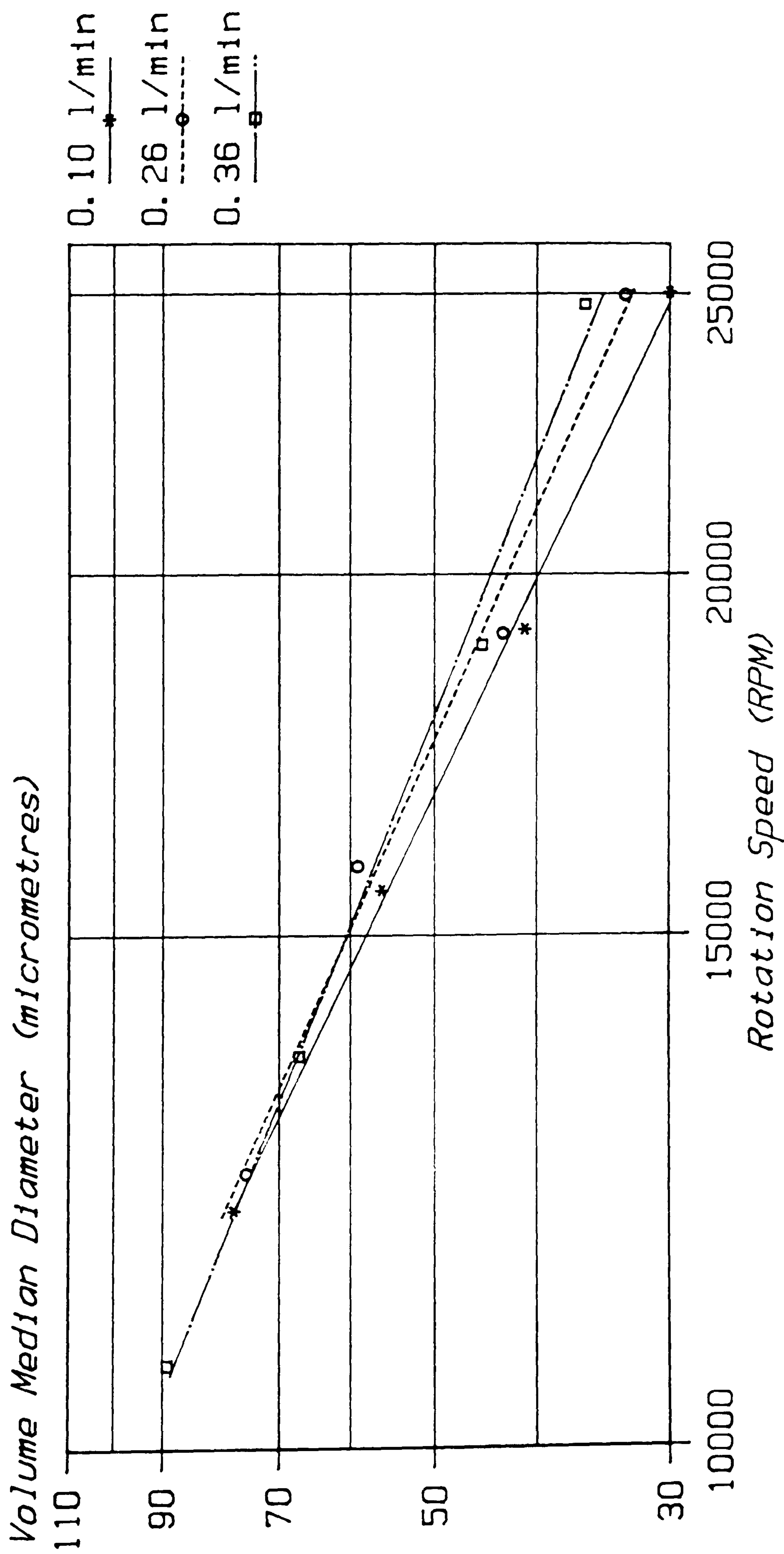


Graph 8.2 Variation in ligament number with rotation speed for a fixed area on the surface of a 25mm diameter sintered plastic cylinder fed with water + 0.1% Agral

Effect of rotation speed on volume median diameter for prototype PRO-1

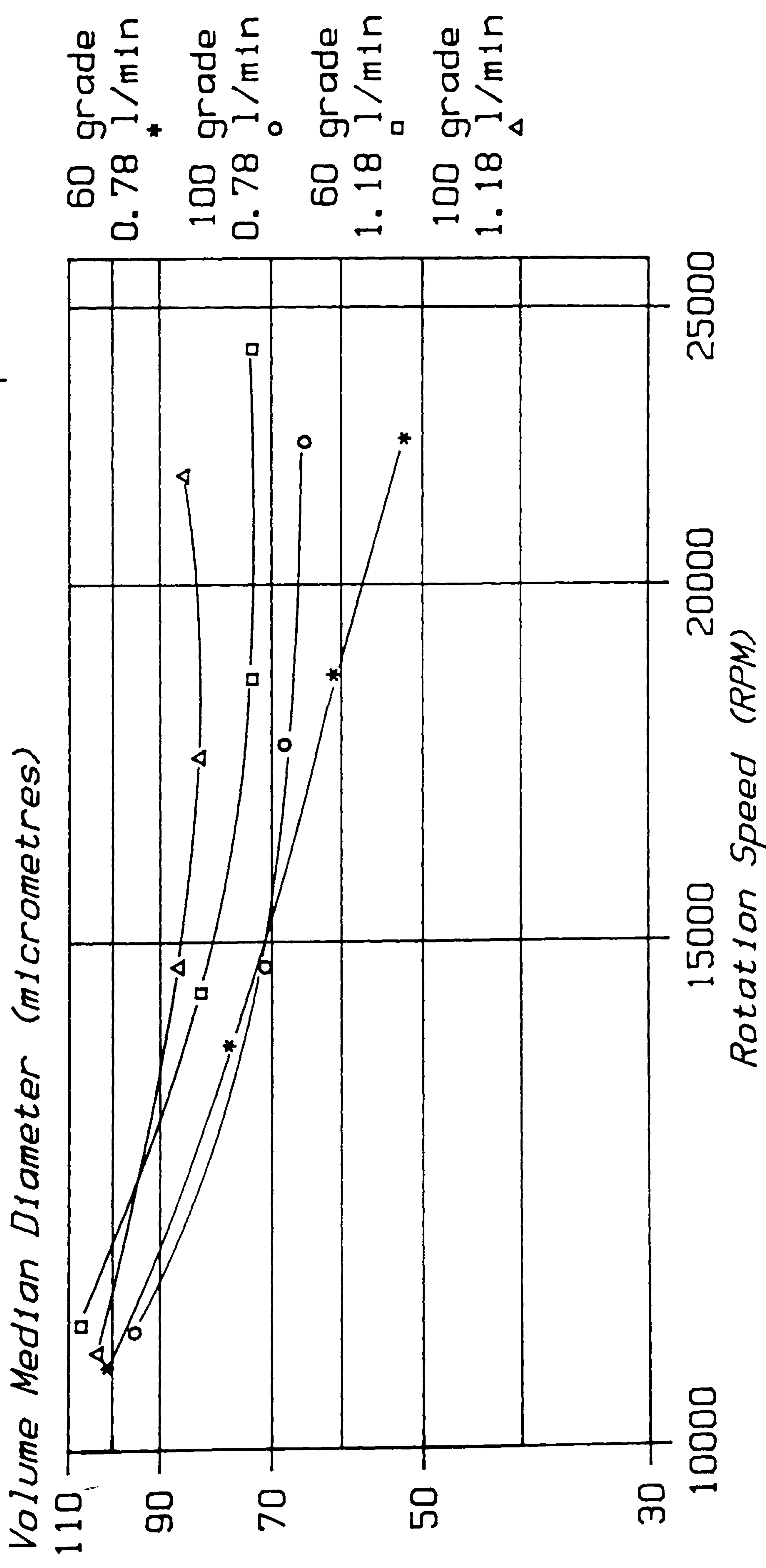


Effect of rotation speed on volume median diameter for prototype PR0-1, modified data (see text)



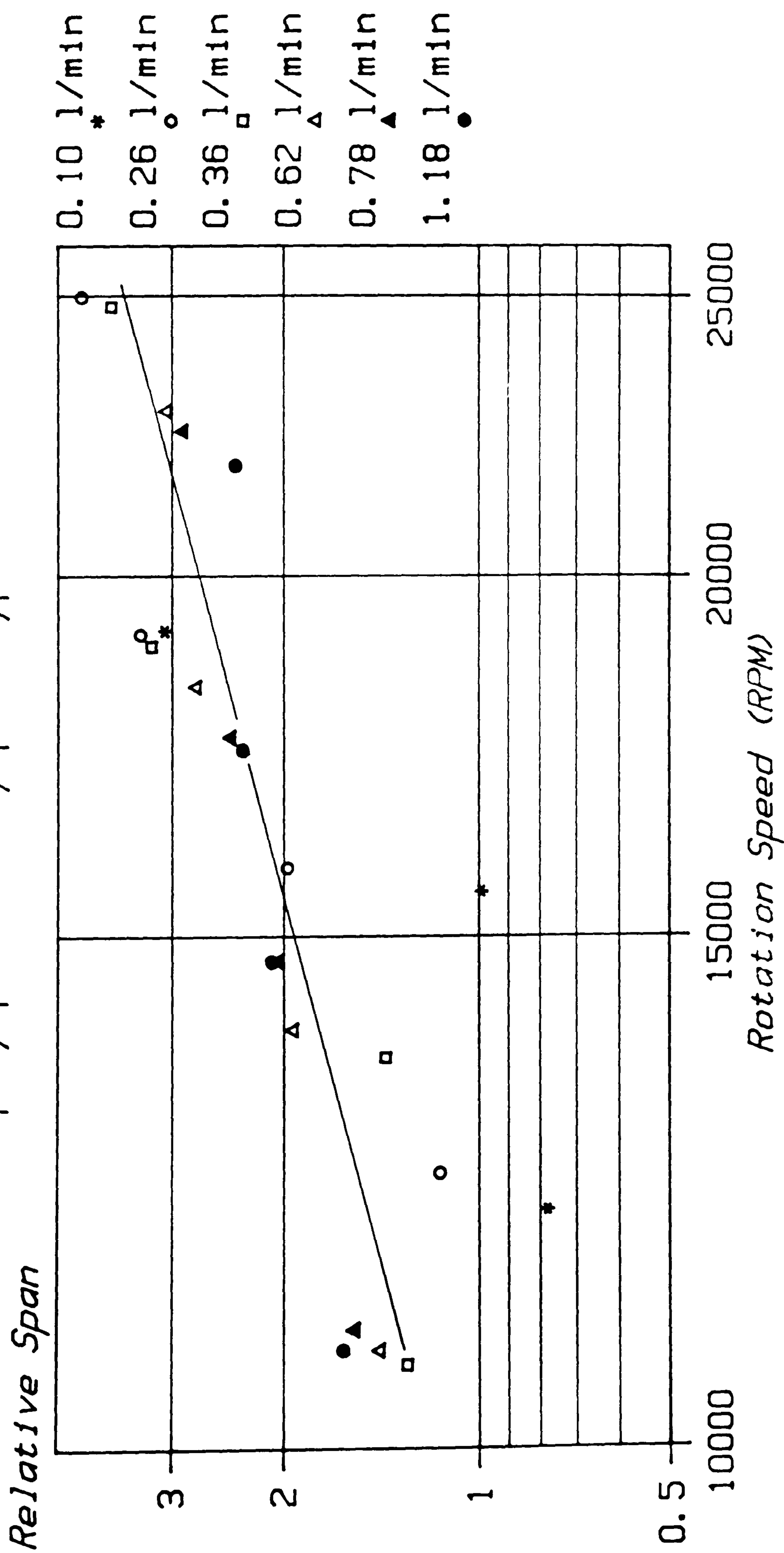
Graph 8.4

Effect of different grades of sintered plastic
on the VMD of spray produced by prototype Pro-1
at various rotation speeds



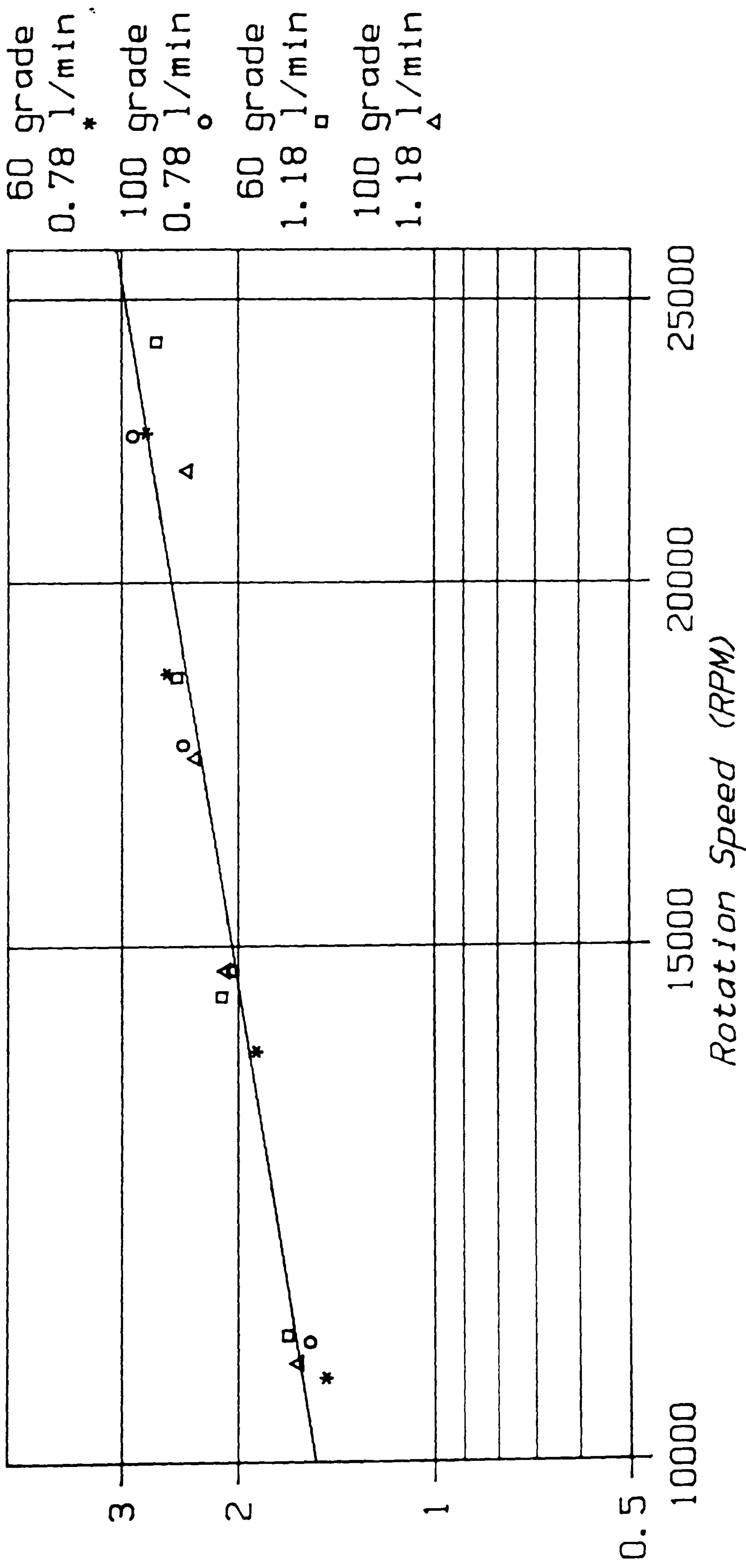
Graph 8.5

Effect of rotation speed on relative span of spray produced by prototype Pro-1



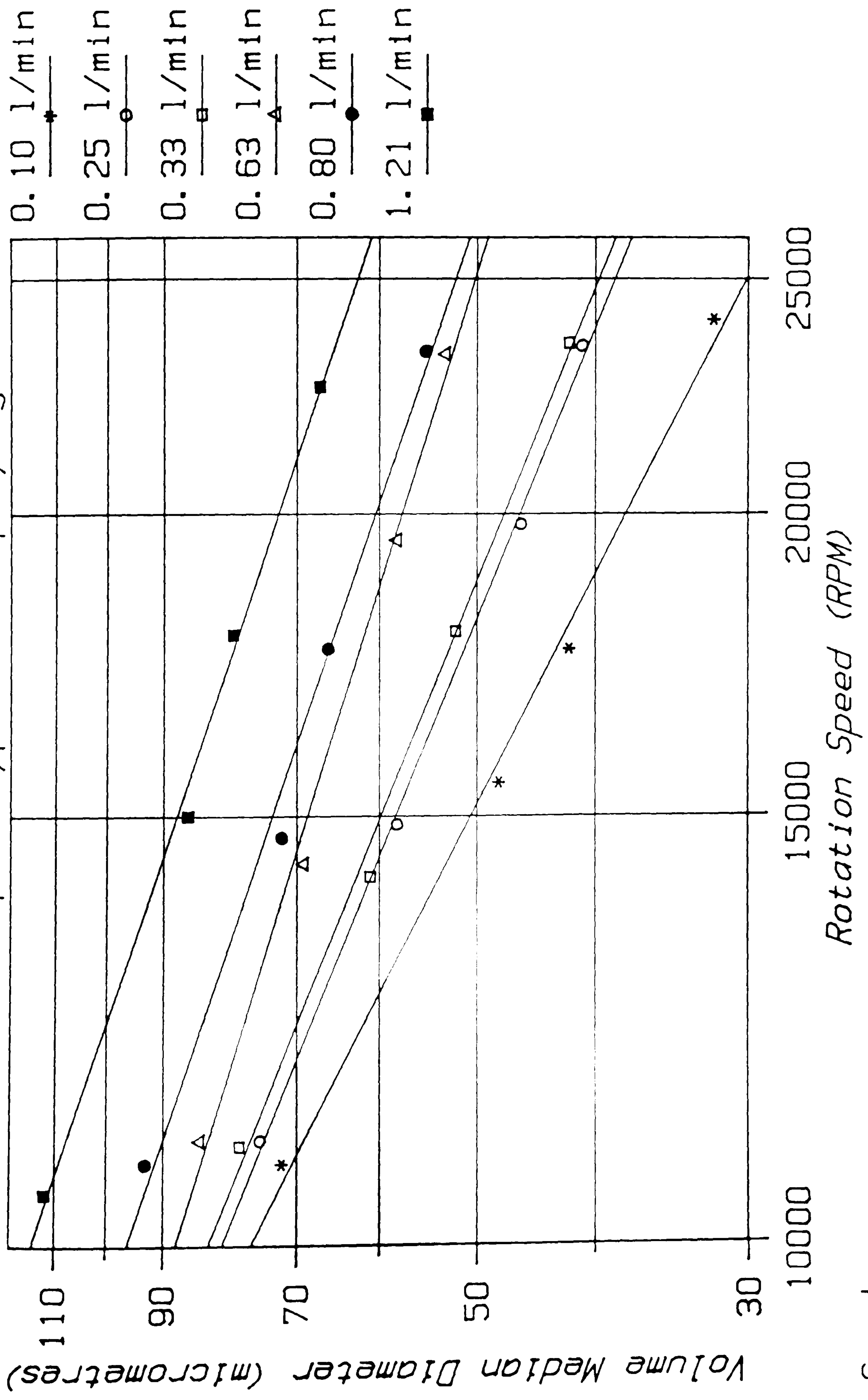
Graph 8.6

Effect of different grades of sintered plastic
on the relative span of spray produced by
prototype Pro-1 at various rotation speeds



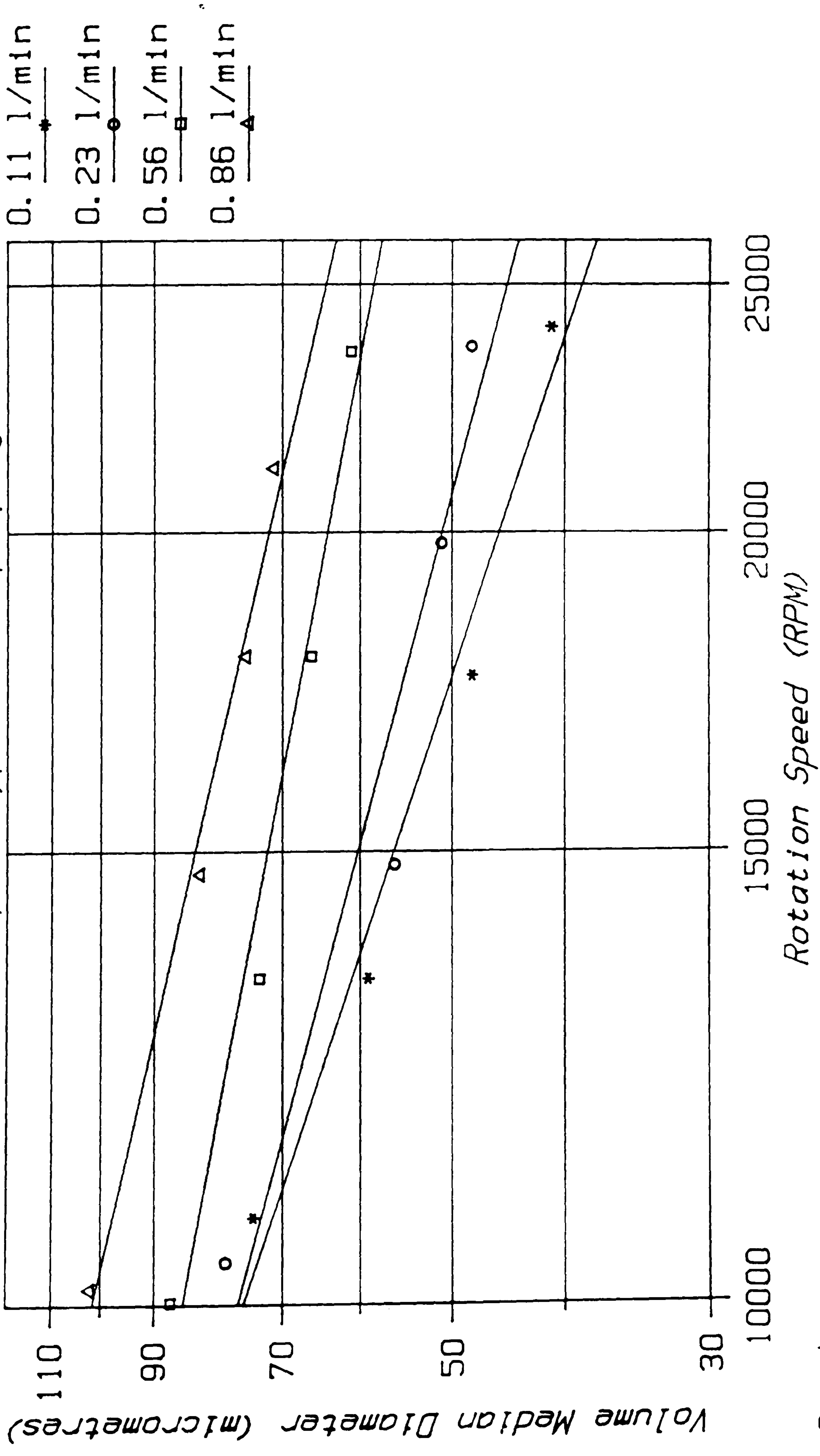
Graph 8.7

Effect of rotation speed on volume median diameter for prototype Pro-2 spraying Thiodan



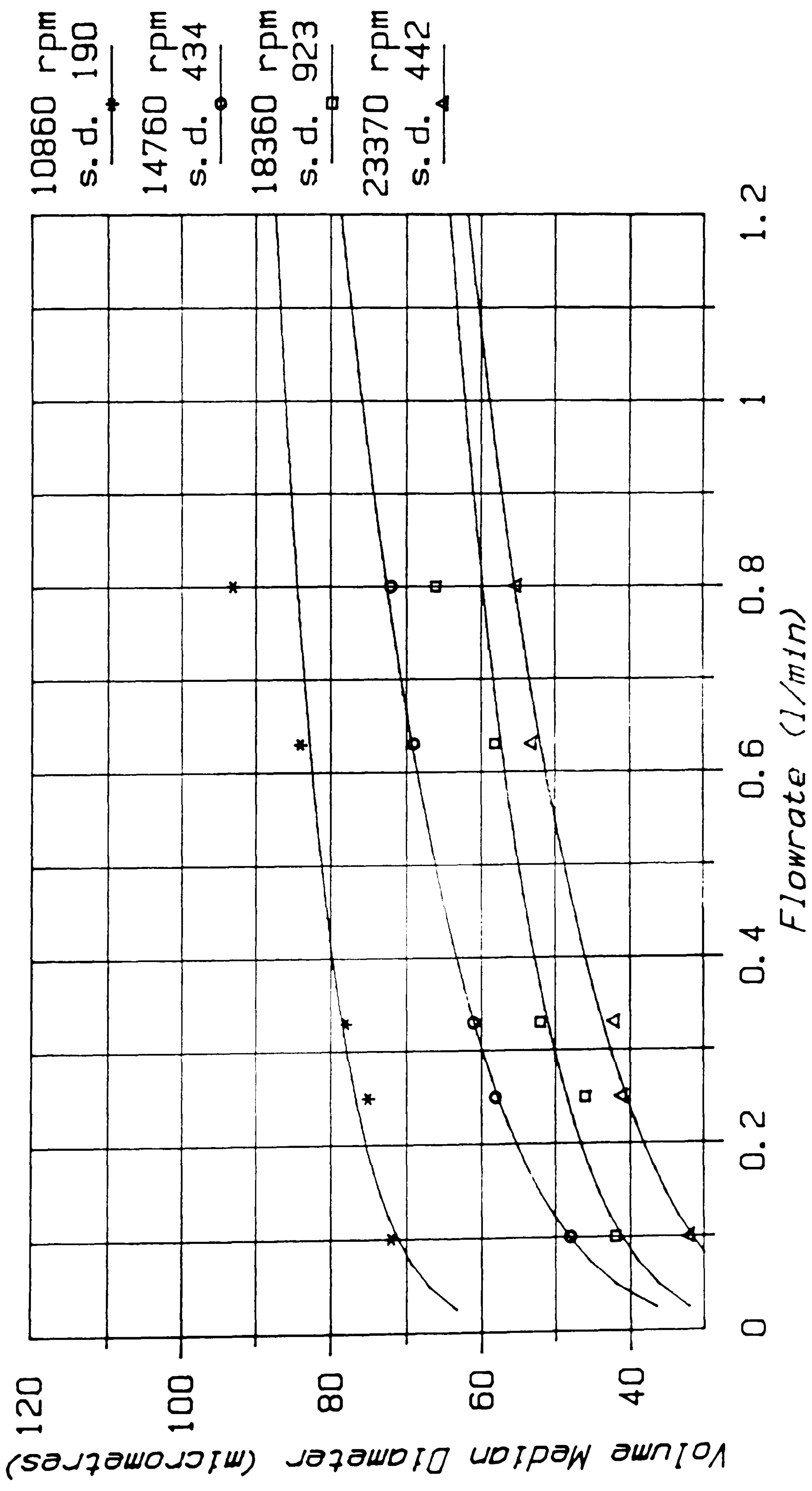
Graph 8.8

Effect of rotation speed on volume median diameter for prototype Pro-2 spraying JF9436



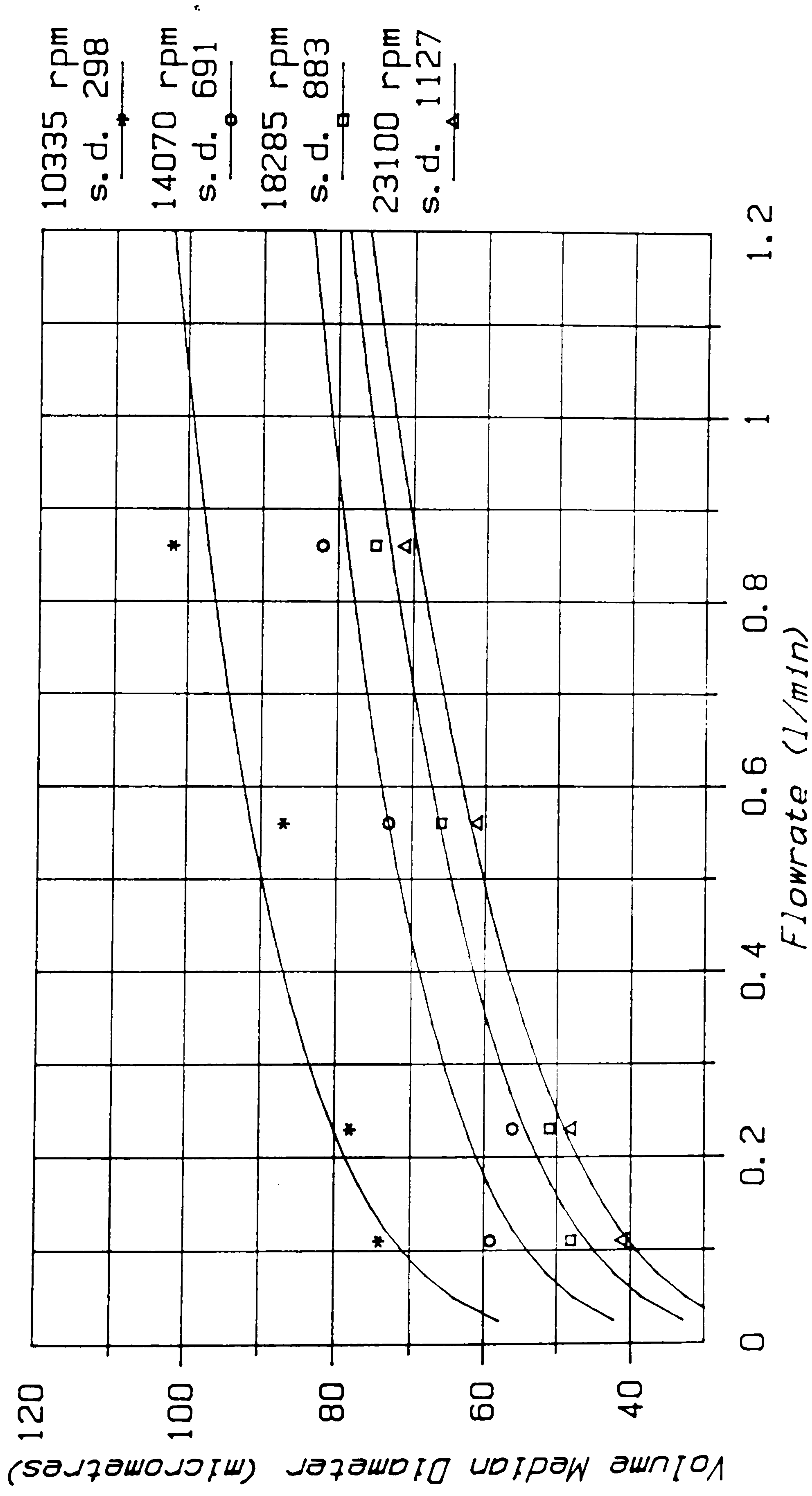
Graph 8.9

Effect of flowrate on volume median diameter
for prototype Pro-2 spraying Thiodan

