A HERBICIDE SPRAYER FOR TROPICAL SMALL-HOLDER FARMERS

by

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ABSTRACT

Sprayers presently available for tropical smallholder farmers are often unsuitable due to the complicated recommendations for herbicide use and the large volumes of water required. A more suitable ground-metered, controlled droplet sprayer was developed in the form of a wheelbarrow.

A peristaltic pump, driven by the ground wheel, delivered the spray liquid from the spray tank to a spinning cup atomiser. The volume per unit area remained constant at all speeds, since the output of the pump was related to the walking speed of the operator. The spinning cup was driven by friction off the ground wheel, and was shrouded to produce a uniform swath of variable width. The physical characteristics of the wheelbarrow sprayer were thoroughly tested to ensure that the components performed reliably and that the spray and swath characteristics conformed with the requirements of farmers. The sprayer applied 20 l/ha, and the spray had a VMD of about 250 µm when the operator walked at 1.0 m/s. The swath width was uniform and did not vary greatly with walking speed.

Weed control obtained using the wheelbarrow sprayer was at least as good as that when using two standard hand-held sprayers. These results were obtained with a range of contrasting herbicides in laboratory comparisons, and in field trials in England and Botswana. There was good evidence of improved spray retention from the wheelbarrow sprayer compared to conventional volume sprays.

The results are discussed in relation to the potential uses of the sprayer in the tropics. It has a number of advantages which may make it easier to introduce to smallholder farmers than presently available sprayers, and it is to be marketed commercially in 1983.

ABBREVIATIONS

coefficient of variation	cv
confidence interval	CI
correlation coefficient	r
degrees (angular)	$^{\circ}$
degrees Celsius	$^{\circ}C$
gram	g
gram of active ingredient	gai
hectare	ha
inch	"
kilogram	kg
kilogram of active ingredient	kgai
kilometre	km
kiloPascal	kPa
least significant range	LSR
litre	l
metre	m
metre per second	m/s
micrometre	µm
microgram	µg
millilitre	ml
millimetre	mm
milliWatt	mW
minute	min
molar concentration	M
nanometre	nm
number mean diameter	NMD
revolutions per minute	rpm
weight for weight	w/w
variance	s^2
volume for volume	v/v
volume mean diameter	VMD

CONTENTS

CHAPTER 1 INTRODUCTION

There is great potential for increasing food production in developing countries by improving the efficiency of small-holder farmers. In contrast to developed countries, agriculture continues to be the main source of income for the majority of people in tropical and sub-tropical regions, particularly in most of Africa where over 70% of the working population is engaged in agriculture (Anon, 1980a). The majority are subsistence or small-holder farmers, and almost 70% of the world's poorest people are engaged primarily in subsistence agriculture (Todaro, 1981), but the major advances in developed agriculture in the last thirty years have hardly affected subsistence farming.

Although small-holder farmers account for a large proportion of domestic food production, e.g. 90% in Nigeria (Anon, 1981) and Kenya (Senga, 1976), the allocation of research into such agriculture is negligible (Ryan & Binswanger, 1979) and food production has rarely kept pace with increasing populations (Mayer, 1976; Akobundu, 1978a). Population increases are often most rapid in urban areas away from the rigours of a rural subsistence life, and where there are usually better medical and social services. This is aggravated by a migration to urban areas with the lure of possible cash employment (Curfs & Rockwood, 1975; Anon, 1977; Terman & Hart, 1977; Prior & McPhillips, 1980), which is more attractive than manual labour on the land, particularly to the increasingly educated youth (Akobundu, 1980a). Compulsory education has also reduced the availability of child labour in a number of countries (Haswell, 1972). Thus in some areas the proportion of the population which must be fed by the agriculturally active sector is increasing, yet the net yield per grower may actually be declining (Okigbo, 1978; Prior & McPhillips, 1980).

Many developing countries have had to import food, although even this does not always provide the recommended nutrition levels (Mayer, 1976). Imports are also required to fulfil the sophisticated demands of urban populations which are not satisfied with local produce, e.g. in Senegal (Franke & Chasin, 1981). This puts a strain on fragile economies and may lead to excessive dependence on a few food exporting nations.

Economic development policies have been generally based upon industrialisation, but these have usually failed, leading to a greater awareness of the need for rural development as a basis for prosperity (Darling, 1975). Industrialisation cannot succeed without a firm agricultural base (Onyemelukwe, 1979), yet agricultural development needs the spending power of a non-agricultural population to demand food (Johnston, 1964). In many countries industrialisation and demand for food have grown more rapidly than agriculture, but there seems to be little chance of offsetting the cost of food imports by increasing industrial exports. This has been recognised in the most recent Nigerian development plan (Anon, 1981) in which agriculture is the only sector where spending has not been cut due to the economic problems.

While there has been a tendancy to increase the size of farms for technical and economic reasons, sociological and political factors are moving the emphasis towards smaller units (Watts, 1977). Small-holder farmers form a very poor group, but have a political potential which governments cannot ignore, and could produce quantities of food which would reduce import bills. External aid and funding policies have become directed more towards helping small farmers, often to try to maintain political stability. However, the farmers must be persuaded to change from self-sufficiency towards raising their output to produce an excess of food for sale to others. They must become commercial, changing their priorities from output per person to output per unit area, but higher financial inputs increase the risk associated with potential crop losses. Where rains are unreliable farmers are unwilling to invest because of the chance of crop failure, unless there are striking advantages in a particular technique (Terman & Hart, 1977; Hildebrand, 1979; Vernon, 1980).

In regions which are easily accessible to small towns, with good transport facilities but few opportunities for employment, this commercial attitude may already exist, as has been reported in Sarawak (Haswell, 1974). This contrasts with the preoccupation with subsistence in very remote areas, and with the vicinities of large urban concentrations and regions of migratory employment, where farms meet subsistence needs, but cash employment is available as a main source of income (Haswell, 1973; Onyemelukwe, 1979). Farming for profit remains a high risk occupation from which only a few innovators can make a good living, and only with the incentive of a two or three fold increase in net income compared to non-agricultural sources will farmers treat agriculture as a business (Haswell, 1974; EFSAIP, 1977). Unfortunately, the introduction of more modern, labour efficient systems of husbandry is likely to be profitable to a few, while increasing the poverty of others because they present fewer opportunities for employment. This is particularly important in the densely populated areas of Asia (Whyte, 1981), where the effects are likely to be most harmful to the least privileged members of the society (Capinpin, 1975; Binswanger & Shetty, 1977). For this reason there is a trend towards thinking of integrating small industry and the service sector into rural development programmes (Villegas, 1974).

The potential for increasing food production is mainly determined by three complex factors: climate and geography, decisions made by the farmer and external influences (governmental, international, etc.). These have been reviewed by many authors (e.g. Johnston, 1964; Haswell, 1974; Darling, 1975; Beaumont, 1977; Watts, 1977; Onyemelukwe, 1979; Wijewardene, 1979; Ruthenberg, 1980). The optimal use of the resources available, by the introduction of low-cost, technical innovations, could expand the farm output in most countries. For example, where labour is a limiting factor, more rapid weeding would increase crop yields by reducing competition, and would allow other crops to be sown at the optimal time (Ogborn, 1969; Shetty, 1979). Such changes require considerable local research to make them appropriate to local conditions and attractive to the farmer.

1.1. Traditional Agriculture

Shifting cultivation and bush-fallow are the predominant traditional practices over most rain forest and savannah regions of the tropics and sub-tropics (Ruthenberg, 1980), providing a means of subsistence for over 200 million people

(Moody, 1975). Although these practices are found mostly in Africa, about a third of farmland in the densely populated parts of S.E. Asia can be included in these categories. The available resources are used in a manner which ensures the survival of the community (Johnston, 1964), but ethnic and environmental diversity cause the details of the systems to vary. Such communities are characterised by a large proportion of manual work, and poor educational, health and amenity services, but they form a stable basis for living (Darling, 1975), in contrast to most national economies. Subsistence farming is discussed in depth by Terra (1959) and Ruthenberg (1980).

Shifting cultivation was the elementary cropping system of the early agriculture of many forested regions (Ruthenberg, 1980) but today it is practised only where the population is sparse. Short periods of cropping alternate with longer periods of fallow, which restore fertility and suppress weeds (Moody, 1975; Akobundu, 1978b). The bush fallow is a more settled system in which land is cultivated according to a rotation of crops, including a fallow. In both systems the fallow period has become shorter under the pressure of increasing populations and limited land availability, e.g. East Nigeria (Olatunbosun, 1975), Indonesia (Suryatna & McIntosh, 1977), Zaire (Terman & Hart, 1977), East Cameroons (Atayi & Knipscheer, 1980) and the Ivory Coast (Deat, 1981). This reduces fertility and increases the weed problem, necessitating the use of extra inputs to maintain crop yields.

The characteristics of small farm economies have become more diverse, ranging from true subsistence through some cash cropping (often cotton) to long term crops such as banana, tea or coffee. In all cases the farming involves low levels of income with limited access to technical advice and finance, which are taken for granted on large farms.

1.2. Traditional Weed Control

Weeds are a major cause of yield losses in least developed agriculture, resulting in a loss of 25% of yield worldwide, even after weed control operations (Parker & Fryer, 1975). Cramer (1967) estimated a net loss of 35% of maize yield to weeds and many authors quote greater losses for specific examples, with complete crop loss if the weeds grow unchecked. They are a major factor restricting the development of cash cropping from subsistence farming (Parker, 1968).

There is a critical period from 10 - 30 days after crop germination when many tropical crops should be kept free from weeds (Nieto et al, 1968; Kasasian & Seeyave, 1969). Although weed control by small-holder farmers is said to be timely in some regions with adequate labour, e.g. N.E. Brazil (Young et al, 1978) and parts of India (Davies & Shetty, 1981), there is an apparent lack of awareness or apathy about the need for timely control in others (Parker & Fryer, 1975; Kasasian, 1978). This could be due to the farmer's inability to cope with the volume of weeds, or an unconscious attempt to minimise erosion and maintain soil moisture by providing a mulch (Ruthenberg, 1980):

Traditional farming systems have evolved to minimise the effects of weeds, with the fallow as the basis of weed control (Moody, 1975; Akobundu, 1978b; Carson, 1978; Nyoka, 1978). The composition of the weed flora changes from relatively easily controlled annual broad-leaved weeds, soon after clearing the natural vegetation, to perennial species which are difficult to control by hand-hoeing (Suryatna & McIntosh, 1977; Moody, 1980). Fallowing provides a natural method of suppressing these weeds.

Multiple cropping is common in shifting cultivation and bush-fallow systems. The complexity of the cropping varies, but weeds are usually less of a problem than in mono-cropping (Moody, 1975) due to greater ground cover reducing the competition by weeds. The inter-cropping of short season crops with long season crops prevents weeds from adapting to the growth cycle of any given crop (Akobundu, 1978b) but mixed crops are more difficult to hand-weed. The actual crops grown also affect weed suppression: maize is better able to compete with weeds than beans, so farmers in Mexico grow a greater area of maize (Nieto et al, 1968).

Cultivations may also be modified to cope with difficult weeds. In Nigeria, the Gichi system of splitting ridges made in the previous season occurs mainly in heavily cropped arable regions, where it is used to control the grass weeds characteristic of these areas (Ogborn, 1979).

During the cropping season weeds must normally be removed from the crop, traditionally by hand-pulling (particularly for parasitic species), hand-hoeing or slashing. Although the development of implements has taken many generations, they may not be ideally suited to their purpose because of the materials available for their construction, and environmental and socio-economic factors (Hopfen, 1969). Hand-hoes tend to be short handled, but there is considerable variation in design (Binswanger & Shetty, 1977; Andrews & Sheldrick, 1979), often with potential for considerable improvement (Druijff & Kerkhoven, 1970b;Druijff, 1972). Ox-drawn inter-row weeders are used in some parts of Africa which are free of tsetse fly (Akobundu, 1980a), but the oxen must be fed in the dry season and their strength is highly susceptible to periods of drought reducing the availability of fodder (Stokes, 1963; EFSAIP, 1977). Intra-row weeds must still be removed by hand.

TRADITIONAL MANUAL WEED CONTROL

Advantages	Disadvantages
low risk	hard work
uses family and other labour	time and labour consuming
involves cultural control	fallows not always practical
familiar to the farmer	poor timing of operations
	fodder required for oxen

1.2.1. Labour and hand-weeding

Weeding takes up a high proportion of the time invested in growing a crop (Table 1.1). The time required for hoeing depends on a number of factors:

i) Volume and species of weed present

Perennial grasses with their underground rhizome systems require much more effort than annual broad-leaved weeds.

ii) Priority given to the crop

Food crops are often given priority for weeding compared to cash crops such as cotton (Parker, 1972; Ogborn, 1977; Carson, 1979) or tobacco (Sharman, 1970), although

Table 1.1 Time Spent Weeding in Small Scale Manual Farming During a Season

Crop	Country	Weeding (Hours/Ha)	% Total Labour	Source
maize	Ethiopia	39	54	Akobundu (1980a)
"	Ghana	43	38	Akobundu (1980a)
"	Malawi	57	48	"
"	Nigeria	30	36	"
"	Upper Volta	42	54	"
"	Zambia	65	48	"
"	"	13	-	Vernon (1980)
millet	Senegal	298	59	Ruthenberg (1980)
upland rice	Nigeria	477	38	Fawole (1979)
"	"	500	-	Wijewardene (1979)
"	Sierra Leone	683	32	Nachtigal (1981)
cassava	Colombia	48	55	Doll *et al* (1977)
"	Nigeria	45	25	Akobundu (1980a)
"	"	112	56	Fawole (1979)
groundnut	Senegal	152	45	Ruthenberg (1980)
yam	Cameroon	120	30	Akobundu (1980a)
"	Nigeria	70	22	"
"	"	396	47	Fawole (1979)
maize & cowpea	"	280	-	Wijewardene (1979)
maize & sorghum	Tanzania	31	27	Ruthenberg (1980)
maize & beans & rice	Costa Rica	329	31	"
rubber	Sri Lanka	60	5	"
"	Thailand	135	45	
sugar cane	India	576	17	"
"	Kenya	480	26	"

Hernandez (1978) reports that food crops in Senegal are sometimes abandoned to allow cash crops to be weeded.

iii) The age of weeds

The time required for weeding increases rapidly with the age and size of the weeds (Druijff & Kerkhoven, 1970a; Renault, 1972; Jennings & Drennan, 1979).

iv) Weather conditions

Weed control operations are carried out mainly in the rainy season when conditions are too wet for effective hoeing (Parker, 1968, 1972; Carson, 1978) and when farm workers are most likely to be in poor health, reducing their output (Terra, 1959; Abalu & D'Silva, 1980).

v) Holidays

Local and other holidays delay weeding

Certain rural regions of the tropics and sub-tropics experience labour shortages at the peak times of labour demand by agriculture. Ruthenberg (1980) suggests this situation often occurs where cropping is highly seasonal and there is a high population density, with under-employment during much of the year but with insufficient labour for the peak requirement at the start of the rainy season. In semi-arid conditions all crop work must be carried out quickly following the first rains. Cultivation, planting and weeding may be concurrent, and timely operations require abundant labour. The peak in demand is usually caused by weeding and, when land is freely available, the size of the farms can be limited by the area which the farmers can weed adequately (Stokes, 1963; Hammerton, 1974; Moody, 1975; Atayi & Knipscheer, 1980; Miller & Burrill, 1980; Ruthenberg, 1980). There are numerous references to areas where labour is becoming increasingly scarce and expensive at peak times, e.g. Brunei (Groome, 1979), Costa Rica (Conklin et al, 1982), Egypt (Zahran et al, 1976), Gambia (Terry, 1981), Guatemala (Hildebrand, 1979), Nigeria (Akobundu, 1980a) and Zambia (Vernon, 1980). In other countries such as Ghana, Mali, Sierra Leone, Uganda (Akobundu, 1980a) and Togo (Zehrer, 1978) the labour is cheap but too scarce to be easily available as required. The problem is more serious because of the tendency towards shorter fallows and, in some regions, because tractors or ox-ploughs cultivate an area too large to be weeded adequately by hand, e.g. Peru (Versteeg & Maldonado, 1978) and West Africa (Cheze, 1979; le Moigne, 1980). The resulting late weeding reduces crop yields, and may lead to the late sowing of crops given a lower priority, which will also yield poorly (Hood, 1979). Improved cultivars of various crops may be less competitive than local varieties, requiring more intensive weed control (Shetty, 1979) particularly since they may not respond optimally to fertilizers without weed control.

Overcoming the weeding bottleneck could increase the potential yield per unit area as well as increasing the area cropped, and relieve the drudgery of weeding, allowing time for other activities (Parker, 1968; Fawole, 1979), but other factors (e.g. harvest) are likely to become limiting in its place.

1.2.2. Improving methods of weed control

Cultural, mechanical or chemical methods can be used to improve traditional weed control techniques. In 1965 a report suggested that agricultural development in Nigeria should be based on improved hand tools, with the introduction of new tools for weeding (Anon, 1965). The situation today is little changed and although improvements can be made on traditional hand-hoes, they are unlikely to increase the output significantly. Inter-row slashing is considerably faster than hoeing, and appears to be as effective in maize (Thomas, 1978). A hand-pushed mechanical weeder has been introduced for inter-row weeding in Rice (de Datta, 1972) but it is now little used in spite of the lower labour requirement compared to hand-hoeing, although no specific reason was given (Navarez & Moody, 1980). Ox-drawn inter-row cultivators are used in some areas, and have a potential saving in labour for weeding of up to 80%, but they are not popular on heavy soils for a variety of reasons (Ogborn, 1979) and they leave weeds in the crop row which must be hand-hoed. Very good control of weeds has been obtained both between and within the crop rows by using a hoe-ridger (Terpstra & Kouwenhoven, 1981), which could be a useful implement for ox farmers.

Herbicides are attractive primarily where labour is scarce and expensive, otherwise their cost is not recouped by increased yield and a reduced labour requirement. This is well illustrated by the use of herbicides in rice in East Asia, primarily in Korea, Japan and Taiwan (de Datta, 1972), although their use is now spreading as wages rise (Birowo, 1977) and transplanted rice is replaced by direct seeded rice. However, herbicide treatments which are sufficiently cheap to be attractive are likely to leave some weeds which must then be hand-hoed. Certain weed species, such as *Cyperus rotundus*, are difficult to control by hand or mechanical weeding alone and an integrated control method involving a herbicide is required (William, 1976).

The prevention of weeds from producing seeds and the sowing of clean crop seed are the basis of a weed control programme, and simply planting the crop in rows on well prepared land would significantly simplify weed control in some areas, e.g. Botswana (EFSAIP, 1977) and Indonesia (Suryatna & McIntosh, 1977). Cultural weed control by manipulating agronomic factors can then be used to maximise the effect of mechanical or chemical methods. The exact requirements for improvement of weed control vary, and are closely related to the resources available to the farmer.

1.3. Status of Herbicide Use by Small-holder Farmers

Herbicide use is virtually unknown on small farms in much of the tropics and sub-tropics, except in regions where the farmers gain cash income from farm crops. On small farms in south-east Asia granular formulations are used in paddy rice (Feuer, 1975; Parker, 1976), where the herbicide is distributed from the granules by water in the paddy, overcoming the need for accurate application methods. In upland rice the introduction of granules has been less successful because of unreliable results due to poor application methods (Parker, 1976). Herbicide use in rice in Thailand has recently been encouraged by the introduction of shaker bottles (Gosney, 1980). In Latin America a greater proportion of small farmers gain a cash income from farming and consequently more herbicides are used. 2,4D has been used for 25 years by small-holders in Colombia (Rogers & Meyhan, 1965) and for several years in Peru and Honduras (Doll, 1976). Farmers in Guyana commonly use 2,4D and propanil for weed control in rice grown for cash, although little herbicide is used in other crops (Croxford, 1980). Shielded sprays of paraquat are used in maize in Columbia (Doll, 1976) and paraquat is now used in no-till farming in parts of Central America (Hayward _et al_, 1981). A few farmers in Kenya (Ngugi, 1978) and Zambia (Parker & Vernon, 1982) now use triazine herbicides in maize.

Herbicides are most commonly used by small-holder farmers who have worked on plantations and seen the advantages of herbicides. Paraquat is used in coffee grown on small farms in Kenya (McPherson, 1980), while pre-emergence herbicides have been introduced in sugar cane in Bolivia (Doll, 1976) and cotton in the Ivory Coast (Deat, 1981). In Costa Rica, herbicides are widely used in plantation crops which has encouraged small farmers to experiment with their use in maize (Conklin _et al_, 1982).

There is a great contrast in the level of technology of weed control between small farms and estates or plantations, where the introduction of herbicides has been relatively easy (Parker, 1972). The few estates and plantations are attractive customers for agrochemical distributors since they provide a large market which is easily serviced, particularly since they often employ experienced expatriot agronomists and have large financial resources. The vast numbers of small farms are not as commercially attractive, and herbicides are rarely easily available in small farm areas due to the packaging, distribution and extension problems.

The reasons for the lack of herbicide use on small farms have been reviewed by Hammerton (1974), Aebi (1976) and Deuse (1978). Small-holder farmers are largely unaware of herbicides. There are few extension workers in most countries: 1 to every 2,500 farmers in Nigeria, 1:200 in India and 1:250 in Kenya (Anon, 1981), and it can be technically difficult to recommend herbicides for use in complicated cropping systems, particularly to illiterate farmers. The cost of herbicides is often restrictive, particularly with the risk of crop failure and the sometimes low market value of the crops. When labour is plentiful the use of herbicides is not socially acceptable or economically viable, while the large volume of water required is itself a disadvantage when water is in short supply, and considerable labour may be required to carry it long distances to the field.

Education, extension and economics are probably the main factors limiting the transfer of modern weed control technology to small-scale tropical farms, but correctly directed research could ease these problems by producing safe, simple and cost effective treatments (Parker, 1976). Unless the application of the herbicide is accurate the herbicide may be over-dosed, harming the crop, or under-dosed, reducing weed control. Either of these results is likely to discourage the farmer from using the herbicide, and a simple but accurate and reliable application method could encourage the acceptance of herbicides by small farmers.

1.4. Constraints for the Design of a Sprayer

In 1975 Ogborn suggested there was an urgent need to develop an improved spinning disc sprayer to overcome the application problems associated with tropical small-holder farmers. A list of constraints was made:

i) Cheap

It must be cheap enough to be economic for use by small-holder farmers over a minimum five year life.

ii) Conditions of use

Small farms less than 10 ha, particularly in areas of dry savannah; terrace agriculture where large machines are impractical; in conjunction with no-till cultivation methods.

iii) Acceptable

It must be completely acceptable to the farmer and economical to use by giving increased crop yields and by saving time and labour.

iv) Low volume spraying

Minimise the spray volume to reduce problems with the availability and transport of water; possibly reduce herbicide dose rate.

v) Ground metering

Link flow rate to walking speed to give a constant application rate independent of the walking speed, to minimise the chance of incorrect dosing.

vi) No batteries

Rotary atomiser driven mechanically or by dynamo to save the inconvenience and expense of batteries.

vii) Minimise drift

Droplets >100 µm in diameter are less likely to drift.

viii) Adjustable swath width

Spray between rows without damaging the crop, or band spray in the crop row to save expensive chemicals.

ix) Manoeuvrable

Small and light to allow use by one person but it must be robust.

x) Easy to use and maintain.