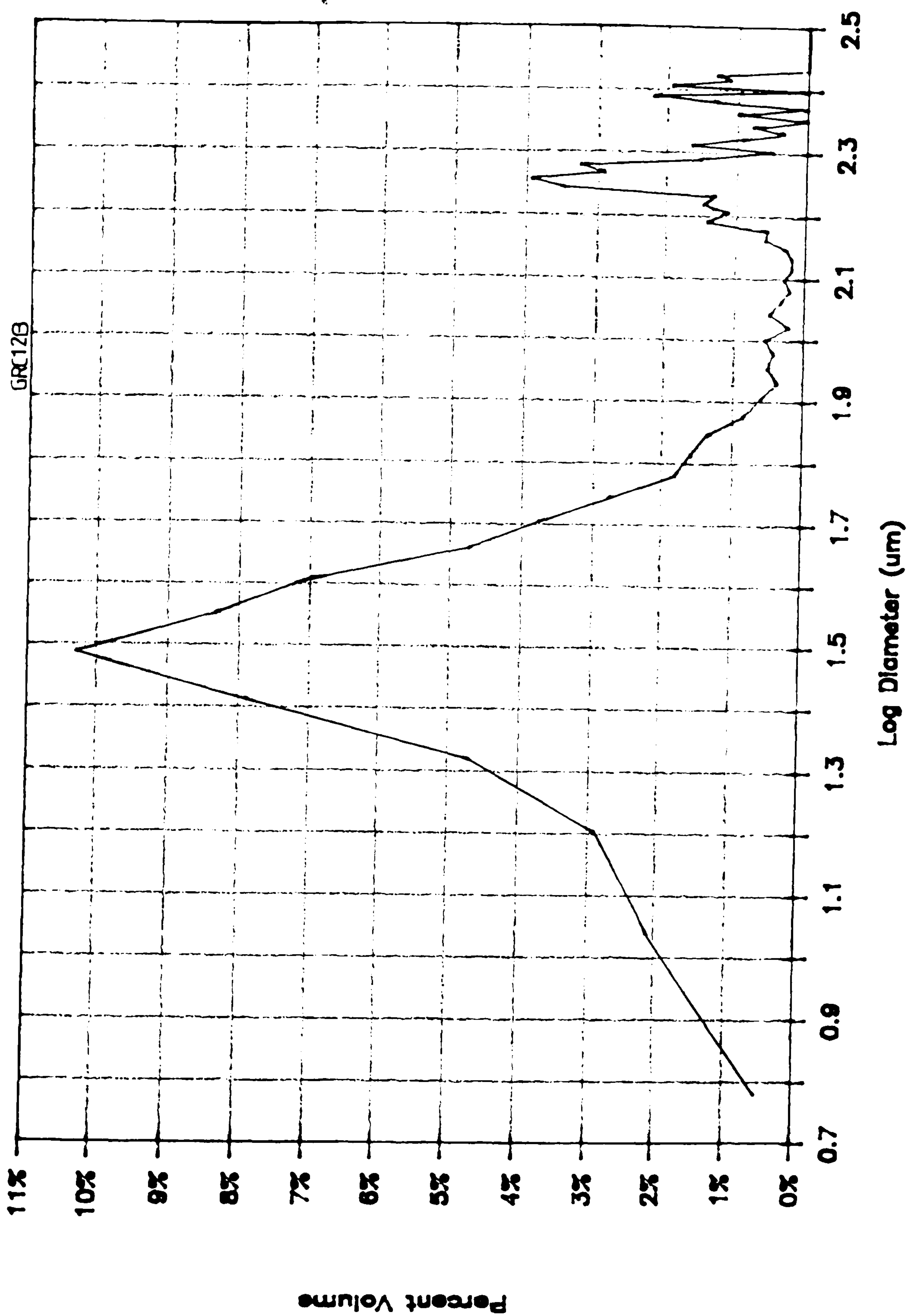


Graph 8.10

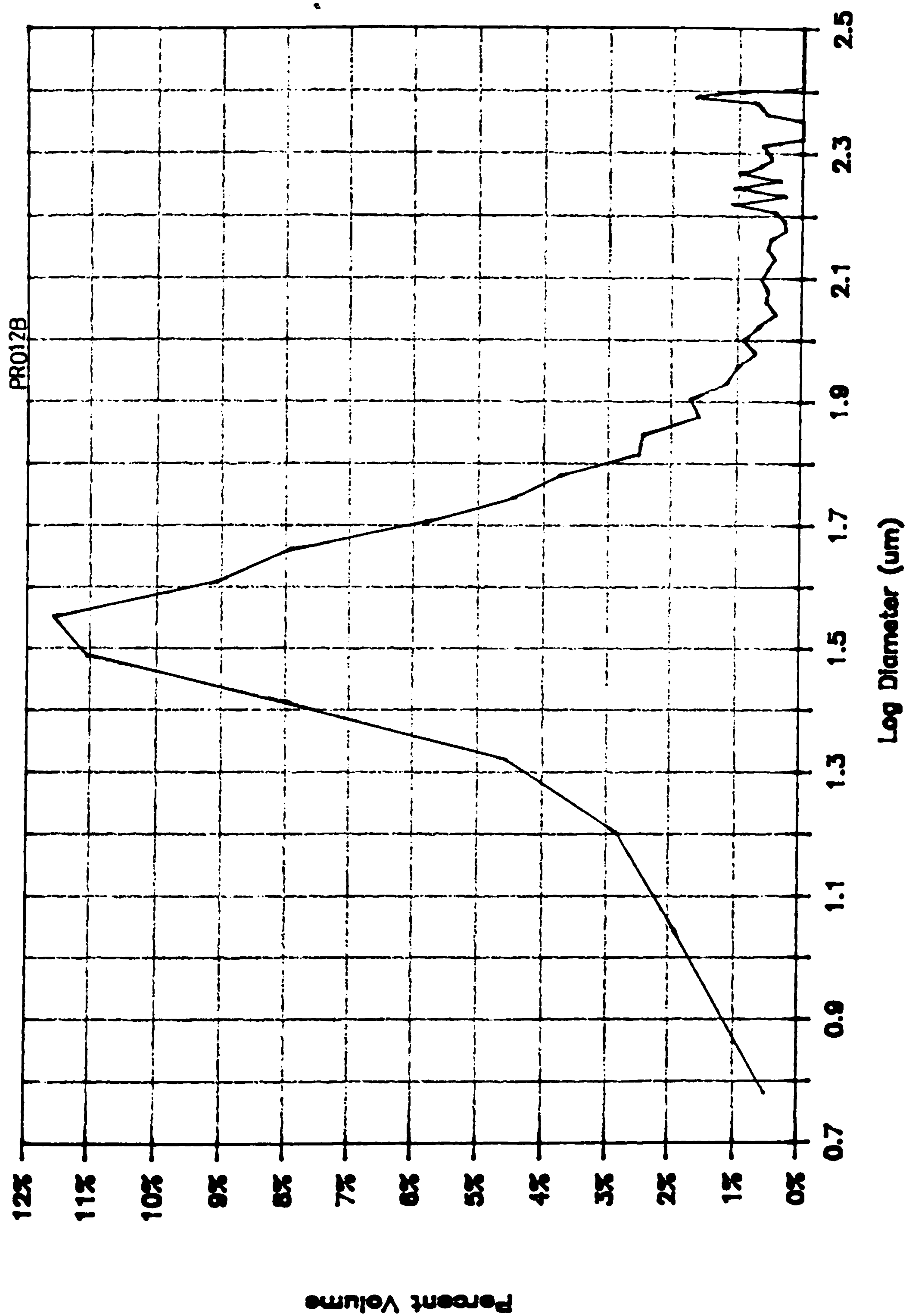
Effect of flowrate on volume median diameter
for prototype Pro-2 spraying JF9436



Graph 8.11

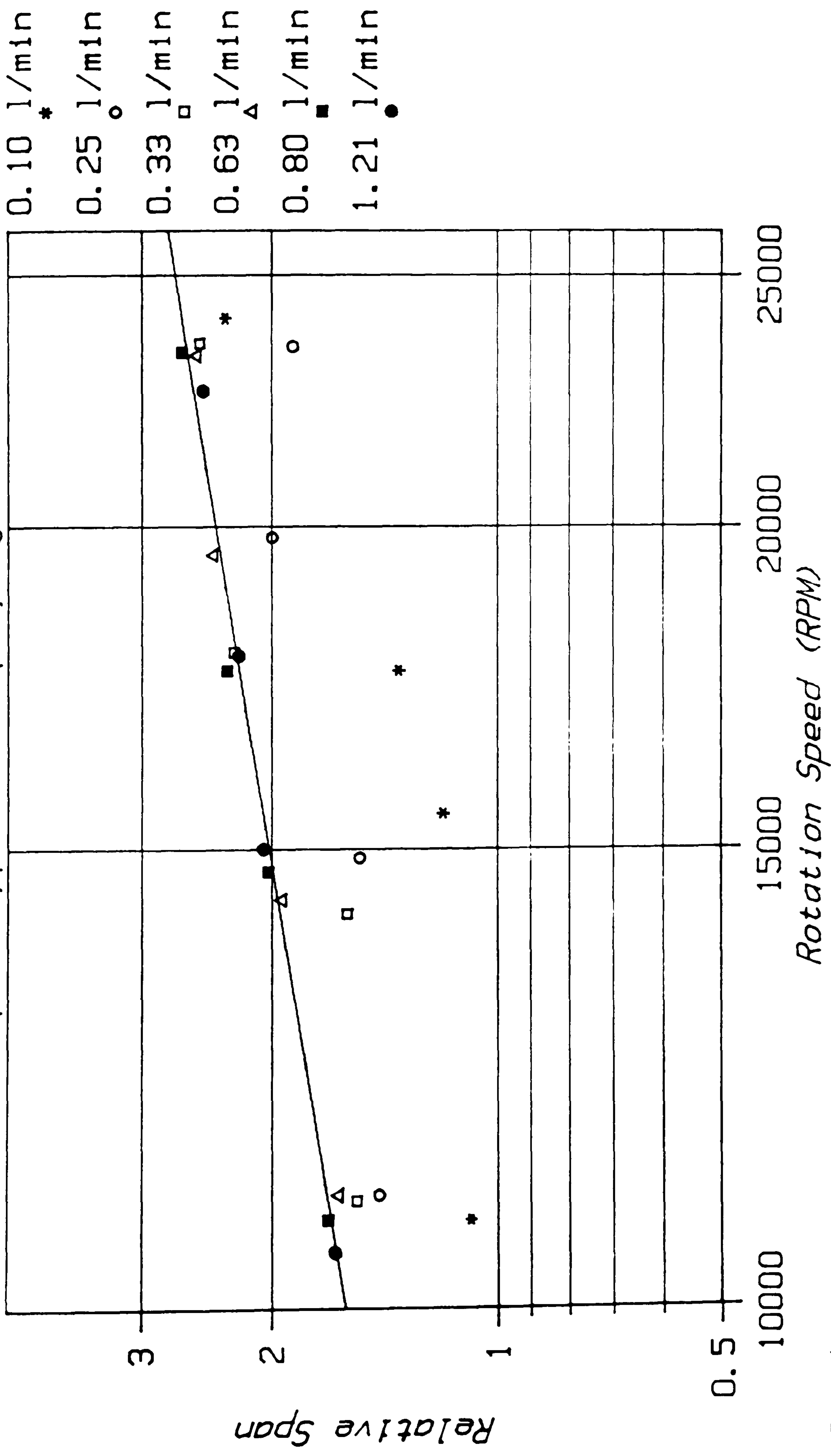


Graph 8.12 Droplet spectrum (volume distribution)
 produced by prototype Pro-1 at 23520 rpm
 with a feed rate of 360 ml/min



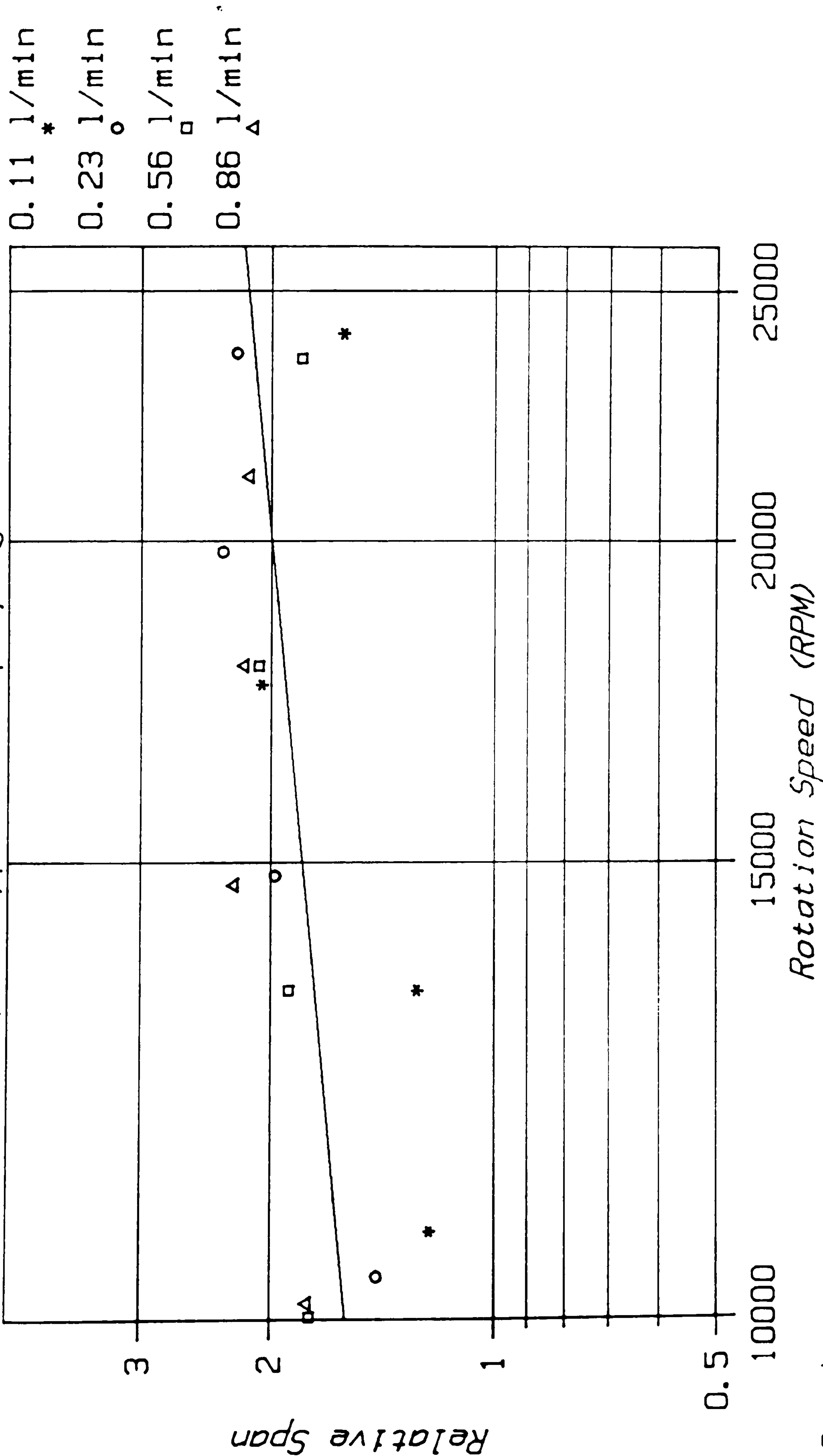
Graph 8.13 Droplet spectrum (volume distribution)
 produced by prototype Pro-2 at 24780 rpm
 with a feed rate of 350 ml/min

Effect of rotation speed on relative span
for prototype Pro-2 spraying Thiodan

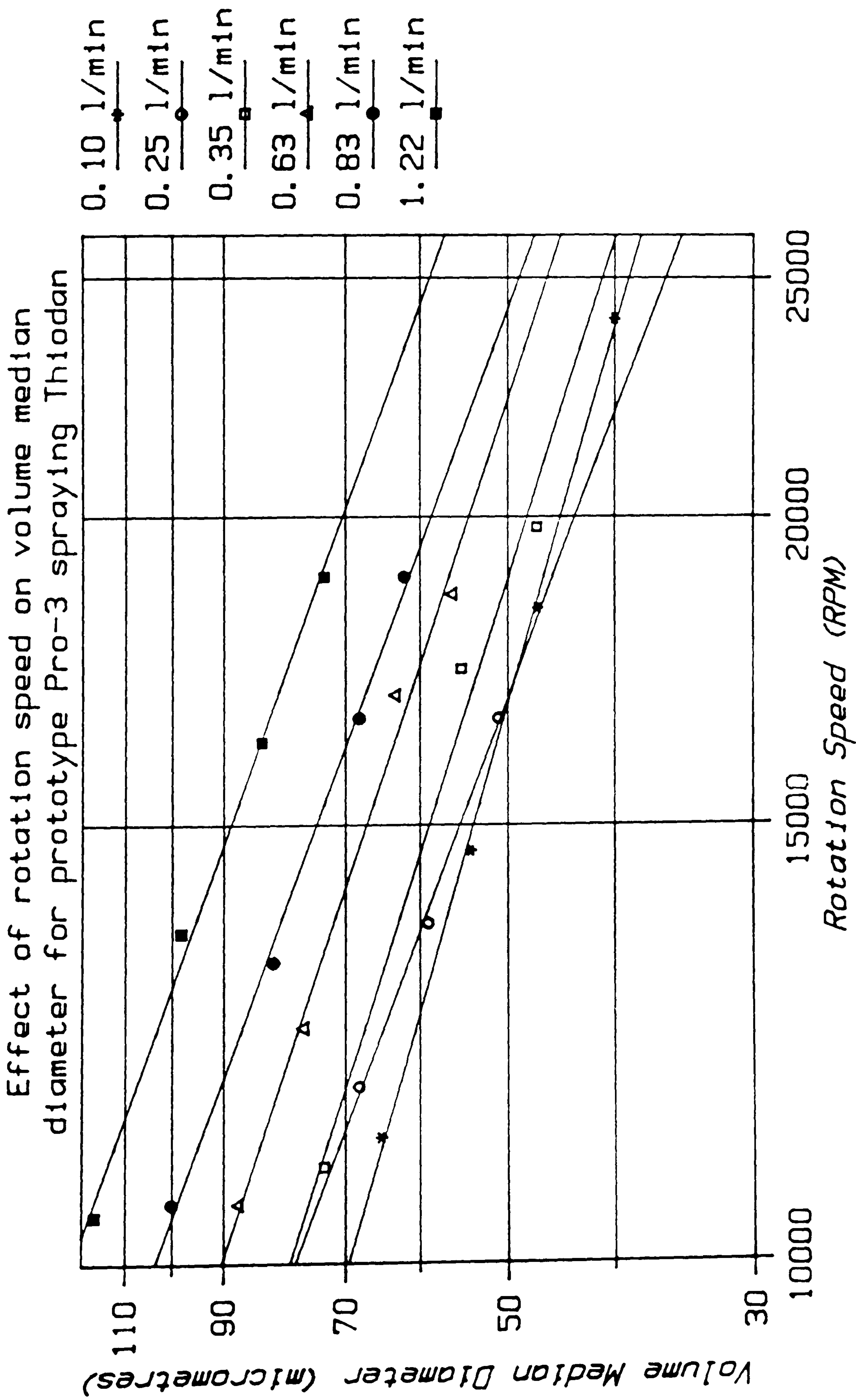


Graph 8.14

Effect of rotation speed on relative span
for prototype Pro-2 spraying JF9436

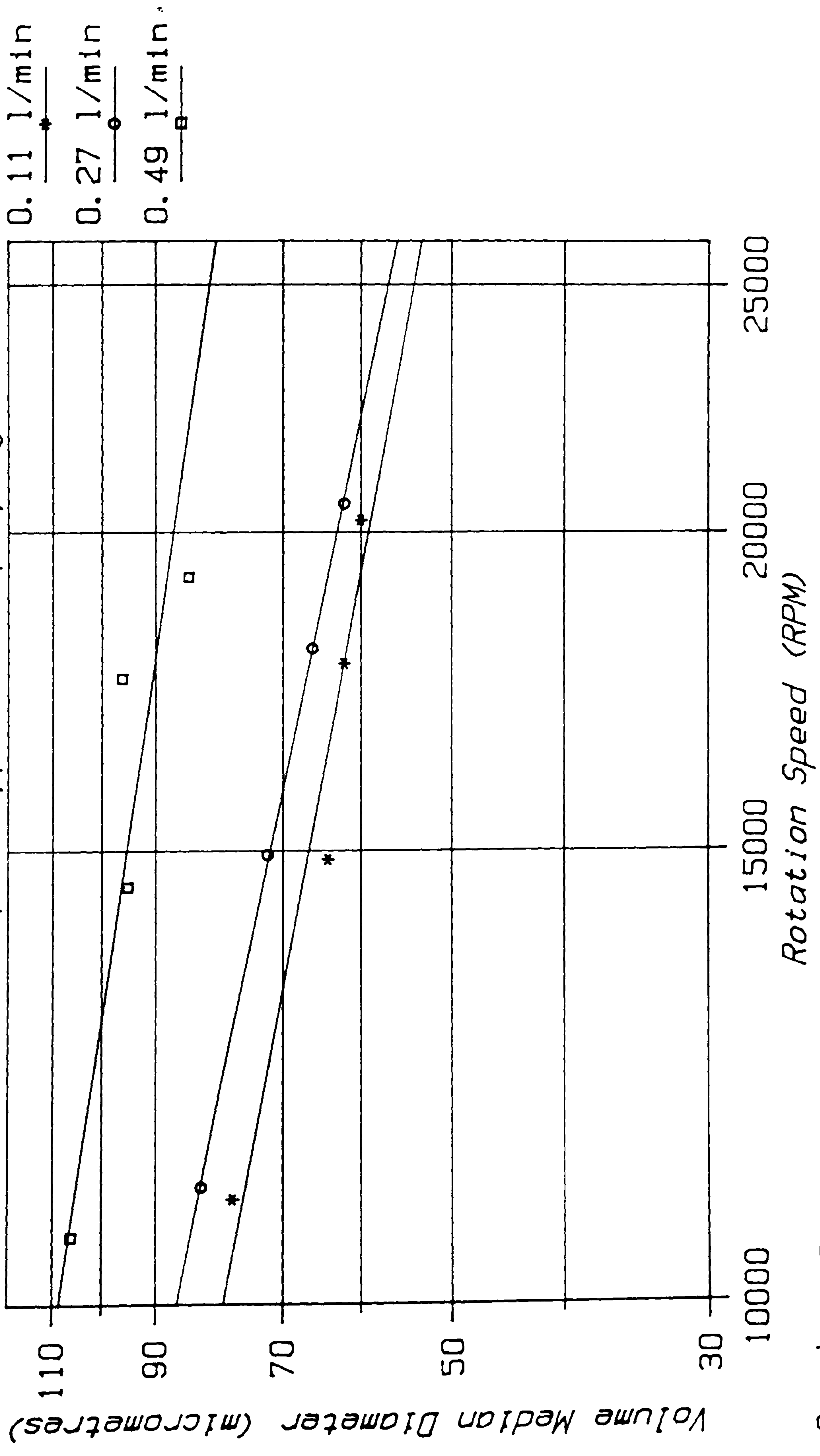


Graph 8.15



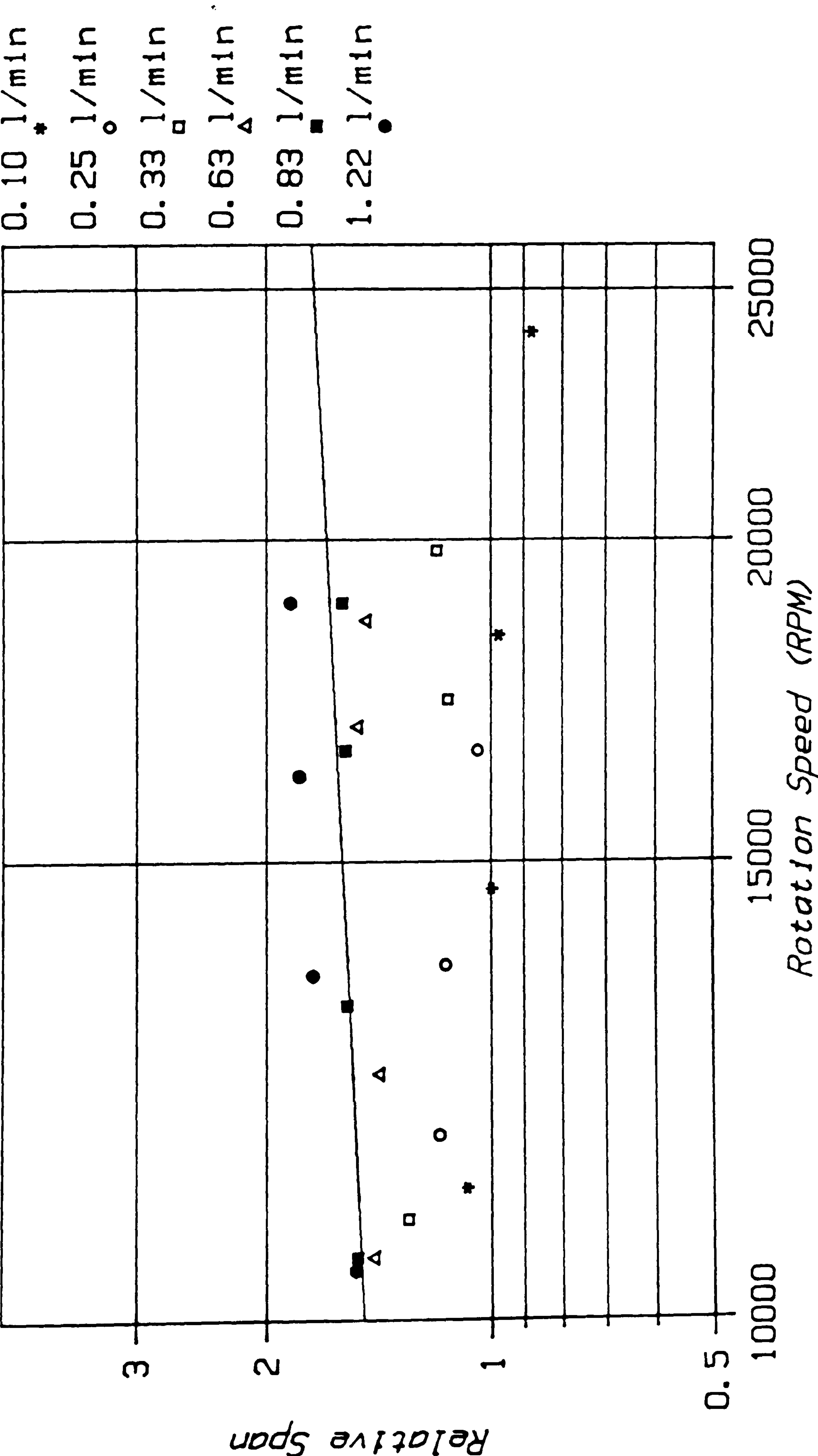
Graph 8.16

Effect of rotation speed on volume median diameter for prototype Pro-3 spraying JF9436



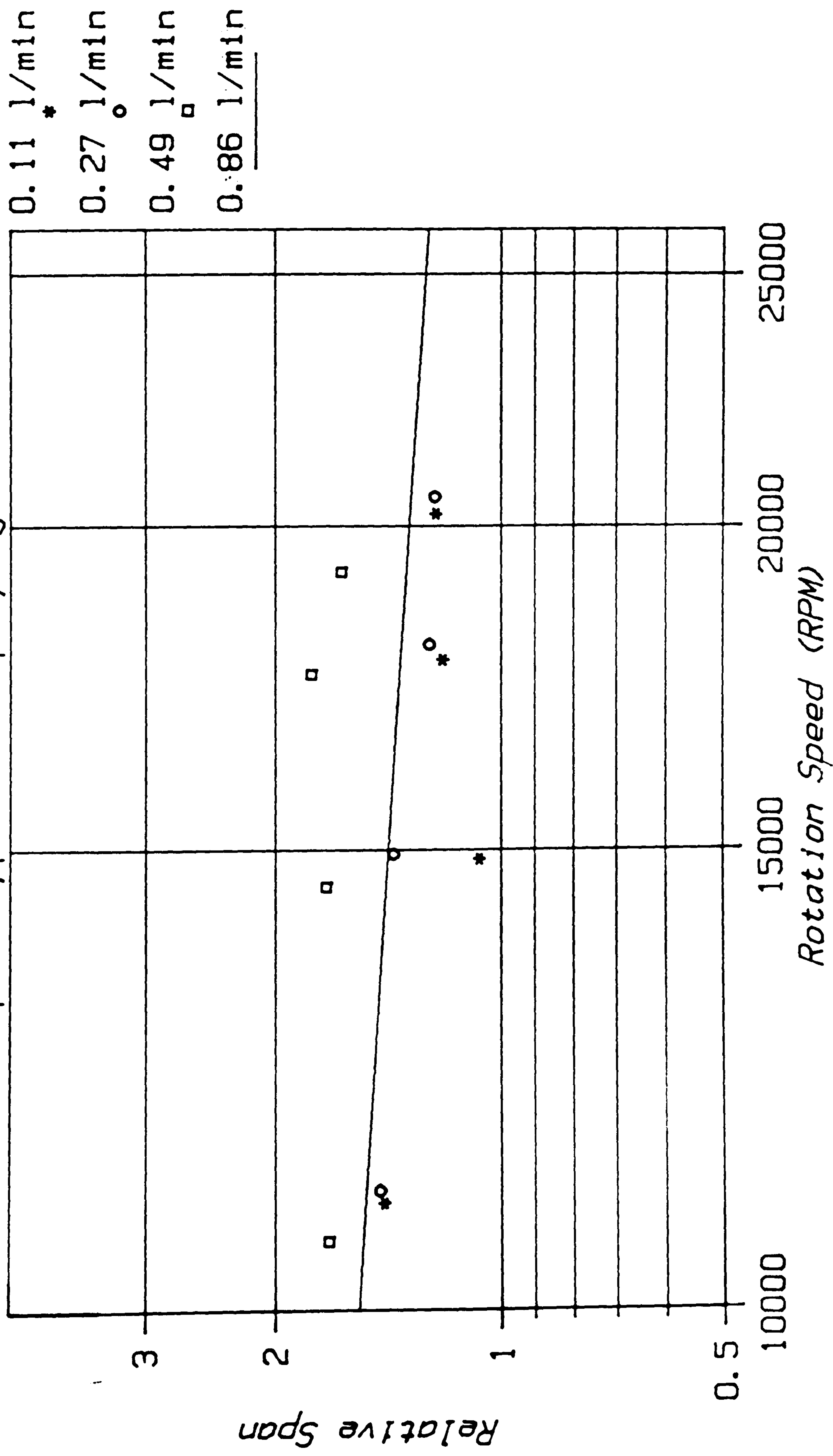
Graph 8.17

Effect of rotation speed on relative span
for prototype Pro-3 spraying Thiodan

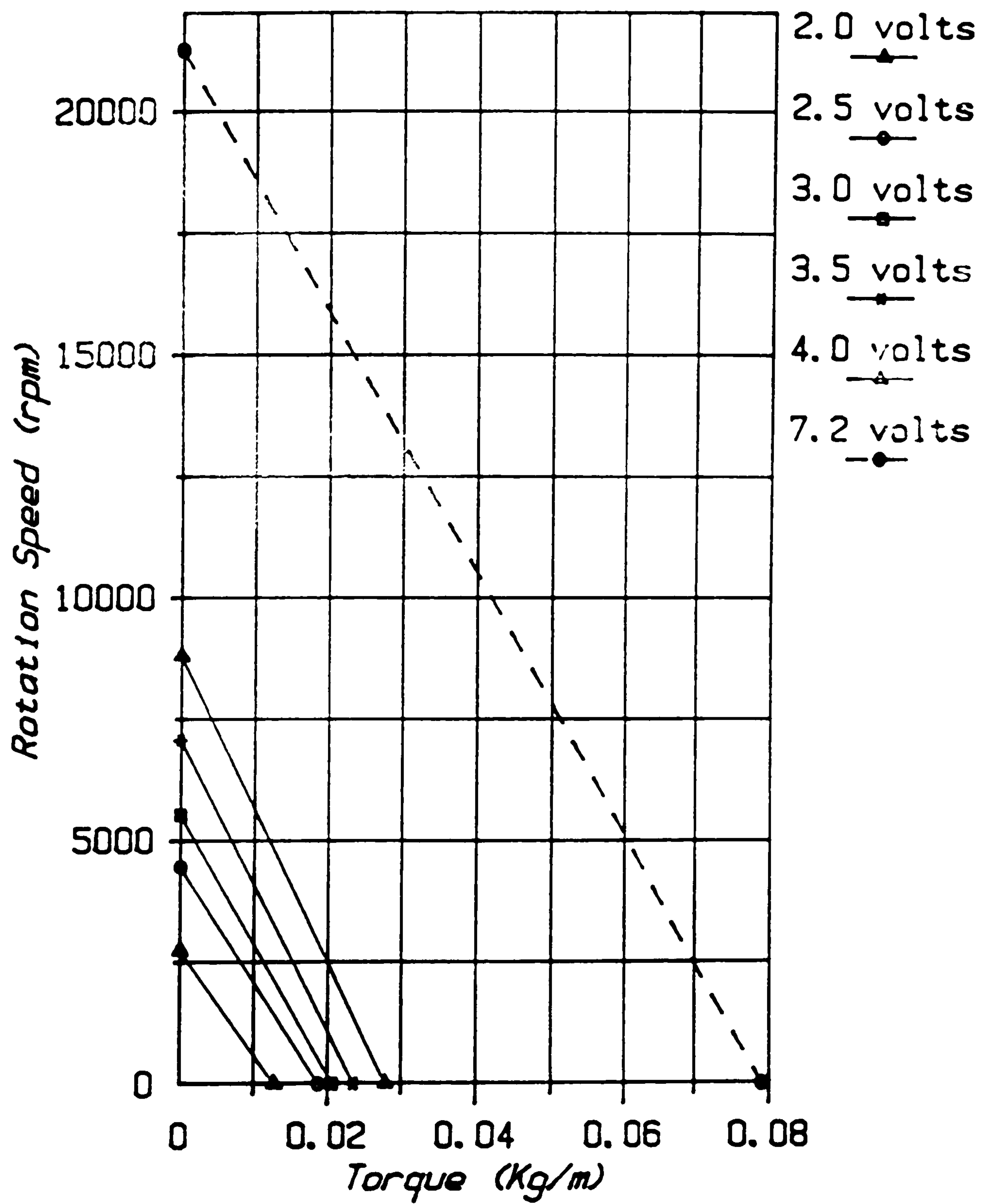


Graph 8.18

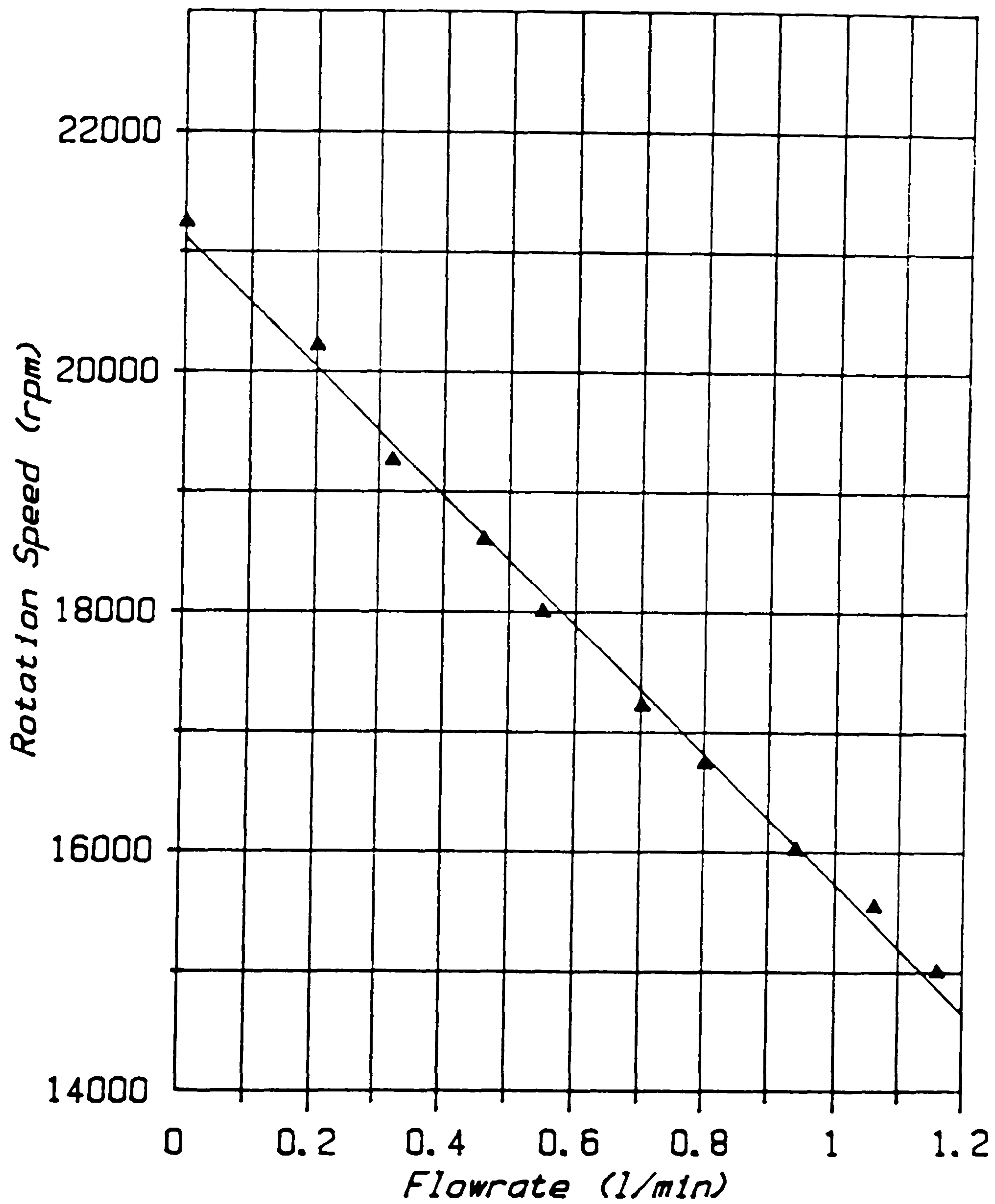
Effect of rotation speed on relative span
for prototype Pro-3 spraying JF9436



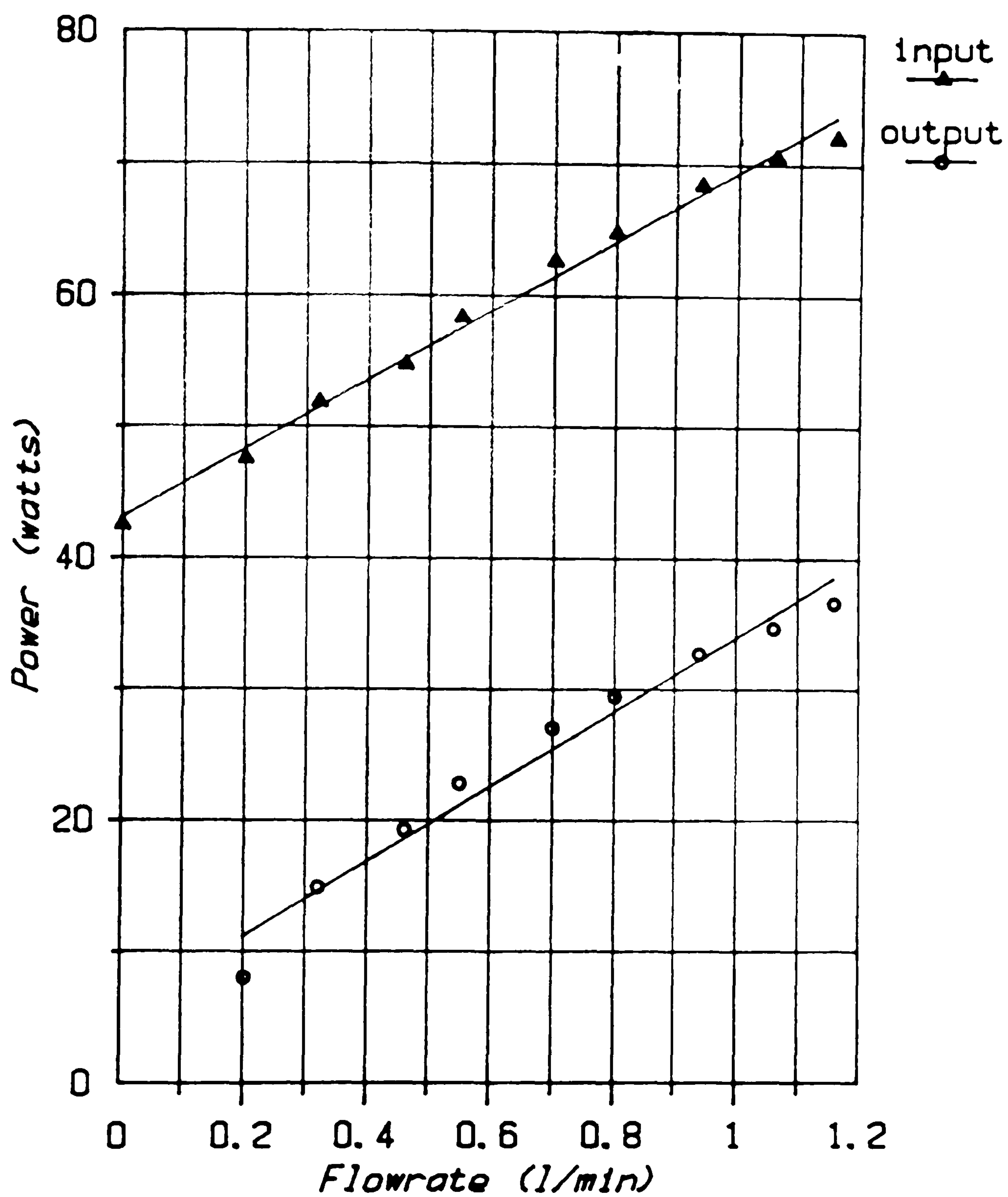
Graph 8.19



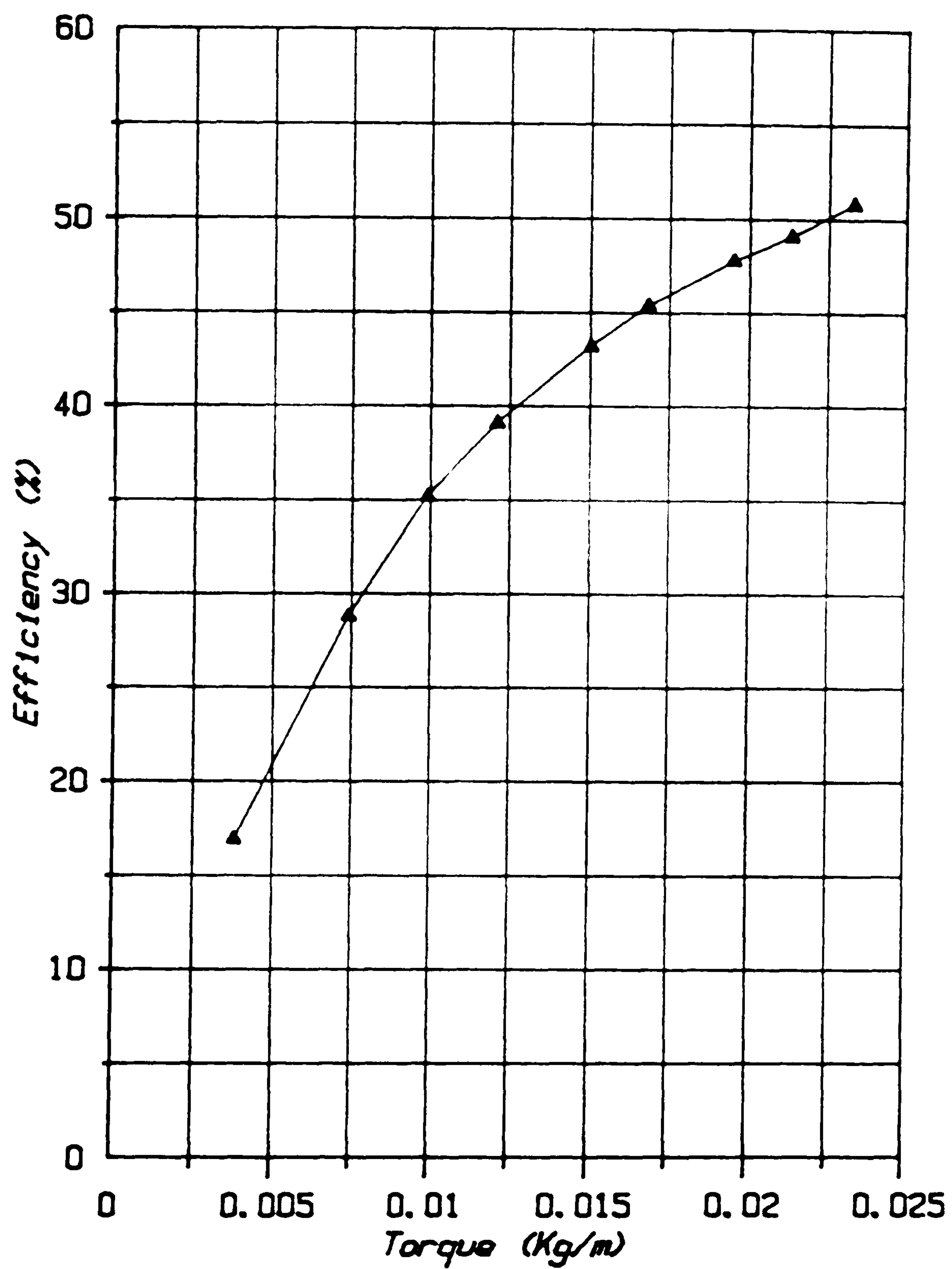
Graph 8.20 Torque-rpm curves for the electric motor used in prototype Pro-4 (7.2 volts by extrapolation)



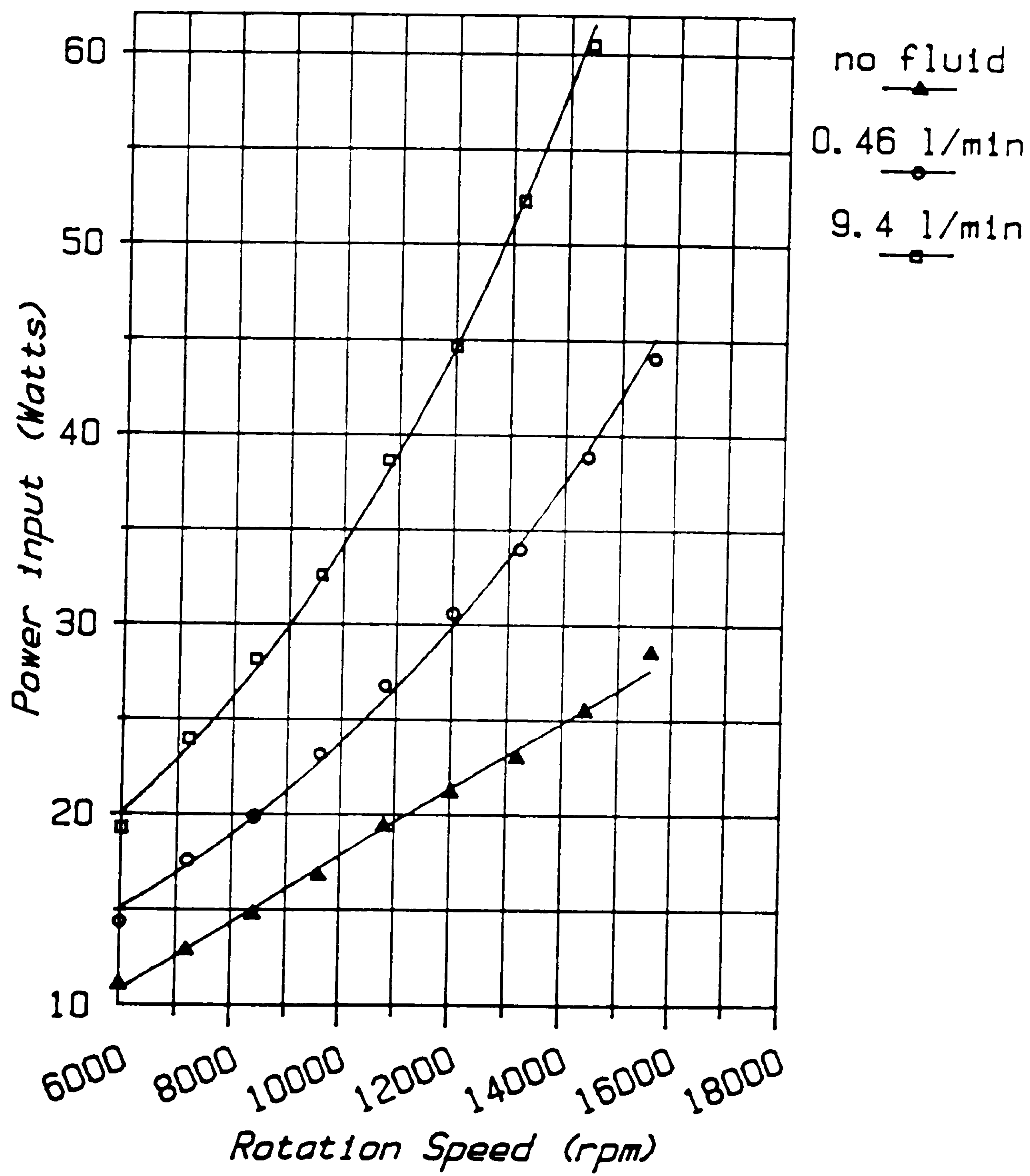
Graph 8.21 Variation of rotation speed with flowrate for prototype Pro-4 running at 7.2 Volts



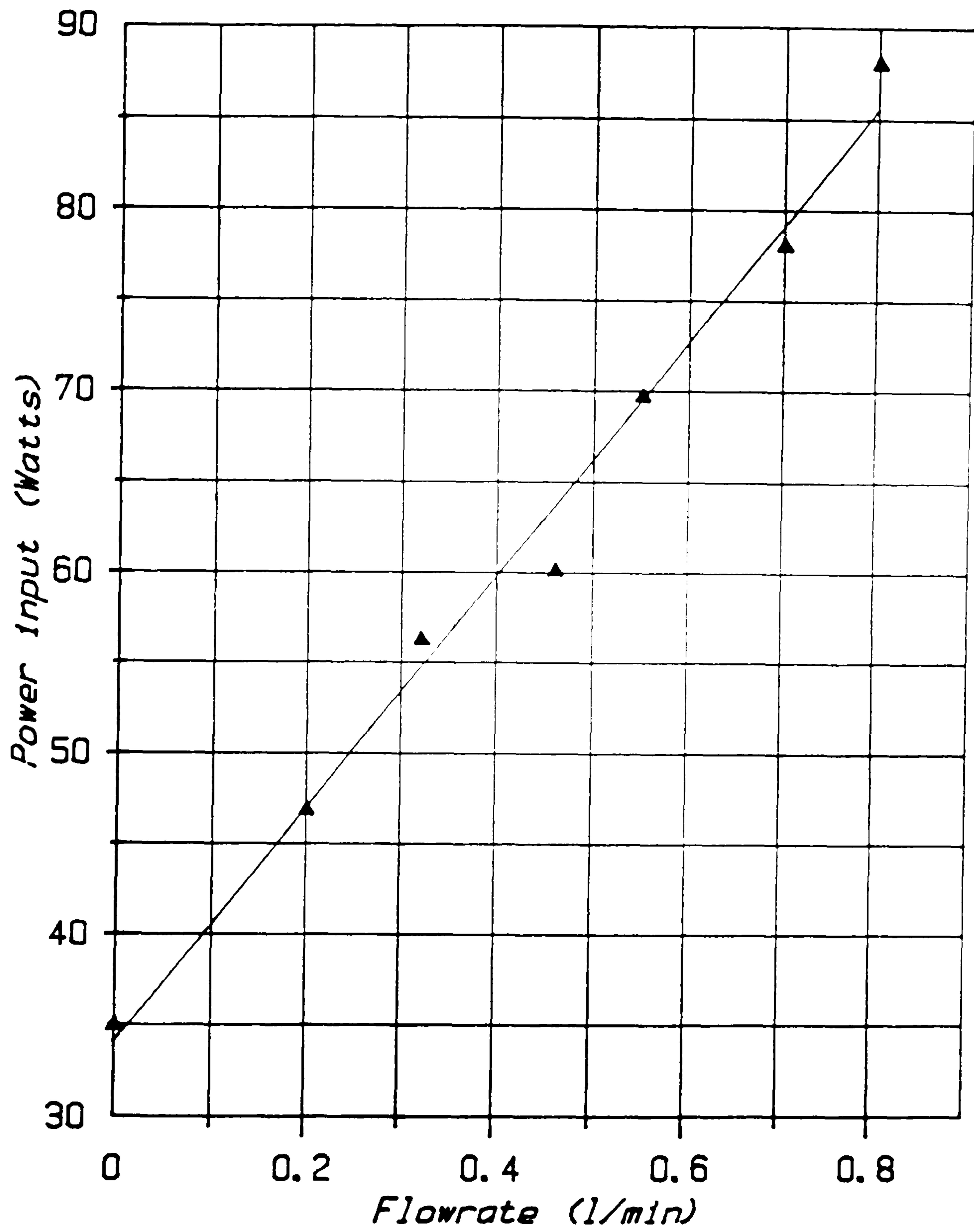
Graph 8.22 Input power and output power
for the electric motor used in
prototype Pro-4



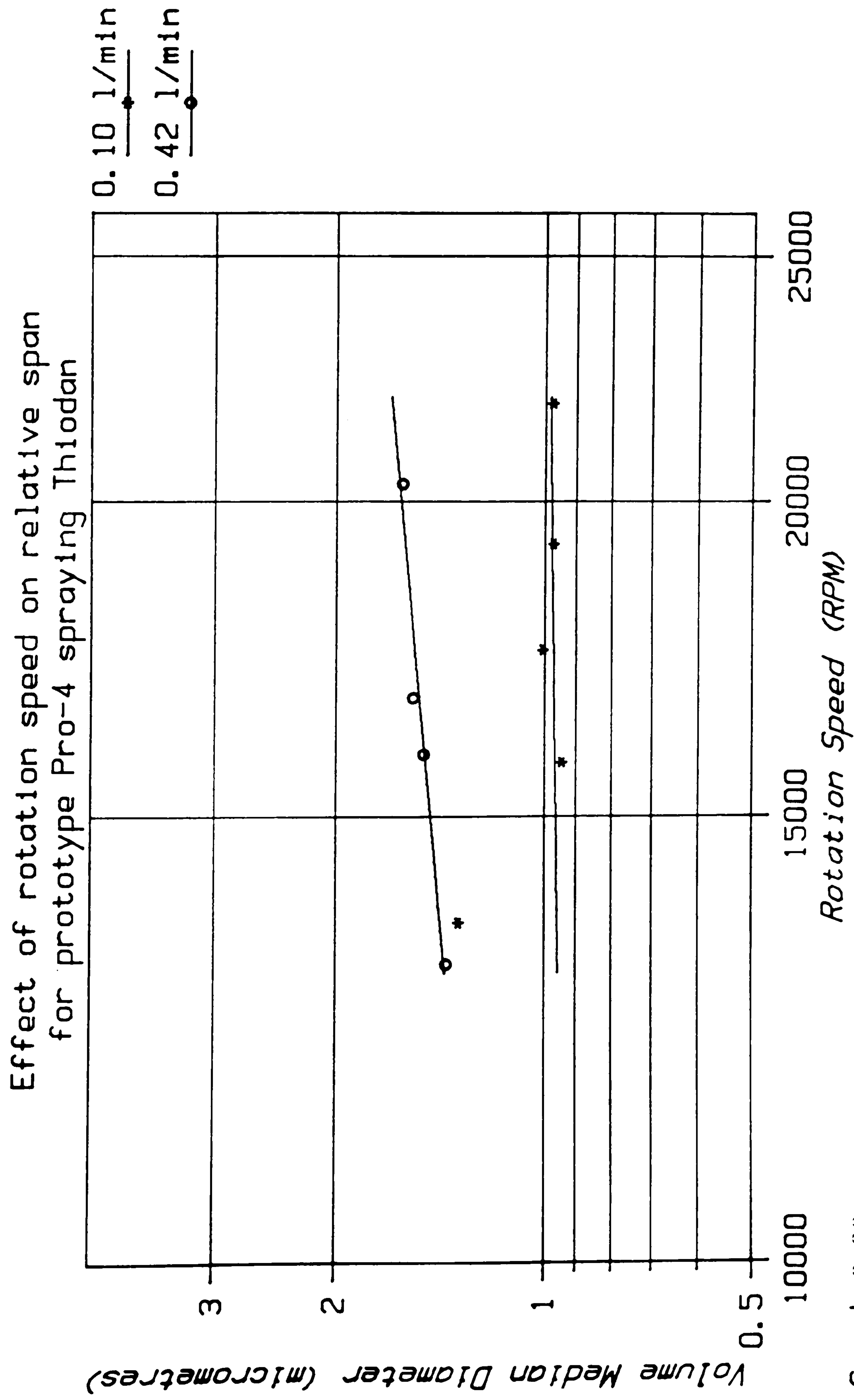
Graph 8.23 Variation of efficiency with torque
for the electric motor used in
prototype Pro-4



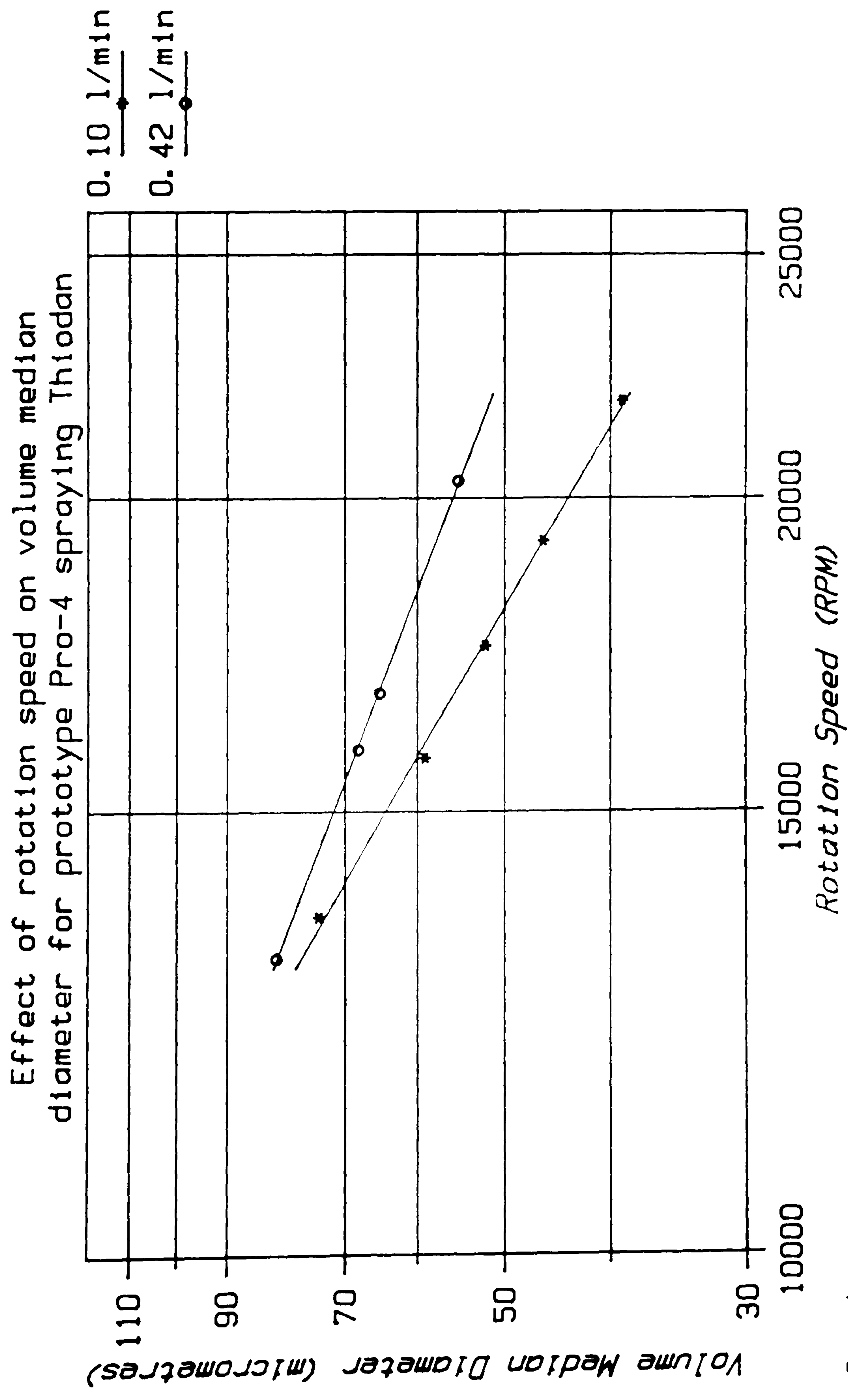
Graph 8.24 Variation in power consumption with rotation speed for prototype Pro-4 at different flowrates