CHAPTER 2 SPRAYER DEVELOPMENT

Spraying techniques and sprayers were surveyed to decide the most appropriate design characteristics for a herbicide sprayer for tropical small-holder farmers. The construction of the sprayers and droplet formation by various nozzles is reviewed by Matthews (1979).

2.1. Hydraulic Nozzles

Hydraulic nozzles are in common use for applying herbicides and have been used successfully for most of this century with little change (Heijne, 1980). They are relatively inexpensive and are available in a variety of types which provide a range of flow rates and spray patterns. However, spray application with hydraulic nozzles is inefficient in a number of ways.

A significant amount of herbicide is wasted because of the wide range of droplet sizes produced by hydraulic nozzles. Small droplets (<150μm) are most easily retained on weeds, particularly on water repellant leaf surfaces and when the spray liquid has a high surface tension (Blackman et al, 1958; Lake, 1977); larger droplets (>150μm) have sufficient kinetic energy to cause them to bounce off the leaf (Brunskill, 1956). Suitable wetters in the spray reduce the contact angle between the droplet and the leaf surface, and droplets up to 350μm can be retained (Brunskill, 1956; Merritt & Taylor, 1978b). In a high volume spray these large droplets will merge and run off the leaf (Lake & Taylor, 1974) leading to up to 90% wastage (Fraser, 1958). However, the variability of field conditions and the need to ensure complete coverage, particularly for contact herbicides, has led to the use of higher spray volumes than should theoretically be necessary, commonly 200-300 l/ha.

Although small droplets may be optimal for retention, they are more susceptible to drift, which wastes chemical and is potentially dangerous to the operator and neighbouring crops (Combellack, 1982). Hydraulic nozzles produce large numbers of small droplets, and those below 100μm in diameter are particularly susceptible to drift (Edwards & Ripper, 1953; Courshee, 1969), so there has been a tendency to use nozzles which produce a high proportion of coarse droplets. In the tropics even large droplets may evaporate rapidly and become susceptible to drift.

High water volumes slow down application rates because of the time needed for frequent refilling of the spray tank. In the tropics the difficulty of collecting large volumes of water has inhibited the use of sprayers in some areas (Ogborn, 1975; Matthews, 1981a).

Attempts have been made to increase the efficiency of hydraulic nozzles by decreasing the drift potential and reducing the spray volume. Recent developments have reduced drift by using low pressure cone nozzles incorporating a second swirl chamber (Brandenburg, 1974; Bouse et al, 1976), but the large droplets produced by such nozzles are liable to bounce off the foliage. Full cone nozzles also reduce drift compared to hollow cones and fan jets (van der Weij, 1970). The VMD' may be increased by certain adjuvants which alter the physical properties of the liquid, and may reduce the number of small droplets liable to drift (Johnson et al, 1974; Bode et al, 1976).

Edwards & Ripper (1953) showed that volumes over 1000 l/ha were not necessary to distribute small amounts of active ingredient. Although contact herbicides performed better at high volumes (620 l/ha) than low volumes (170 l/ha) because of the improved plant coverage, this was not essential for hormone herbicides, for which 60-220 l/ha was recommended for spraying in cereals.

Recent results confirm these trends. Low volume spraying using hydraulic nozzles has been most reliable with soil acting herbicides. No differences were observed in the efficacy of chlortoluron, isoproturon or terbutryne comparing 70 l/ha with 255 l/ha in field trials or in a farm use survey (Anon, 1979a). Similar results with isoproturon are reported by Ayres (1980) and Hudson (1981), and with propazine and atrazine by Chamberlain et al (1972). Koula et al (1979) showed that thirty three herbicides had a greater activity at 50 l/ha than 200-400 l/ha, but linuron, chlorpropham and simazine were less effective at 80 l/ha than either 160 or 320 l/ha (May & Ayres, 1978), possibly because of the poor distribution of the small

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droplets produced by the low volume nozzle.

The spray volume can significantly affect the efficacy of post-emergence sprays. In a survey of 278 comparisons of post-emergence applications, there was no difference in the weed control at 100 l/ha compared to 400 l/ha in only 85 cases, and 100 l/ha was generally less reliable, particularly on moderately susceptible species (Maas, 1979). A difference in the response of weed species to changes in volume and droplet spectrum was also noted by Taylor et al, (1974). With many materials, including hormones, there is a loss of efficacy if the spray volume is reduced significantly below 100 l/ha (Bailey et al, 1978b;Lavers & Stovell, 1978; Phillips, 1978). This may be related to the nozzle characteristics since a formulated mixture of dicamba, CMPP and MCPA sprayed at 100 l/ha using an 80015 nozzle gave similar results to applications at 200 l/ha with an 8003, but both were more effective than 100 l/ha with a finer spray using an 800067 nozzle (Harris, 1978). In contrast, there was no difference in weed control by a mixture of ioxynil, bromoxynil and mecoprop at 60, 120 or 240 l/ha, when each spray had a similar VMD of over 300 µm (Ayres, 1982). Similar results were reported by Ayres & Cussans (1980). However, field and laboratory results must be interpreted with care, since the growth stage and growing conditions of the plants can affect the response to changes in volume (Hibbitt, 1969; Merritt & Taylor, 1978b).

Crop penetration is likely to be a problem with post-emergence, low volume applications, since even with conventional nozzles and volumes Hebblethwaite & Richardson (1966) showed that, while 54-64% of a spray penetrated a 150 mm high barley crop, only 26-53% penetrated a 300 mm high crop.

2.1.1. Lever operated knapsack sprayers

These are the sprayers most widely used by tropical small farmers, particularly where insecticides are applied to cotton (Sharman, 1970) or rice crops (Pickin et al, 1981). Their operation and maintenance is summarised by Sutherland (1979). High spray volumes are used, often 400-500 l/ha, and considerable skill is needed to pump and walk at constant speeds, while keeping the nozzle at a constant height above the ground. As most operators walk their body sways and the nozzle height varies, even if a chain is hung from the lance to gauge the nozzle height. When a sprayer is full the operator tends to spray more quickly to lessen the load.

There have been few recent developments in these sprayers (Matthews & Garnett, 1983). The major change has been from an all metal construction to almost entirely plastic sprayers with injection or blow moulded tanks. Uniform herbicide application is facilitated on a few machines by a control valve in the compression chamber. Impact nozzles are widely used for herbicide application with knapsacks, since they produce large droplets to avoid spray drift and can produce a wide swath, although most of the spray is concentrated at its edges (Matthews, 1979). A small orifice impact nozzle, preceded by a conical venturi, has been used on knapsack sprayers to apply as little as 30 l/ha at low pressures of 100-200 kPa (Wijewardene, 1981; 1982). Nozzle blockages are likely at such low volumes and the swath pattern and the droplet spectrum, though acceptable, are not ideal (Cooper & Johnstone, 1982). Promising results have been obtained with these nozzles using pre-emergence applications of ametryne, and post-emergence applications of paraquat (Gresley, 1982). Kasasian (1964) successfully used ordinary cone and fan nozzles with a knapsack sprayer at low volumes (<100 l/ha), and found no difference in weed control compared to high volumes (200-450 l/ha).

Sharman (1970) reviewed the application methods available for use in cash crops grown by small farmers in Zimbabwe. Knapsacks were considered suitable for areas less than 4 ha, and an ox-drawn cart with a spray boom was recommended for larger areas. A hand held boom with a knapsack sprayer and tractor sprayers were not considered suitable due to the time spent refilling the tanks.

Although much weed control research has been conducted with small farmers around the world, little consideration has been given to the application method, invariably a lever-operated knapsack sprayer. Several authors (e.g. Doll, 1976) point out the difficulties of using knapsack sprayers without considering the alternatives. Herbicide screening is often carried out with tractor mounted sprayers, but the results are difficult to translate into the practicalities of using knapsacks due to the differences in scale and accuracy, and the different nozzles used.

2.1.2. Ground actuated sprayers

Several problems of using knapsack sprayers are overcome by ground actuated sprayers. The pumping speed is directly related to walking speed and so compensates for variation in the operator's walking speed, while the nozzle is automatically held at a fixed height above ground.

There are several machines available commercially, all of which use conventional nozzles and require large spray tanks, which are heavy and unstable when full. The first was produced in 1888 (Hudson, 1981), and Mason (1932) describes an early ground actuated sprayer which used a piston pump, driven by an armature from the wheel axle. The Universal-Gerwin "2995 wheelpump" sprayer, the Jaydon "Polyrow" sprayer and the similar Triomf "Norman King" sprayer all use peristaltic pumps with tubing stretched over rollers on the ground wheel. Eho-Kone use a camwheel on a bicycle wheel to drive a single diaphragm pump, and a similar mechanism is used on the Puteaux "Herbi-net junior".

A prototype peristaltic pump sprayer tested in Nigeria showed several advantages over knapsack sprayers (Anon, 1975a). As well as being easy to use and applying a constant dose of spray over a range of walking speeds, there was the possibility of local manufacture since there was no need for an expensive pump. However, water was scarce and the high volumes of water required slowed down the spraying operation due to the time taken for filling and carriage from the water source The "Norman-King" sprayer, which was developed from this prototype, has been used successfully by small farmers in Swaziland to apply residual herbicides (Fowler, 1981), but the range of appropriate walking speeds is limited by the effect on the pressure at the nozzle, and, therefore, on the droplet spectrum.

2.2. Spinning Discs

The use of spinning discs for applying herbicides is limited to hand-held sprayers in the tropics and in forestry, and a small number of tractor mounted sprayers which are being developed and tested in the U.S.A. (Bode & Butler, 1981) and in Europe (Petrie, 1981). A more uniform droplet spectrum is produced than is possible with hydraulic nozzles, and this has led to the concept of "controlled droplet application" (CDA). CDA emphasises the importance of applying the correct droplet size for a particular target, and the need for uniformity of droplet size, to optimise the use of the minimum volume and dose to achieve effective control (Matthews, 1978). The physical aspects of droplet formation are reviewed by Hinze & Milborn (1950), Masters (1972) and Frost (1978), and disc design is reviewed by Bals (1978) and Matthews (1979).

2.2.1. Hand-held sprayers

In the early 1970's the first commercial spinning disc herbicide sprayer (the Micron "Handy") used an 85 mm diameter ULVA disc. A 6v motor with a mechanical governor turned the disc at 1840 rpm which produced 280 µm droplets (Taylor & Merritt, 1975). These have a low drift potential, but are small enough to impact on the foliage when falling under gravity, and are sufficient in number to give an adequate spray cover. The disc is angled to the ground, so some droplets are thrown into the air and may contaminate the crop when used after crop emergence. Extensive field trials produced very good results with flowable herbicides (Lerch, 1974), and this machine is now sold commercially for the application of residual herbicides, particularly metolachlor, ametryne and atrazine. The "Handy" gave slightly poorer weed control than a conventional knapsack sprayer when using atrazine plus metolachlor in trials in Zambia, but this probably resulted from the farmers walking too fast and therefore under dosing the herbicide (Parker & Vernon, 1982). After extensive field trials in the Ivory Coast (Deat, 1977), its introduction for applying herbicides in cotton is thought to have stimulated the rapid growth in herbicide use during 1979 and 1980 (Deat, 1981). The low volume of water required compared to knapsack sprayers, was a major factor in the acceptance of the technique. In Senegal spinning disc sprayers and knapsack sprayers have been recommended to small farmers for the application of residual herbicides (Hernandez, 1978).

An improved disc design was used on a subsequent sprayer, the Micron "Herbi". The disc can be held close to the ground in the horizontal plane to minimise drift and crop damage in post-emergence situations, or angled for pre-emergence spraying when wind displacement of the droplets is less important. An 80 mm diameter toothed disc is rotated at 2000 rpm by a governed motor, and a flow rate of 30 ml/s onto the disc produces droplets with a diameter of about 250 µm (Bals, 1975; Lake *et al*, 1976; Johnstone *et al*, 1977). Contamination of the operator by the spray is reduced by using a long handle. Although drift is minimised by using large droplets, wind may cause the overall displacement of the swath (Lake *et al*, 1976; Vernon, 1980) which probably accounts for the missed and under dosed areas which have been reported. A "horned" spray distribution is obtained, so a 100% overlap is required to give an even coverage (Ogborn, 1975; Johnstone *et al*, 1977). Since this doubles the spraying time per hectare a two disc unit was developed, which improved the uniformity of the swath pattern and allowed an increased ground speed while maintaining a suitable application volume (Anon, 1976a). A similar sprayer has been developed for spraying oil palm circles in Indonesia (Turner & Jollands, 1983). Several other modifications have been made to the "Herbi". A unit was powered by solar cells whose output was stabilised by nickel-cadmium cells which also stored the excess power generated in sunlight (Wijewardene, 1978a). A spinning disc supplied from a knapsack tank has been used to reduce the number of spray refills required (Anon, 1980b). As part of a new mechanisation system for small farmers, the "Groom system", a pair of "Herbi" heads have been mounted on a boom carried on a transporter pulled by a two wheeled power unit (Anon, 1980c).

There are now several similar hand-held machines on the market which have differing attributes for spraying; a combination of components from different machines could offer the best CDA system (Combellack *et al*, 1978). These sprayers are now widely used in forestry, where there are managerial advantages of using low volumes of water (Rogers, 1975), and for spot treatments of weeds.

The hand-held spinning disc sprayer has several inherent disadvantages:

i) Swath width is fixed and the ground spray pattern is characteristically "horned" when the disc is horizontal, similar to that of a cone nozzle.

ii) The droplet size depends on the flow rate, which is affected by the viscosity of the spray liquid and the "head" of liquid in the spray bottle (Johnstone *et al*, 1977; Deat, 1977). The angle at which the sprayer is held will influence the flow rate from the spray bottle when it is positioned remotely from the disc (Fuller-Lewis *et al*, 1980)

iii) Droplet size and swath width depend on disc speed. On the "Herbi" a governed motor maintains a constant disc speed when the supply voltage is between 12 and 4 volts (Johnstone et al, 1977), but on other sprayers the disc speed can fall as the voltage of the batteries declines with age (Arnold, 1983). This is particularly important in hot, humid countries where batteries have a short service life (Matthews, 1976) and deterioration has frequently started before they reach the retailer. These climatic conditions can also cause corrosion of the battery holder, reducing the life of the sprayer and the batteries.

iv) Motors are sometimes unreliable in hot, humid climates and on some models spray liquid can leak into the motor causing it to fail (Parker & Vernon, 1982; Arnold, 1983).

v) Sprayers with plastic lances may be too frail to withstand constant field use (Robertson, 1975; Combellack *et al*, 1978).

2.2.2. Ground-actuated sprayers

A prototype ground-actuated sprayer used a peristaltic pump to feed a "Herbi" disc, which was shrouded so that the spray swath could be varied (Choudhury & Ogborn, 1979). The disc was angled at 45^{o} to improve the uniformity of the swath, and the spray caught by the shroud was recycled. Unfortunately, the disc could not cope with the high flow rate required to maintain an adequate output from the shroud window at a reasonable walking speed, but promising field results were obtained from pre-emergence applications of trifluralin, dinitramine and diuron in cotton (Ogborn, 1978b). A similar prototype sprayer, with the disc driven by a speedometer cable from the ground wheel, has been designed in the U.K. (Johnson, 1978).

The Richmond-Gibson "Vortex" is a hand-pushed unit with a gravity feed onto a centrifuge driven by a "V" belt off the ground wheel. A series of holes in the periphery of the centrifuge form very large spray droplets.

2.2.3. Tractor mounted sprayers

Most field trial work with spinning disc sprayers in the U.K. has involved tractor sprayers, where the disc design had to be altered to cope with higher flow rates required to maintain the spray volume at high speeds. There have been two approaches to this problem: several small discs mounted on a single shaft (Farmery et al, 1976; Taylor et al, 1976), and a large spinning cup (Heijne, 1978) or vertical disc (Morel, 1981).

In the first, several discs are fed individually to avoid over feeding a single disc and to maintain a more uniform droplet size. The top discs were shrouded to produce an even swath, and the spray liquid collected by the shroud drained onto the bottom disc. The design has been commercially developed as the "Microdrop" applicator (Farmery, 1978).

The large spinning cup, now marketed as the "Micromax", was designed to apply 1.0 l/min at 2000 rpm to produce 250 µm droplets, but can give a fairly uniform droplet spectrum over a wide range of flow rates and rotational speeds (Heijne, 1978). The cup has 180 grooves which allow individual streams of liquid to feed each tooth on the periphery of the cup.

2.3. Comparisons of Hydraulic and CDA Spraying

The precise interpretation of the results from different authors is difficult because most do not report all the spray parameters. When comparing hydraulic and CDA spraying, a number of authors have come to different conclusions. This is partly due to the suitability of different types of herbicides for CDA spraying. The herbicides were usually developed and formulated for spraying at 200 l/ha rather than 20-40 l/ha, yet the formulation requirements for these two spray volumes may be very different (Merritt, 1976). Some of the variability of the results using spinning discs has been attributed to poorly designed equipment and untrained operators (Lush & Palmer, 1976) and to a variable flow rate onto the atomiser (Mayes & Blanchard, 1978). In dense crops penetration to the weeds may be poor using CDA sprayers, causing reduced control compared to conventional volumes (Ayres, 1978 ; Anon, 1979b). Unsprayed shadows may occur behind clods of soil or large plants when droplets fall under the momentum given to them by the movement of the sprayer. This effect is less obvious with hydraulic nozzles.

The large number of papers on CDA sprays with a VMD of 200-250 μm give a similar picture to low volume hydraulic spraying: contact herbicides are less reliable than with conventional spraying using CDA but similar results can be obtained with translocated materials.

i) Activity similar with CDA

Most soil acting herbicides give similar results by CDA or conventional applications (Barzee & Stroube, 1972; May & Ayres, 1978 ; Robinson, 1978, 1982; Anon, 1979b). The water component of the spray acts primarily as a carrier of the herbicide from the atomiser to the soil, and the distribution of the herbicide within the soil then depends on soil factors. The droplet density was shown to be of little importance if spaced up to 20 mm apart when using chlortoluron, terbutryne and propyzamide, but nitrofen lost its activity at the 20 mm spacing, possibly because it is strongly absorbed and less mobile than the other materials (Addala, 1982). This is in contrast to the suggested requirement for a minimum of 5-7 droplets <200 μm per cm^2 for residual herbicides (Lerch, 1974). The apparent difference in results is probably related to the net dose applied in the various droplet densities.

Foliage applied herbicides must be distributed over the target plant by the actual spraying process. The water component of the spray acts as a diluent to provide sufficient cover of the foliage for herbicide to enter the plant. Translocated herbicides distribute themselves within the plant and do not require such complete coverage as contact herbicides. In most tests, hormone herbicides have shown similar, or only slightly inferior, efficacy when sprayed with a spinning disc delivering 250 μm droplets, compared to hydraulic nozzles (Sokolov et al, 1970; Bailey & Smartt, 1976; Lush & Palmer, 1976; Merritt & Taylor, 1977; Erickson & Duke, 1981; Walker, 1981; Robinson, 1982) although there is some evidence that 40 l/ha might give better results than 20 l/ha (Harris, 1978; Mayes et al, 1978; Phillips, 1978; Bailey et al, 1982b). Other translocated materials have also shown similar efficacy with the two application techniques: barban (Wilson & Taylor, 1978), benzoyl-prop ethyl (Lavers & Stovell, 1978), cyanazine mixed with a hormone (Lavers & Stovell, 1978), diclofop-methyl (Ayres, 1978b). There is no positive evidence that the dose of the active ingredient can be lowered when using CDA.

ii) Activity reduced with CDA

Contact herbicides, such as ioxynil and bromoxynil (Ayres and Merritt, 1978), and bentazone (Merritt & Taylor, 1977), are less active at low volumes, with the poorest control usually at the lowest volume tested (Robinson, 1978). This is probably due to a combination of poor coverage of the foliage, and the high concentration of active ingredient in each droplet, which tends to burn a hole in the leaf (Taylor et al, 1981; Merritt, 1982a). With ioxynil and bromoxynil, alone and mixed with 2,4DP, conventional and CDA applications gave similar results with only two out of four weed species (Robinson, 1978), suggesting that the weed spectrum could explain the reduced activity of the mixture with CDA noted by O'Keefe et al (1976).

The type of surfactant and its concentration are important when comparing spraying methods. Applications of difenzoquat at 15-20 l/ha were more reliable at lower than normal surfactant concentrations, particularly with more hydrophilic surfactants (Merritt, 1976). The droplet cover achieved by a spray is probably more important than either droplet size or water volume alone (Phillips et al, 1980). In order to maintain the level of cover with low spray volumes, a reduction in droplet size is required, since the number of droplets produced by a given volume of spray will theoretically increase eight fold when the diameter of the droplets is halved. A mixture of ioxynil, bromoxynil and

CMPP, applied using a spinning disc gave improved weed control with droplets of 157-175 µm diameter compared to 250-265 µm (Bailey et al, 1982a), but this difference is not consistent (Ayres, 1982; Robinson, 1982). A coverage of at least 1% for translocated herbicides and 5% for contact materials was recommended by Sokolov et al (1978) when spraying below 25 l/ha.

iii) Activity improved with CDA

Glyphosate was more active at 15 l/ha (Turner & Loader, 1978) and 20 l/ha (Caseley et al, 1976) than at conventional volumes, and similar results were obtained by Bruge & Jean (1977). This effect appears to be correlated with the surfactant concentration, which significantly affects glyphosate activity (Sandberg et al, 1978), although even when the surfactant concentration remains constant, the activity will increase with glyphosate concentration (Merritt, 1982 b).

Another translocated material, asulam, was also more active when sprayed at 20 l/ha using a tractor mounted spinning disc sprayer, than using a conventional sprayer at 200 l/ha or a drift sprayer producing very fine droplets, at 20 l/ha (Robinson, 1978).

2.4. Granules

Granular formulations of herbicides have several advantages over sprayed formulations. They need no dilution, eliminating a major source of error, unless they are home-made as suggested by Zahran et al, (1976). There is no need for expensive application equipment since they may be applied by hand or using a pre-packed shaker bag (Terry, 1981), although wheelbarrow and knapsack applicators are available (Walker, 1961; Anon, 1980c). Granules allow easier use of highly volatile herbicides which would otherwise require incorporation into the soil (Zahran & Ibrahim, 1975), but they are not suited to the cloddy conditions commonly found on small farms (Fowler, 1981). Herbicides and fertilisers have been combined into granules (Ogborn, 1975, 1978b; Deuse, 1978) but these tend to be unstable because of pH effects. Granules are more expensive to produce than other formulations, and are very bulky which may cause problems with transport to remote areas. Some formulations may coalesce under humid conditions becoming unsuitable for use.