Graph 8.25 Variation in power consumption with flowrate for prototype Pro-4 running at 20000 rpm



Graph 8.26



Graph 8.27

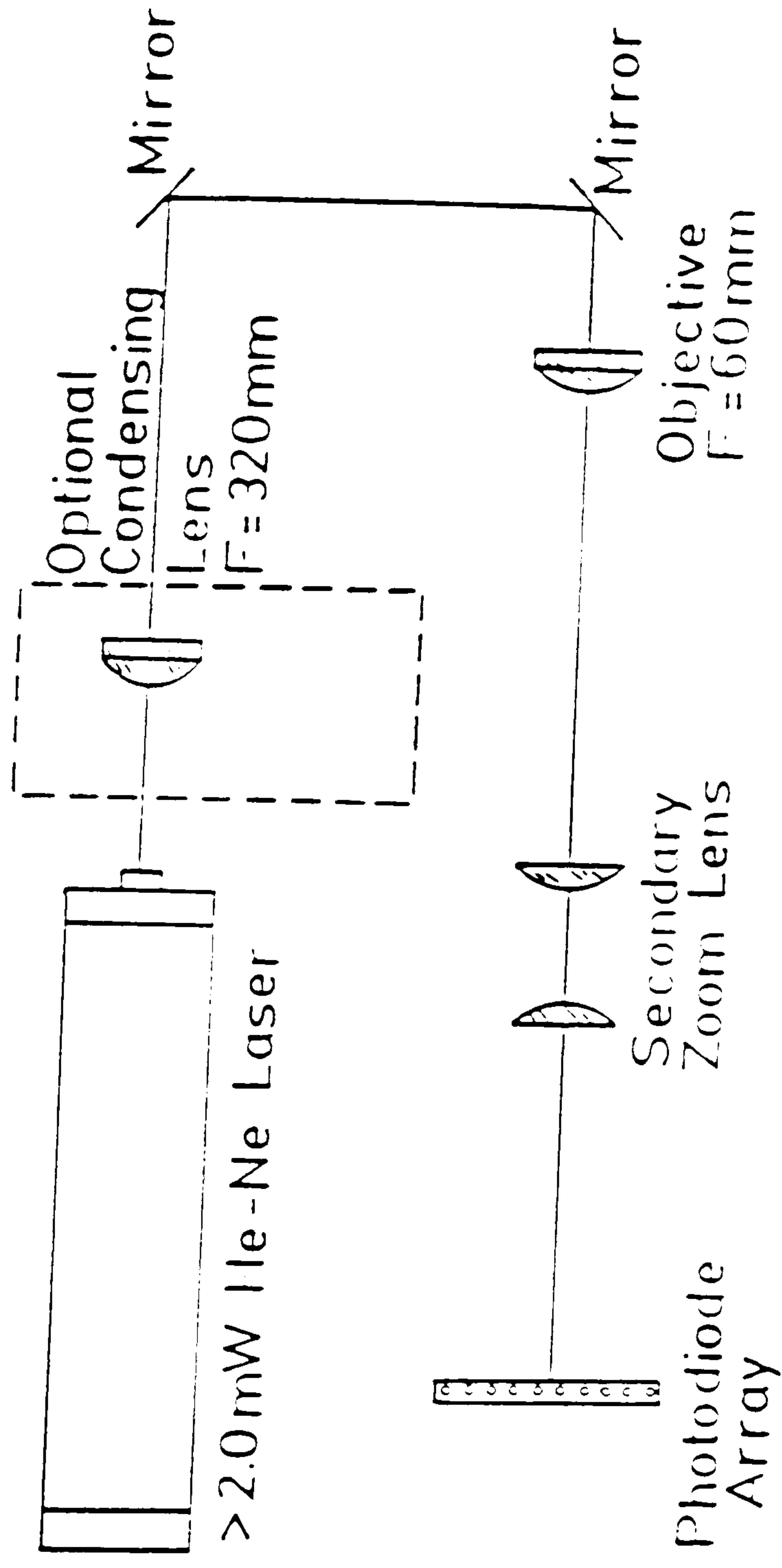


Figure 2.1 Schematic diagram of the optical system of the

PMS OAP-260X

(taken from vanVliet and Picot 1988)

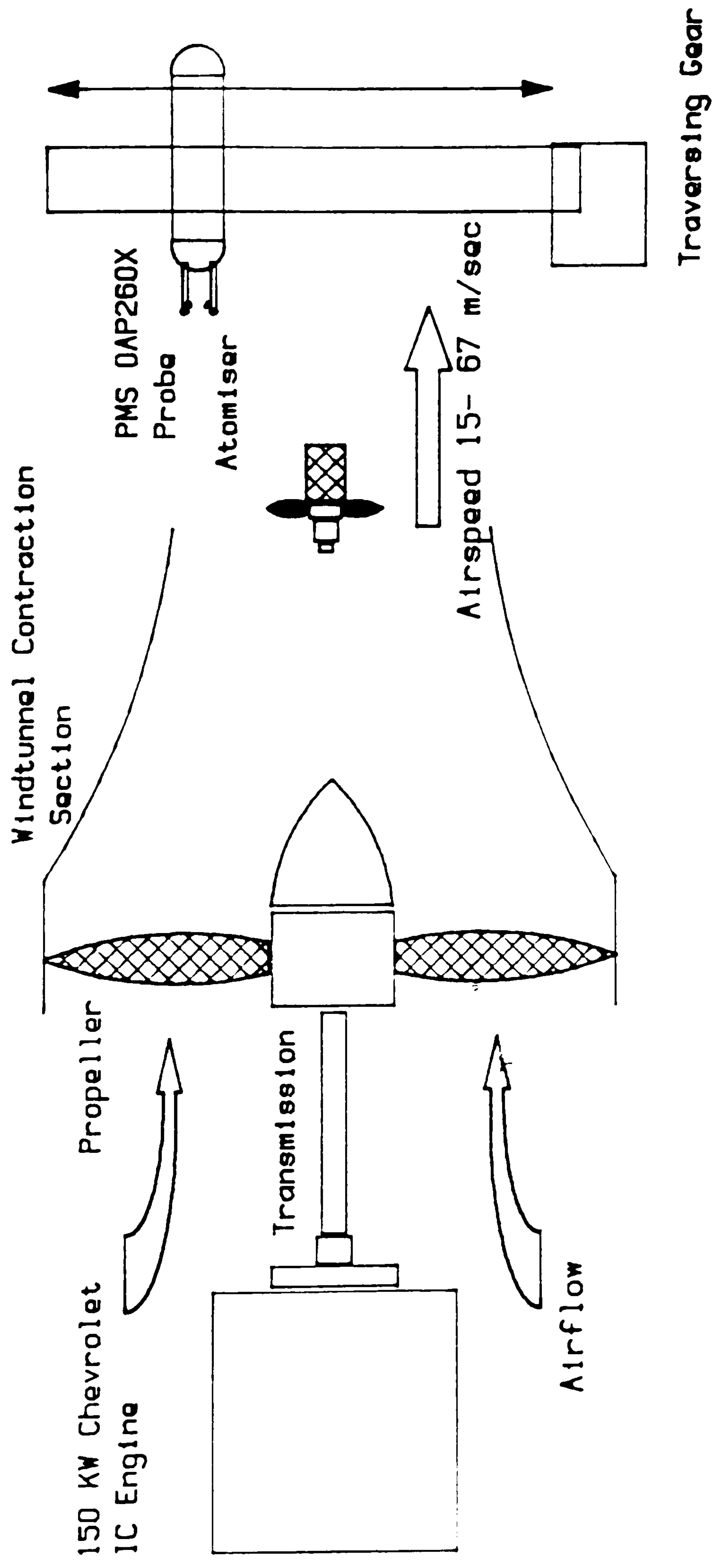


Figure 4.1 schematic plan view of the Cranfield aerial atomiser test facility

(from an original drawing by J. Wyatt)

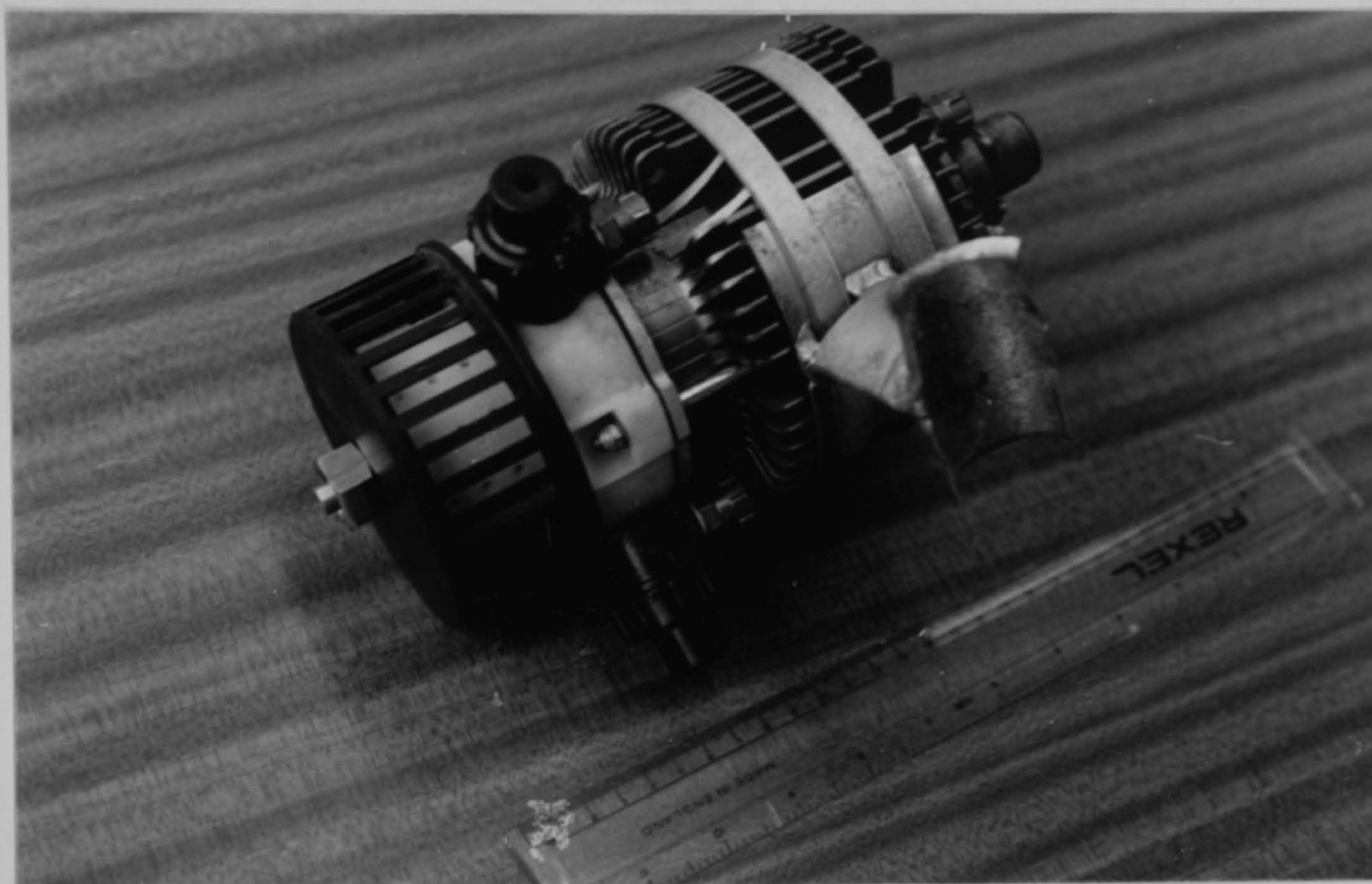


Figure 4.2 The Unirot-4 atomiser

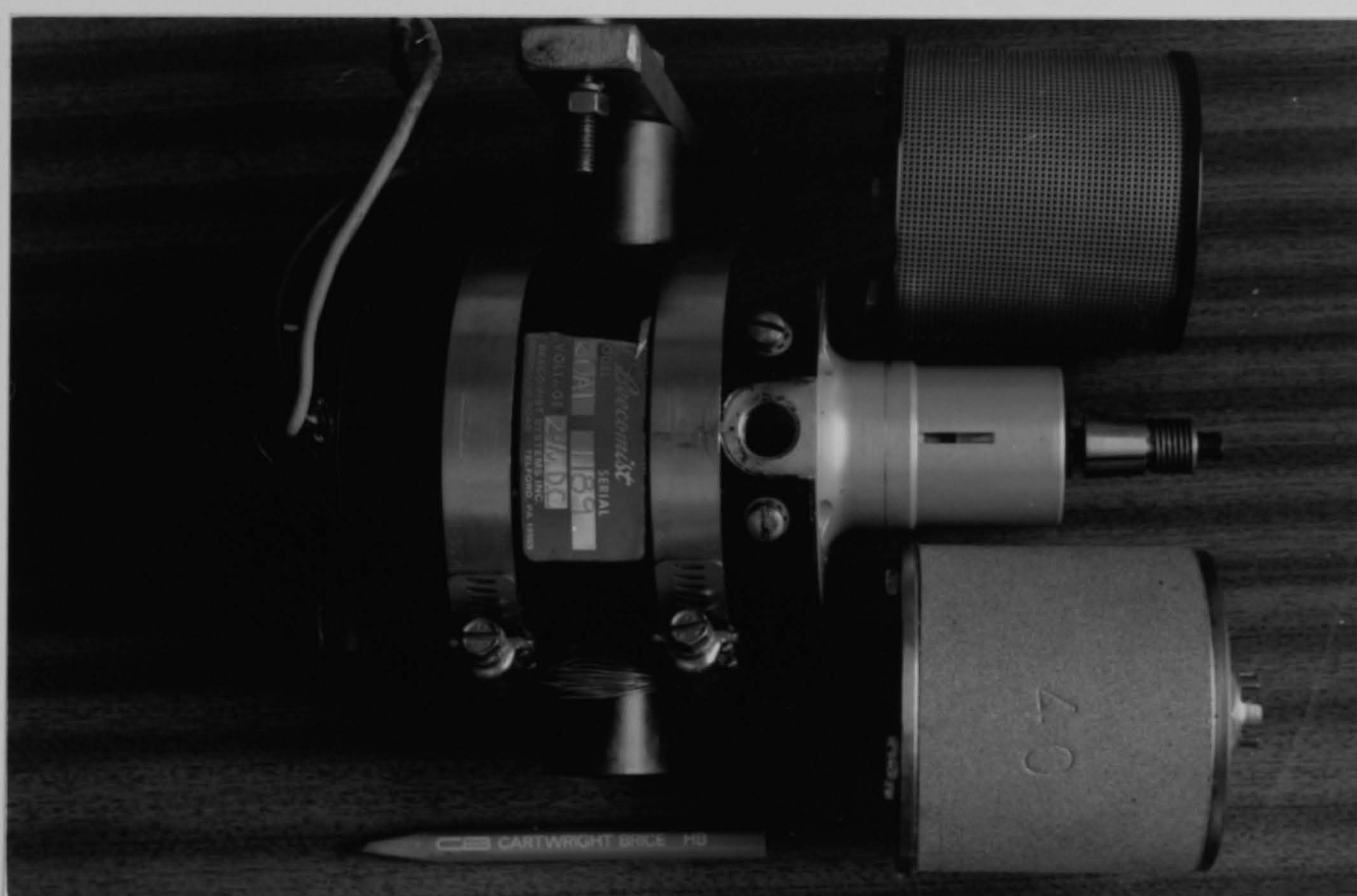


Figure 4.3 The Beecomist 360A atomiser showing feed slot and the two available heads

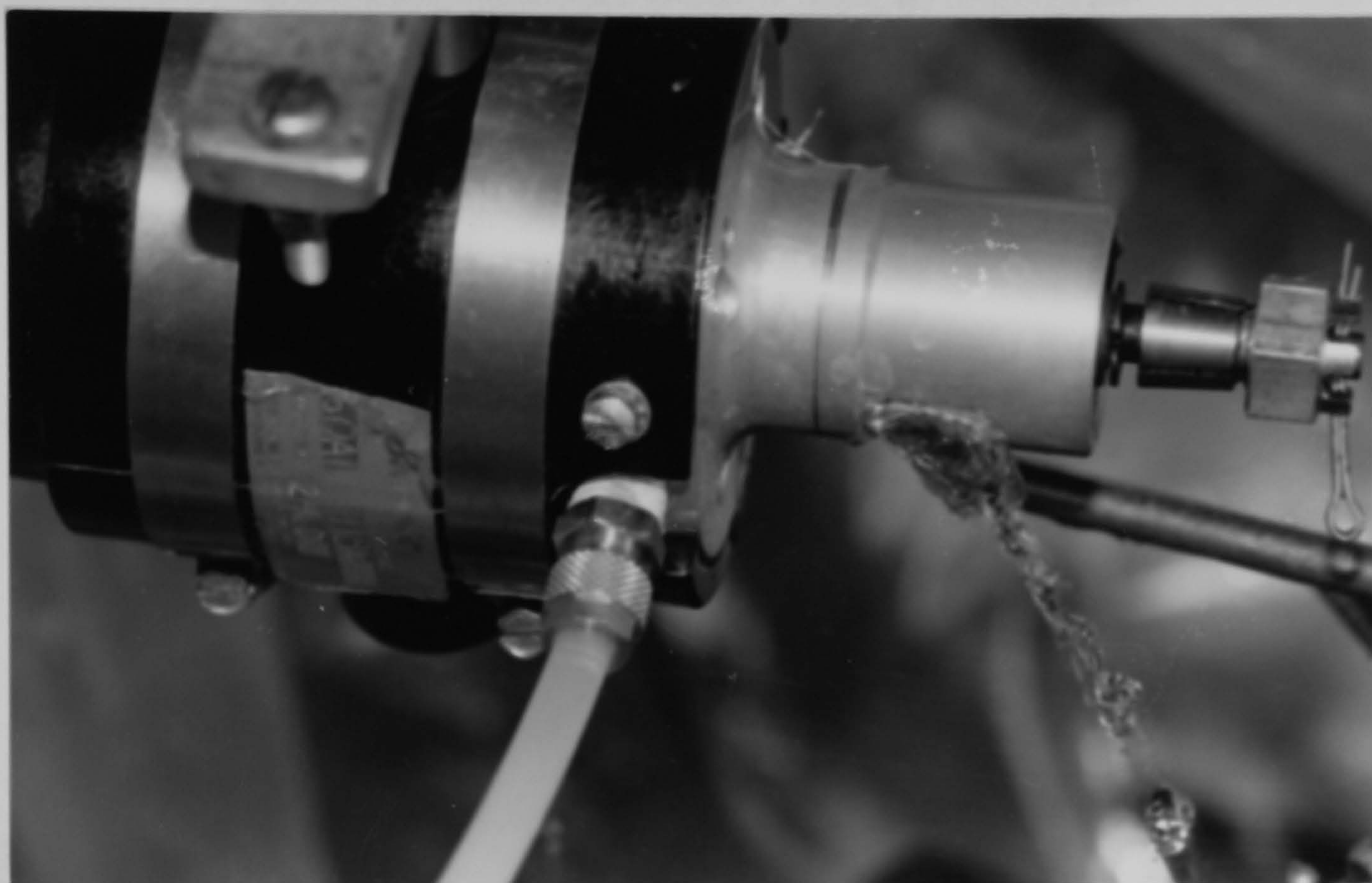


Figure 4.4a The feed system of the Beecomist 360A emitting water at low flowrate



Figure 4.4b The feed system of the Beecomist 360A atomiser emitting water at higher flowrate



Figure 4.5a The feed system of the Micron X-15 emitting
Glossinex at 0.2 litres/minute

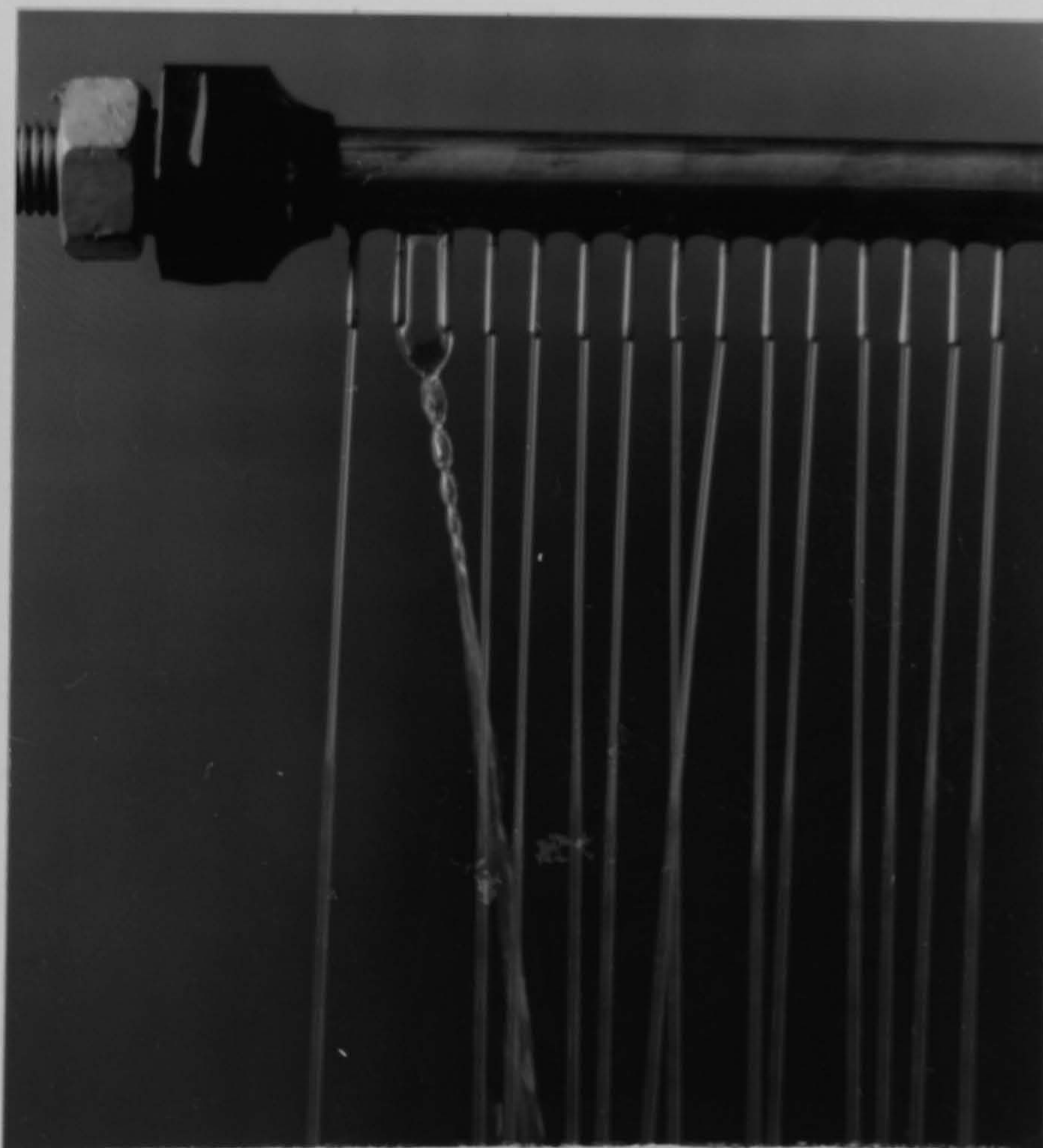


Figure 4.5b The modified Micron X-15 feed system emitting
Glossinex at 0.2 litres/minute



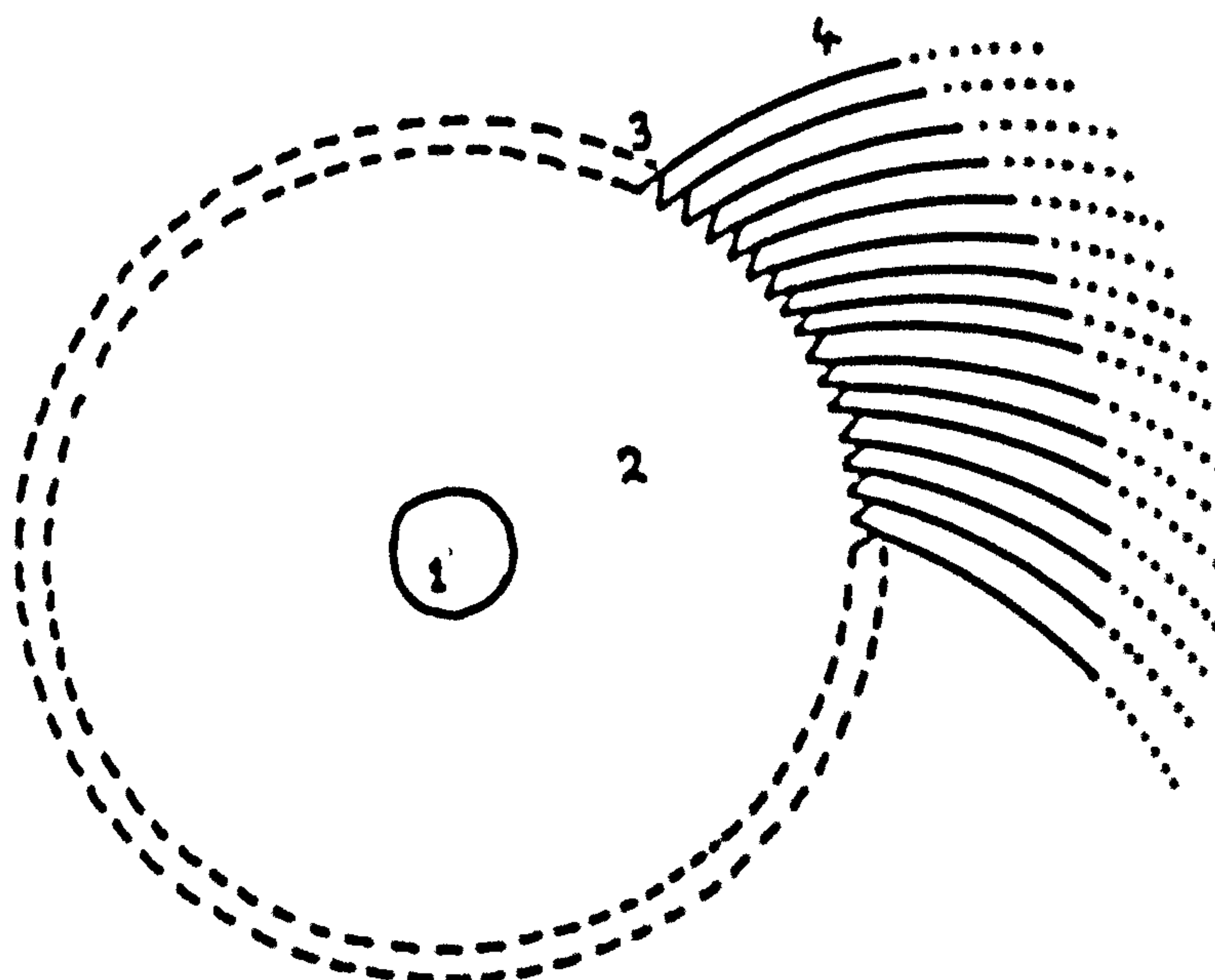
Figure 4.6 The Micronair AU4000 atomiser



Figure 4.7 The Micronair AU5000 atomiser



Figure 4.8 The Micron X-1 atomiser



- 1 Fluid feed
- 2 Fluid transported to atomising surface
- 3 Separation from atomising surface
- 4 Free fluid disintegrates into droplets