2.5. Choice of Sprayer Design

Tractor mounted sprayers are unsuitable for most small farms due to their size and cost, although the Geest "Groom System" (Anon, 1980d) may be useful for some richer farmers. The most common alternative is the knapsack sprayer, or a hand-held spinning disc sprayer. Although these are relatively cheap, they are not completely satisfactory for use on small farms in the tropics,where applicators must be particularly reliable and easy to use (Steele, 1965; Watts Padwick, 1968; Parker, 1976) to minimise the occurrence of unacceptable results.

The dose applied by knapsack sprayers depends on four variables: the concentration of the herbicide in the spray solution, the walking speed of the operator, the pressure maintained in the spray tank, and the height of the nozzle above ground. In high volume spraying the operator must always measure the concentrate and dilute with water, which are major sources of error because of inaccurate measurement or misunderstanding the dose recommendations. When the tank is full the operator tends to walk more quickly to lessen the load, as he tires it becomes difficult to maintain the pressure, and as he walks his arms sway and the nozzle height varies. All result in incorrect dosing. The collection of large volumes of water for spraying wastes time and energy, and where water is scarce spraying competes with drinking and washing.

The dose applied by spinning disc sprayers depends primarily on the herbicide concentration in the spray bottle and on the walking speed of the operator. However, several ready formulated products are now sold in bottles which screw directly on to the sprayer, so that no dilution is required, e.g. Primagram Moto (10% atrazine & 10% metolachlor).

The maintenance of a uniform walking speed is necessary with both types of sprayer. Metronomes have been designed to help the operator gauge his speed (Arnold & Thornhill, 1978), but if the operator is distracted from spraying he is likely to slow down, resulting in an over-dose of the herbicide. Only by directly relating the spray volume to the ground speed can this be overcome. Although a number of mechanisms are available for tractor mounted equipment (Allan, 1980) they are unsuitable for use on hand operated sprayers. The only practical way to apply a constant spray volume along a swath is to relate the flow of liquid to the nozzle to the walking speed, using a ground wheel as the metering device.

The low water requirement and the possibility of avoiding the need to dilute the herbicide make hand-held spinning disc sprayers attractive for farmers in the tropics. However, Parker (1976) suggested that a more rugged design was needed, using man-power and mechanical propulsion rather than batteries and electric motors. The introduction of a large spinning cup allowed a higher volume to be sprayed than is feasible with spinning discs (Bals, 1978). It can be shrouded giving control over the swath width while maintaining an application rate of over 20 l/ha, at which a large range of herbicides is likely to be effective. In combination with ground-metering, a shrouded spinning cup forms a suitable basis for the design of a sprayer in the form of a wheelbarrow.

2.6. Physical Considerations For The Sprayer Design

The basic components of the sprayer are the spinning cup, a shroud, a wheel, a pump to draw liquid from the spray tank, and a handle for the operator. Although the spinning cup will probably be imported, the other parts should be designed with the aim of local production.

2.6.1. Spinning cup drive

There are several possible drive mechanisms for the spinning cup:

i) Friction drive: the spinning cup is fixed to a spindle which is pressed against the rim of the ground wheel.

ii) Chain or belt drive from the wheel axle, converted by gears to drive the cup.

iii) Speedometer cable drive from the wheel axle or rim.

iv) Hydrostatic drive: the spray liquid is fed from a ground wheel driven pump on to a Pelton wheel before it is fed onto the cup.

v) Ungoverned electric motor powered by a dynamo linked to the ground wheel, so that the voltage produced increases with the walking speed.

The friction drive was chosen for its simplicity, although blockages could be forseen in muddy conditions. The spinning cup axis must be on a radius of the wheel and the cup must be close to the wheel so that the spindle is not too long. This limits the position for mounting the spinning cup compared to the indirect drive mechanisms.

2.6.2. Shroud mounting configurations

A shroud is mounted around the spinning cup to produce a uniform swath of variable width. There are three alternative positions for the shroud (Fig. 2.1): on a cantilever either in front or behind the ground wheel, or mounted directly above the wheel. Only the third position is possible if a direct drive is used. The stability of the sprayer, and the degree to which the movements of the operator change the position of the swath, are both affected by the configuration chosen.

There are three components to movements of the sprayer and its swath when the operator walks:

Operator Movement	causing	Swath Movement
Deviation from straight course		Lateral (horizontal plane)
Swaying of the body		Lateral (vertical plane)
Up and down while walking		Up and down

The actual change in swath position resulting from a 20° change in handle position has been calculated geometrically for the second prototype sprayer, assuming the spray has a horizontal throw of 0.8 m, and the shroud window is 120°. Three spinning cup mounting positions were tested, with a 20° lateral movement of the sprayer handles in the horizontal plane (Fig. 2.2). The effect on the swath movement was magnified when the shroud was mounted further from the operator. In contrast, the lateral movement of the swath in a vertical plane had a minimal effect on the swath width under most circumstances, but the effect of the up and down

Fig. 2.1 <u>Sprayer Configurations</u>

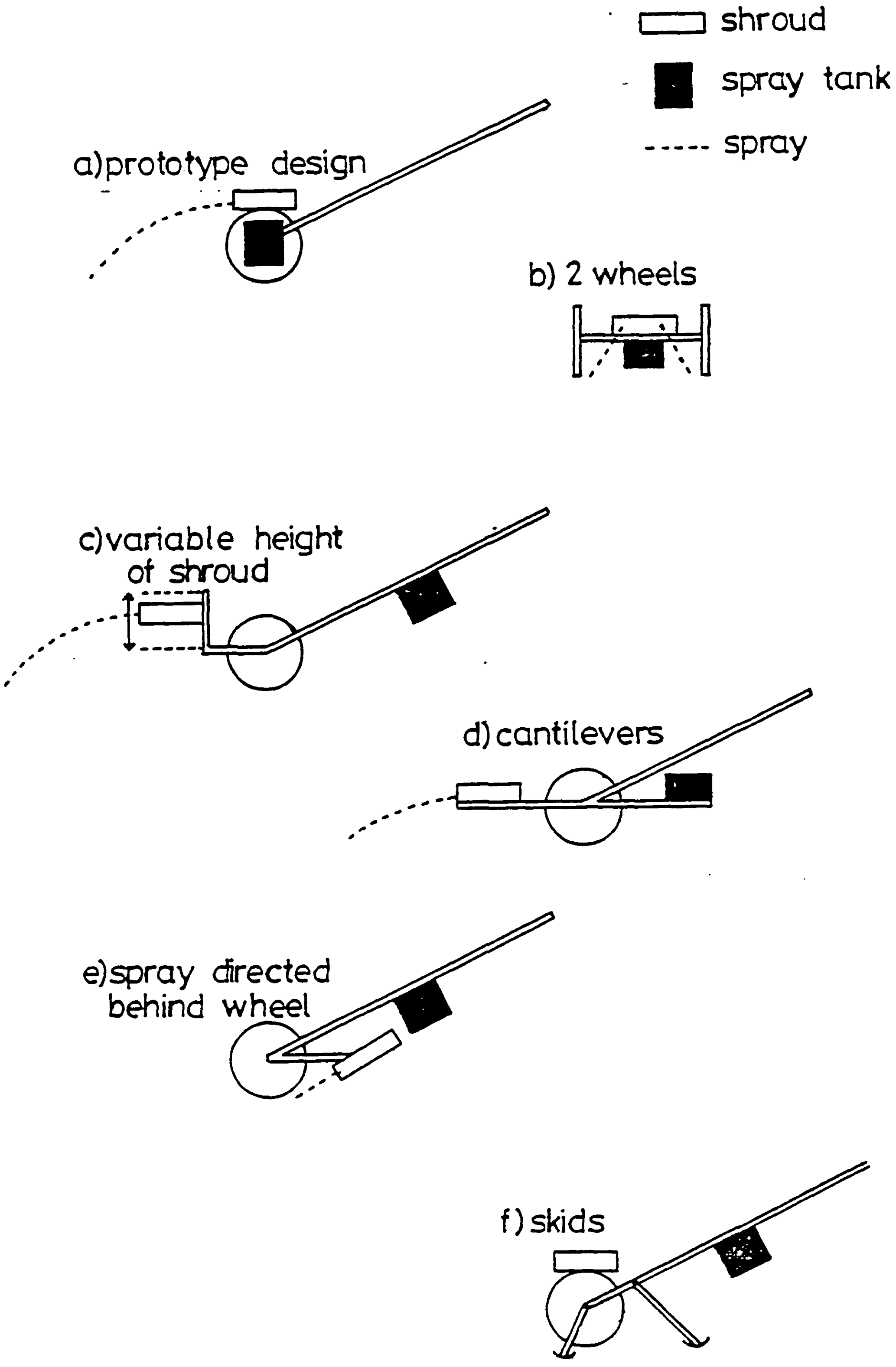
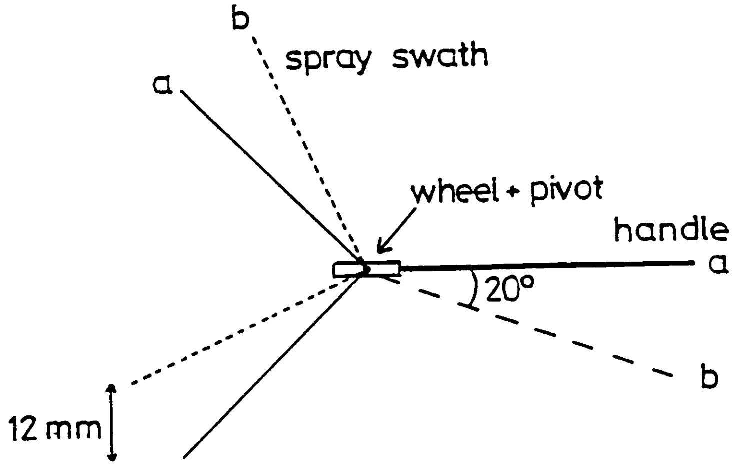
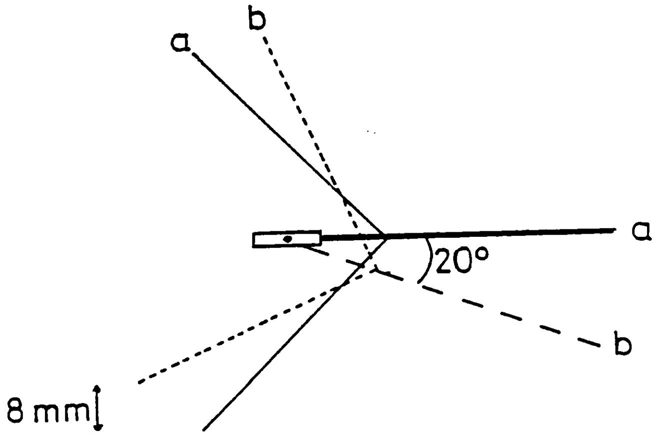


Fig. 2.2 Effect of Lateral Movement of Sprayer Handles on the Position of the Swath

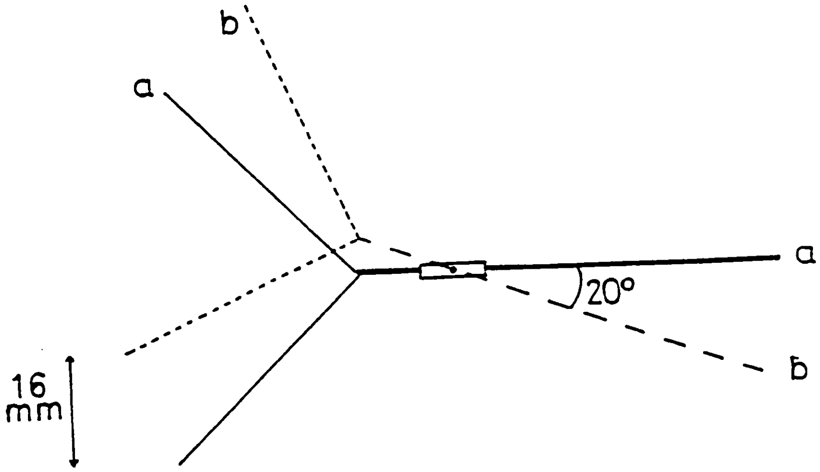
a) shroud above wheel



b) shroud behind wheel



c) shroud in front of wheel



movement is least when the cup is mounted directly above the pivot point. The degree of movement transmitted from the operator to the sprayer is reduced when a longer handle is used (Table 2.1). A long handle (>1.0 m) will accommodate the heights of different operators, and since hand height varies less than total height, there should be no need to adjust the angle of the handle. The handle must be long enough to prevent the operator kicking the sprayer as he walks, but if it is too long the sprayer becomes unstable and difficult to control. The swath movement is least when the shroud is between the operator and the wheel, and angled to spray a swath which hits the ground immediately behind the wheel (Fig. 2.1e).

Table 2.1 Theoretical Effect of Handle Length on the Transmission of the Operator's Movements

Handle Length (m)	Change in Handle Angle for a 0.2 m Change in Hand Height (°)
0.5	22
0.75	15
1.0	11.5
1.5	8

The position of the shroud affects the centre of gravity of the sprayer. A small ground wheel with a low shroud is the most stable option, but a very small wheel has poor traction, increasing the risk of wheel slip and inaccurate metering of the spray liquid. The shroud must be at a height which allows most weeds to be sprayed, while not being so high that the spray becomes very susceptible to drift. A height of 0.3-0.5 m above the ground is probably the optimum, but using a transmitted drive would allow the height to be varied as required.

Any configuration of shroud mounting will allow some swath movement, which may be minimised by the use of skids to balance the sprayer and maintain the correct angle. A skid behind the wheel and one on either side are required (Fig. 2.1). The skids should have a limited vertical play so that they glide over uneveness on the ground without affecting the sprayer, but if a transmitted drive is used to turn the cup the shroud unit may be mounted on a separate skid unit pulled behind the ground wheel. The swath would then be unaffected by most movements of the operator.

A two wheeled sprayer with the shroud mounted between the wheels would have great stability, but the swath would constantly change due to the independent vertical movements of each wheel. The manoeuvrability is poor, and the cost and weight are greater compared to a single wheeled unit.

2.6.3. Pump and spray tank mounting

The pump may be either mounted directly on the wheel axle, or separately with a chain drive off the wheel. The latter is necessary if gearing is required to turn the pump at a different rate to the wheel. The pump should be enclosed to prevent vegetation from becoming entangled with the mechanism.

The spray tank should be mounted low to maintain a low centre of gravity, particularly since the swilling of liquid in the tank can have a marked effect on the stability of the sprayer. The tank should also be below, but close to, the shroud, to allow the liquid to drain rapidly to the tank. The length of tubing from the tank to the pump and the shroud should be as short as possible so that the spray will be emitted from the shroud soon after the operator begins to walk. A single tank placed behind the wheel is most convenient for filling and cleaning. Its capacity should be sufficient to spray 0.5 ha, to minimise the number of refills.

2.6.4. Ground wheel

The wheel must have good traction to prevent slippage with the ground (which affects the pump output) and with the friction drive (which affects the rotational speed of the spinning cup). The wheel rim should be about 50 mm wide, which has proved adequate to prevent sinking and slippage of the metal wheeled Norman-King sprayer (Fowler, 1981). A rubber rim would minimise slippage of the friction drive, but the rubber must be solid to avoid punctures, although solid rubber wheels may be less easily available than bicycle wheels.

2.7. First Experimental Prototype

The first prototype (Fig.2.3) was built to explore the practicality of using a wheelbarrow design, and was used as a basis on which improvements could be made. Detailed diagrams of the design are given in Appendix 1.

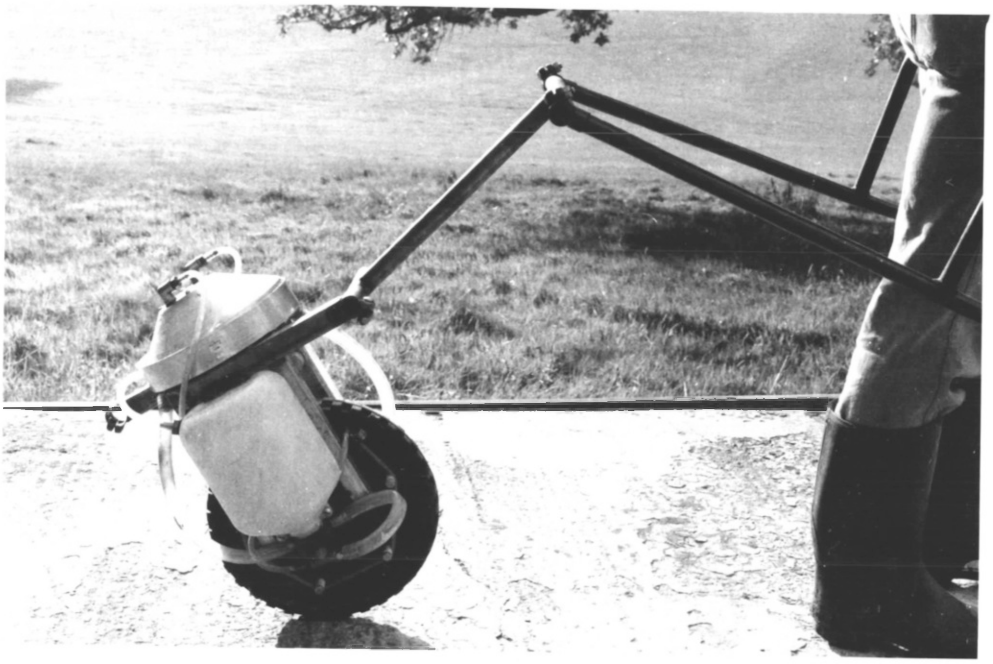
A shrouded "Micromax" cup was mounted on a wheelbarrow framework, with a peristaltic pump mounted on each side of the wheel. The pumps consisted of a length of tubing stretched over a ring of six rollers, each 0.1 m apart, with one end connected to the output from the spray tanks, and the other end attached to the feed to the spinning cup. The connectors at the ends of the tubing were hooked on to the sprayer framework to hold it in place. As the wheel rotated, the rollers pressed against the tubing, forcing slugs of liquid along it to a nozzle in the shroud top. This fed into a fixed cone which funnelled the liquid into the base of the spinning cup. The shroud window released a 90° sector of the spray produced by the cup.

The spinning cup was rotated by a friction drive with a spindle pressed against the drive wheel by a spring acting against the main framework. This allowed for any unevenness on the wheel rim, but caused the cup to move slightly within the fixed shroud,which affected the position of the swath on the ground. Both the spinning cup and the pump were directly related to the walking speed, and varying the flow rate and atomiser speed in proportion should theoretically maintain a similar droplet spectrum over a range of walking speeds.

The framework of the sprayer folded into a compact unit suitable for easy packing and transport, with the handles folding back over the sprayer to protect the moving parts.

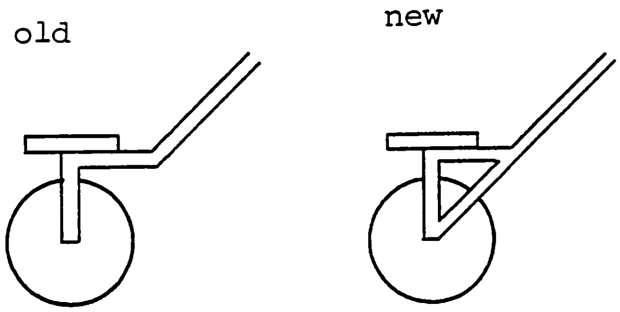
Preliminary testing of the sprayer encountered serious problems with the peristaltic pump, and showed several design faults (Garnett, 1978). The pump tubing walls were too thin for the tension required to produce an adequate flow rate, and split after less than thirty minutes use. The tubing life was also reduced by the poor method of connecting it to the framework. This pump was replaced by a commercially available, three roller peristaltic pump with more suitable characteristics.

Fig. 2.3 First Prototype Wheelbarrow Sprayer



In these early experiments the sprayer was pushed, but, due to the method of attachment of the handles, they collapsed if the ground wheel was pushed against an obstacle. This was overcome by attaching the handles to the wheel axle which directed the pushing force to the axle rather than to the shroud above the axle (Fig.2.4).

Fig. 2.4. Attachment of Handles to Sprayer



The shroud window was widened for later experiments, and sliding plates added to allow the swath width to be varied. While spraying, liquid did not drain adequately from the shroud and this was not improved by the incorporation of an air bleed in the system. The problem was overcome by returning the liquid to the top of the spray tanks rather than the bottom. It was difficult to drain the tanks and pipes for cleaning without disconnecting them, and they had to be filled by pouring liquid into the shroud which then drained into the tanks.

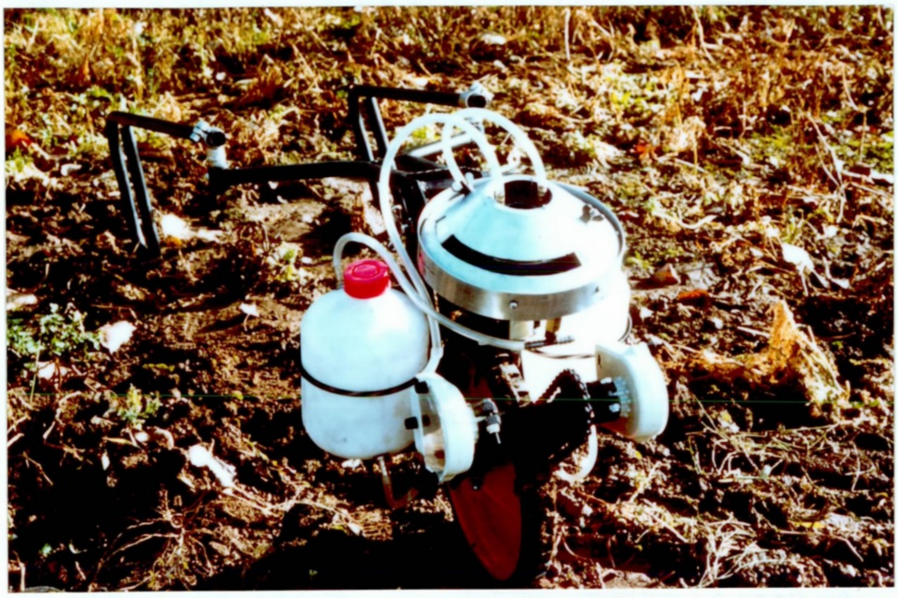
Other problems specific to particular components are discussed in Chapter 4.