Figure 5.1 Stages in atomisation from a rotary atomiser

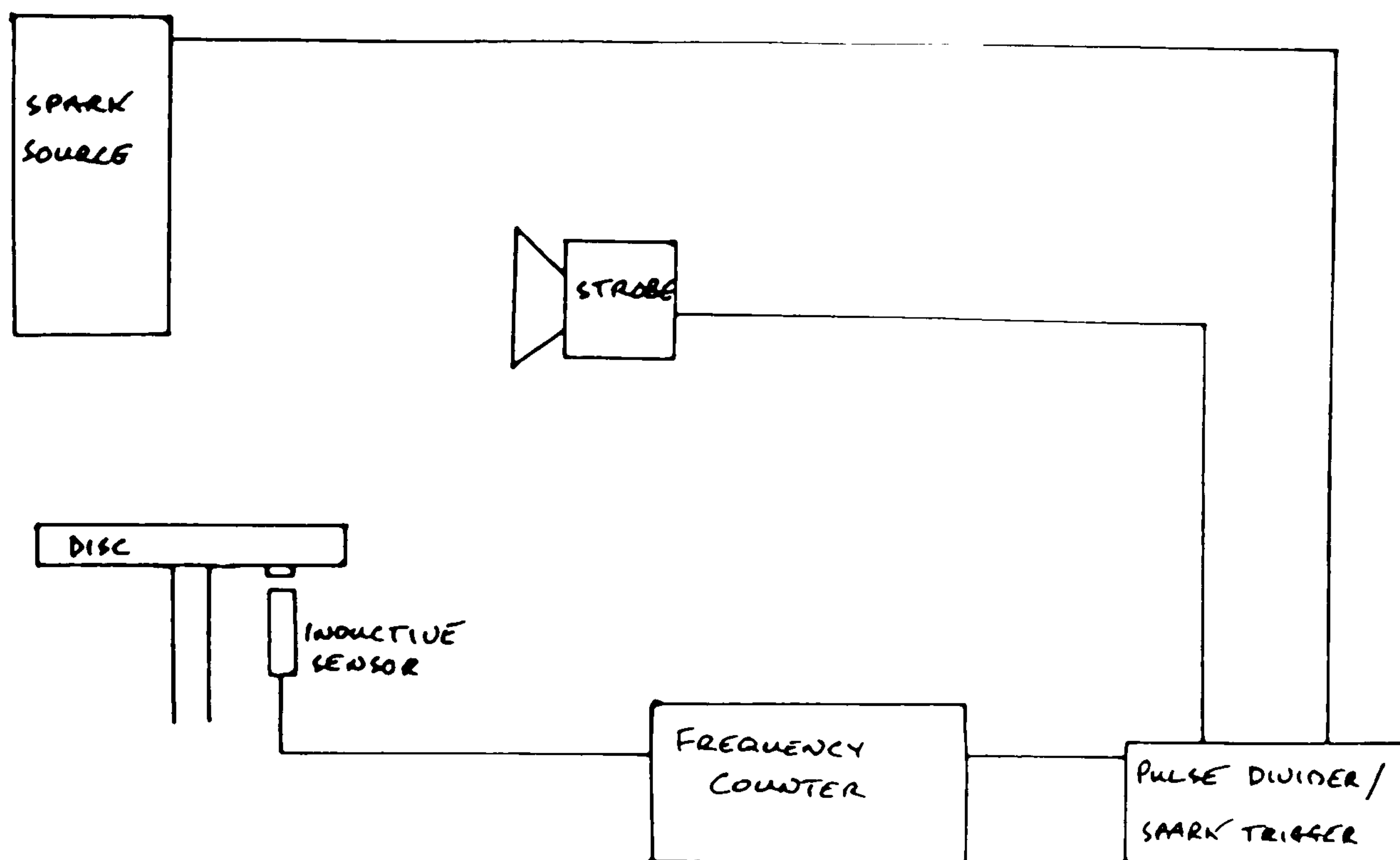


Figure 6.1a Components of the disc observation system

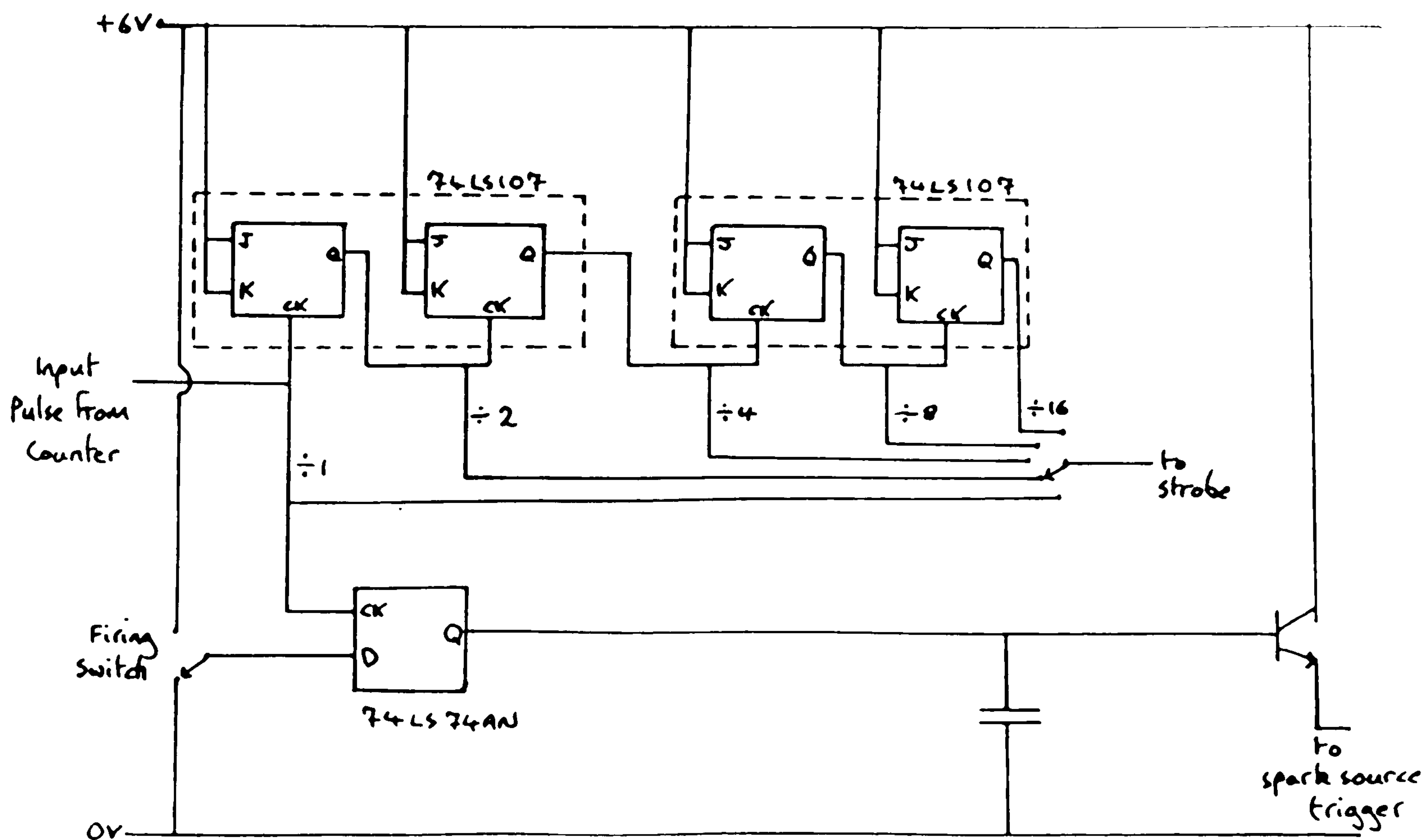


Figure 6.1b Circuit diagram of strobe/spark trigger

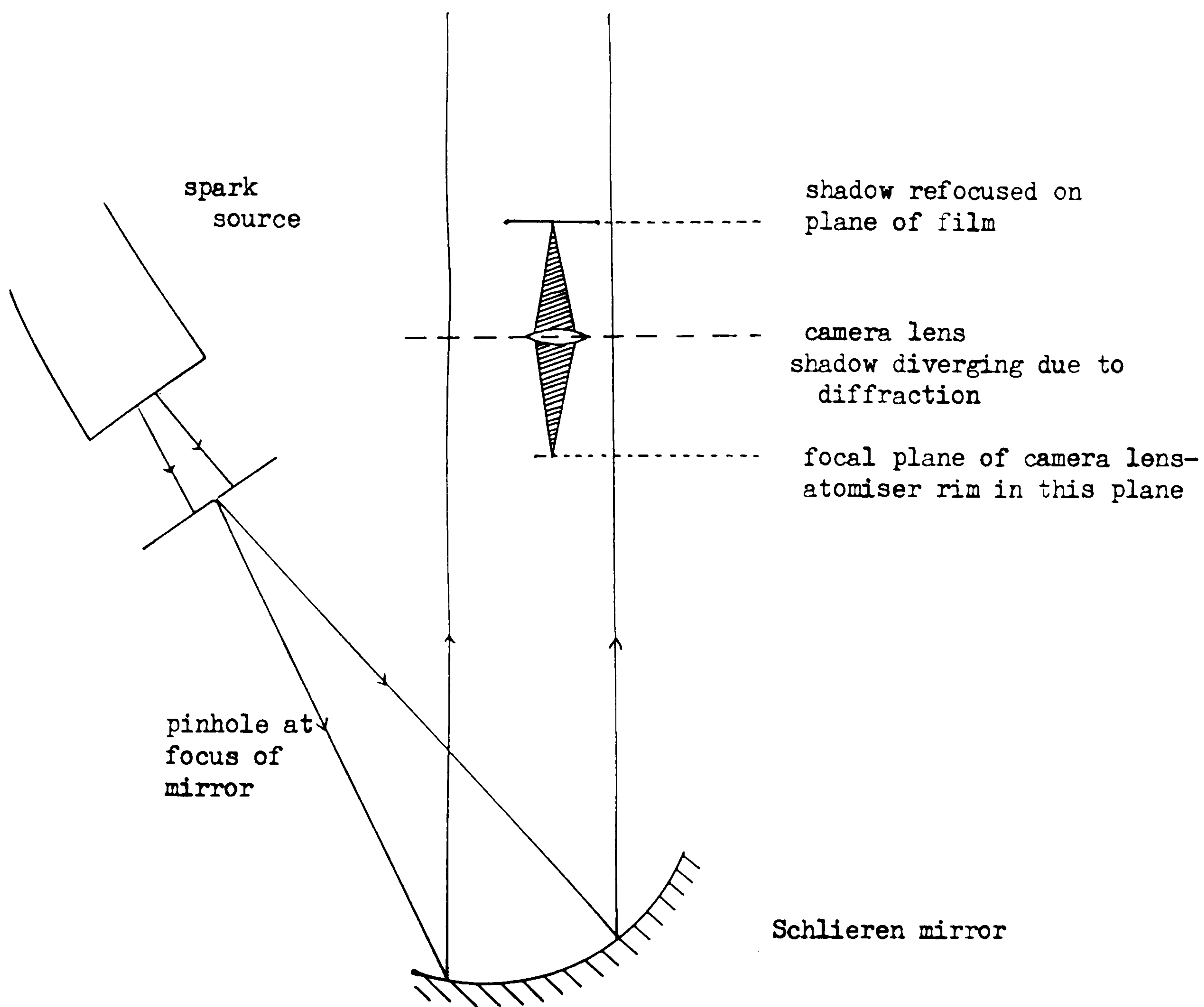


Figure 6.2 The spark photography system



Figure 6.3 Spiral vortices forming in liquid
flowing over a 100mm diameter
rotating disc

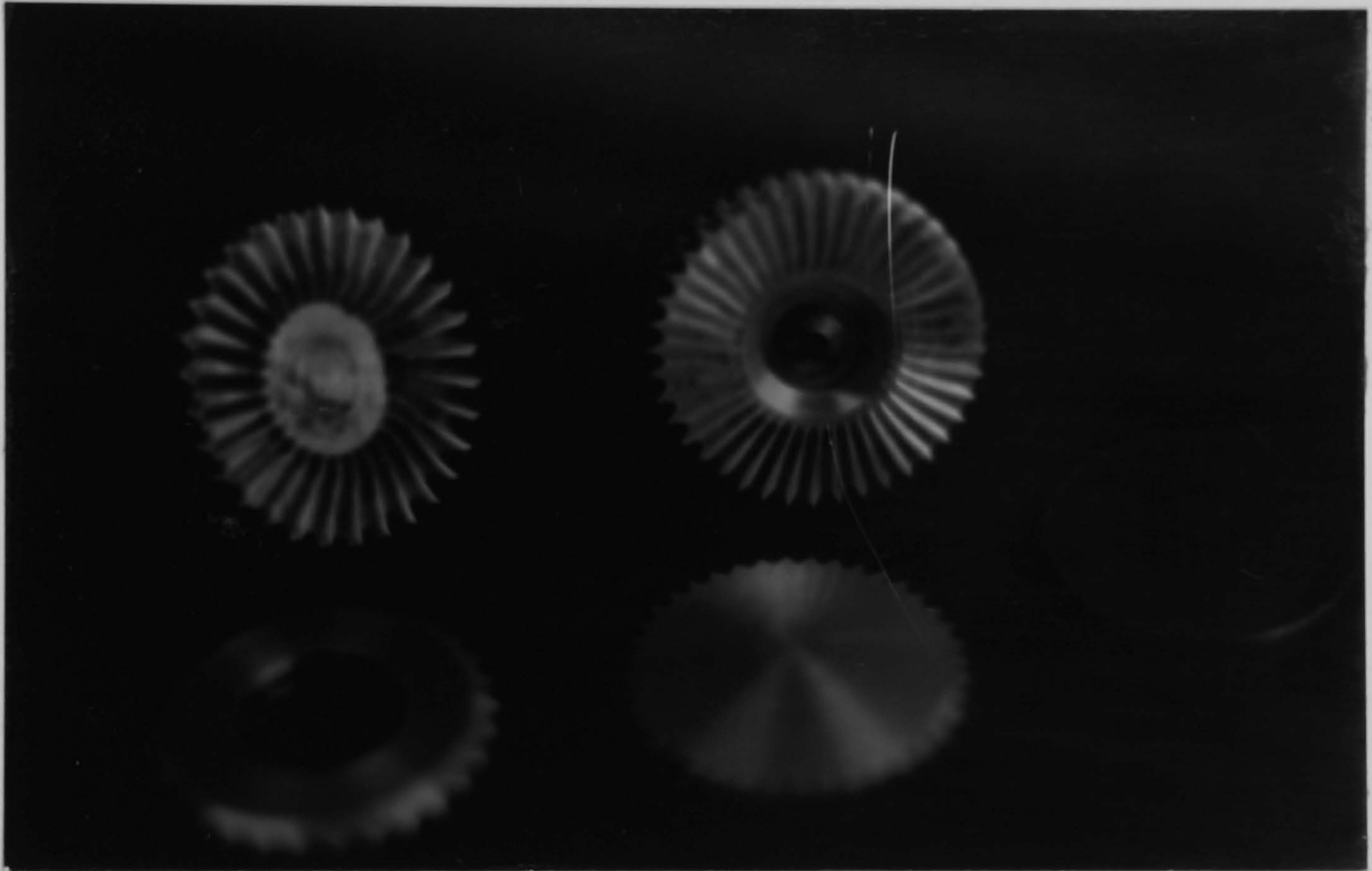


Figure 6.4 Trial ligament generators of type TR1
(with 1p coin to indicate scale)

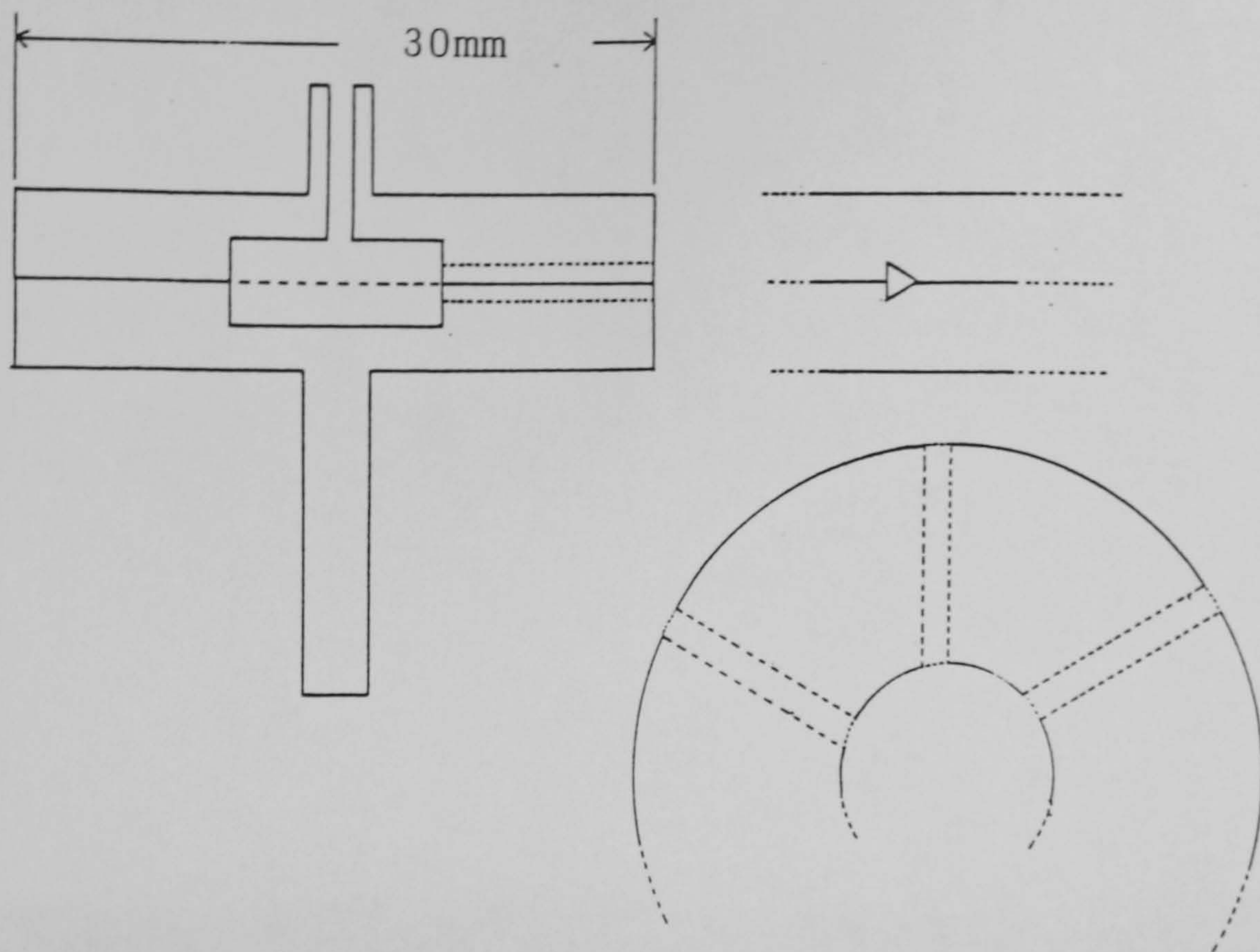


Figure 6.5 Trial ligament generator TR3

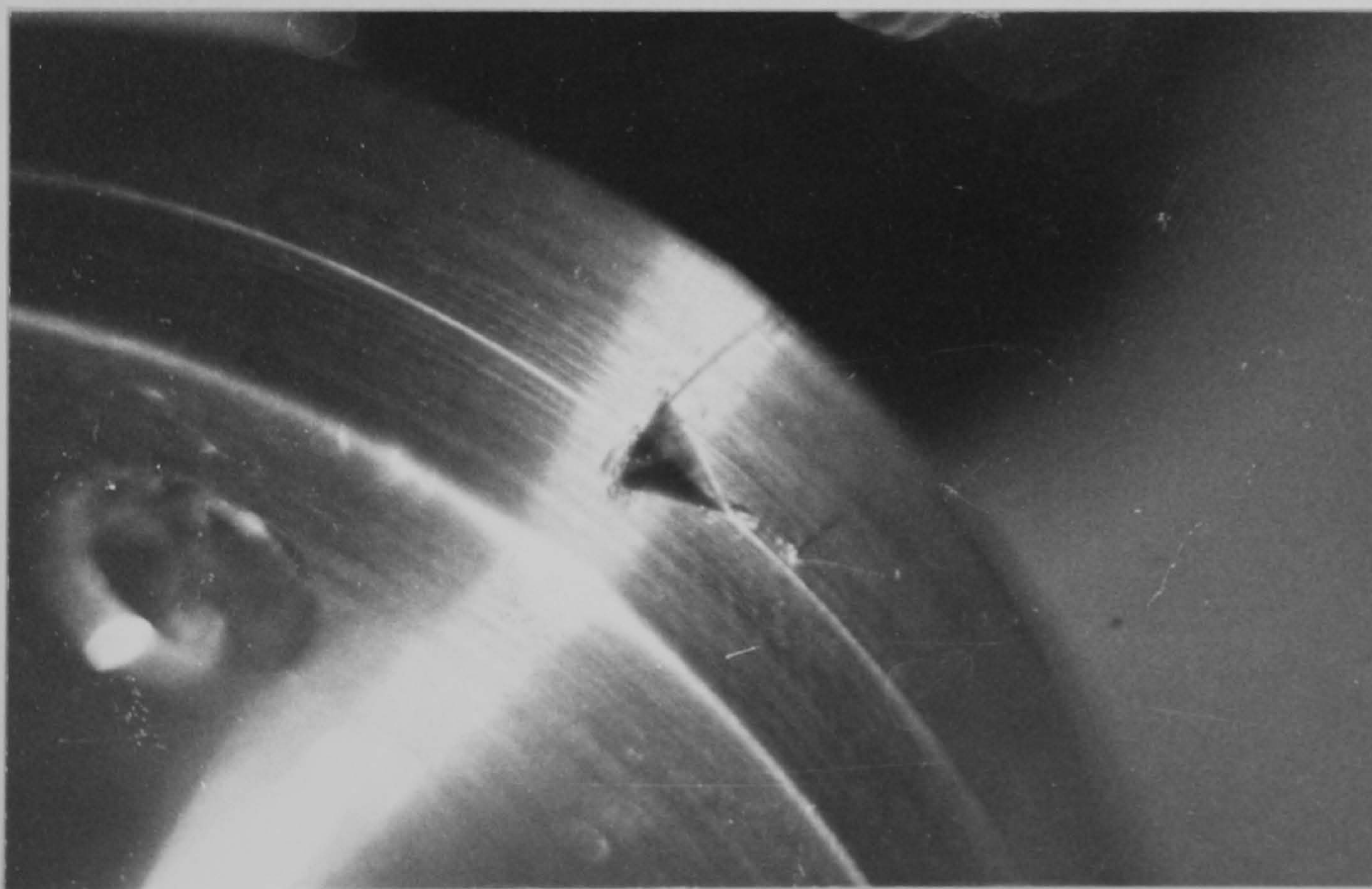


Figure 6.6 Erratic separation of liquid ligaments from TR3.



Figure 6.7 Trial ligament generator TR4

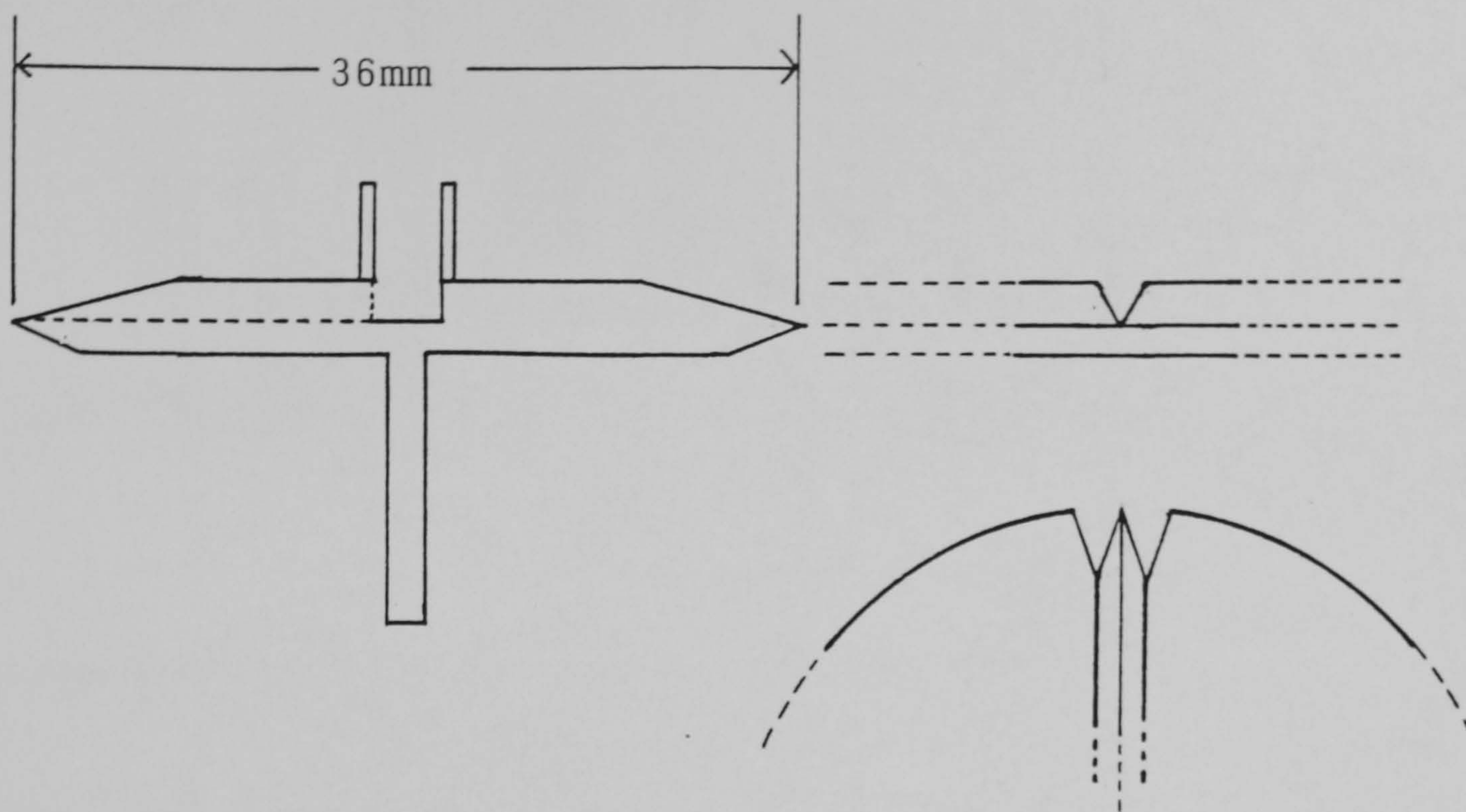


Figure 6.8 Trial ligament generator TR5

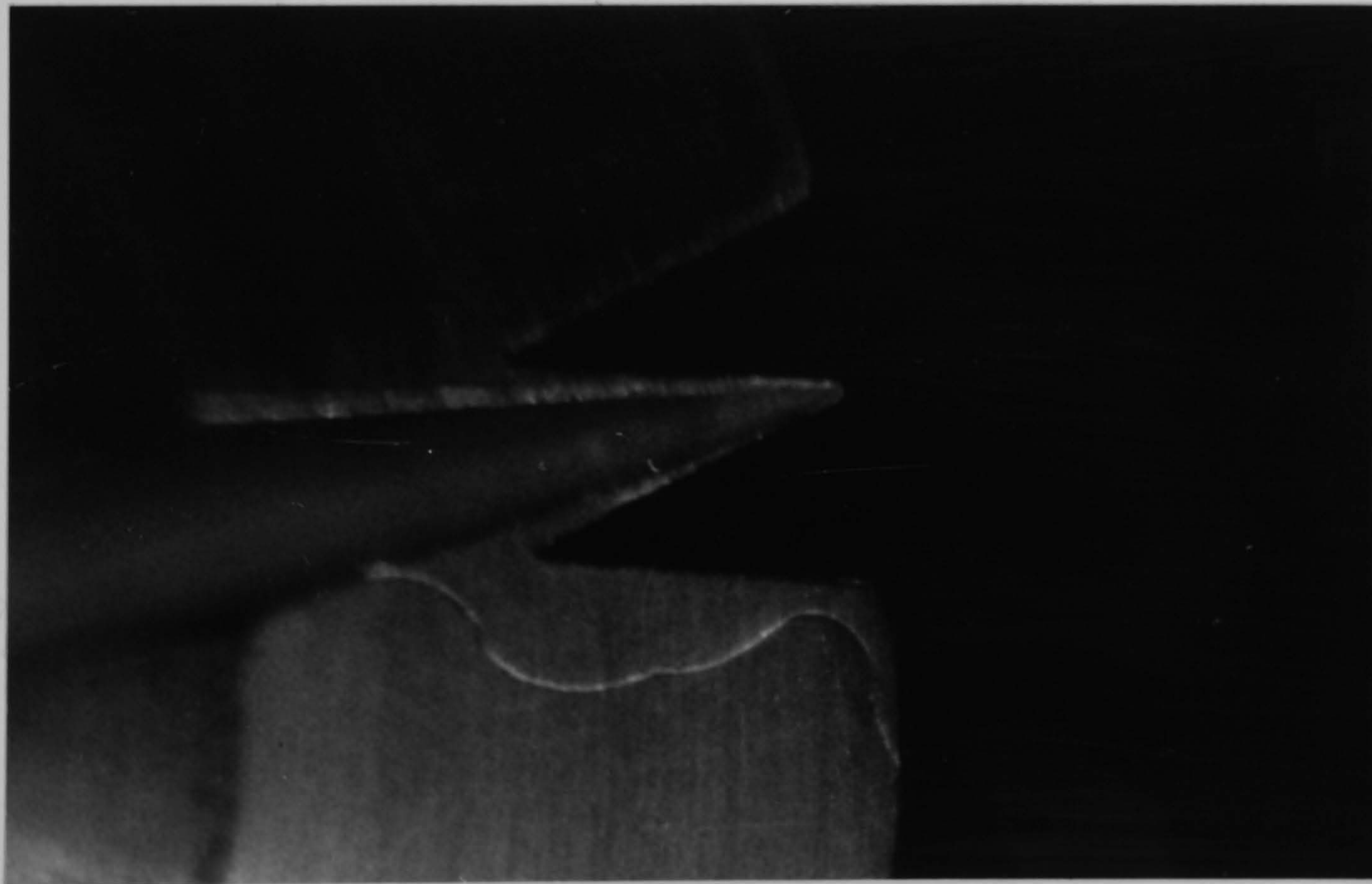


Figure 6.9 Liquid escaping from the groove in TR5

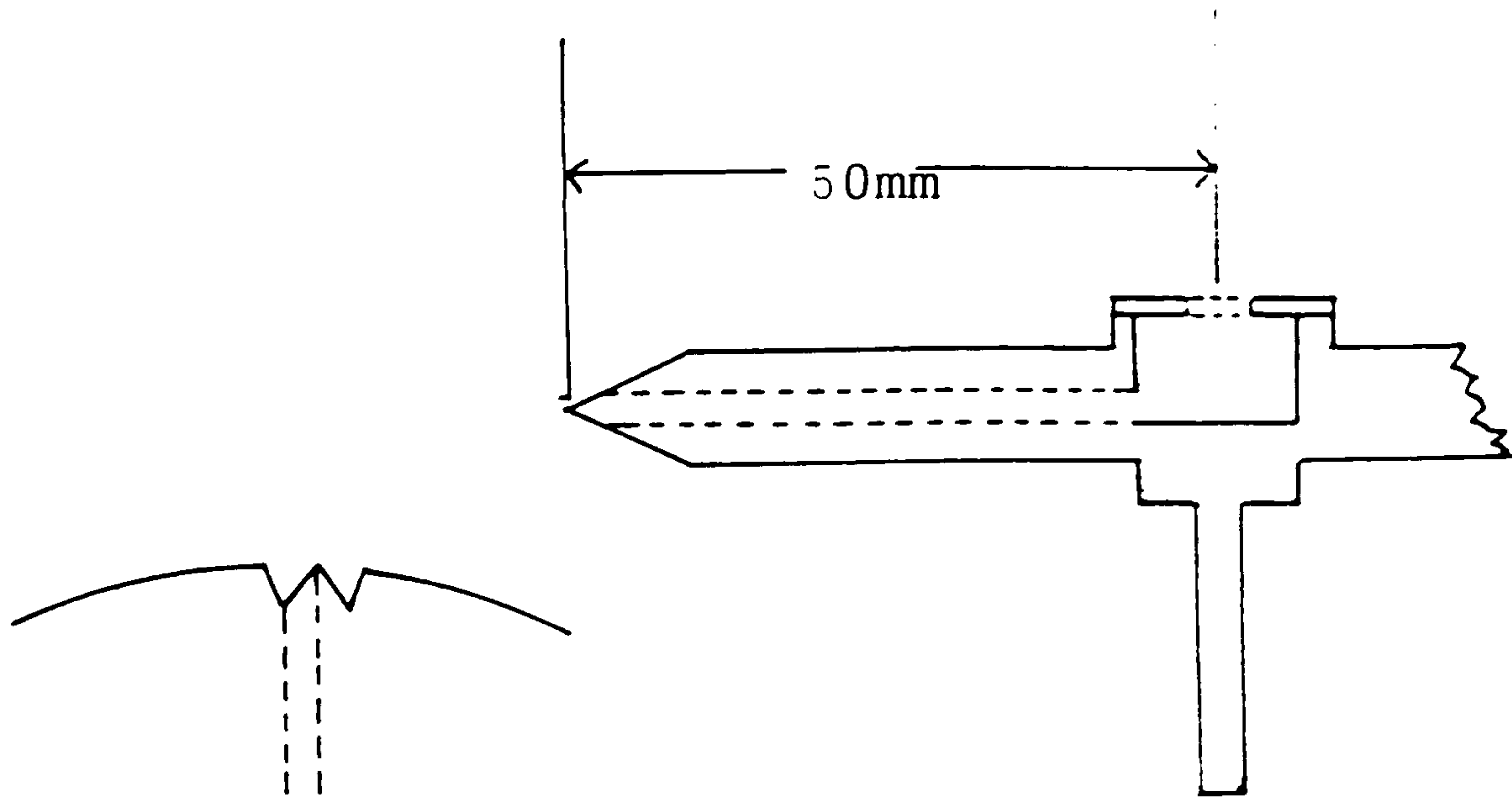


Figure 6.10 Sketch diagram of disc TR6

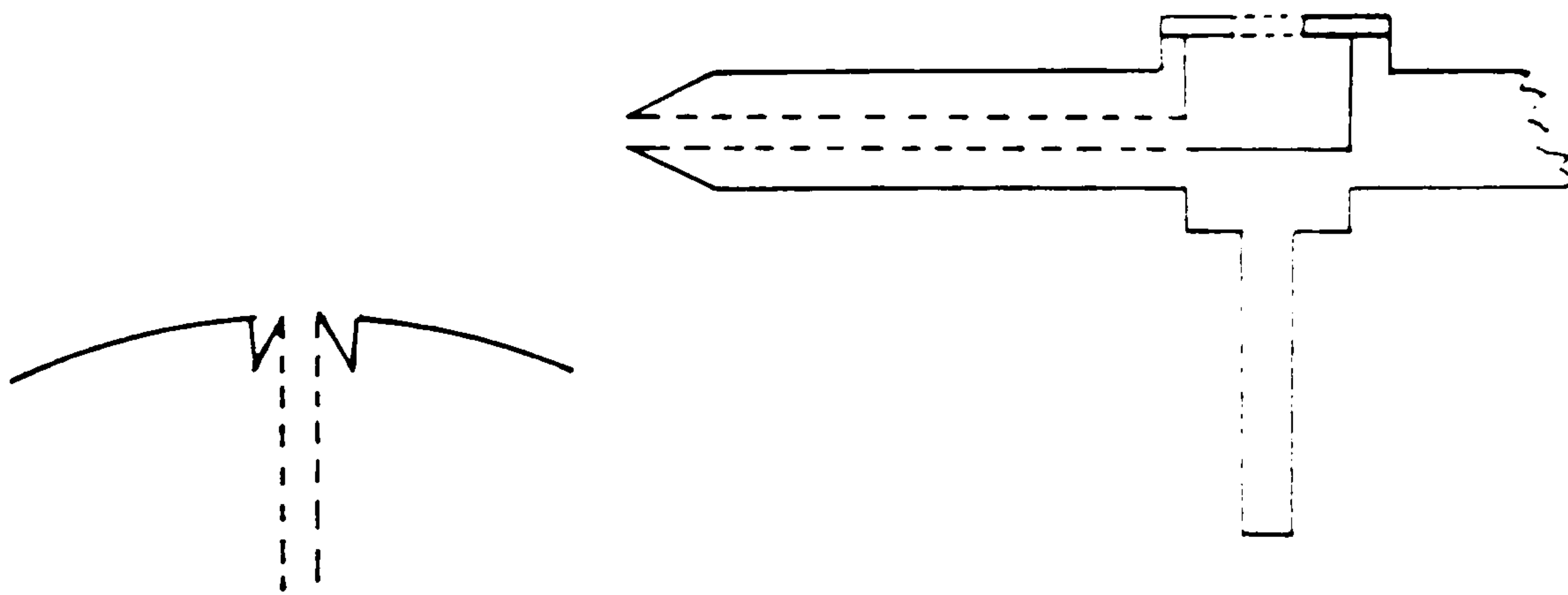


Figure 6.11 Sketch diagram of disc TR7

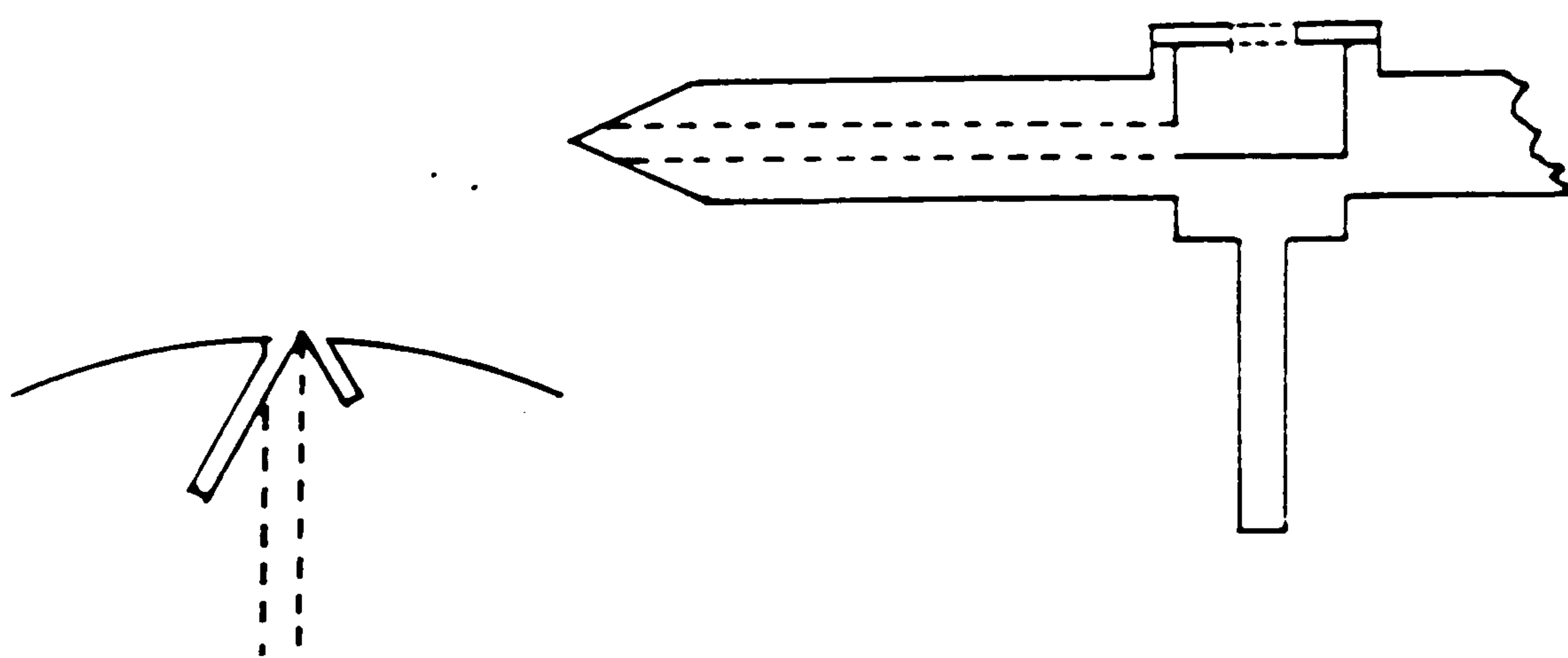


Figure 6.12 Sketch diagram of disc TR8



Figure 6.13 Erratic separation of liquid from TR7

The photographs in figures 6.14 to 6.33 were taken using the spark photography rig in figure 6.2. They show the ligament of liquid formed from ligament generator TR8 at rotation speeds of 6000 to 30000 rpm and liquid feed rates of 0.37 to 4.39 ml/minute