2.8. Second Prototype

The second prototype (Fig.2.5) used the same drive mechanism as the first, but it was built on a new frame incorporating several major improvements to the design which are illustrated in detail in Appendix 2.

A pair of commercially available Glen Creston two roller pumps were set 90° out of phase and their outputs were combined to produce a flow of liquid which pulsed less than the output of the pump used on the first prototype. The pumps were fixed to a shaft turned by a chain drive from the ground

Fig. 2.5 Second Prototype Wheelbarrow Sprayer



wheel axle.

The rim of the ground wheel was not perfectly uniform. On the first prototype this caused the spinning cup to move within the fixed shroud, but on the second, the cup and shroud were combined in a unit which moved as a whole. The shroud unit could be lifted to either side of the wheel so that the sprayer could be pushed or pulled in experiments, provided that the tubing to and from the pumps was reversed. The mounting was more complicated than that of the first prototype but it was more robust and useful for experimental work.

The second prototype was more manoeuvrable than the first since the handles were attached to the axle rather than to the top of the frame. The method of attachment of the handles to the framework was also improved. The framework consisted of ¼" flat steel which was cheaper and probably more easily available in the tropics than the box sections used on the first prototype. However, the latter were lighter and possibly more suitable if the sprayer is to be built in the U.K. for export.

The spray tanks were upright for easy filling, and they could be removed for cleaning.

Specific components are discussed in Chapter 4, and field testing is described in Chapter 5.

CHAPTER 3 MATERIALS AND METHODS

3.1. Stationary Drive Unit for the Sprayer

The sprayer was held stationary on a framework to allow it to be observed in action. The wheel was turned by a universal motor with a variable speed control. The angle of the sprayer could be adjusted to allow horizontal or angled spraying, and a digital counter measured the number of turns of the wheel, from which the equivalent walking speed could be calculated:

60 m/min = 62.6 revolutions of the wheel per minute.

The drive unit was used in patternator and droplet sizing experiments.

3.2. Peristaltic Pump Testing

The physical characteristics of the pumps were examined by measuring the flow rates produced under a range of operating conditions. The first pump to be tested was mounted on the ground wheel of the sprayer which was turned by the stationary drive unit. Subsequently pumps were driven directly by the motor.

Two methods were used to measure the flow rate. The total flow per minute was taken in a measuring cylinder, while an electronic flow meter, based on a Pelton turbine (Wemyss, 1978), measured the instantaneous flow rate. The flow was measured at the end of a 35 mm length of tubing to correspond with that on the sprayer. The second method estimated the variability of the flow, although its response time was too slow to measure accurately the pulses of liquid produced by the pumps. Water was the normal test liquid, but, since the meter was sensitive to viscosity, it was recalibrated when other materials were tested. All gave a linear response in the range of flow rates involved.

3.3. Materials Testing

The reaction of several sprayer components to potential spray liquids was tested using a method similar to that of the British Crop Protection Council Central Testing Scheme.

Small sections (5-10 g) of the material were weighed, submerged in the test liquids for 48 hours, then carefully washed, dried and re-weighed. Any changes in appearance were noted.

A second length of the two types of pump tubing was treated similarly for 48 hours, but then placed in a clamp for 24 hours to determine if the tubing remained occluded once the pressure was released. This simulated the effect of a pump roller compressing the tubing.

3.4. Droplet Sizing

3.4.1. Description of droplet spectra

The most commonly used parameter of droplet size in agricultural spraying is the volume mean diameter (VMD). The VMD is the diameter which divides the spray into equal halves by volume, one half containing droplets smaller than that diameter and the other half, larger droplets. A second parameter is the number mean diameter (NMD), which is the diameter that divides the spray into equal numbers of smaller and larger droplets. A single parameter is inadequate to describe the spray since a few large droplets can account for a large proportion of the volume of a spray containing many small droplets. The ratio of VMD:NMD can be used to express the uniformity of the spray. Johnstone (1978) suggested that both VMD and VMD:NMD should be adopted as basic spray parameters, and that, for controlled droplet application, the ratio should be no greater than 1.4, compared to 3 or more for many hydraulic nozzles. Both parameters were used in the droplet size analysis for the wheelbarrow sprayer.

3.4.2. Method of droplet sizing

A laser droplet analyser was used to measure the droplet spectra of airborne sprays. This should give a more accurate estimate of droplet size than methods based on the collection of droplets on sampling surfaces (Matthews, 1978), which may select certain droplet sizes and usually underestimate the number of very small droplets.

i) technical background

A 2mW helium-neon laser produces a beam which is spatially filtered, then expanded and collimated in a beam expander to give a uniform 6 mm output beam. The spray is passed through the beam, which is diffracted and focused by a Fourrier transform lens onto a multi-element photo-detector placed at the focal plane of the lens. The diameter of the diffraction pattern is inversely proportional to the diameter of the droplet, and, since parallel light always focuses on its axis, the movement of droplets through the beam will not affect the diffraction pattern. The photo-detector consists of 31 concentric, photosensitive semi-circles, each of which is most sensitive to a particular droplet size. The light energy falling on any element of the detector is then the sum of the contributions from all the droplets in the spray cloud. The output from each element is converted to a ten bit number which is stored in the computer as a measurement of the light energy distribution across the photo-detector.

The measured light energy distribution is compared to a distribution calculated from the Rosin-Rammler formula (Swithenbank _et al_, 1977), in which the weight or volume fraction of particles larger than size x is given by R,

where $R = e^{-(x/\bar{x})^N}$
N is a measure of the spread of the size distribution, such that it is infinity for a disperse spray.
$\bar{x}$ is the characteristic size when 62.3% of the droplets are smaller than $\bar{x}$.

The computer obtains the best fit of the actual energy distribution to the calculated distribution,by iteratively varying the mean parameter, $\bar{x}$, and the spread parameter, N, until the sum of squares of the differences between the actual and calculated values for each droplet size reaches a minimum.

Using this result (indicated by the error value, E, in print out, Fig. 3.1), the computer prints out values of PE (for $\bar{x}$) and W (for N). A table is then produced showing the volume percentage (P) and number percentage (N) of droplets within each size category (D). The table also shows the actual (A) and the calculated (C) values for the energy distribution.

Fig. 3.1 Computer Print Out

```
PE= +241.0 W=    +3.3 E= 00027000

D= ******* > +697.03 P=   +0.00% R= +100.00% N=   +0.00% C= 0537 A= 0511
D= +697.03 > +426.89 P=   +0.14% R=  +99.86% N=   +0.00% C= 0309 A= 0877
D= +426.89 > +300.58 P=  +12.44% R=  +87.42% N=   +0.64% C= 1192 A= 1257
D= +300.58 > +224.48 P=  +32.75% R=  +54.67% N=   +4.47% C= 1563 A= 1559
D= +224.48 > +171.98 P=  +26.67% R=  +27.99% N=   +8.46% C= 1912 A= 1778
D= +171.98 > +133.93 P=  +14.59% R=  +13.40% N=  +10.07% C= 2044 A= 2047
D= +133.93 > +103.49 P=   +7.44% R=   +5.96% N=  +10.99% C= 1395 A= 1900
D= +103.49 >  +80.66 P=   +3.30% R=   +2.66% N=  +10.43% C= 1508 A= 1608
D=  +80.66 >  +63.16 P=   +1.47% R=   +1.20% N=   +9.74% C= 1176 A= 1216
D=  +63.16 >  +49.46 P=   +0.66% R=   +0.54% N=   +9.15% C= 0915 A= 0852
D=  +49.46 >  +38.81 P=   +0.29% R=   +0.24% N=   +8.48% C= 0710 A= 0633
D=  +38.81 >  +30.44 P=   +0.13% R=   +0.11% N=   +7.91% C= 0547 A= 0560
D=  +30.44 >  +24.35 P=   +0.06% R=   +0.05% N=   +6.78% C= 0417 A= 0438
D=  +24.35 >  +19.02 P=   +0.03% R=   +0.02% N=   +7.00% C= 0318 A= 0341
D=  +19.02 >  +15.22 P=   +0.01% R=   +0.01% N=   +5.89% C= 0242 A= 0268
```

Heijne (1978) describes the conversion of the parameter (PE) to the standard spray parameters:

$$\mathrm{VMD} = \mathrm{PE} \sqrt[W]{-\log_e 0.5}$$

NMD is calculated by a computer programme based on the volume percentage figures (P).

A number of alternative distributions are available (Masters, 1972) which may be more suitable in certain circumstances than the Rosin-Rammler distribution.

ii) use of droplet analyser

The laser analyser was fitted with a 799 mm focal length Fourrier transform lens. A shorter focal length lens should be used for sprays finer than those produced by the sprayer.

After the photo-detector had been aligned correctly, a background measurement of PE and W was taken. This was automatically subtracted from the spray readings to remove the effects of stray light and of drift in the electronic counters. The spray was then passed through the laser beam and the signal strength was measured to ensure that the droplet density was not too low or too high. The optimum condition is that the droplets should give 20-30% obscuration, but up to 50% is considered acceptable (Felton, 1978). The energy distribution across the photo-detector was then sampled 200 times and the averaged results were processed immediately or stored.

iii) experimental procedure

The "Micromax" must be shrouded to produce a narrow swath suitable to pass through the laser beam. To avoid possible effects due to air turbulence or the shattering of droplets which occurs on solid surfaces placed close to the atomiser, a large hessian screen was used. The spray passing through the beam was caught in a second hessian screen and both screens drained the liquid into a deep tray. In later experiments other methods of shrouding were compared.

A motor driven spinning cup was used to investigate the basic spray characteristics. It was placed so that the vertical centre of the spray passed through the centre of the laser beam, and, based on the results of preliminary experiments, with its perimeter 0.15m from the beam. A 12v electric motor with a constant power supply unit turned the spinning cup via a belt drive. The voltage could be varied to alter the rotational speed, which was monitored by an optical tachometer. The unit was clamped firmly to minimise vibrations which could affect droplet production.

A constant feed on to the "Micromax" was maintained from a pressurised cylinder containing the spray liquid, via a flow regulator. A double feed was used, with the line of the two nozzles parallel to the beam, as it is on the sprayer. In most experiments a standard solution of 0.1% Agral wetter was used, but herbicide solutions were used in later experiments.

The spray produced by the spinning cup mounted on the wheelbarrow sprayer was also analysed. The sprayer was mounted on the stationary drive unit (section 3.1) with the cup 0.15 m from the beam for the second prototype, or 0.45 m for the first prototype.

The impact and fan nozzles used in the biological efficacy experiments (section 3.7.3) were tested with the nozzle 0.15 m from the beam, sampling the complete swath.

3.5 Patternator Experiments

The transverse swath uniformity of nozzles and sprayers can be tested on a patternator. This gives the average distribution over a period of time in the relatively still air of a laboratory, but the data is useful to identify nozzles and sprayers which give inherently poor uniformity.

3.5.1. The patternator

The spray was caught by a 3x3 m plastic sheet with corrugations at a 32 mm separation. Liquid from each corrugation drained into a tube so that the column of liquid could be measured. The wheelbarrow sprayer was mounted on the stationary drive unit, which was placed at a set position at the edge of the patternator. The spinning cup was then 0.6 m above the patternator, so that, even when the sprayer was angled at 45°, the droplets fell mainly under their own momentum at impact. The rounded corrugations gave adequate separation of the spray into the collecting tubes, but knife-edges are better for nozzles producing droplets under pressure, when the airflow may influence droplet trajectory (Hebblethwaite & Richardson, 1961). A smaller patternator with 24 mm sharp edged corrugations was therefore used to test the hydraulic nozzles used in the biological work.

3.5.2. Description of swath uniformity

The uniformity of matched adjacent swaths was estimated using the coefficient of variance:

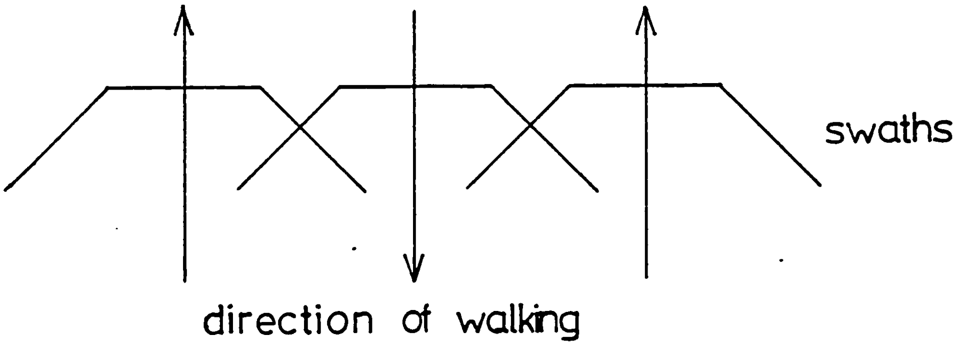
$$cv = \frac{s}{n}.100 \quad \%$$

where s = standard deviation

and n = number of samples

Since single nozzles are used on the sprayers and the most likely method of spraying would be to walk up and down the field, adjacent swaths are reversed (Fig. 3.2).

Fig. 3.2 Swath Matching



In practice, it is the minimum and maximum doses of herbicide which will be reflected in poor weed control or crop damage. These values have been given as a percentage of the mean ($\bar{x}$):

$$\frac{\bar{x} - \min \%}{\bar{x}} \quad ; \quad \frac{\max - \bar{x} \%}{\bar{x}}$$

3.6. Ground Spray Patterns

Patternator tests give an indication of swath uniformity, but more detailed work is required to discover the droplet size distribution across the swath, the instantaneous transverse swath pattern and the longitudinal spray pattern.

3.6.1. Background

The first investigation of an instantaneous pattern was made by Riley (1909) with a nozzle which sprayed over a slot moving across a sample paper. There was little further work until the advent of low volume 2,4D spraying (down to 45 l/ha), when an even distribution was more important than for the very high volumes used for other materials. A large number of analysis techniques have been developed since that time: droplet counting methods, involving the collection of droplets on sampling surfaces, and volumetric methods with direct or indirect measurement of the spray volume.

The droplet counting methods require the estimation of droplet size in order to calculate the spray volume and the droplet size parameters. The droplets are categorised into size ranges by eye, or with the aid of an image analysing computer (Matthews, 1975). A coating of magnesium oxide on a microscope slide (May, 1950) is useful for laboratory and small field experiments since the spread factor is constant over a wide range of droplet sizes. Unfortunately, the surface is easily damaged and various types of paper and other surfaces are more practical for large scale field experiments. Dyes in the spray solution aid measurement by staining the paper, or the surface may be treated chemically to react with the spray solution forming stains where the droplets land (Turner & Huntingdon, 1970). These methods require the calibration of a spread factor, dependent on the characteristics of both the spray and the sampling surface, which may be calculated using an absolute method of sizing such as an oil-vaseline matrix (Matthews, 1975).

Most volumetric methods use surfaces to catch spray containing a tracer, which is then washed off and the concentration of tracer estimated. Colorimetry has been used to examine spray retention by plants, but fluorimetry is more sensitive for the analysis of low volume sprays (Byass & Charlton, 1964; Bode et al, 1968). Fluorescent tracers were first used in the 1940's (Isler, 1963) and their use has been thoroughly investigated and reviewed by Staniland (1960), Yates & Akesson (1963) and Sharp (1974). A scanner has been designed to read the intensity of fluorescence directly off a sprayed paper strip (Liljedahl & Strait, 1959), but, though more rapid, this technique is not as accurate as methods in which the spray is washed off the collecting surface for analysis in a fluorimeter.

3.6.2. Preliminary experiment

A series of sheets of "Kromecote" paper were placed along and across the swath and sprayed with a lissamine scarlet solution using the first prototype wheelbarrow sprayer. There was a visible change in the number of large droplets across the swath, and there was a banding of large droplets along the swath. The following experiments were designed to test these observations quantitatively.

3.6.3. Droplet sampling experiment

Magnesium oxide coated slides were used to collect the spray droplets. Magnesium ribbon was burnt below each of a series of slides placed on a frame, such that a 25x25 mm square of magnesium oxide was formed on every slide. The optimum thickness of this layer was given by burning a 100 mm length of ribbon beneath each slide. A thicker layer became very fragile, while large droplets (>300 μm) broke through a thinner layer and hit the glass beneath, making sizing inaccurate.

Four rows of seven slides were laid either side of a track along which the sprayer was pulled at 1.0m/s maintaining a constant spraying angle. The spray solution was 0.1% Agral wetter. A Fleming particle size analyser type 526 (Matthews, 1975) was used to count the droplets on each slide. The analyser was fitted with a X4 lens and calibrated for droplets up to 300 µm in diameter. The droplets were categorised into eleven size ranges and the VMD and NMD were calculated using a graphical method (Appendix 3).

An Optomax image analyser was also used to count the droplets on the slides. This method was less rapid where the droplet density was relatively low, and it was difficult to obtain a suitable contrast of the image against the background because of the wide range of crater sizes in the magnesium oxide.

3.6.4. Longitudinal spray distribution

Fluorimetry is a sensitive and relatively quick method of tracing spray. Fluorescein sodium is a suitable dye, being easily soluble in water, and perceptible under acidic conditions. The peak excitation wavelength is 493 nm, and the emission (fluorescence) wavelength is 514 nm. A concentration of 0.5 % w/v fluorescein sodium was used with the wheelbarrow sprayer, and 0.05 % w/v for the knapsack sprayer to give a suitable level of fluorescence in the spray solutions.

A solution containing the dye and 0.1% surfactant sprayed onto lengths of 40 mm wide chromatography paper strips, which had been marked at numbered 40 mm intervals. After spraying the strip was cut into 40 mm squares which were soaked in 20 ml of 0.005 M sodium hydroxide for two minutes after which there was no detectable increase in the concentration of dye in the solution. Direct sunlight was avoided at all stages and the extracted solution was stored in darkness. The extract was sub-sampled by an automatic sampler attached to a Jobin Yvon Spectrofluorometre JY3, which had been set for the required excitation and emission wavelengths. The fluorescence readings for each subsample were compared to a standard curve which had been prepared by extracting known doses of dye applied to chromatography paper using an Agla microsyringe.

The spray distribution from the wheelbarrow sprayer was compared with that of a knapsack sprayer fitted with an impact nozzle. The wheelbarrow sprayer was pulled along a track, while the impact nozzle was held at a constant height above the track to give a 1.5 m swath. Chromatography paper strips were placed 0.15 m to either side of the track and across the swath. The minimum sampling length was 1.5 m, to collect at least 4 pulses of the Watson-Marlow pump fitted to the wheelbarrow sprayer, and the sampling size of 40 x 40 mm had previously been shown to be large enough to minimise the variation between samples (Clipsham, 1980). A 32 mm high bump was incorporated into several experiments to simulate the effect of rough ground in the field. The uniformity of the swaths was analysed using the coefficient of variance.

3.7. Biological Efficacy: Laboratory and Greenhouse Experiments

A series of laboratory experiments was carried out to investigate the efficacy of weed control using the wheelbarrow sprayer.

3.7.1. Plant raising

Two plant species were chosen for their contrasting susceptibilities to herbicides and for their uniform growth in a glasshouse at 8-12°C. Seeds of fodder radish (Raphanus sativus, cv Long Black Spanish) and cultivated oat (Avena sativa, cv Peniarth) were sown 15 mm deep in a sandy loam containing a slow release base fertilizer. The soil surface was lightly compacted to give a uniform depth of sowing. Single plants were grown in 90 mm pots which were lightly watered from above until they had been sprayed, after which water was applied to the soil only. The pots were weeded regularly throughout the experiments. Both species were used in all the experiments except those with 2,4D, when only radish was sprayed.

For pre-emergence spraying two rows of four seeds were sown in trays, which presented a large surface area to allow the herbicide to permeate the soil with minimal edge effects. The trays were watered lightly from above three times a day.

3.7.2. Choice of herbicide doses

Herbicides with contrasting modes of action were used at sub-lethal doses (Table 3.1) to give a dose response curve. Very low doses of paraquat and glyphosate were required, but

Table 3.1 Details of Herbicides

Common Name	Product	(gai/l)	Formulation	Doses (gai/ha)
paraquat	Gramoxone	(200)	as	10;20;40
glyphosate	Roundup	(480)	as	10;20;40
2,4D amine	-	(320)	as	225;450;900
2,4D ester	-	(475)	ec	225;450;900
atrazine	Vectal sc	(500)	sc	250;500;1000
pendimethalin	Stomp	(330)	ec	250;500;1000

as : aqueous solution
ec : emulsifiable concentrate
sc : suspension concentrate

Table 3.2 Sprayer Characteristics

Sprayer	Nozzle type	Nozzle ht. above pots (m)	Pressure (kPa)	Swath Width (m)	Volume (l/ha)
wheelbarrow	"Micromax"	0.3	(1900rpm)	0.8	15
CP3 knapsack	red "Polyjet"	0.5	100	1.5	300
laboratory sprayer	8001 fan	0.5	200	0.8	180

Table 3.3 Treatment and Assessment Times

Treatment	DAYS FROM: Sowing to Spraying	Spraying to visual assess.	Spraying to harvest
paraquat	21	3	8
glyphosate	21	16	16
2,4D amine/ ester	24	-	18
atrazine	0.5	22	37
pendimethalin	0.5	21	21 (radish) 25 (oats)

the top dose of the hormone and soil applied herbicides was similar to the commercially recommended rates (Merritt & Taylor, 1975; 1978a).

3.7.3. Spraying

The first prototype of the wheelbarrow sprayer, fitted with a Watson-Marlow pump, was compared to an impact nozzle on a knapsack sprayer and a fan nozzle on a laboratory sprayer (Table 3.2). The laboratory sprayer was calibrated by weighing the spray caught in a petri dish (Taylor & Richardson, 1972), while the others were calibrated using fluorescent tracers (section 3.6.4.). The wheelbarrow sprayer was pulled along a track raised to the top of the plants pots. The lance of the knapsack sprayer was held directly above the track to give a 1.5 m swath at plant pot height, while the nozzle in the laboratory sprayer was held 0.5 m above the top of the pots. All the sprayers travelled at 1.0 m/s, and the temperature at spraying was 15-20°C.

In pre-emergence tests, six trays were placed end to end, 0.15 m either side of the track. Soil samples were taken from spare trays to measure the moisture content at spraying, and after spraying the trays were arranged in a greenhouse following a randomised block design.

For post-emergence sprays, twelve pots of one species were arranged with a row of six pots 0.15 m either side of the track, and with a 0.15 m space between adjacent pots to prevent shadowing of one plant by another. When the spray had dried the plants were transferred to a greenhouse and arranged in a randomised block design, with individual pots separated to minimise competition and to avoid any transfer of chemical by contact between plants.

3.7.4. Assessments

Visual assessments of phytotoxicity were made at different periods after application depending on the mode of action of the herbicide (Table 3.3). Quantitative assessments of fresh weights were taken when the most severely affected plants had died and the least affected plants were beginning to recover. The time of harvest was therefore different for each herbicide (Table 3.3). The plants were not watered for four hours before harvest to ensure there was no water on the leaf surfaces. Each plant was cut at soil level for weighing, and, in some experiments, the plants were also dried for 48 hours at 86°C and then re-weighed. In the pre-emergence experiments the total weight of all the plants in each tray was measured, but in post-emergence experiments individual plants were weighed.

3.7.5. Herbicide residues in the soil

An attempt was made to explain the poor results given by pendimethalin by measuring the amount present in the sprayed soil. At harvest soil samples were taken from the top 20 mm of several trays. These were mixed and a 25 g subsample was extracted in 50 ml of methanol. The level of pendimethalin was determined with a gas-liquid chromatograph fitted with an electron capture detector, following the method of Walker & Bond (1977).

3.7.6. Measurement of spray retention

The retention of spray liquid on the plants was measured to estimate the amount of herbicide they intercepted. Immediately after the herbicide application experiments, plants were picked at random from the original batch and sprayed with a solution of 0.1 % Agral and fluorescein (0.5 % w/v for the wheelbarrow sprayer, and 0.05% w/v for the knapsack and laboratory sprayers. The addition of surfactant improves spray retention, to simulate herbicide application (Hibbitt, 1969), and improves the efficiency of washing the solution from the foliage to over 95%, even from dried deposits (Sharp, 1976). The background fluorescence of the wetter is negligable.

The plants were arranged for spraying in the same manner as for the herbicide experiments, and a strip of chromatography paper was laid down at the level of the top of the plant pots to estimate the ground spray volume. Immediately after spraying the plants were harvested and pairs of plants (one from each side of the track) were washed in 20 ml of a 0.005 M solution of sodium hydroxide. The concentration of fluorescein in these samples and in the extracts from the chromatography paper was measured using a fluorimeter (section 3.6.4.) The pairs of washed plants were dried at 86°C for 48 hours to determine the dry weight as a measure of the size of the plants at spraying.

3.8. Outdoor Pot Experiments: The Biological Effects of Spray Pulsing

A series of pot experiments, using low doses of paraquat, was used to investigate the effects of the pulsing of the spray, as it was difficult to find uniform populations of weeds in the field. Complementary field trials are described in section 3.9.1.

3.8.1. Plant raising

A uniform, dense mat of vegetation was produced by sowing 56 seeds of winter wheat (Triticum aestivum, cv Flanders) in a 7x8 grid pattern in 0.16 x 0.22 m trays containing sand. The plants were grown outdoors and watered twice each day.

3.8.2. Experimental procedure

A reduced dose of paraquat was sprayed when the crop had 2-3 leaves fully expanded. Lengths of 19 adjacent trays were laid out with their centres 0.15 m from the track which guided the sprayers.

When the phytotoxicity symptoms were most pronounced, at 5 days after treatment, pairs of rows covered a distance of 60 mm along the spray swath. Each sample was immediately weighed and, in one experiment only, the chlorophyll content was determined using the method of Vernon (1960) modified to facilitate the rapid handling of a large number of samples (Garnett, 1978). The plants were homogenised in 100 ml of 80% acetone for one minute, the extract was filtered and the absorption readings at 649 nm, 665 nm and 700 nm were taken using a Beckman DB GT spectrophotometer. The first two wavelengths correspond to the absorption peaks of chlorophyll a and b respectively in acetone, and the 700 nm reading gave an estimate of the quantity of other materials in the filtrate. If the 700 nm reading reached 10% of the other readings a new subsample was filtered from the original extract. Vernon (1960) calculated the absolute chlorophyll content using the following relationship:

$$\text{chlorophyll (mg/l)} = 6.45\ (A\ 665) + 17.72\ (A\ 649)$$

(where A 665 and A 649 are the absorption readings)

$$\text{i.e. chlorophyll concentration} \propto A\ 665 + 2.75\ (A\ 649)$$

The fresh weights and the chlorophyll data were analysed using two-term variance (TTLV). Several techniques have been developed by plant ecologists to analyse for patterns which may occur in vegetation (Kershaw, 1973). TTLV is a development of pattern analysis, a hierarchical process in which the data from a series of contiguous samples is grouped into progressively larger blocks. Adjacent data are paired into blocks containing 1,2,4,8,16....2^n of the original units, and the variance of each block of units is compared (Appendix 4). The pattern occurs at the block size with the highest variance. In TTLV the variance is calculated for all possible block sizes (Hill, 1973). The results of this analysis must be interpreted with care, but they provide a useful indication of the size and intensity of the pattern being investigated (Usher, 1975).

3.9. Field Trials in the U.K.

The trials were carried out at Silwood Park, Sunninghill, Berkshire (lat. 51°25'N, long. 0°39'W), on a fine sandy loam which was ploughed and harrowed to give a fine tilth before drilling. Trials details are given in Table 3.4. and swath matching was related to crop row width (Fig. 3.3).

3.9.1. Spray pattern trials (trials 1-3)

Three trials were designed specifically to test if irregularities, both in the spray pattern along the swath and in swath matching, affected the levels of weed control in the field. The trials were unreplicated to allow the maximum plot size, with several long, adjacent swaths. An untreated strip was left between each treatment.

The sprayers had been calibrated before use. In trial 1, the first wheelbarrow prototype with a Watson-Marlow pump delivered 15 l/ha, but the second prototype was used in the others, spraying 20 l/ha. The CP3 knapsack sprayer was fitted with an impact nozzle which sprayed 300 l/ha at 100 kPa (Table 3.2). Lower than recommended doses of the herbicides were tested to emphasise any areas of the trial

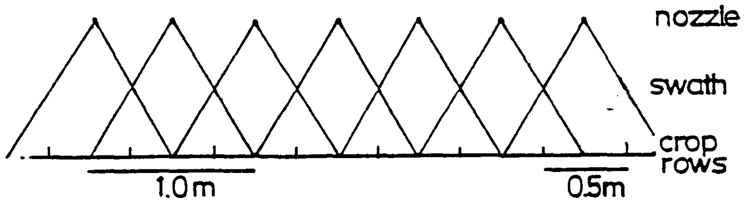
Table 3.4 Details of Field Trials in the U.K.

Trial no.	Crop	Cultivar	Sowing date	Application date	Crop stage	Plot size (m)
1	pea	Pioneer	19/5/79	14/6/79	4 - 5 leaves	4x15 (unrep)
2	"	"	25/4/80	3/6/80	0.1 m high	7x15 (unrep)
3	sweet corn	First of all	22/5/80	3/6/80	pre-emergence	6x15 (unrep)
4	potatoes	Maris Piper	29/4/80	6/5/80	pre-emergence	5x20 (rep)

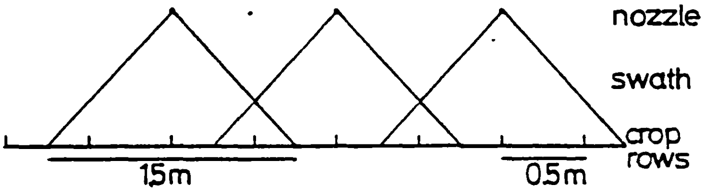
Fig. 3.3 Sprayer Swath Matching in Field Trials in the U.K.

1) Pea Trials

a) wheelbarrow sprayer: 100% overlap; ½ dose in each swath.

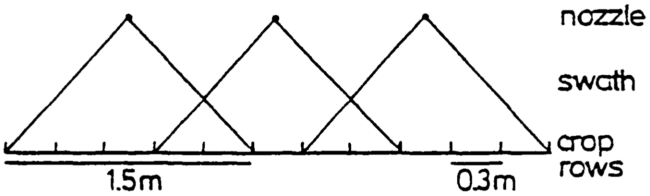


b) knapsack sprayer: 66% overlap; full dose in each swath.



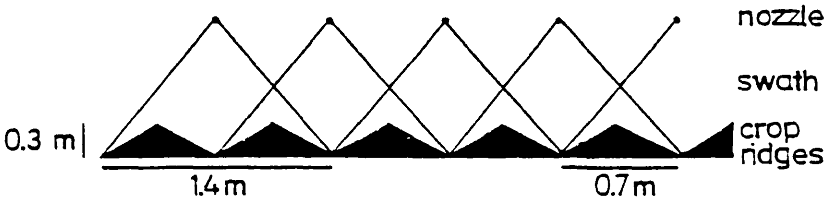
2) Sweetcorn Trial

wheelbarrow & knapsack sprayers: 80% overlap; full dose in each swath.

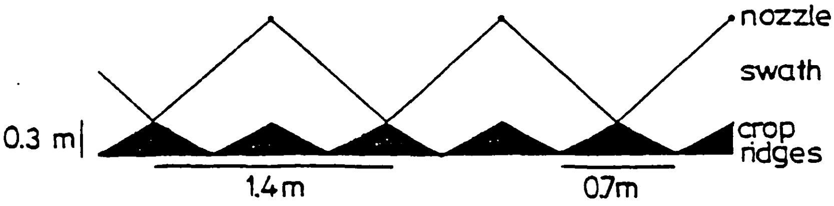


3) Potato Trials

a) wheelbarrow sprayer: 100% overlap; ½ dose in each swath.



b) knapsack sprayer: no overlap; full dose in each swath.



where poorer weed control occurred. In trial 2 narrow lengths of black paper were laid down to sample the white spray droplets, to show the spray distribution along and across the swaths.

Each site was assessed visually for percentage weed control and notes were made on the positions of any areas of poor weed control. A more detailed analysis of pattern was undertaken in trial 2, where there was a fairly uniform 90% ground cover of Spergula arvensis averaging 0.15 m tall. At the peak of the phytotoxicity symptoms (20 days after spraying) transects were taken along and across the swaths, harvesting the weeds in contiguous 0.1 m quadrats. This quadrat size was chosen since it approximated to half the expected smallest scale of pattern (Kershaw, 1957), i.e. the 0.25 m pulsing effect of the paired Glen Creston pumps. The transects were taken adjacent to the strips where spray had been sampled. The fresh and dry plant weights were analysed graphically, and using two-term local variance (section 3.8.2.).

3.9.2. Spray penetration into the vegetation canopy

When the droplets from the sprays of cyanazine, used in trials 1 and 2, dried on weed leaves they formed white globules which could be counted with the aid of a binocular microscope. Spray penetration was estimated by counting the number of droplets on the leaf whorls, which were at average heights of 20, 50, 90 and 130 mm above soil level. After the spray had dried, the plants were picked at random and the droplets were counted on the upper and lower surfaces of the leaves from each whorl.

3.9.3. Spraying in a ridge crop (Trial 4)

A crop of potatoes was chosen to test the use of a wheelbarrow sprayer in a ridge crop. A replicated, randomised block design was used. All the treatments were applied pre-emergence of the crop but there were some weeds at the cotyledon stage (Spergula arvensis, Stellaria media, Polygonum aviculare). The sprays were applied to a dry soil and no rain followed for 14 days. Later in the season the untreated plots were hand hoed.

3.9.4. Continuation of a preliminary field trial

Preliminary field testing of the sprayer was carried out with paraquat and glyphosate at reduced doses sprayed at three times of day (Garnett, 1978). The spray volume was 13 l/ha, using the wheel mounted pump, on a 0.8 m swath. Although assessments were made soon after spraying (Garnett, 1978), the best estimate of the efficacy of glyphosate on perennial weed species is to assess the regrowth the year after spraying. The regrowth of the rhizomes of *Holcus mollis* was assessed using a logarithmic scale of 1-9 (Johannes, 1964) six and twelve months after spraying.

3.10. Botswana Field Trials

A number of field trials were undertaken in Botswana to test the wheelbarrow rigorously under semi-arid, sub-tropical conditions (Table 3.5).

3.10.1. Location of field trials and climatic conditions

The trials were carried out on the Agricultural Research Station farm at Sebele near Gaborone (lat 24°34'S, long. 25°57'E) at a height of 1100 m. The average annual rainfall of 510 mm falls mainly in the spring and summer months (October to March), when it is erratic and often falls in very localised and intense thunderstorms. Evaporation is rapid, with an average summer air temperature of 32°C and relative humidity of about 50%, and a precipitation of 10 mm or less is considered ineffective for agriculture under summer conditions (EFSAIP, 1977). There is a probability of complete crop failure one year in six due to the unreliable rainfall (Anon, 1978). The first significant rain of the spring usually determines the start of crop sowing by the small-holder farmers, and the first frosts mark the close of the arable cropping season during June.

The soil is a medium grained sandy loam with a very low field capacity. Samples from the farm contained less than 15% clay, with some as low as 4%. The soils are very susceptible to capping, which can cause severe run-off of rain and may reduce crop emergence.

The research farm is managed with a more intensive and mechanised cropping system than the local farms, and is

Table 3.5 Details of Field Trials in Botswana

Trial no.	Crop	Cultivar	Sowing date	Application date	Crop stage	Plot size (m)
1	sorghum	Savannah 5 & Segaolane	-	23/11/79	>0.3 m high	3x10
2	"	Savannah 5	21/11/79	27/12/79	8-9 leaves	3x15
3	maize	Kalahari Early Pearl	29/11/79	30/11/79	pre-emergence	"
4	"	"	"	14/12/79	3-4 leaves	"
5	"	"	"	28/12/79	9-10 leaves	"
6	"	"	-	19/12/79	0.4 m high	"
7	sunflower	-	14/12/79	14/12/79	pre-emergence	"
8	"	-	"	3/1/80	4-6 leaves	"
9	no crop	-	-	26/11/79	-	"
10	"	-	-	28/11/79	-	"
11	"	-	-	19/12/79	-	"

based on a rotation of sunflower, sorghum, cowpea, maize and grass (Morei, 1979). In consequence the weed flora is very different from the surrounding areas.

Weeds have long been recognised as a major constraint to Botswana agriculture (e.g. Anon, 1954), and a recent survey showed the weeds to be "particularly pernicious" (EFSAIP, 1977). However, yield losses due to weeds have not been thoroughly investigated and little work has been undertaken to develop weed control methods. No herbicide work was carried out until some crop safety work in 1974-5 (Mazhani, 1979). Unfortunately these trials are difficult to interpret, but it is known that there is a significant difference in the susceptibilities of South African sorghum varieties to 2,4D (Marshall & Nel, 1981). In view of the uncertainties, the wheelbarrow sprayer trials were carried out on the research farm only. A few recent trials have compared chemical and mechanical weed control (Mazhani, 1978), but these are also inconclusive.

3.10.2. Site preparation

All the fields sown with crops had been mouldboard ploughed, giving an uneven seedbed with clods which broke down during the season. The first crops were sown after the first significant rains in mid-November, using a John Deere seeder set at a 0.75 m row spacing for all crops, with a simultaneous application of fertiliser. Several trials were sprayed on uncropped land which had been fallowed since the previous autumn. A three to five times replicated, randomised block design was used with 20 m long plots, which were 3 to 4 m wide to allow several adjacent sprayer swaths.

3.10.3. Choice of herbicides

Herbicides are not readily available in Botswana, although they are used in certain irrigated areas. Those chosen were commercially available and well tested in South Africa, and represented a range of modes of action. Certain potentially useful herbicides, such as trifluralin and EPTC, were not used as they required incorporation into the soil, which was not considered practical for small-holder farmers. Without incorporation trifluralin volatilises rapidly and its activity is reduced (Walker, et al, 1976). The herbicide doses were chosen according to South African recommendations.

3.10.4. Spraying

Three sprayers were compared (Table 3.6) and the calibration of each was checked. The herbicides did not affect the spray volume of the wheelbarrow or the knapsack sprayers, but certain spray solutions reduced the flow of liquid onto the spinning disc, and the walking speed in the field had to be adjusted to maintain 11 l/ha in all treatments. After spraying each treatment, the volume of liquid remaining in the sprayer was measured to confirm the application rate. The swaths were matched as in Fig. 3.4, and the uniformity of the spray patterns on the ground achieved by the overlaps was checked visually by spraying a dye onto Kromekote paper.

Table 3.6 Details of Sprayers used in Botswana

Type	Nozzle	Pressure (kPa)	Swath width (m)	Volume (l/ha)
wheelbarrow	"Micromax" (1700rpm)	-	0.7-1.5	24
knapsack	red "Polyjet"	100	2.0	250
"Herbi"	spinning disc (1800 rpm)	-	1.2	11

All the trials were sprayed in the morning (5.00 - 11.00 hrs), except when several application times were compared, and notes were made on soil and weather conditions. Farm weather records are given in Fig. 3.5. The walking speed was timed for each treatment and always fell within 10% of the target speed. Notes were made on the handling of the sprayers in all trials.

Several trials had treatments which were hand-weeded using a Dutch hoe. Weed removal in the trials was generally better than would be expected by local farm labour.

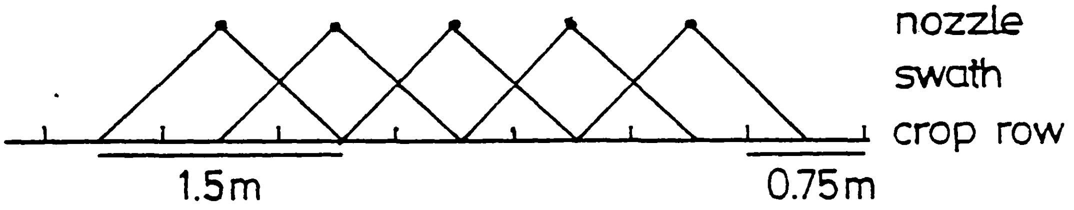
3.10.5. Assessments

Crop germination counts were made in pre-emergence trials, two weeks after crop emergence. All trials were visited weekly to check for phytotoxicity symptoms.

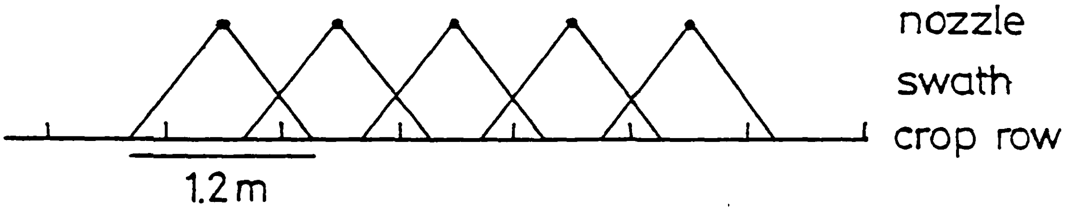
The weed population on the farm proved to be patchy,

Fig. 3.4 Sprayer Swath Matching in Field Trials in Botswana

a) wheelbarrow sprayer: 100% overlap; ½ dose in each swath.



b) hand-held spinning disc sprayer: 80% overlap; full dose in each swath.



c) knapsack sprayer: 50% overlap; full dose in each swath.

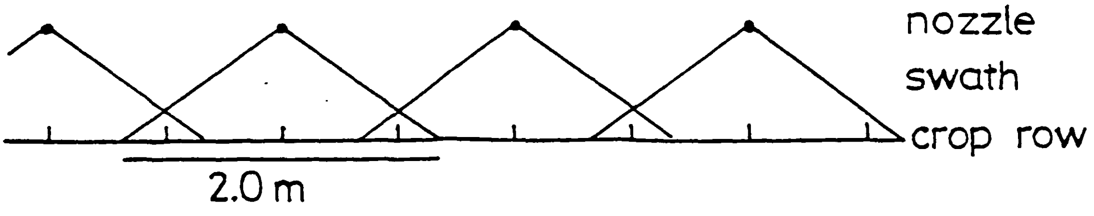
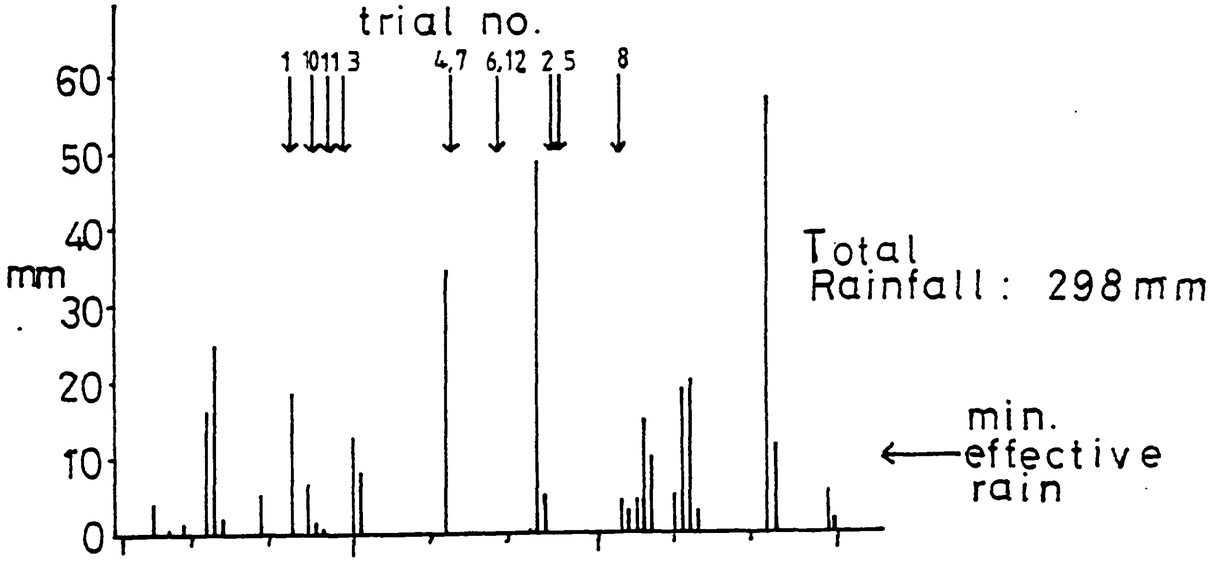
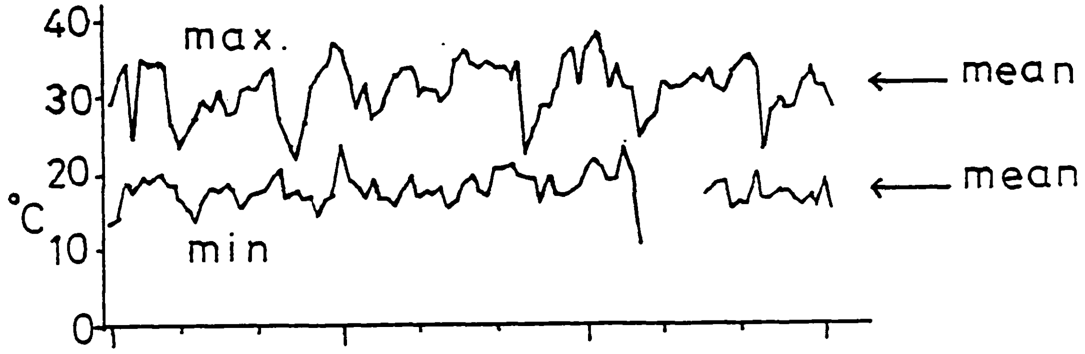


Fig. 3.5 Botswana Meteorological Records.
(Mid Station, Sebele)

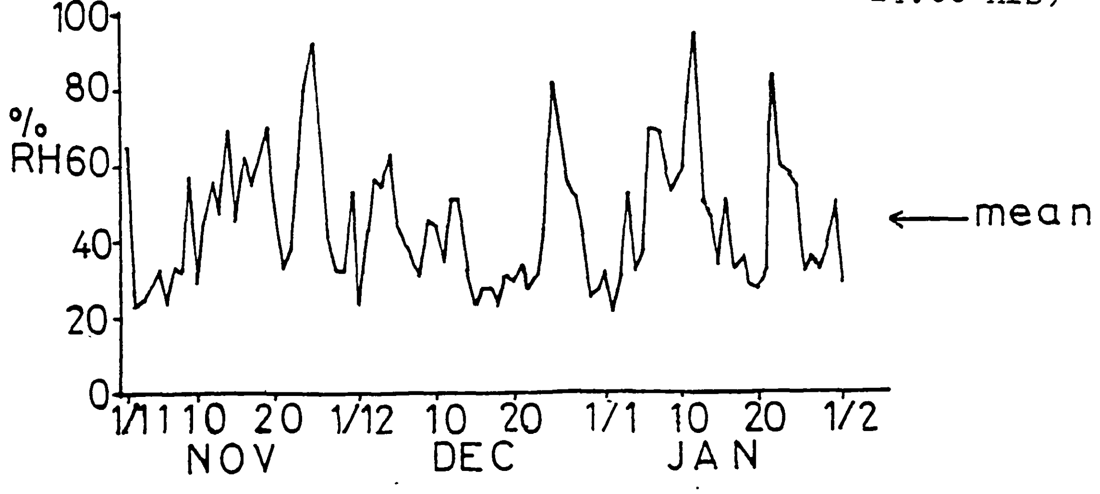
a) Rainfall, Nov.1979-Jan.1980



b) Temperature, Nov.1979-Jan.1980



c) Relative Humidity, Nov.1979-Jan.1980 (readings taken at 14.00 hrs)



particularly in pre-emergence trials, which could not be arranged to coincide with the most uniform populations. Visual observations of weed control were followed, in most trials, by weed counts in four or five 0.5 m quadrats per plot. For certain post-emergence applications, where weeds were not completely killed, visual estimates were made of the percentage reduction of green leaf area compared to untreated plots. The main assessments were made at one week after treatment for paraquat sprays, at two weeks for other post-emergence sprays, and at four weeks after pre-emergence sprays. The weed species were identified according to Field & Kidner (1976), Henderson & Anderson (1976) and Wild (undated).