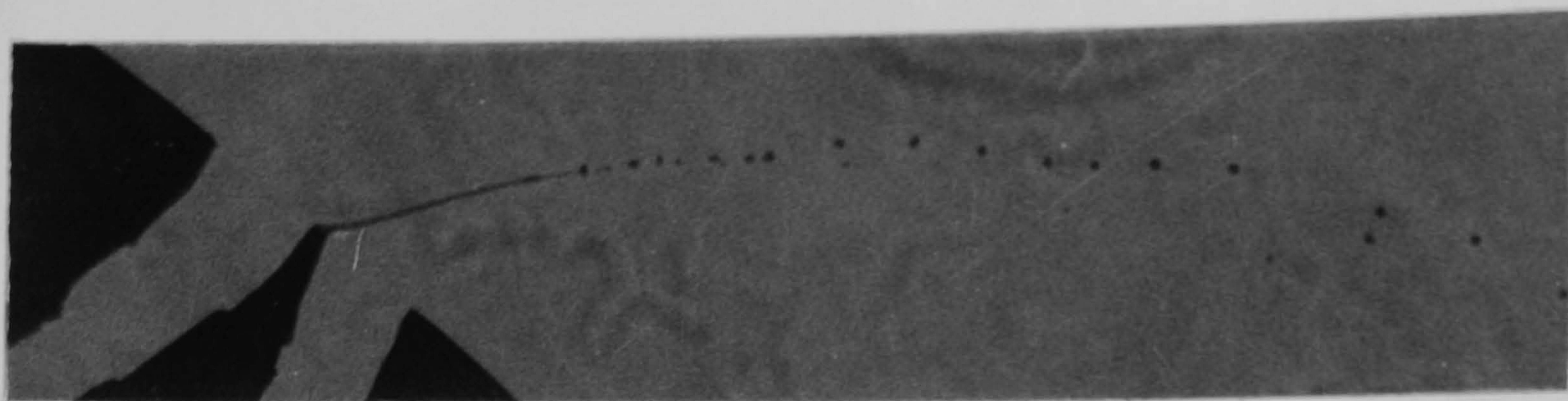


Figure 6.14 0.37 ml/minute 6000 rpm

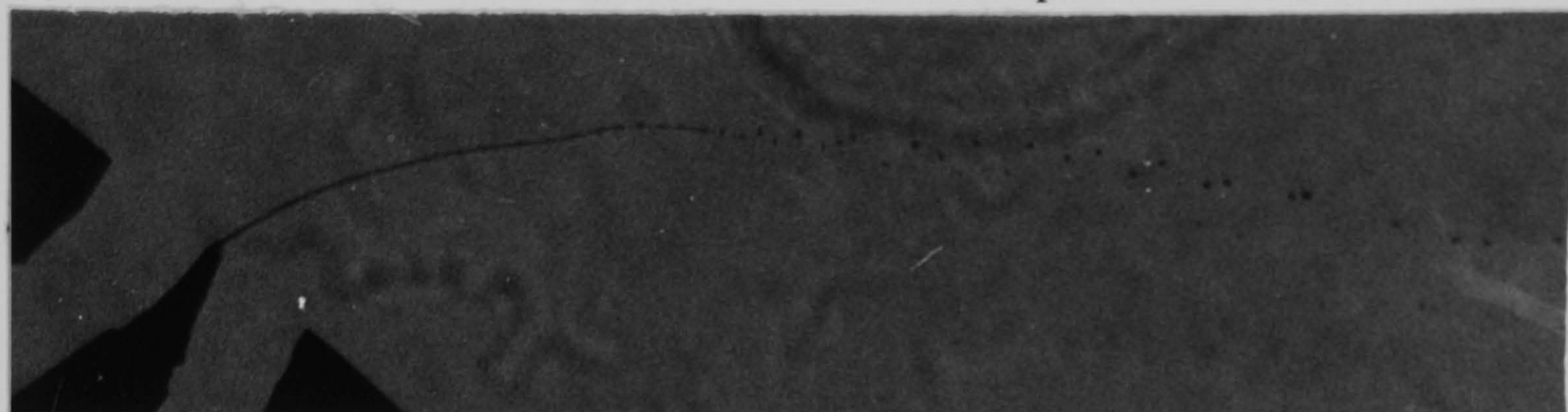


Figure 6.15 0.37 ml/minute 12000 rpm

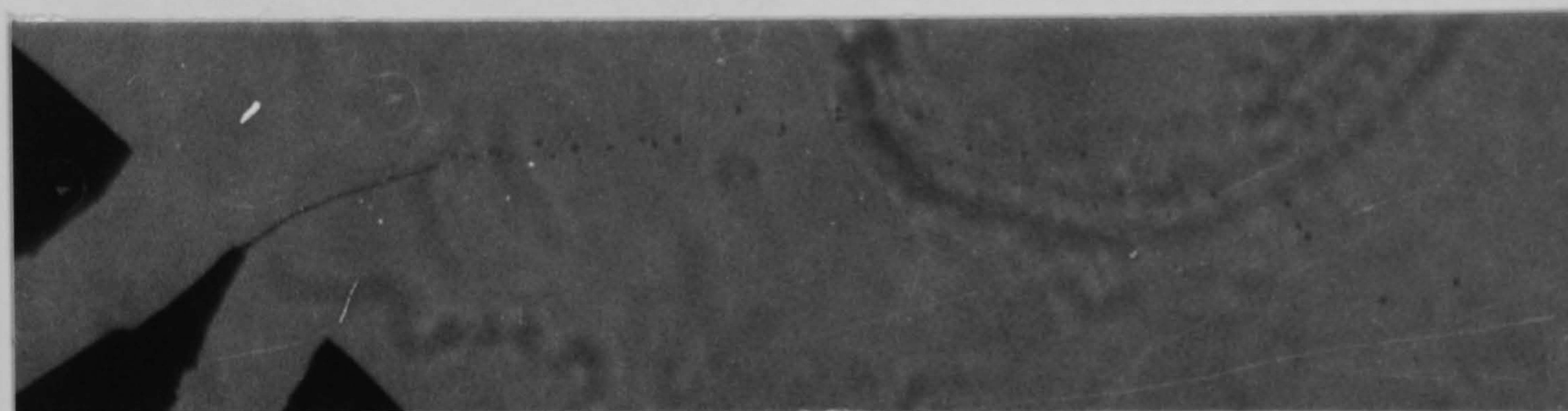


Figure 6.16 0.37 ml/minute 18000 rpm

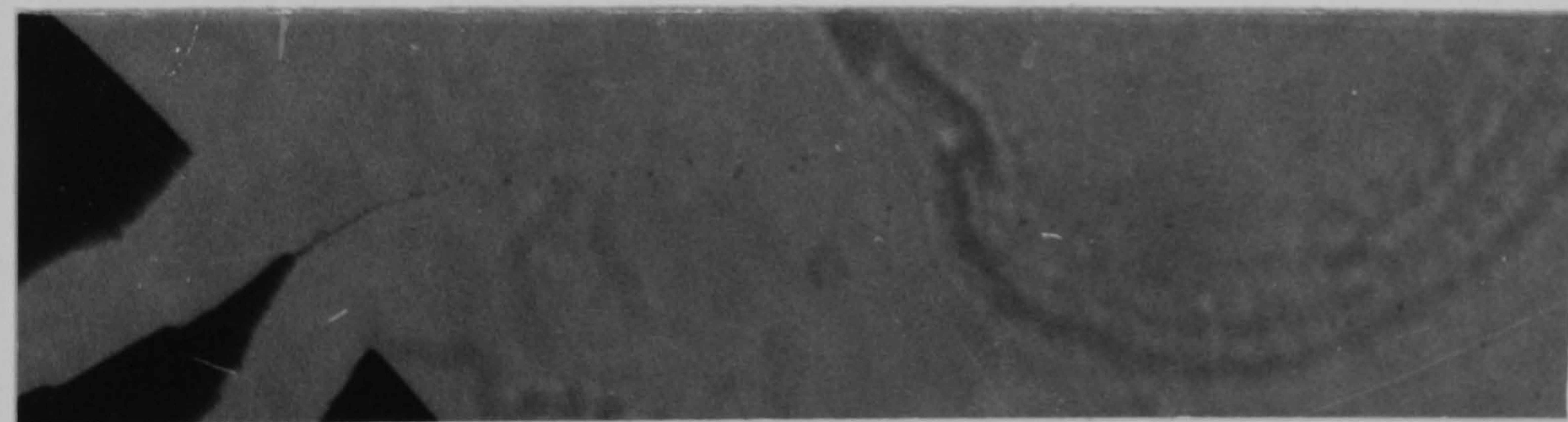


Figure 6.17 0.37 ml/minute 24000 rpm



Figure 6.18 0.37 ml/minute 30000 rpm

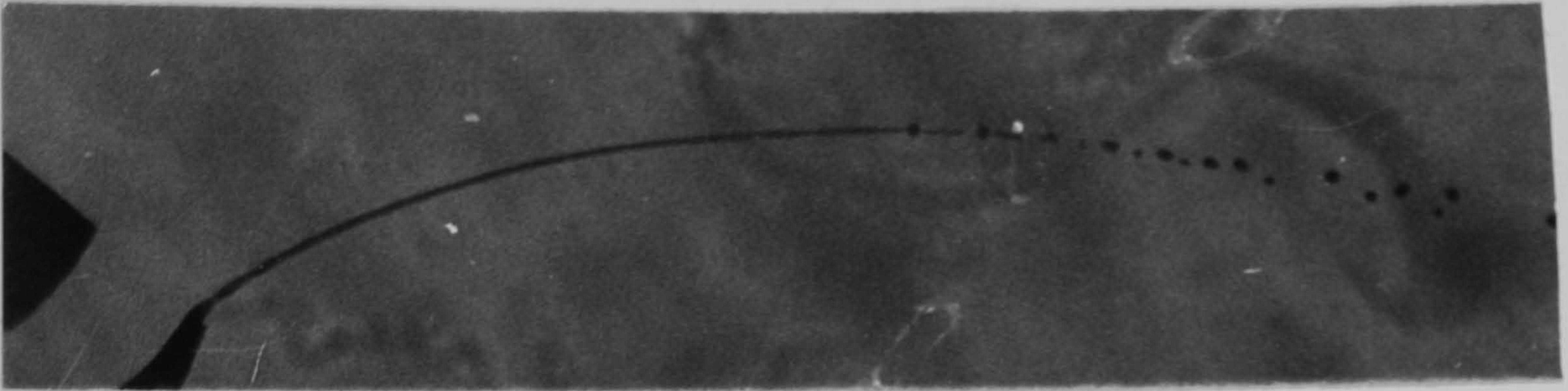


Figure 6.19 0.93 ml/minute 6000 rpm

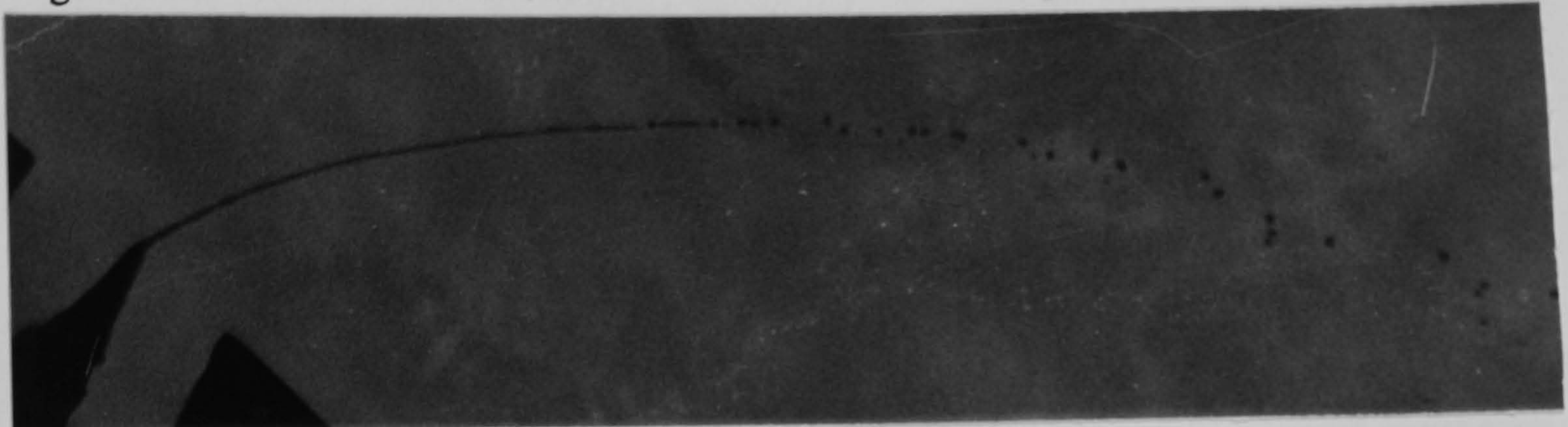


Figure 6.20 0.93 ml/minute 12000 rpm



Figure 6.21 0.93 ml/minute 18000 rpm

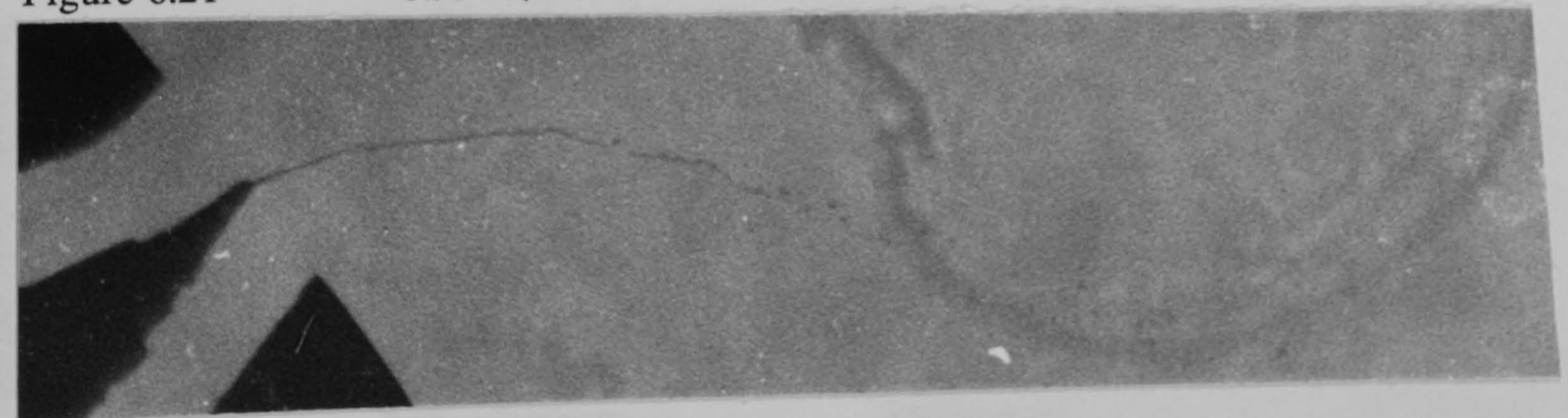


Figure 6.22 0.93 ml/minute 24000 rpm

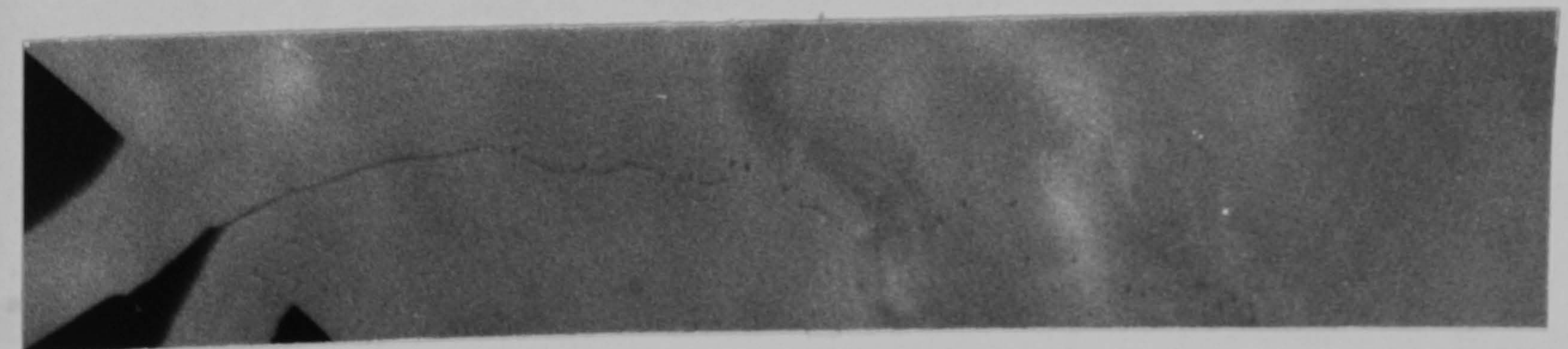


Figure 6.23 0.93 ml/minute 30000 rpm

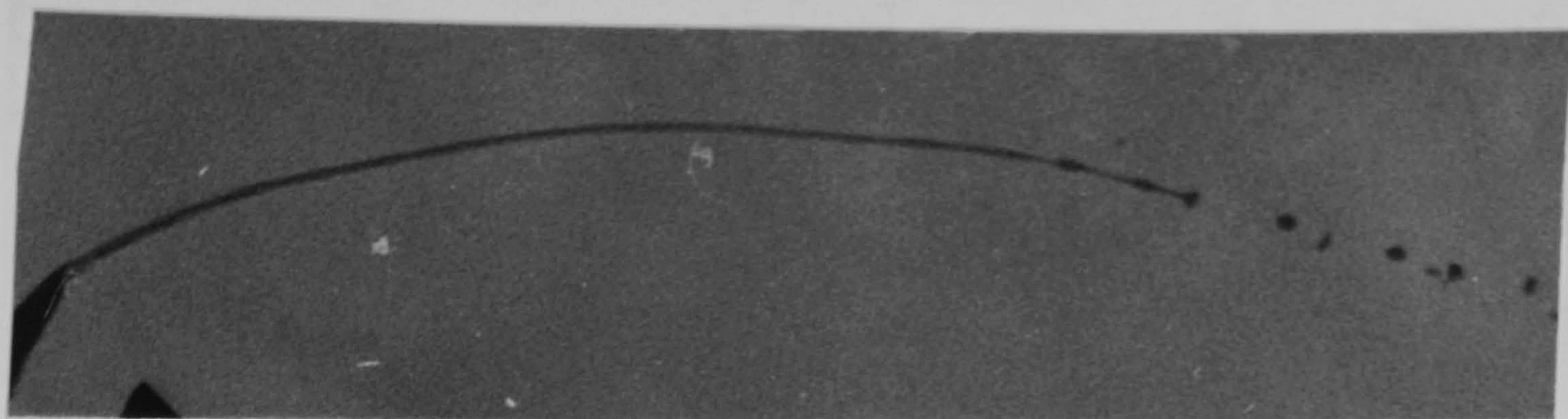


Figure 6.24 2.06 ml/minute 6000 rpm

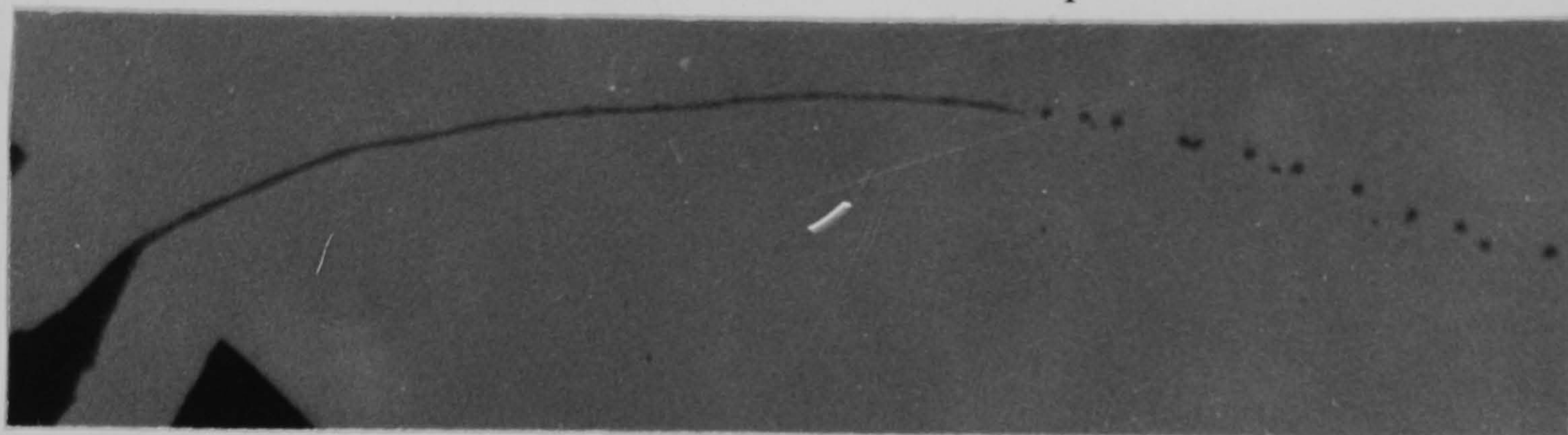


Figure 6.25 2.06 ml/minute 12000 rpm

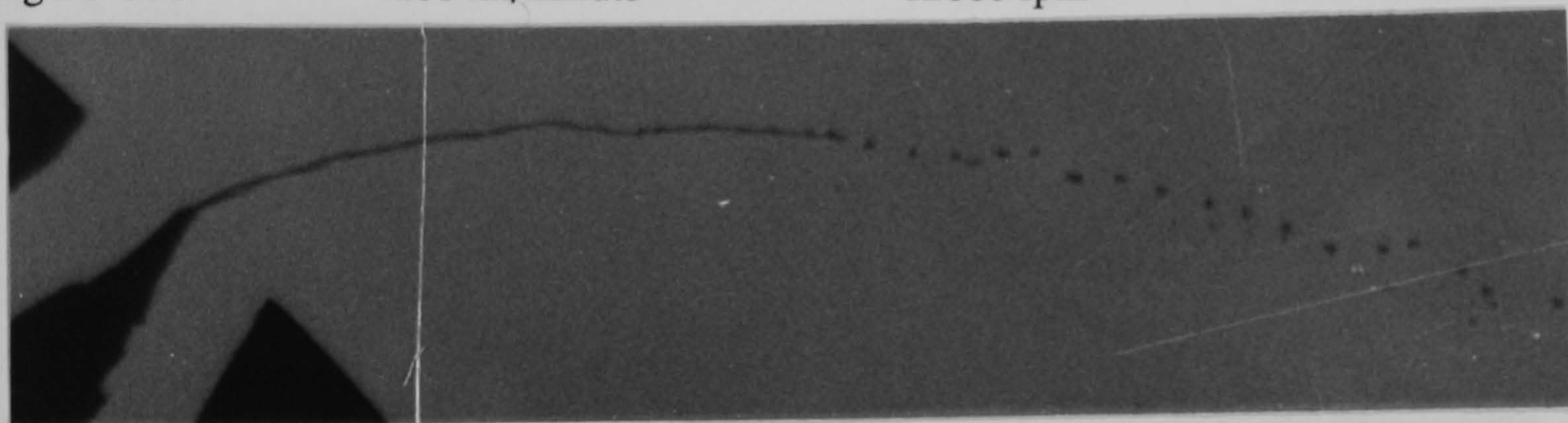


Figure 6.26 2.06 ml/minute 18000 rpm

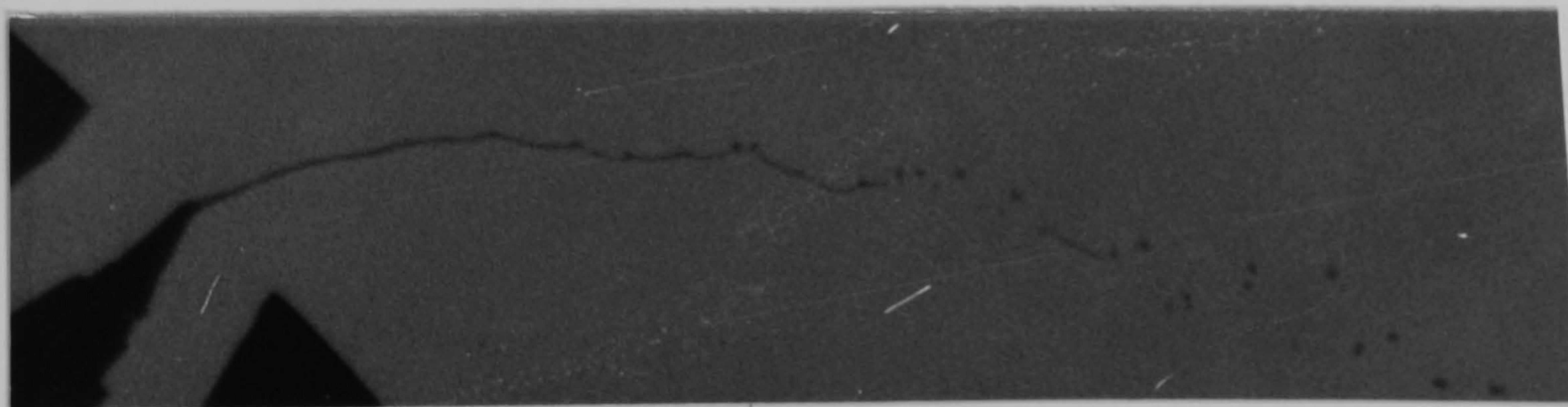


Figure 6.27 2.06 ml/minute 24000 rpm

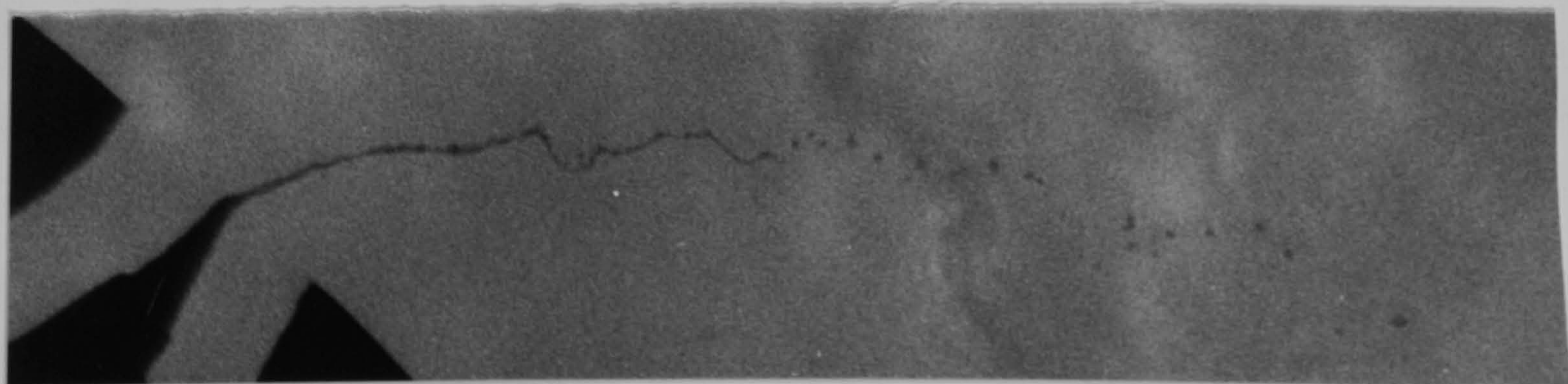


Figure 6.28 2.06 ml/minute 30000 rpm



Figure 6.29 4.39 ml/minute 6000 rpm

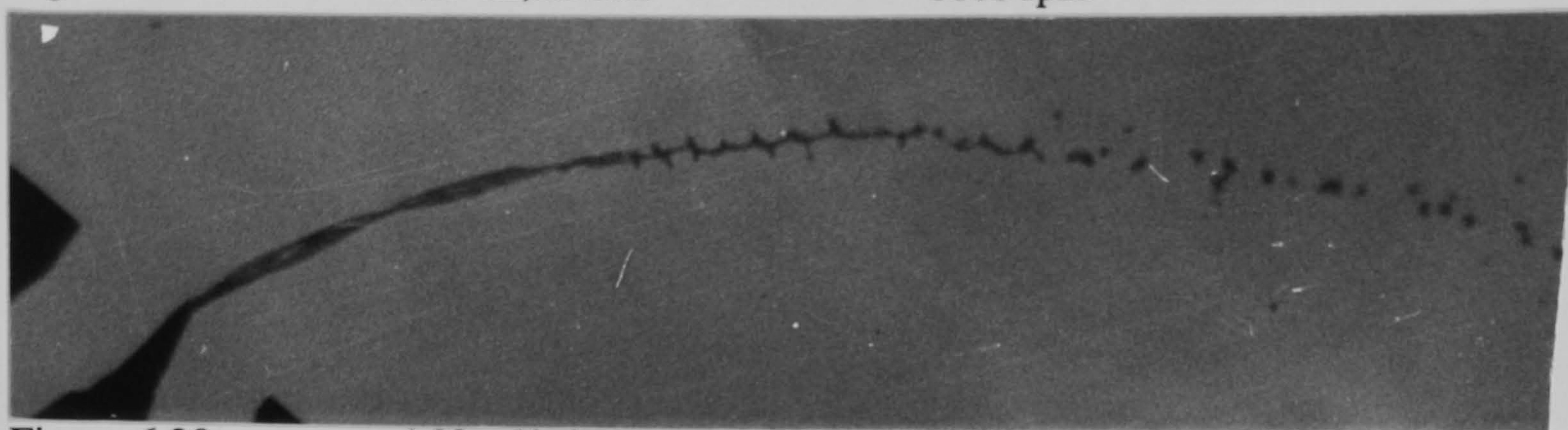


Figure 6.30 4.39 ml/minute 12000 rpm

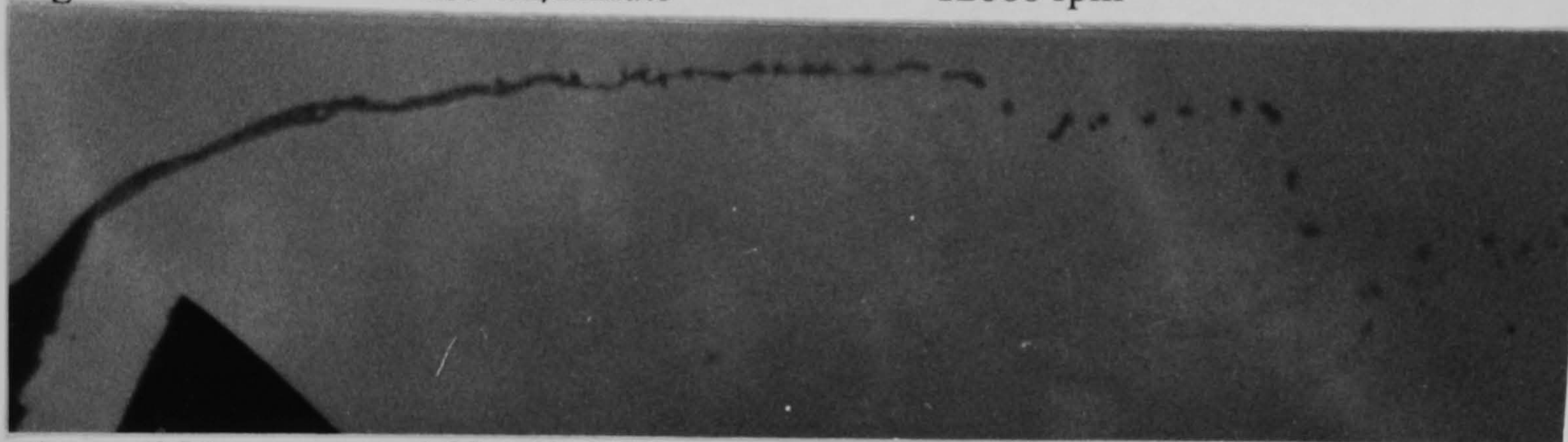


Figure 6.31 4.39 ml/minute 18000 rpm

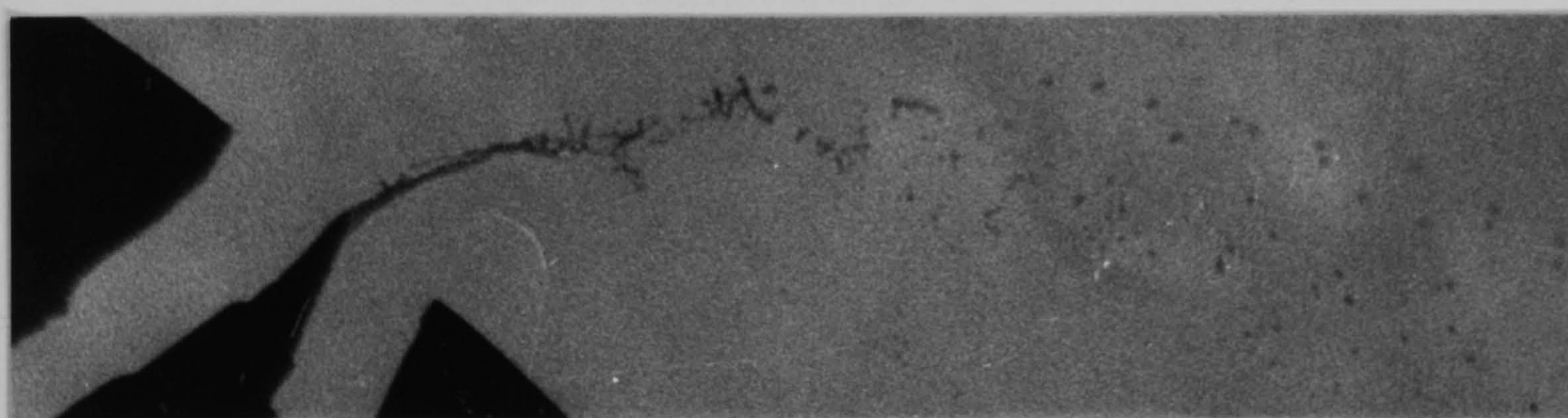


Figure 6.32 4.39 ml/minute 24000 rpm

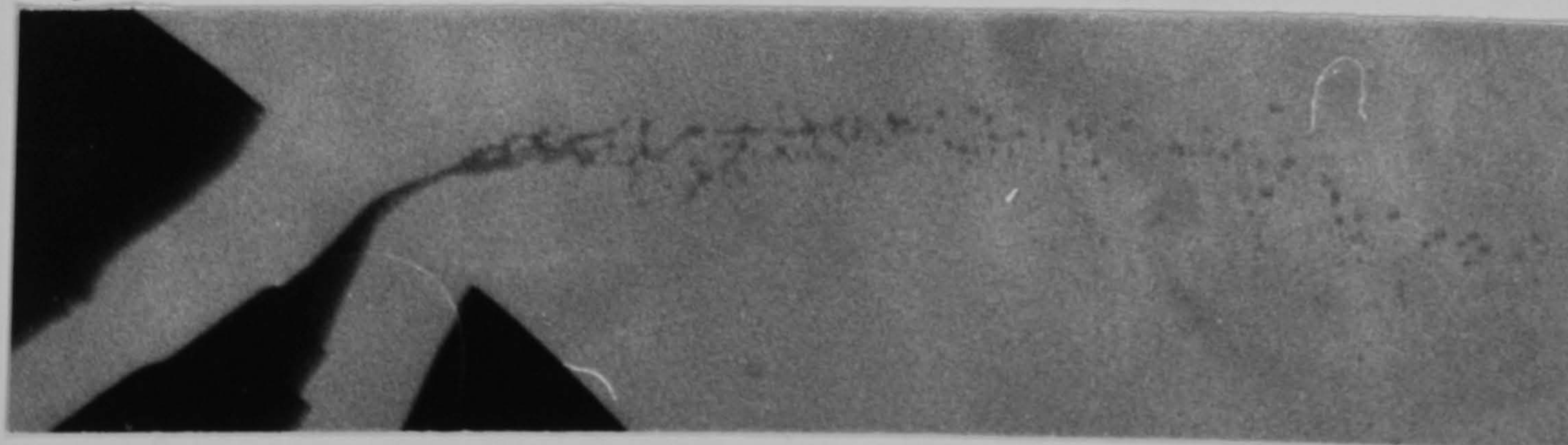


Figure 6.33 4.39 ml/minute 30000 rpm

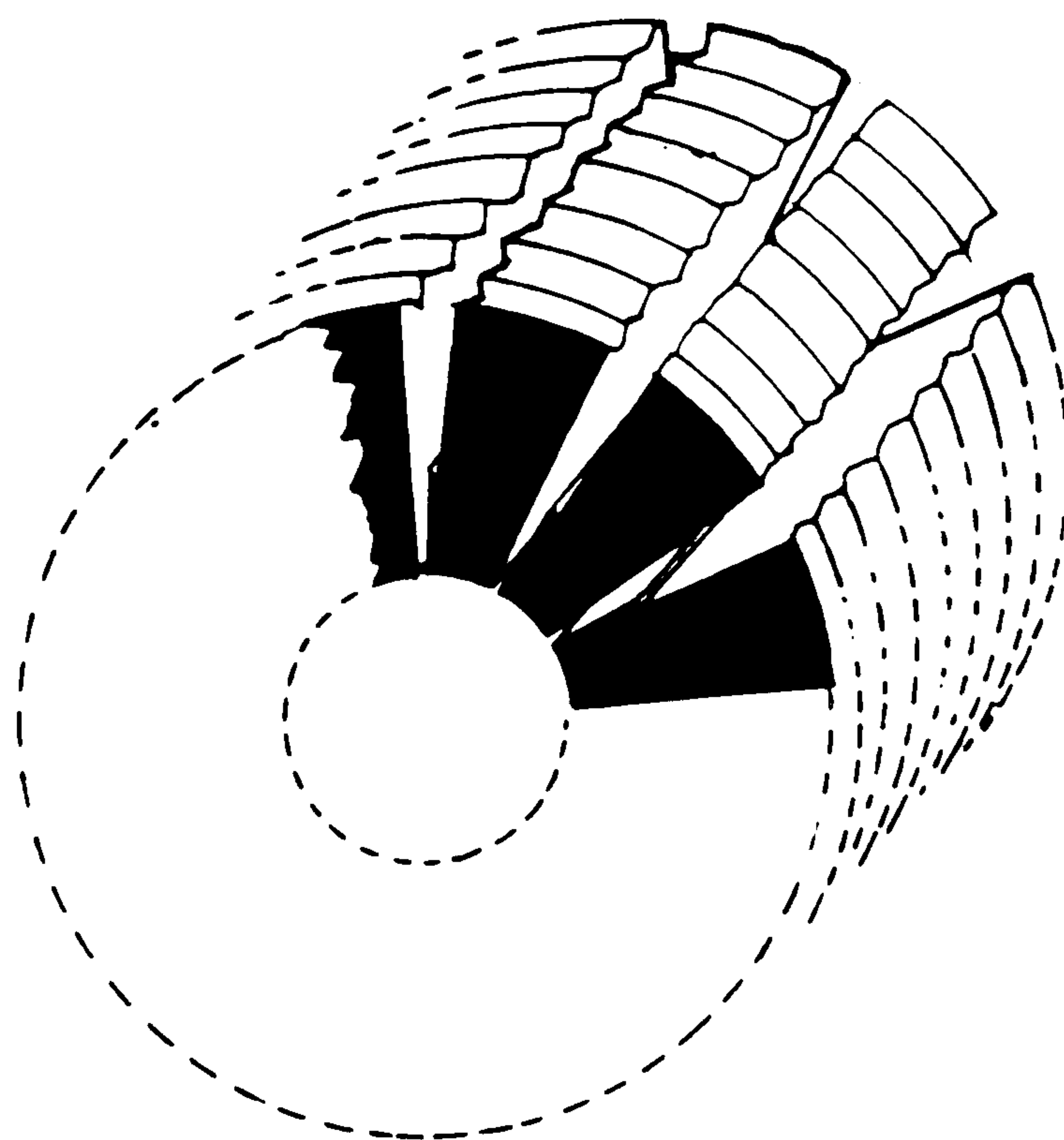


Figure 7.1 Sketch of original design proposal for a multi-issuing point atomiser based on a series of segments

(All measurements in mm)
Aluminium

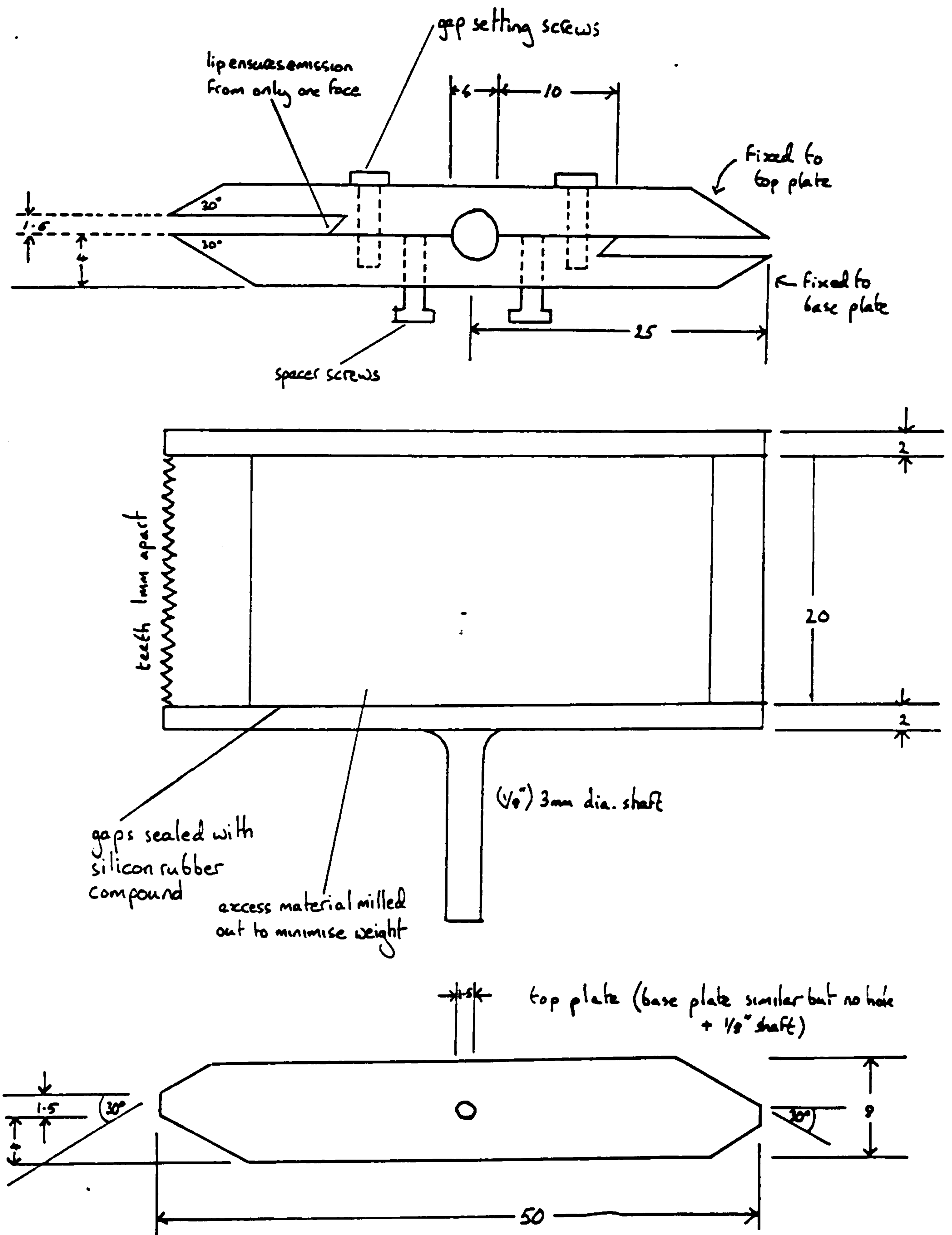
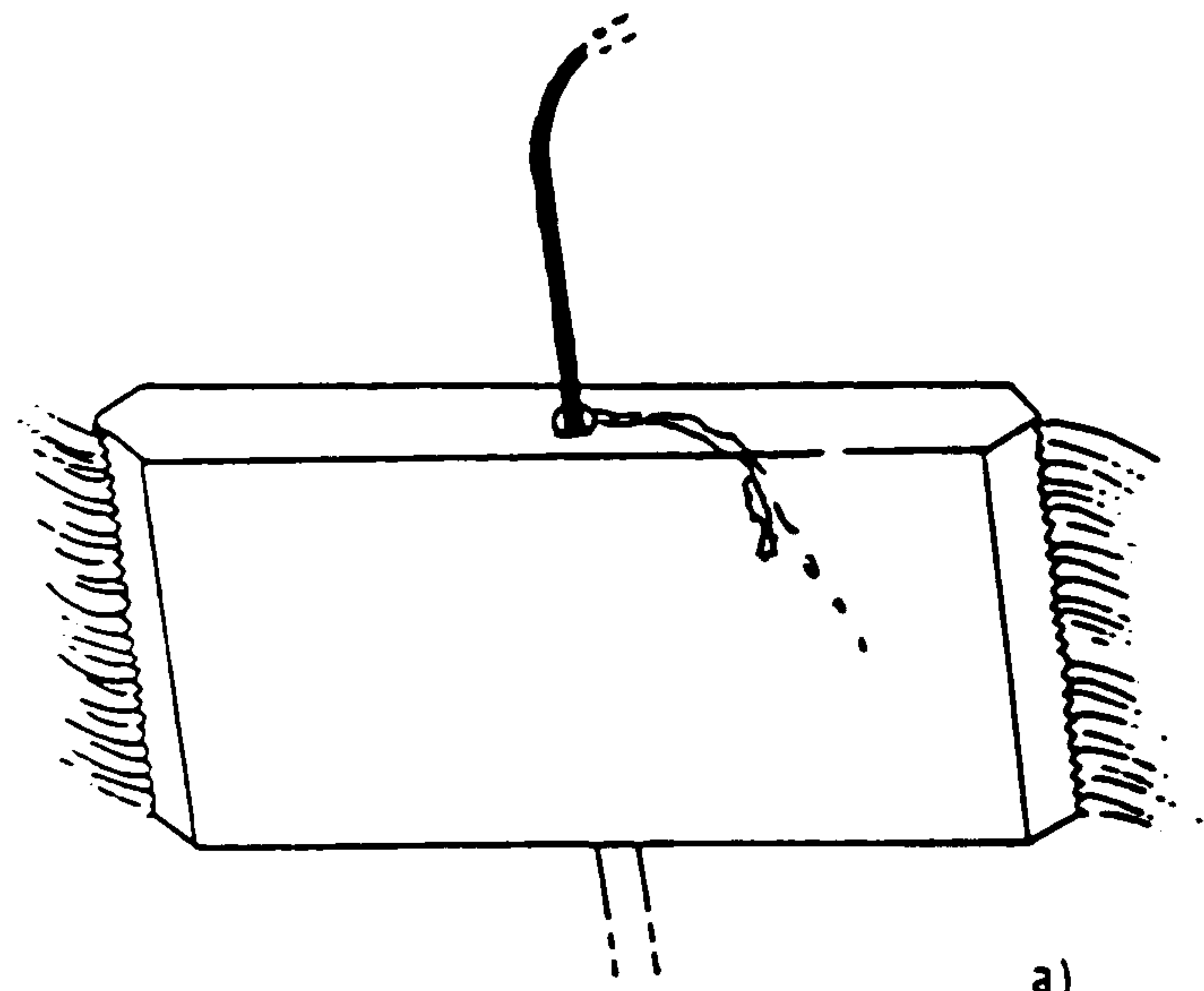
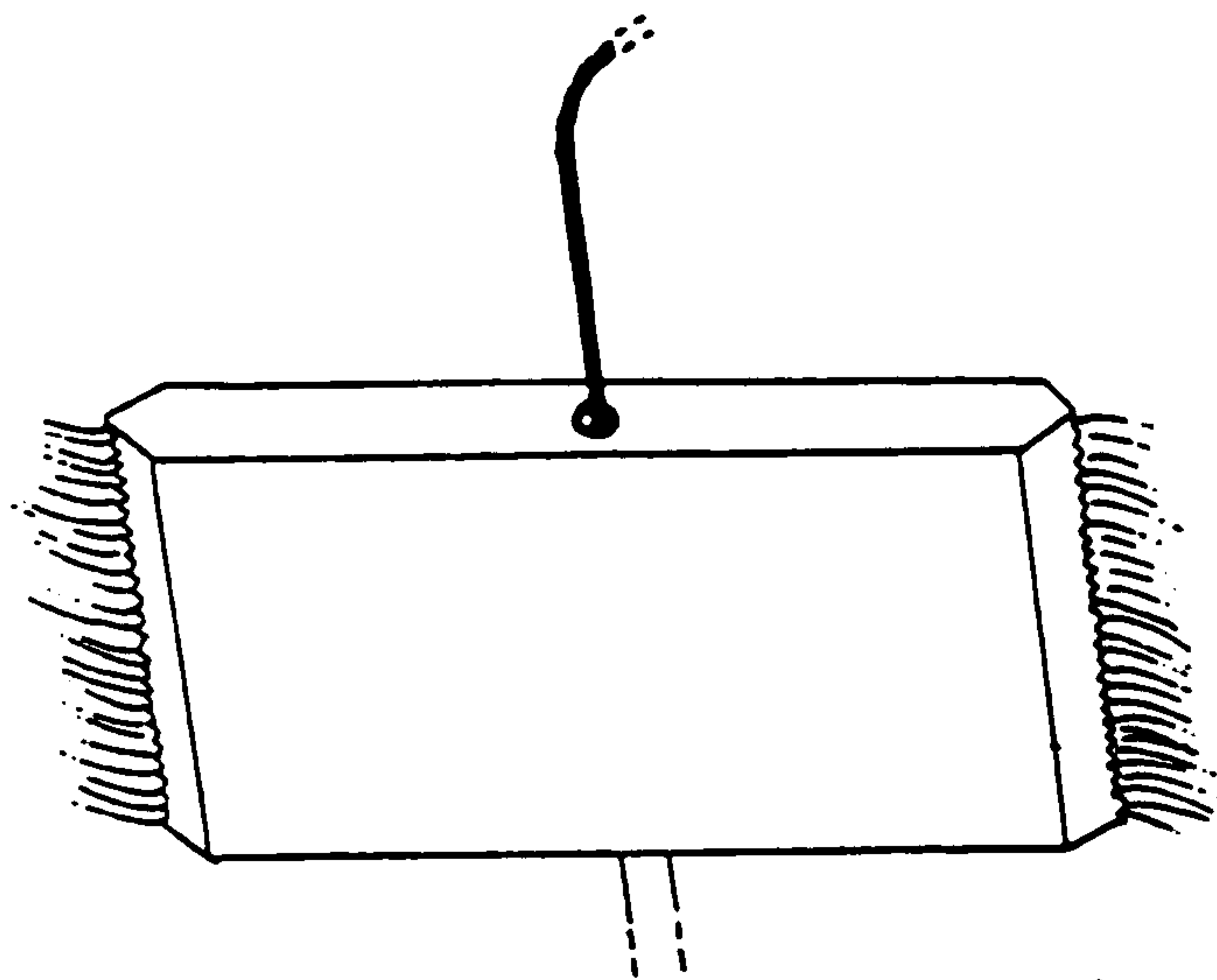