One trial only was harvested, since the other trials had very patchy crops with uneven weed infestations, and there was a heavy infestation of *Striga* sp. in the sorghum trials. Two 15 m lengths of maize row were harvested and weighed for each plot.

CHAPTER 4 COMPONENT TESTING

The components of the sprayer were tested both individually and when assembled into the sprayer, to ensure that they, and the sprayer, performed reliably and accurately. The testing of sprayers has been reviewed by Hebblethwaite & Richardson (1961), Matthews et al (1969), Rice (1970) and Thornhill (1982).

4.1. Spinning Cup Drive

The spinning cup is rotated by a spindle which is held against the ground wheel,so its speed is directly related to the walking speed of the operator (Fig. 4.1) up to 2.0 m/s, above which slight slippage may occur between the spindle and the wheel. The rotational speed is not affected by feeding liquid onto the cup, although the speed of motor driven units varies with the feed rate (Bode & Butler, 1981).

The drive characteristics are summarised as follows:
ground wheel diameter 0.305 m; circumference 0.958 m.
i.e. ground wheel turns at 62.6 rpm, walking at 1.0 m/s.

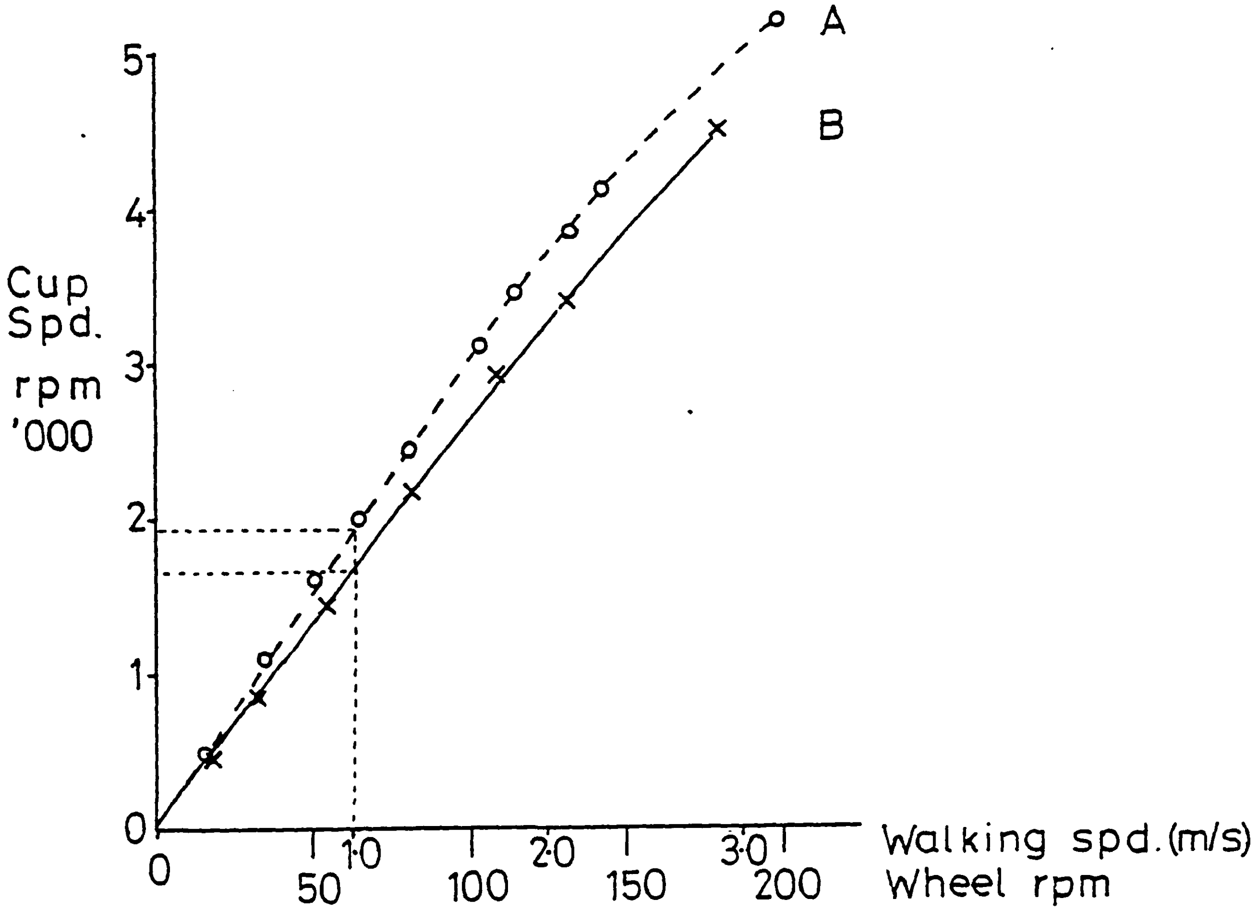
At the point of contact with the spindle:
ground wheel diameter 0.26 m; circumference 0.82 m.
spindle diameter 9.5 mm; circumference 30 mm.
i.e. spindle turns 27.3 revolutions per turn of the ground wheel.

At a walking speed of 1.0 m/s, the cup rotates at 1700 rpm, which is similar to the speed expected from the regression in Fig. 4.1.

4.2. Pump

The pump is required to transfer an accurately metered flow of liquid from the spray tank to the nozzle. If the pump is directly related to the ground speed, then a constant volume of spray should be applied, overcoming the dosing problems associated with the more arbitrary metering mechanisms on hand-held spinning disc and knapsack sprayers. The range of pumps available on sprayers is reviewed by Matthews (1979), but most are designed to cope with much higher flow rates than those required for a spinning cup.

Fig. 4.1 Change in Speed of Spinning Cup Rotation with Walking Speed



A: 1st Prototype
$y = 277 + 1635x$ ($r = 0{\cdot}995$)

B: 2nd Prototype
$y = 107 + 1583x$ ($r = 0{\cdot}997$)

A survey of commercially available pumps showed that those with a suitable output were either the smallest of a range of industrial pumps, or the largest of a range of expensive laboratory pumps (Appendix 5). The most readily available small pumps were those found in washing machines and cars, but these were unsuitable for use when in contact with herbicides, particularly with the high concentrations used in low volume spraying. The particles in wettable powders or flowable formulations may cause excessive wear on moving parts, and the solvents in emulsifiable concentrates can affect metals and plastics. Peristaltic and piston pumps were chosen as most suitable for further investigation.

4.2.1. Piston pumps

Piston pumps use positive liquid displacement to produce a flow which is directly proportional to the speed of pumping, but which is pressure independent. No suitable piston pumps were available commercially, so a pump was designed specifically for the wheelbarrqw sprayer (Bals, 1979). Unfortunately, this proved difficult and expensive to produce because of the great accuracy required in machining the components.

4.2.2. Peristaltic pumps

The mechanism of peristaltic pumps is very simple. The spray liquid contacts only the tubing, reducing wear and corrosion of moving parts. Abrasive particles in the liquid are cushioned in the soft rubber wall of the tubing during compression and cause little damage to the tubing. The pumps are completely self-priming and can be run dry without damage, yet they require minimal maintenance and cleaning. There are three basic types:

i) tubing stretched over rollers

A flexible tube is stretched over a series of rollers arranged in a ring. The tubing kinks and is occluded at the point of contact with each roller, and when the rollers are moved along the tubing this point of occlusion forces the liquid along the tube. However, the relationship between the internal and external diameter of the tubing affects its suitability for use on a pump. The walls of the tubing used on the first prototype pump were too thin to withstand the tension and the pumping action, so the tubing broke after a short period of use. If the tubing is not robust, pin-hole leakages can develop, as occurred on prototypes of the Norman-King sprayer (Matthews, 1979).

ii) external track

Rollers press a flexible tube against a track forming a point of occlusion. As the rollers move the occlusion pushes liquid along the tube, and when the occluded area recovers it creates a powerful suction which draws in more liquid. The tubing is more durable than in the system described above since it is not stretched. The Watson-Marlow "HR Flow Inducer" and the Glen Creston "WAB Tube Pump" are both of this type.

iii) internal track

Planet wheels fixed to a larger wheel press the tubing against an internal track. There are no advantages over the external tracked pump, although it may be less likely to pick up dirt and grit on the internal track. This has been used on two prototype, ground metered, spinning disc sprayers (Johnson, 1978; Ogborn, 1980).

Peristaltic pumps have found a wide range of industrial uses for transferring virtually any fluid. Although the flow rate depends on the rotational speed of the pump, the range of flows obtainable can be varied by the choice of a suitable tubing diameter. A wide bore produces a stronger pulsation in the flow than a narrow one, but the rollers move more slowly for a given flow rate, so the life of the tubing is longer. The pulsing can be reduced by running two or more pumps out of phase or by incorporating a simple expansion chamber on the pump outlet.

A variety of tubing materials is available for pumping different fluids, but silicone rubber is particularly suitable for a herbicide sprayer since it withstands a wide range of chemicals and solvents, and is highly resistant to wear. Other types of rubber eventually harden and perish and must be replaced at intervals dependent on the type of use.

4.2.3. Peristaltic pump testing

Three types of pump were tested: the wheel-pump, with tubing stretched over rollers on the ground-wheel of the first prototype, the Watson Marlow "HR Flow Inducer" and the Glen Creston"WAB Tube Pump" (Fig. 4.2).

i) response of output to pump speed

All three pumps produced a linear flow response over the range of speeds likely to be encountered with the sprayer (Fig. 4.3). New tubing required several minutes of use before its output stabilised. This effect was dependent on the elasticity of the tubing, and was most pronounced with the stretched tubing on the wheel-pump, which required 15 minutes to reach its normal output.

ii) relationship between flow rate and type of tubing

The flow rate increases linearly with the cross-sectioned area of the tubing (Fig. 4.4). Although experimental results with the 6 mm silicone rubber tubing gave results similar to those in the manufacturer's technical leaflet, the 8 mm neoprene tubing gave a much reduced output compared to silicone rubber tubing. This is possibly because of the greater elasticity of the silicone rubber which results in a smaller depression in the tubing as a roller passes over (Fig. 4.5).

Fig. 4.5 <u>Compression of Tubing</u>

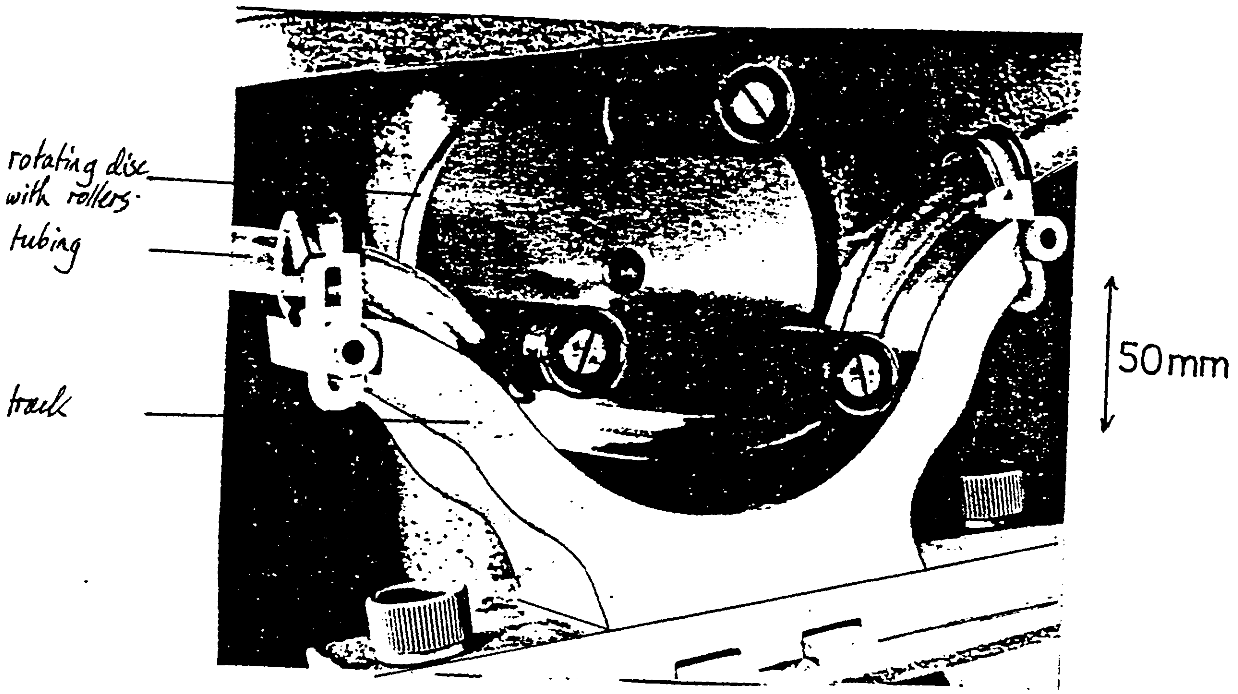
i) silicone rubber

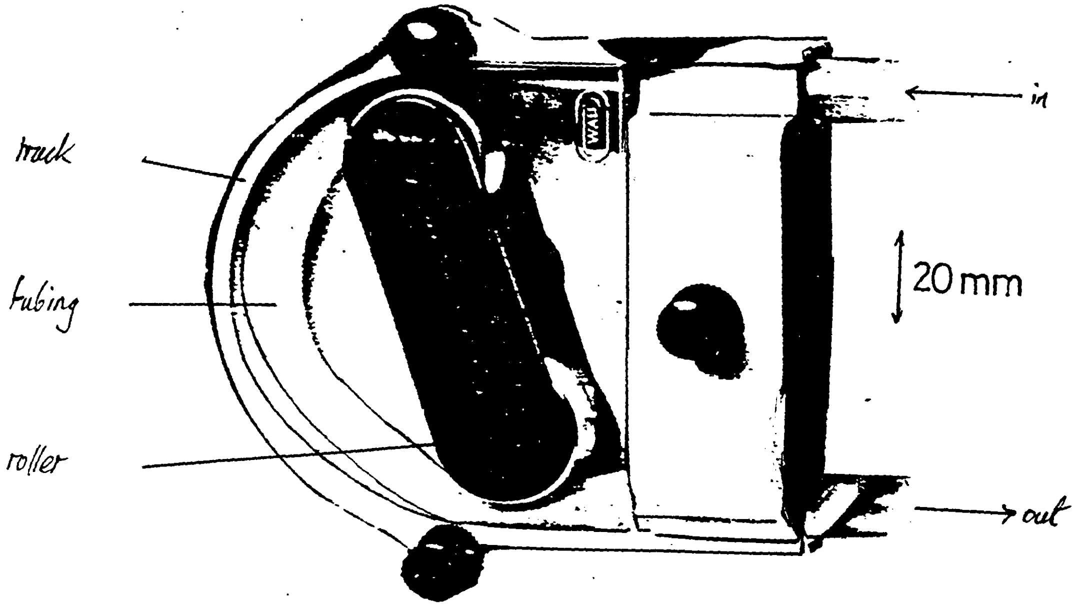
ii) neoprene rubber

The tension of the tubing stretched across the rollers also affects the flow rate. When a longer length of tubing was used the tension was reduced and the flow rate fell, approximately following an exponential regression (Fig. 4.6). The length of tubing required for the wheel-pump was limited by the immediate breakage of lengths less than 370 mm, the very short life of lengths from 370-390 mm, and by the loose fit over the rollers of tubing over 420 mm long.

Fig. 4.2 Peristaltic Pumps

a) Watson Marlow HR Flow Inducer





b) Glen Creston WAB Pump

Fig. 4.3 Linear Increase of Flow with Pump Speed

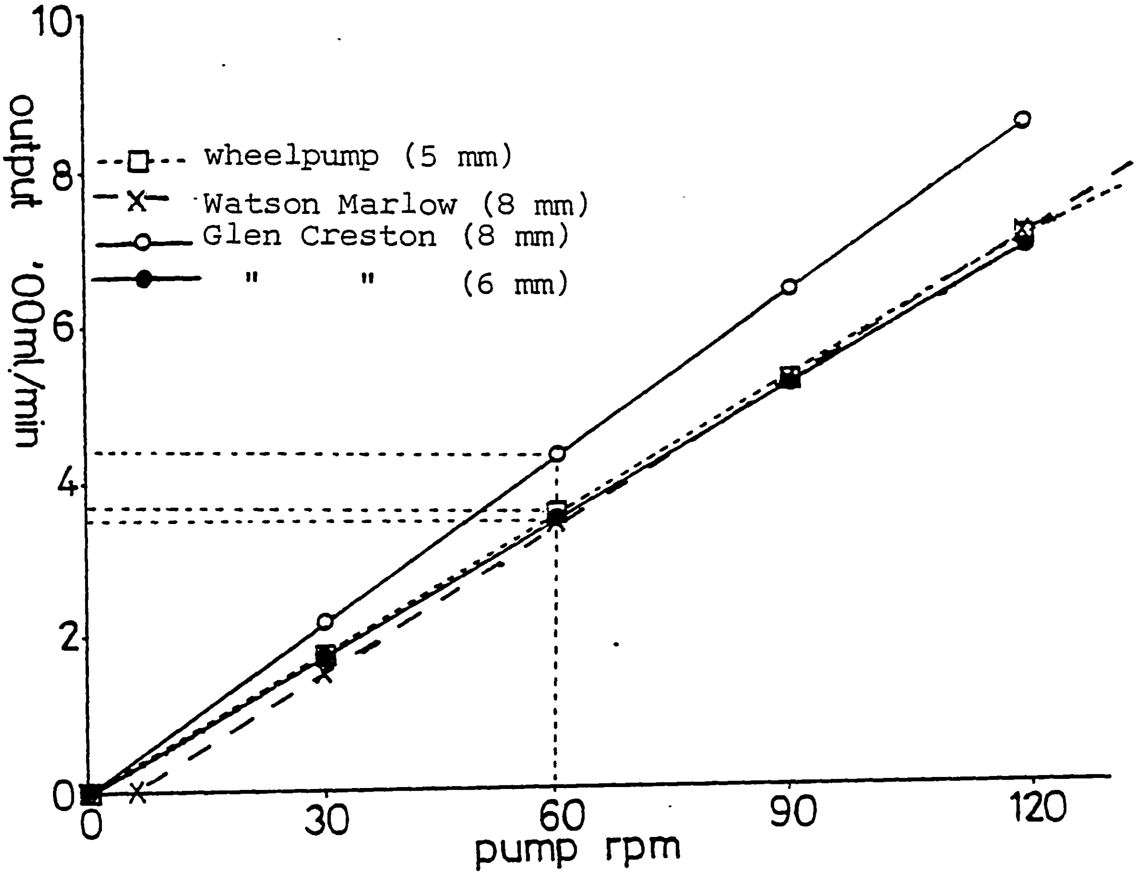


Fig. 4.4 Relationship Between Flow Rate and Tubing Cross-Sectional Area (Glen Creston pump at 60 rpm)