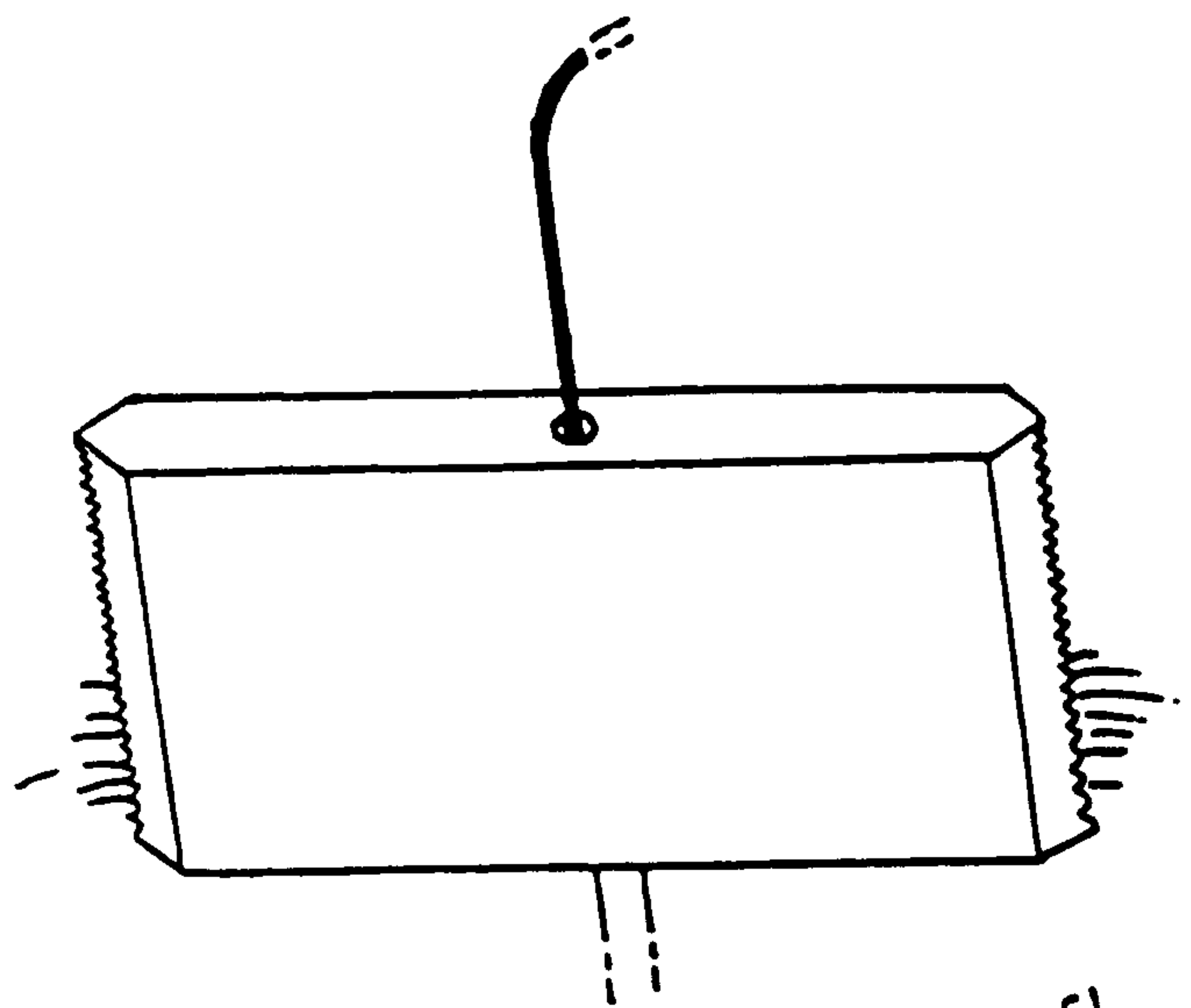
Figure 7.2 Rig designed to test the distributive abilities of various widths of slit



a)



b)



c)

Figure 7.3 Behaviour of the rotating slit test rig at various liquid feed rates

- a) feed rate exceeds pumping rate
- b) feed rate equal to pumping rate
- c) feed rate less than pumping rate

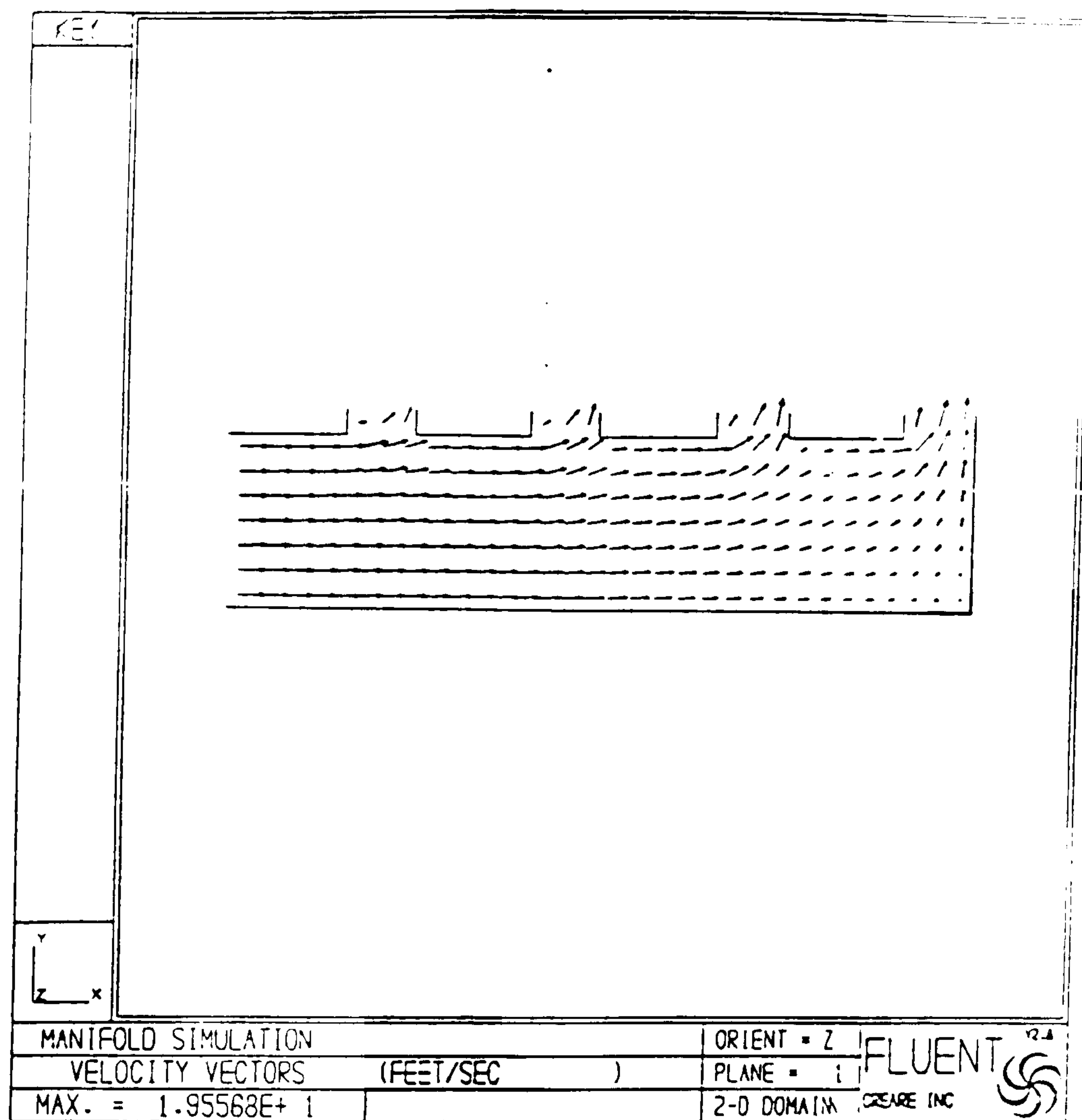


Figure 7.4 Computational Fluid Dynamic simulation of flow distribution from a manifold

(Produced by Flow Simulation, Suite 26, Hutton's Buildings
146 West Street, Sheffield s1 4ES)

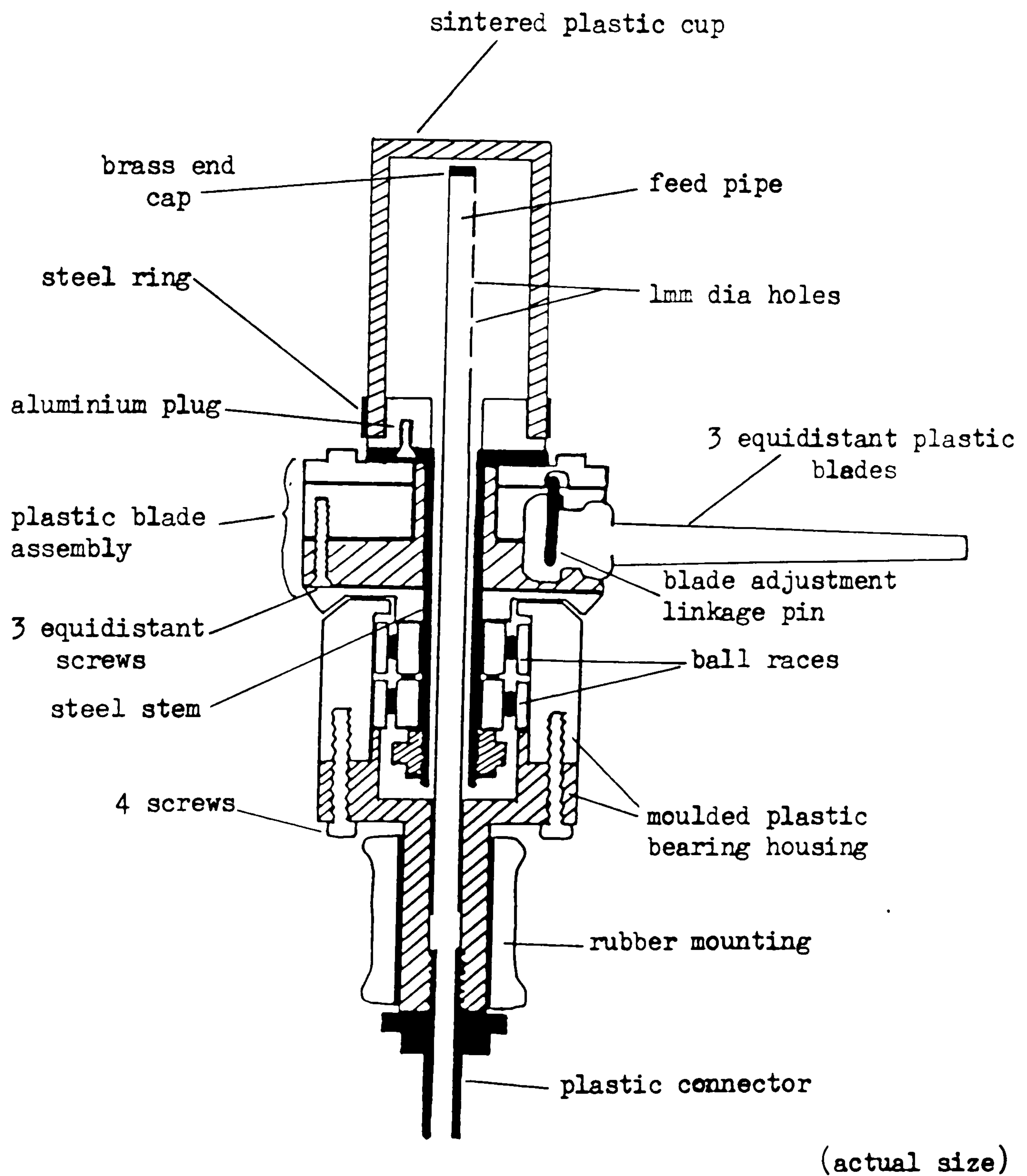


Figure 7.5 Rig for testing the distributive abilities of sintered plastic cylinders under wind-tunnel conditions

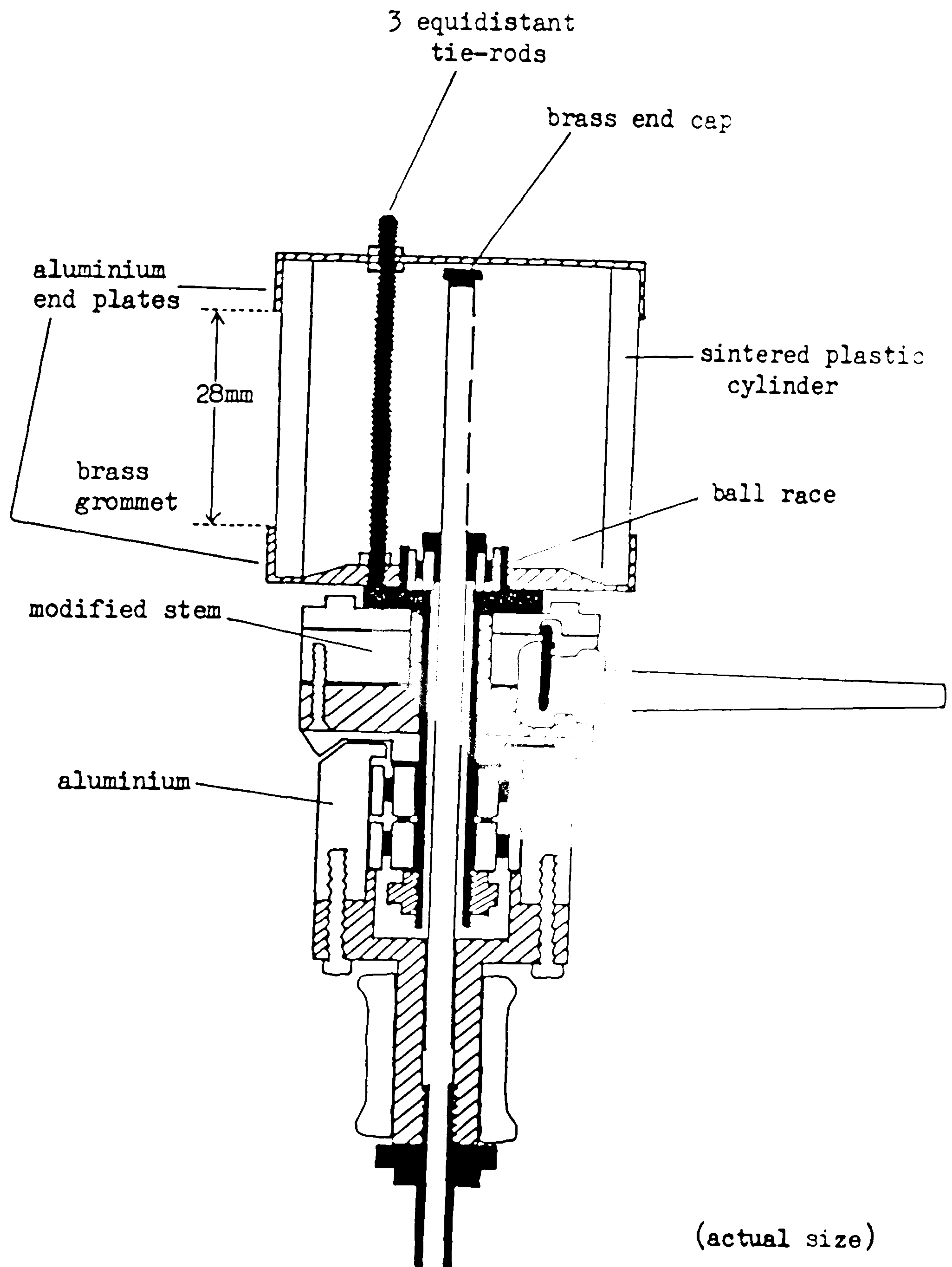


Figure 7.6 Modified rig for testing the distributive abilities of sintered plastic cylinders under wind-tunnel conditions

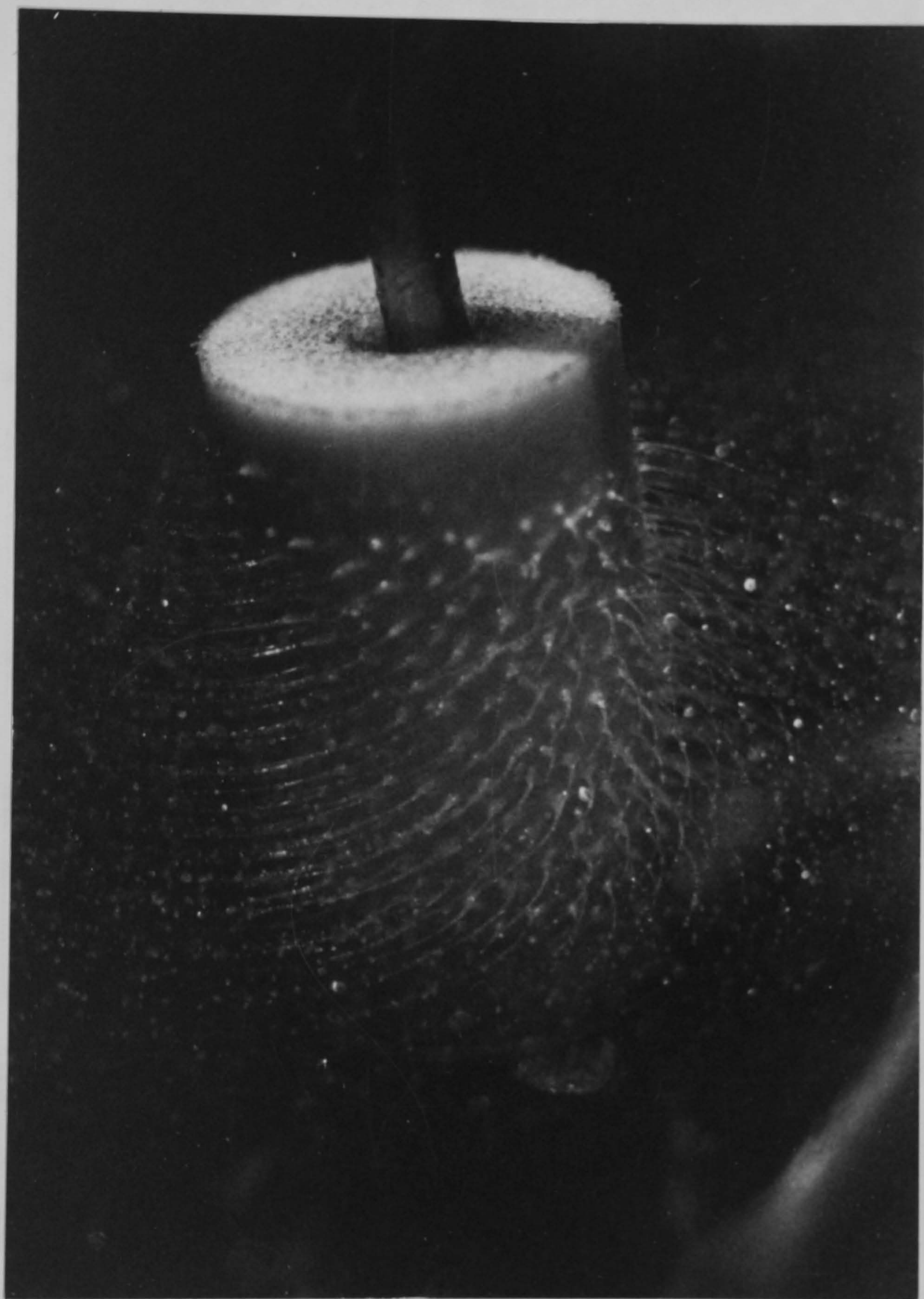


Figure 8.1 Liquid ligaments produced from a 25mm diameter sintered plastic cylinder rotating at 9000 rpm with a feed rate of 0.4 litres/minute (liquid used: water + 0.1% Agral)



Figure 8.2 Liquid ligaments produced from a 25mm diameter sintered plastic cylinder rotating at 15000 rpm with a liquid feed rate of 0.4 litres/minute (liquid used: water + 0.1% Agral)

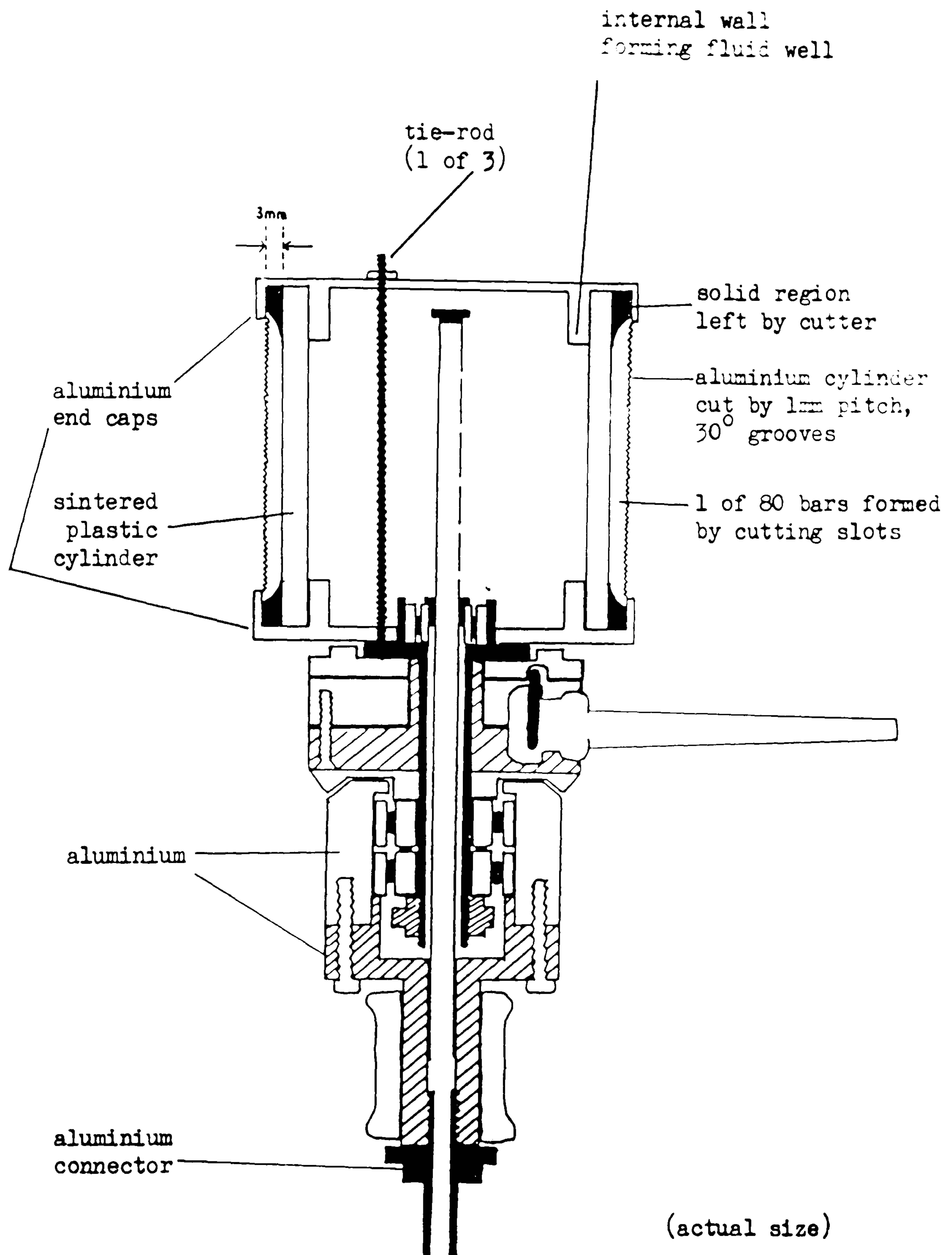


Figure 8.3 Prototype atomiser Pro-2

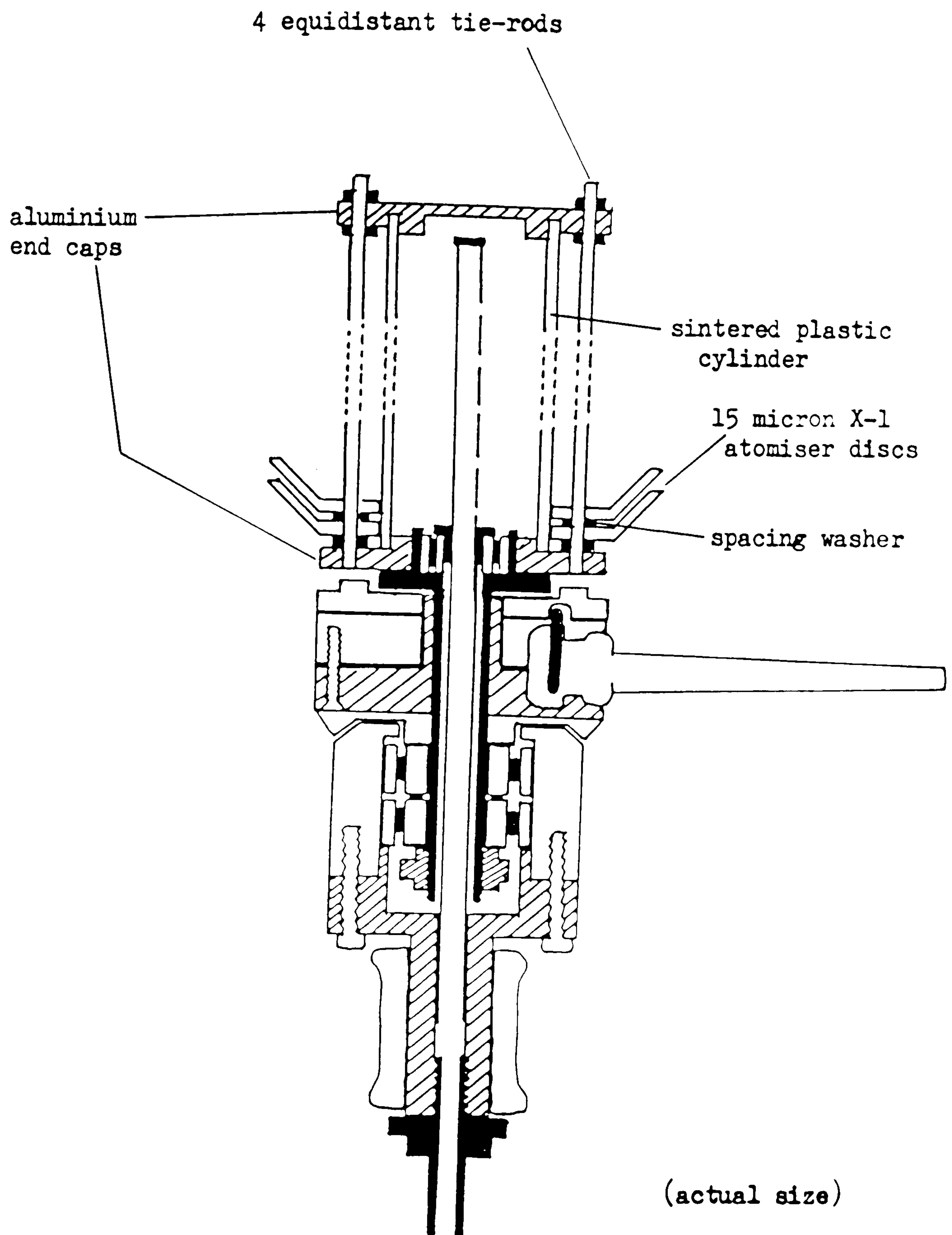


Figure 8.4 Prototype atomiser Pro-3

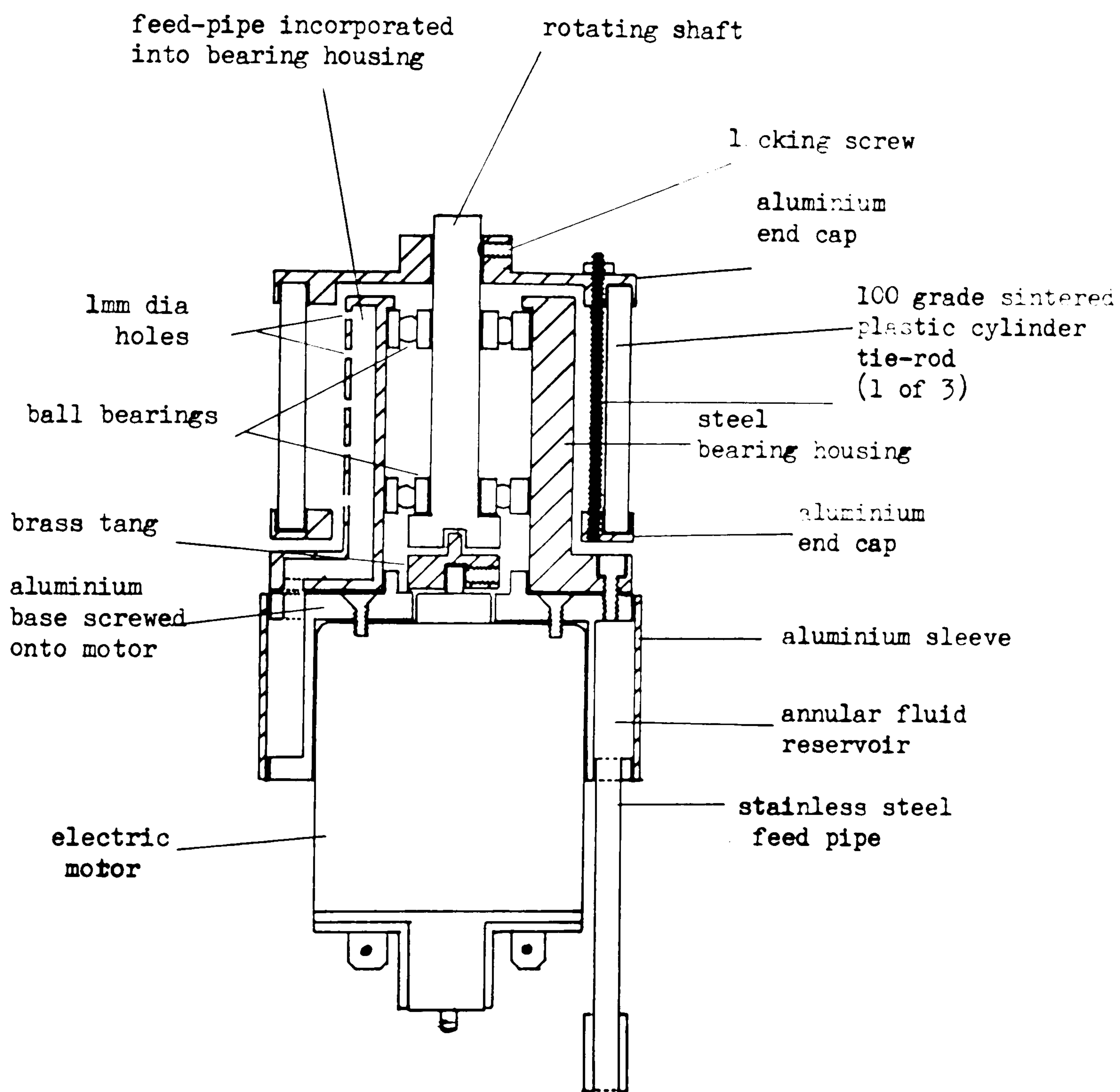


Figure 8.5 Prototype atomiser Pro-4

On the subject of PhDs.....

"...a life of mistakes, the offspring of a certain spiritual grandeur ill-matched with the meanness of opportunity; perhaps a tragic failure which found no sacred poet and sank unwept into oblivion. With dim lights and tangled circumstance they tried to shape their thought and deed in noble agreement; but after all, to common eyes their struggles seemed mere inconsistency and formlessness....."

George Eliot 1872 (Middlemarch)

" Four years to design a nozzle? Why don't you just buy one from the Garden Centre?"
Dr Philip Rowlands, 1988 (also 1989, 1990,etc)