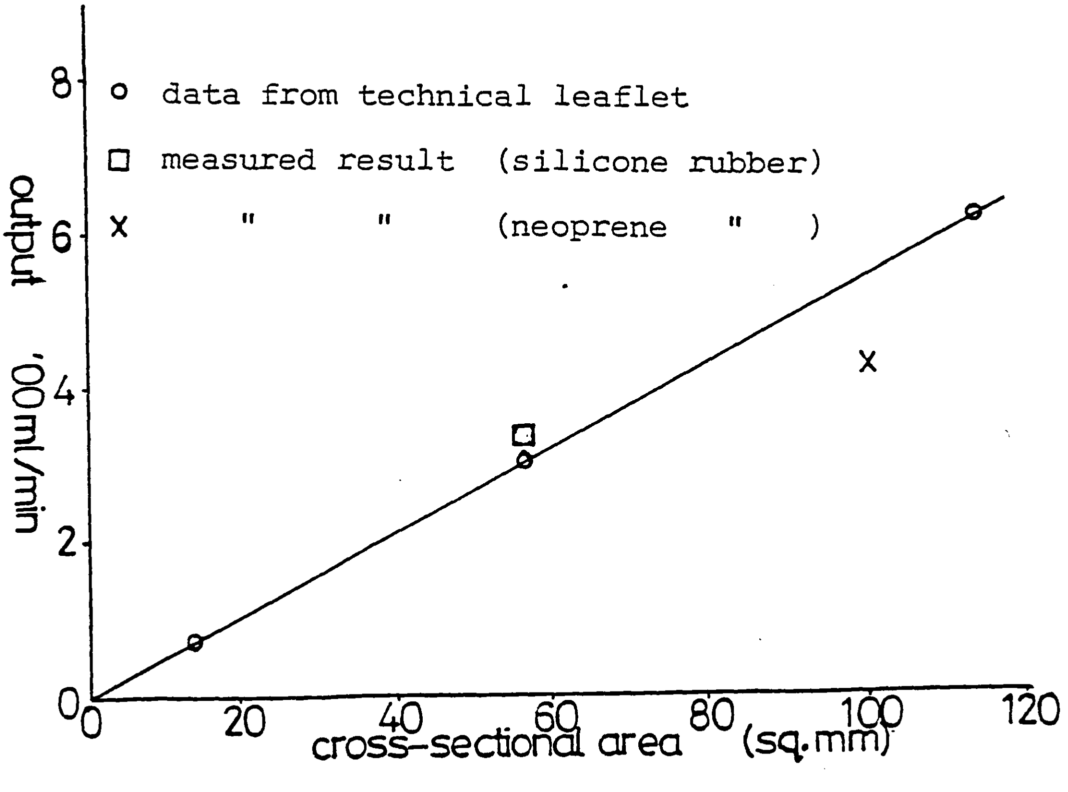
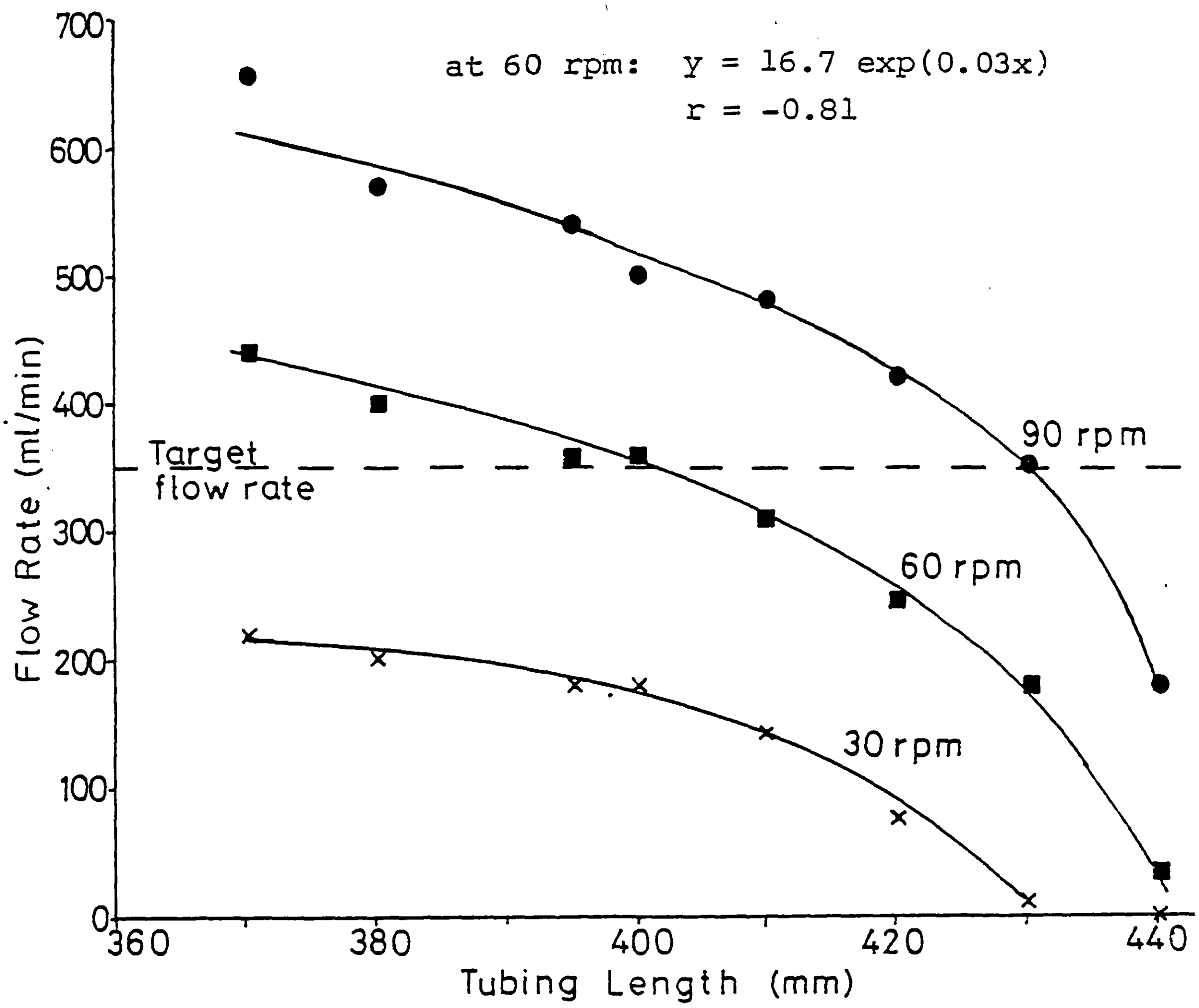
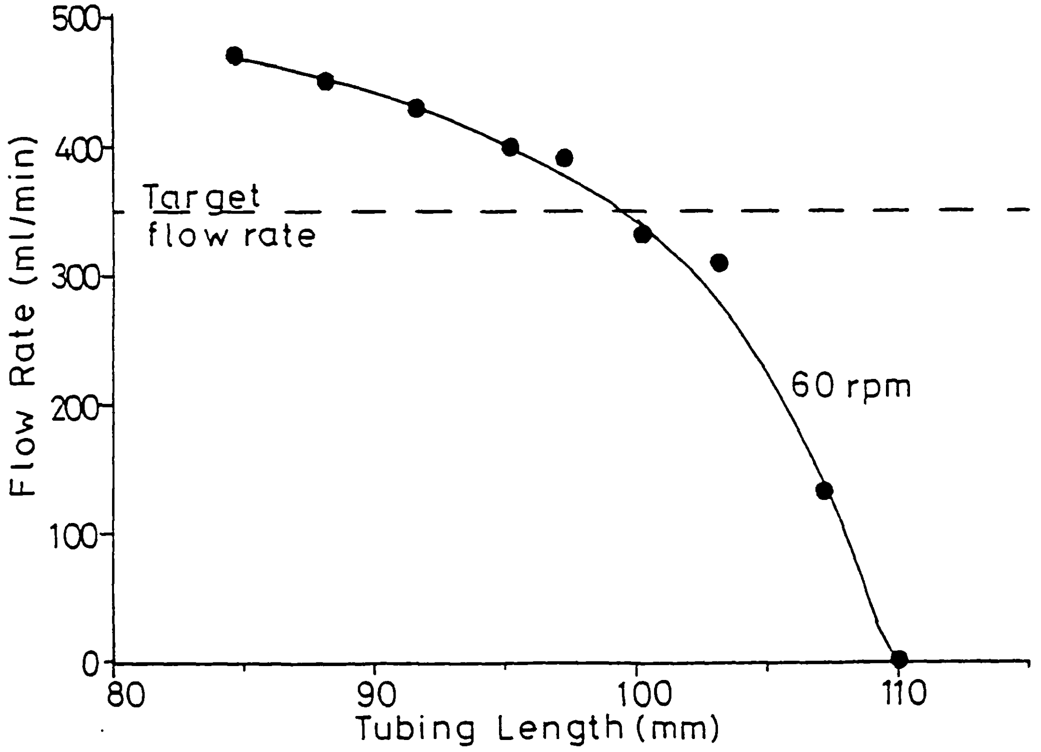


Fig. 4.6 Effect of Tubing Length on the Output of Peristaltic Pumps

a) wheel pump (5 mm silicone rubber tubing)



b) Watson-Marlow pump (8 mm neoprene rubber tubing)



On the tracked pumps, the correct length of tubing is that which exactly fits the track. This was easily judged for the shaped track on the Glen Creston pump, but it was more difficult to fit the tubing correctly on the Watson Marlow pump, although a 100mm length gave a suitable flow rate without being too stretched.

iii) effect of temperature on flow rate

Temperature affects the elasticity of the pump tubing as well as the viscosity of the spray liquid. A 9°C variation in temperature during a day caused a 5% variation in the flow rate (Fig. 4.7), and the output at 30°C in Botswana was 12% higher than that expected from calibrations made at 15°C in England.

iv) pump durability

A Glen Creston pump fitted with 8 mm neoprene tubing was run continually for over 400 hours at 60 rpm, pumping water. This is equivalent to spraying approximately 200 ha, which is more than the sprayer is likely to cover in one season.

The pump reached its normal output after two minutes of use, and then the flow was constant for the following 100 hours, except for the variations due to temperature (Fig. 4.8). After this the output slowly decreased by 17% over a period of 300 hours, probably due to the loss of elasticity by the neoprene tubing. There was superficial wear on the neoprene within a few hours of use, but this did not visibly increase during the experiment and no cracks or pin-holes developed in the tubing.

The tubing life could be reduced by spray materials which attack neoprene, but even a 50% reduction in life-time would allow the tubing to be used for a complete spraying season. Silicone rubber should be more durable than neoprene tubing.

v) effect of spray solution on flow rate

A range of liquids were tested through the Watson Marlow pump. Water diluted materials all gave similar results to water alone, but the flow rate was slightly greater for the same pump speeds using oil-based liquids (Fig. 4.9). This difference would not significantly affect the sprayer application volume, whereas the formulation does affect the output of a pressurised feed onto a spinning cup (Bode &

Fig. 4.7 Variation of Flow with Time of Day (water)

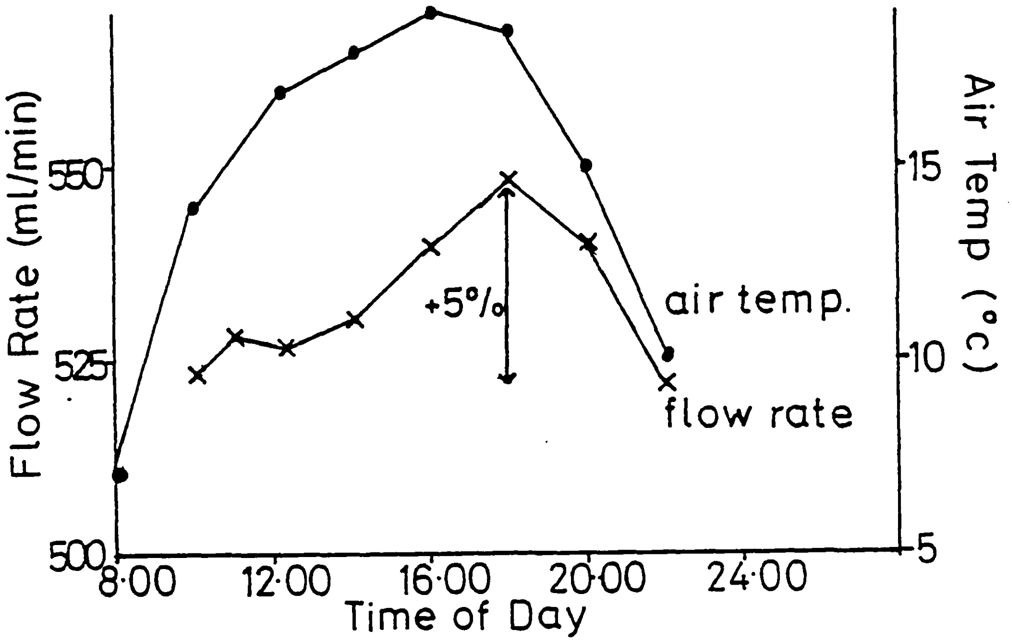


Fig. 4.8 Change of Flow Rate with Length of Time of Pump Use (8 mm neoprene tubing, Glen Creston pump)

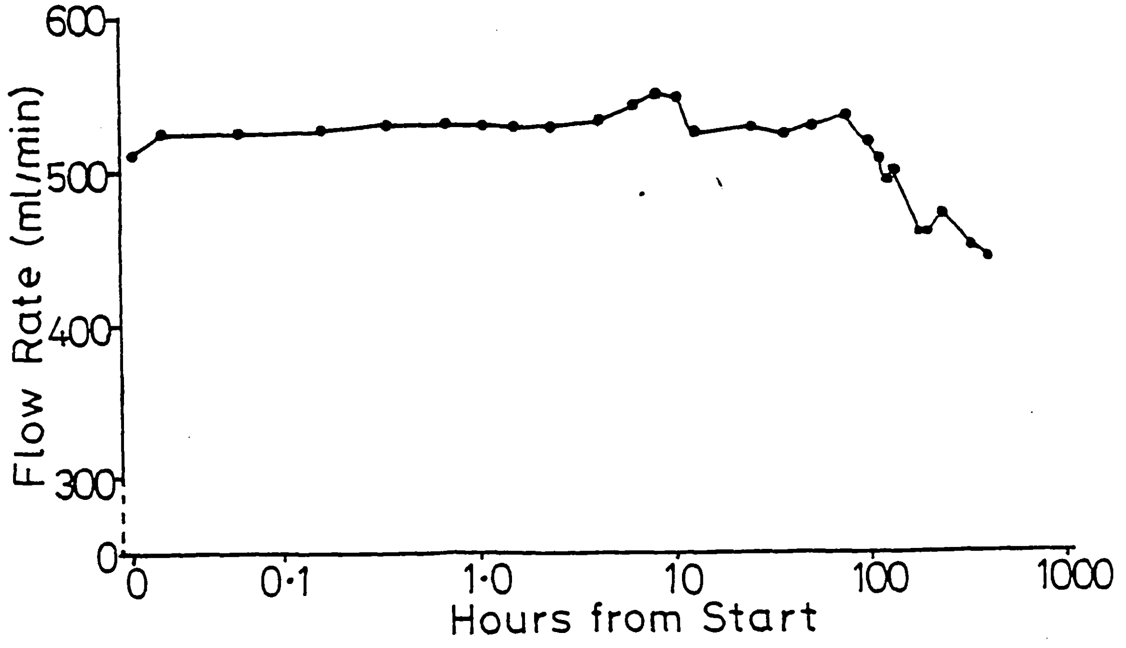


Fig. 4.9 Effect of Spray Solution on Flow Rate : Watson-Marlow Pump

Key to Spray Materials:

1 : water

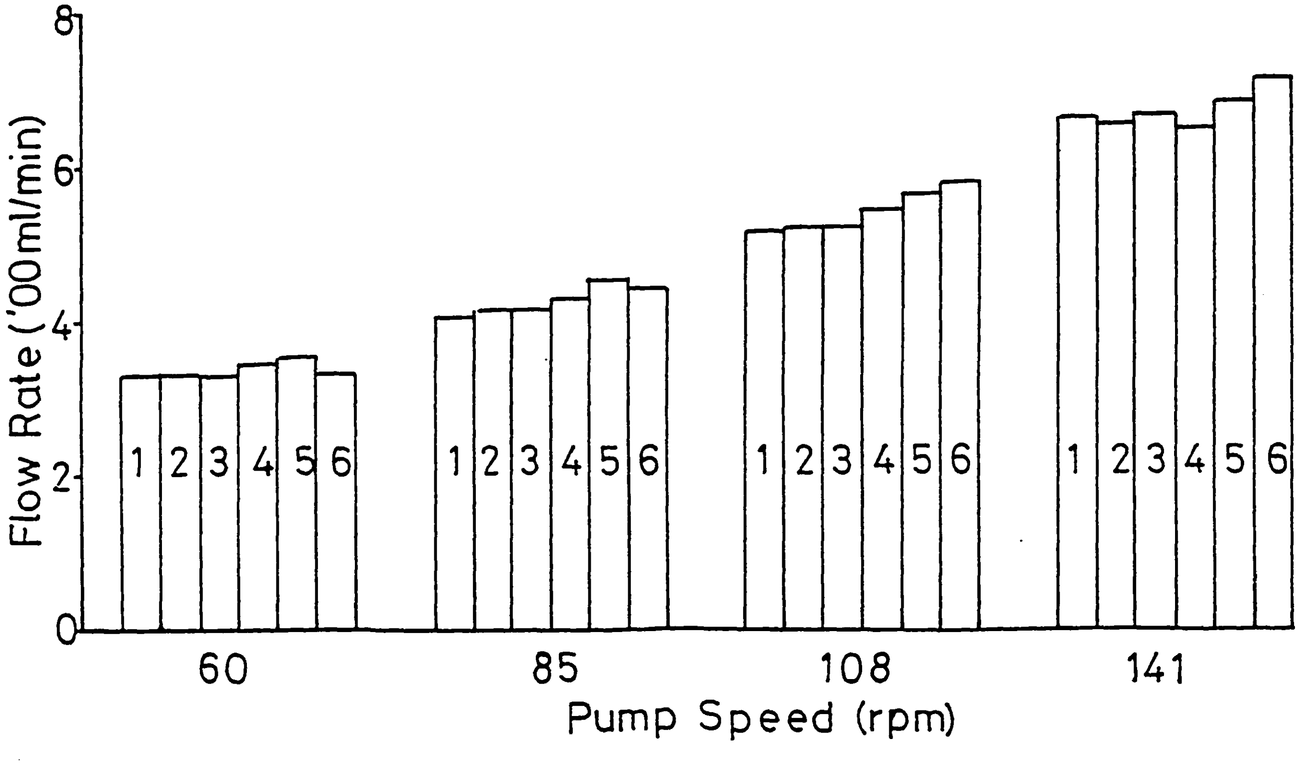
2 : water + Ulvapron 20% w/v

3 : water + Tribunil (methabenzthiazuron) 10% w/v

4 : Bellater (cyanazine + atrazine: conv. formulation) 100%

5 : Holtox (" " : ULV formulation) 100%

6 : LB180/78 (" " : new ULV formulation) 100%



Butler, 1981). The gravity feed on hand-held spinning cup applicators is particularly susceptible to variations in flow rate due to the formulation and even the rheological history of the liquid may significantly affect the flow rate (Bacon, 1978).

vi) effect of the number of rollers on the pump

The rollers on the pump produce an output composed of discrete slugs of liquid (Fig. 4.10), which can be observed to gradually merge along a length of tubing to give a more even flow. Unfortunately it is difficult to measure the instantaneous flow over the short duration of a pulse in the flow (about half a second with a two roller pump turning at 60 rpm). An estimate of the size of the pulses may be made using an electric flow meter. Although the response time is too long to measure individual pulses, the lowest and highest instantaneous readings over a period of time will show the range of outputs.

The results suggested that the pulses were smaller at higher flow rates (Fig. 4.11), presumably because they merged to a greater degree. There was also evidence that tubing with a wider bore gave larger pulses, because there were fewer revolutions per minute to give the same flow rate. The smallest variation in output was at the flow rate of 700-800 ml/min, which is the pump output on the wheelbarrow sprayer when walking at 1.0 m/sec.

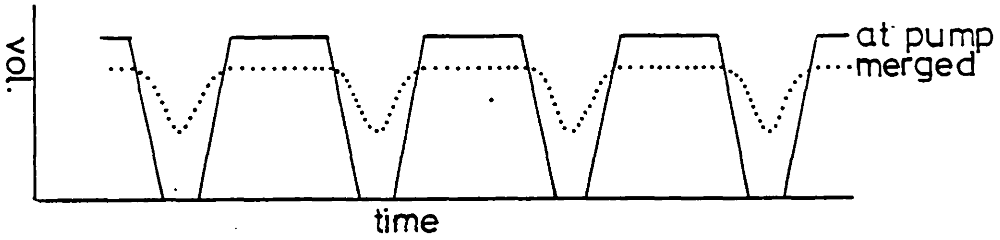
Although there was a slight reduction in the size of the pulses when using a three roller (Watson Marlow) pump compared to a two roller (Glen Creston) pump, the flow rate was similar whether three or six rollers were used on the wheel pump (Fig. 4.12).

4.2.4. Choice of peristaltic pump for the prototype sprayer

The output properties of all three pumps tested were acceptable, and the main differences were in their durability and construction. The wheel pump was very simple, but extensive testing showed that it had a very short life and was too crude in design. The Watson Marlow pump performed satisfactorily but was replaced on the second prototype by the Glen Creston pump, which had several advantages. It was more robust and the pump tubing and rollers were enclosed in

Fig. 4. 10 Pulsing of Peristaltic Pump Output

a) pulses partially merge after leaving pump



b) two pumps 90° out of phase reduce the variation in flow rate (see p.42)

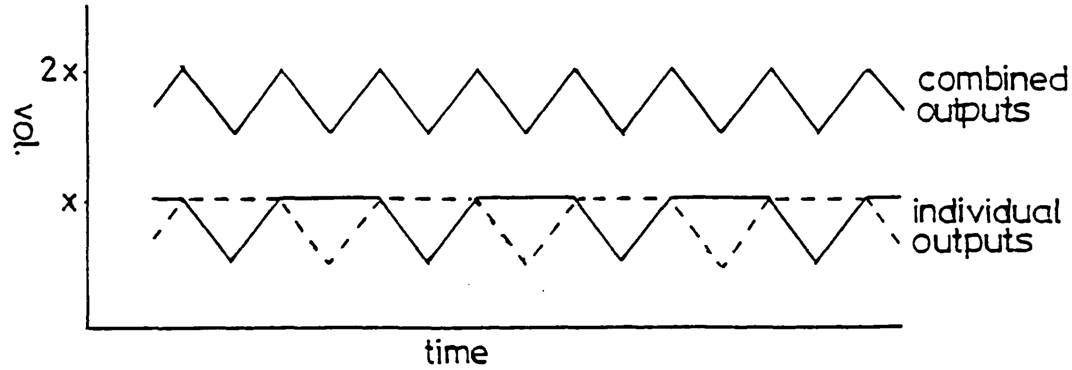


Fig. 4.11 Variation in Flow Rate due to Pulsing

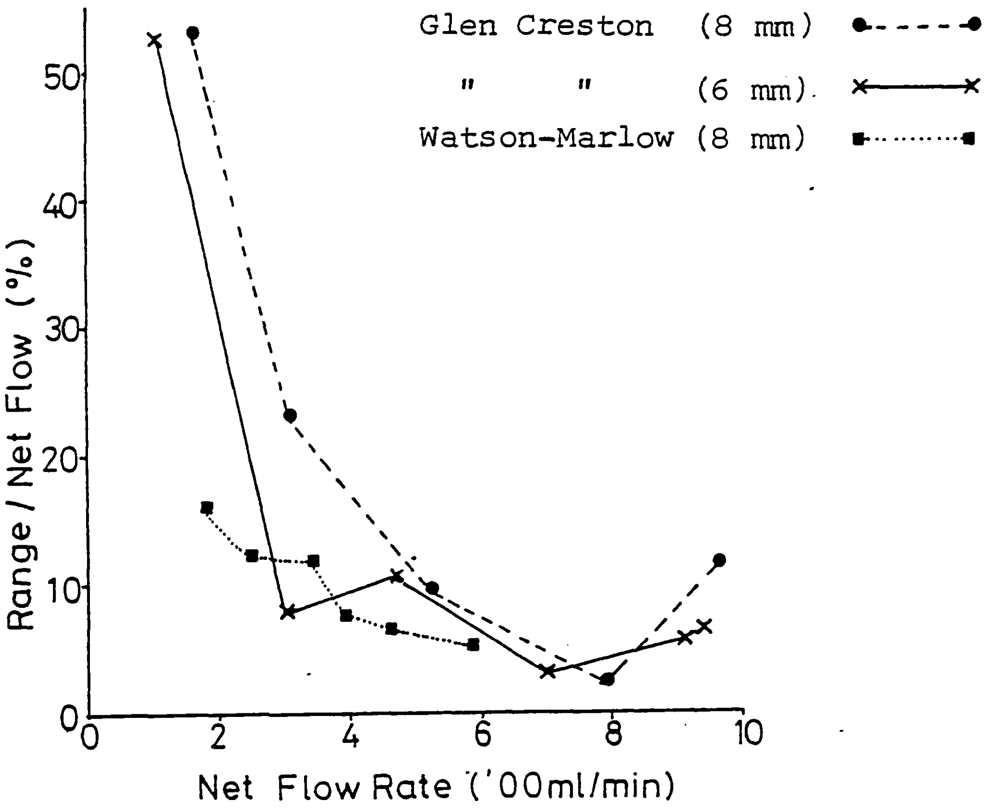
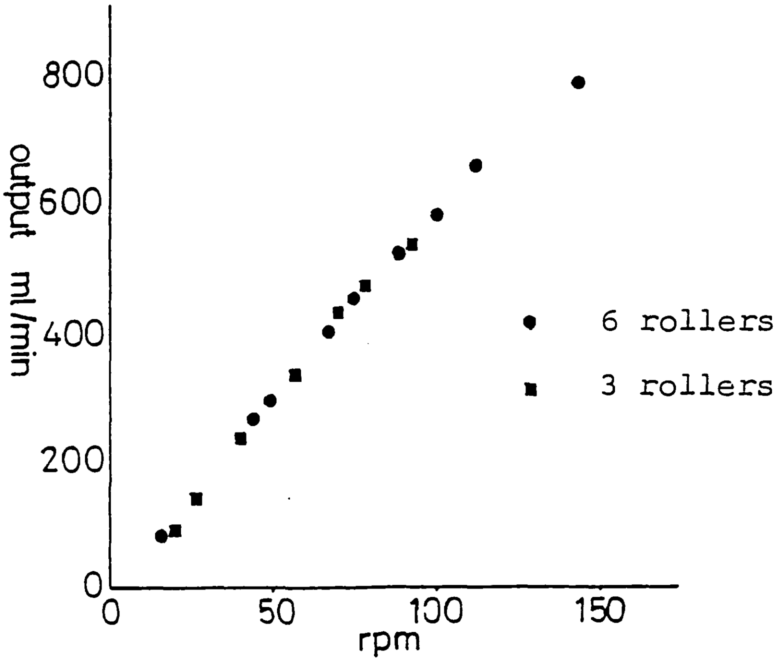


Fig. 4.12 Effect on Flow Rate of the Number of Rollers on the Pump (wheelpump)



a compact unit, yet were accessible.

Summary of the Glen Creston "WAB Pump" characteristics:

Dimensions:	112 x 112 x 81 mm
Weight:	0.5 kg
Output at 60 rpm:	6 mm tubing - 350 ml/min
	8 mm tubing - 430 ml/min

The output increases linearly with rotational speed but varies slightly depending on the type of fluid, and is susceptible to large fluctuations in temperatures.

4.3. Materials Testing

Materials in contact with the spray liquid may react with it and perish or corrode, reducing the efficiency and durability of the sprayer. Each of the five types of plastic on the prototype sprayer which could contact the spray liquid, were tested for their reaction with a range of herbicide formulations, a surfactant and several oils, some of which are commonly used as solvents in emulsifiable concentrate formulations (Table 4.1).

None of the herbicides significantly affected any of the plastics tested. The two tubing materials showed no sign of deterioration after being soaked in the herbicides, and even after it had been compressed for 12 hours, the tubing regained its original shape when the pressure was released. During laboratory spraying experiments with the sprayer, neoprene tubing, in which paraquat had been left for over 70 hours, remained occluded where the roller had pressed. No other instances were noted during many laboratory and field experiments using a wide range of herbicides.

The oils significantly affected the tubing materials, but, except for Duterex 217EC on the PVC tubing, they had little effect on the plastics. The silicone rubber doubled its weight after soaking in Essol D200/240 and kerosene, but the oils would not normally be used at concentrations over 30% in the herbicide formulations, and, when further diluted with water for spraying, are unlikely to produce such great effects.

Table 4.1 Materials Testing: % change in weight after 48 hours in chemical(i)

	concentration in water (%)	silicone rubber tubing	neoprene tubing	PVC tubing	polypropylene spinning cup	polyethylene spray tank
Surfactant						
Agral	50	+4	+1	0	+1	+1
Oils						
Duterex 217 EC	100	+15	+19	+6	+2	+1
Essol D200/240	100	+94(ii)	+6	-2	-3	-1
Kerosine	100	+94(ii)	+5	-2	+4	+1
Ulvapron	100	+8	+2	0	+1	+1
Herbicides						
atrazine (flowable) (Weedex 500L)	30	+2	0	0	+2	0
atrazine (wp) (Atrazine 80WP)	20	0	+2	+1	0	0
difenzoquat (wp) (Avenge)	13	-1	-1	0	0	-1
glyphosate (water sol) (Roundup)	4	0	-1	-3	-1	+1
pendimethalin (ec) (Stomp)	3	+2	+3	+1	0	+2
Water		+1	+1	+5	0	0

(i) change greater than 5% considered significant

(ii) tubing diameter nearly twice original size

4.4. "Micromax" Spray Characteristics

The droplet spectrum of a spray has a considerable effect on its coverage and retention on foliage, and its susceptibility to drift. The spray characteristics are particularly important with low volume applications which cannot rely on a high volume of water to distribute the active ingredient over the target. It is, therefore, important to know the droplet spectra produced by the wheelbarrow sprayer over the range of atomizer speeds and flow rates likely to be encountered during use. The speed and flow rate can then be adjusted to give the best droplet spectrum.

Droplet spectra were measured using a laser droplet analyser. After preliminary experiments to investigate the use of the analyser with a spinning cup, more detailed experiments were carried out with the spinning cup on the wheelbarrow sprayer.

4.4.1. Preliminary tests on the droplet analyser

i) focal length of laser beam lens

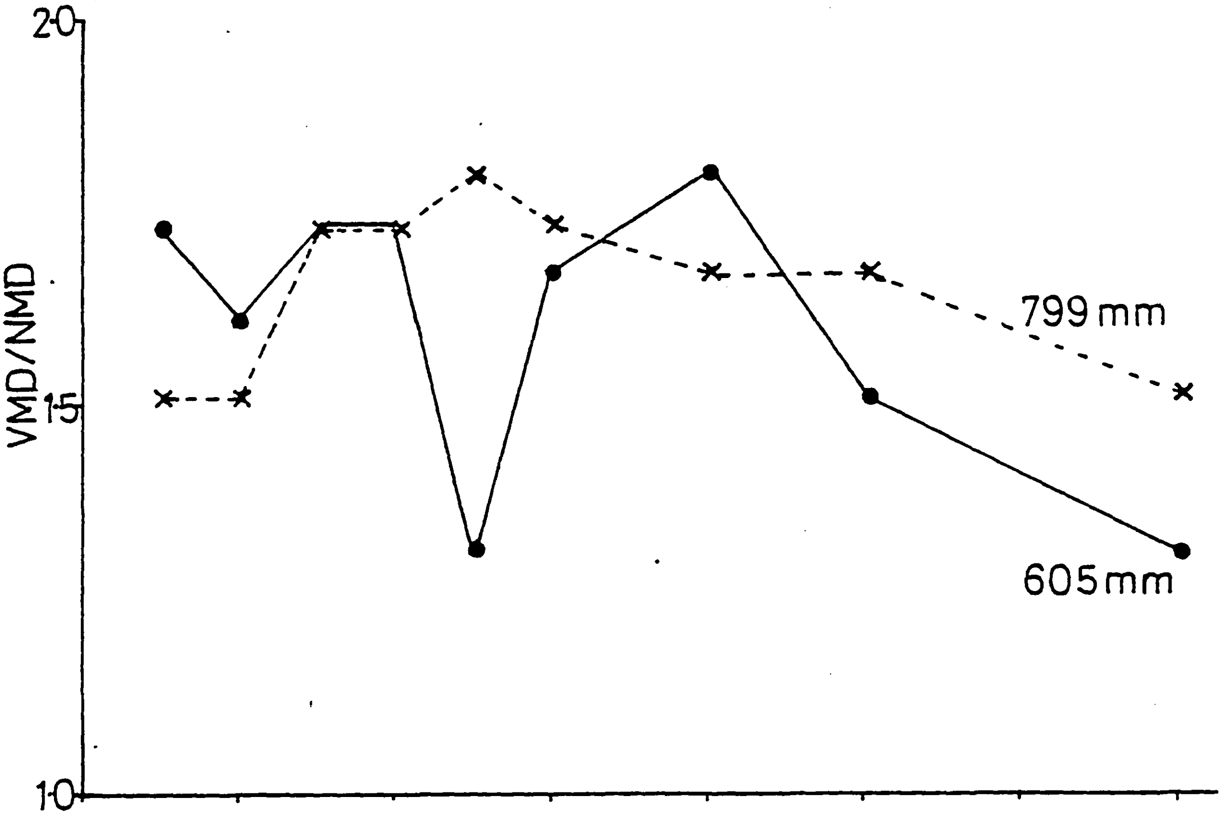
The focal length of the Fourrier transform lens is chosen to be appropriate for a particular droplet size range (Felton, 1978). Two lenses, with focal lengths of 605 mm and 799 mm, were compared. The 799 mm lens consistently gave the higher VMD (Fig. 4.13), by a similar proportion over the range of droplet sizes tested. The effect on the VMD/NMD ratio was less clearly defined, but when the VMD was greater than 280 µm the 799 mm lens gave a higher ratio. The results may reflect differences in efficiency of the lenses for counting droplets at both extremes of the size spectrum.

ii) distance between atomiser and laser beam

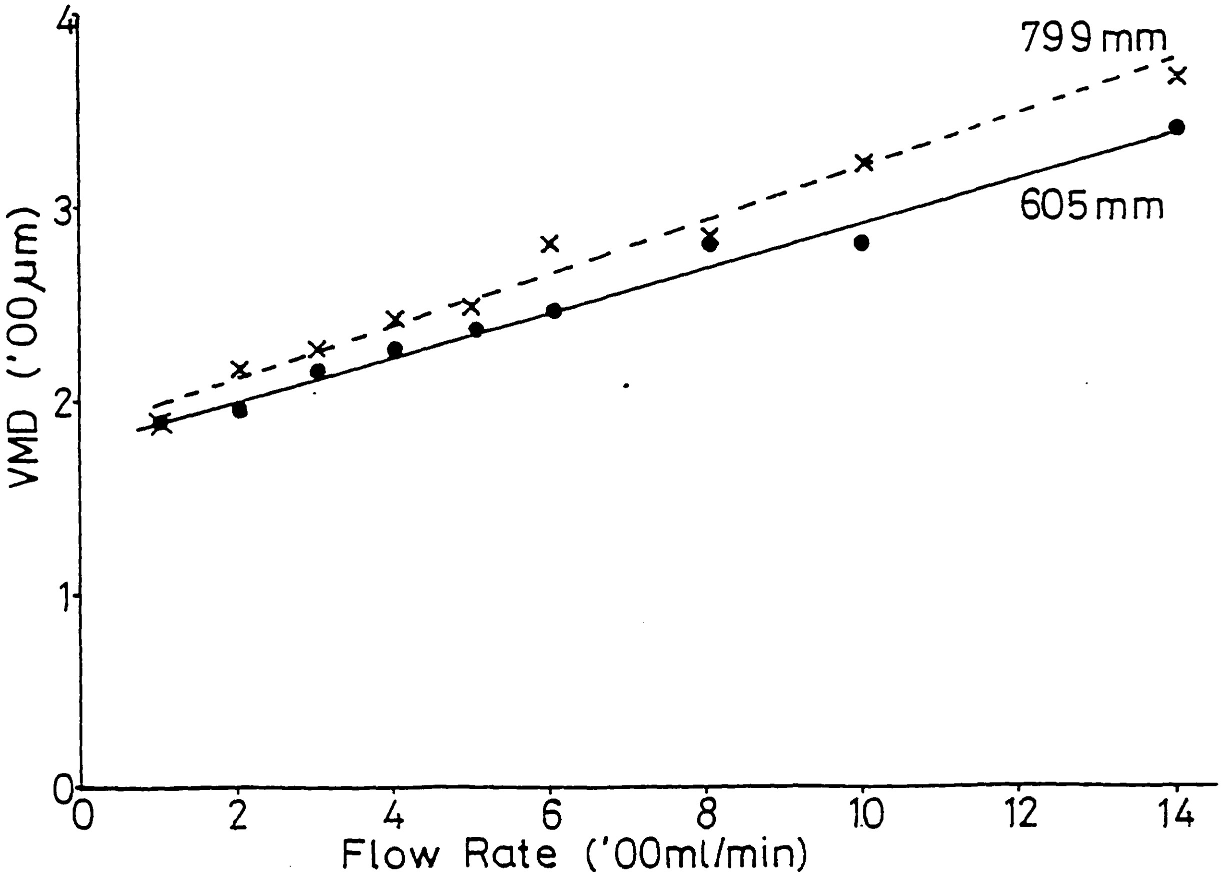
Droplets become more disperse as the distance from the edge of the spinning cup increases, so the section of the spray cloud through which the laser beam passes could influence the calculated spray parameters. The spinning cup was positioned at varying distances from the laser beam, and for each position the exact angle of the cup was adjusted so that the centre of the spray cloud hit the centre of the laser beam.

Fig. 4.13 Comparison of Results Using Two Lens Sizes on the Droplet Analyser

a) VMD/NMD



b) VMD



The most representative sample of the complete droplet spectrum was obtained within 0.20 m of the cup perimeter. There was no significant change in the VMD when the perimeter of the spinning cup was 0.05-0.20 m from the beam, but the VMD increased beyond this distance (Fig. 4.14). The VMD/NMD ratio declined as samples were taken further from the spinning cup, approaching 1.0 at distances over 0.3 m. This reflects the rapid settling out of very small droplets due to their low momentum, which could be observed by eye. The droplet spectrum did not vary significantly between samples taken at different points in a vertical transect of the swath (Table 4.2).

iii) effect of surfactant concentration on droplet size

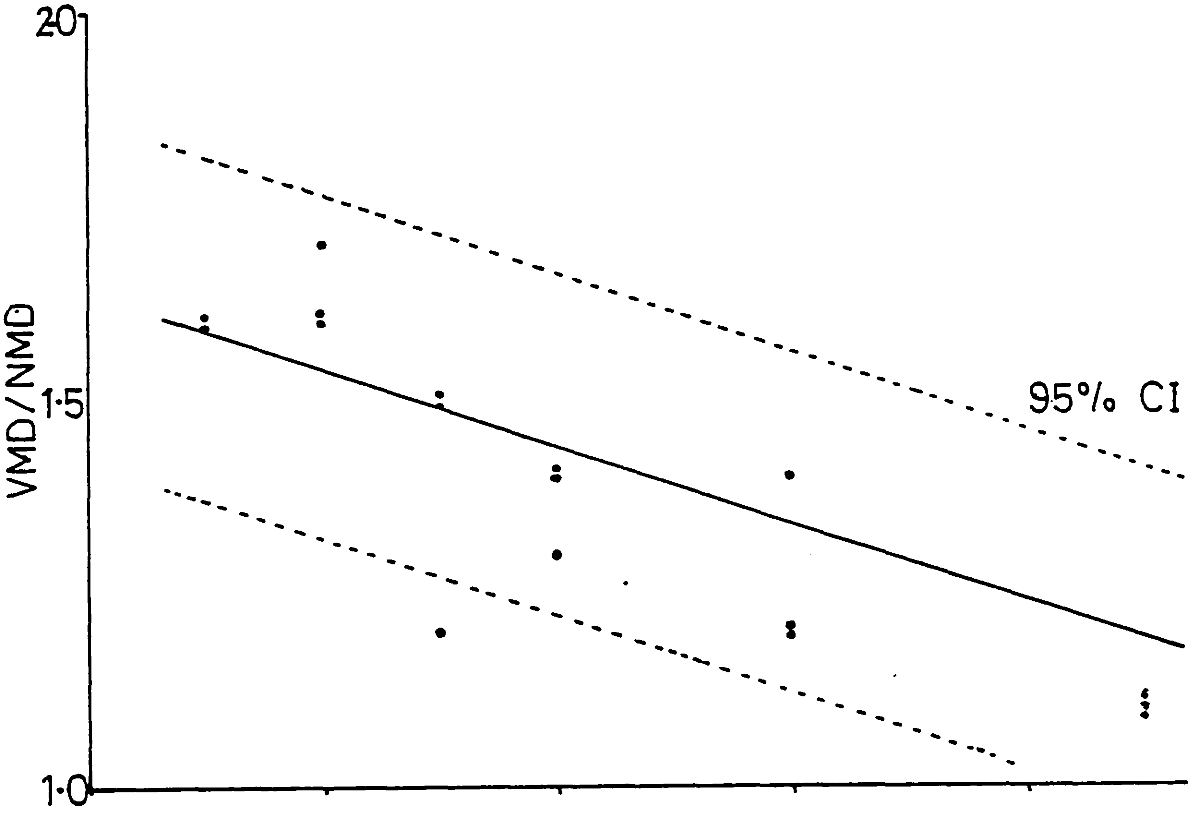
When water is used as a material for spray testing, a surfactant is normally included to ensure wetting of the spinning cup, and simulate the presence of a herbicide in the spray. A range of surfactant concentrations were tested for their effect on droplet size. The addition of 0.01-1.0% v/v of surfactant to tap water had virtually no effect on the VMD, but it was sharply reduced when 5% v/v was added (Fig. 4.15). This pattern was repeated at each flow rate tested. The VMD/NMD ratio gave more variable results, but tended to decline as the surfactant concentration was increased with the 400 and 1200 ml/min flow rates, while with 800 ml/min no distinct trend was shown.

iv) discussion

When interpreting the results from a droplet sizing experiment, the exact method of obtaining the results should be considered. Heijne (1981) used a 300 mm Fourrier transform lens on the droplet analyser to measure VMD's predominantly less than 250 µm. In the following experiments a larger VMD was expected so a 799 mm lens was used. The perimeter of the spinning cup should be 0.15 m from the laser beam. Hydraulic nozzles should be sampled at a distance of 0.2-0.3 m from the nozzle (Arnold, 1983a), but at this distance from a spinning cup the spray will be disperse and small droplets will be under-estimated. Most other authors have not stated the sampling distance. A 0.1% surfactant solution was used in the following experiments, in accordance with previous authors (Frost & Green, 1978; Heijne, 1981).

Fig. 4.14 Effect of Distance Between Spinning Cup and Laser Beam on the Measured Droplet Size

a) VMD/NMD $y = 1.64 - 0.01x$ $(r = -0.85)$



b) VMD $y = 266.5 + 0.46x$ $(r = 0.63)$

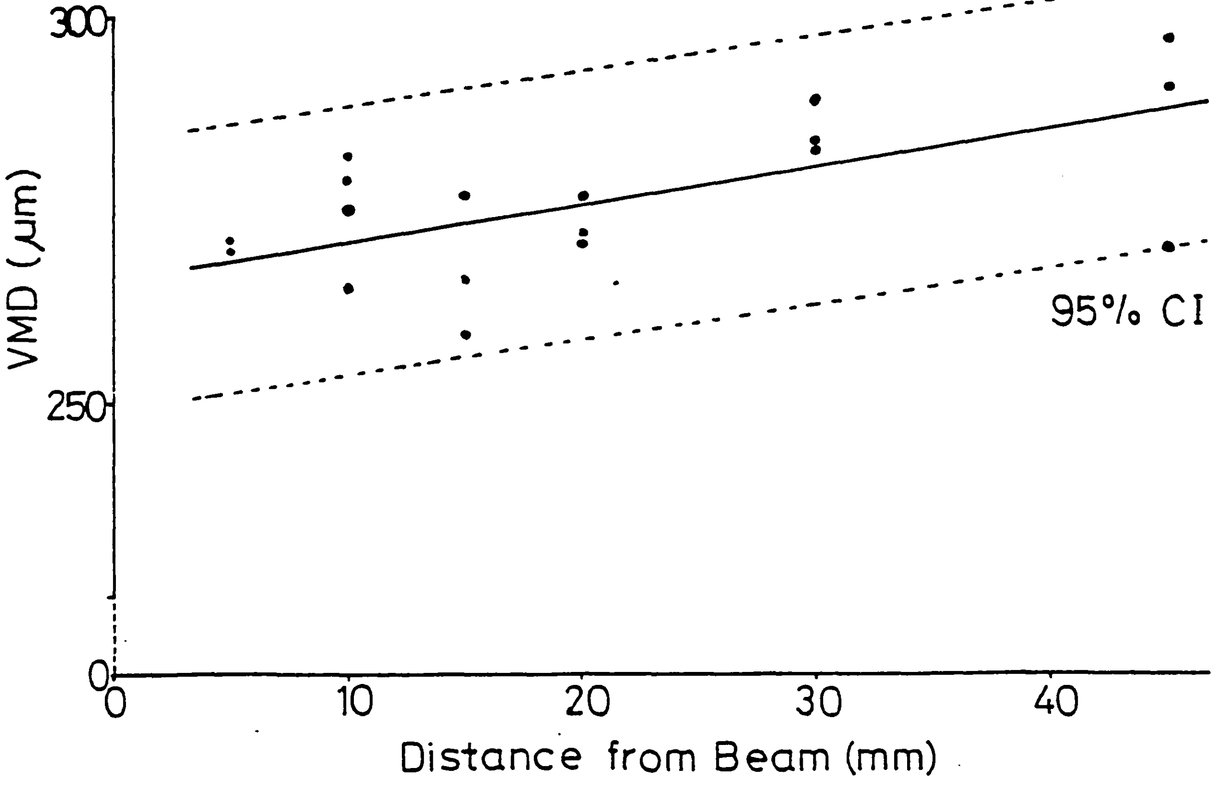
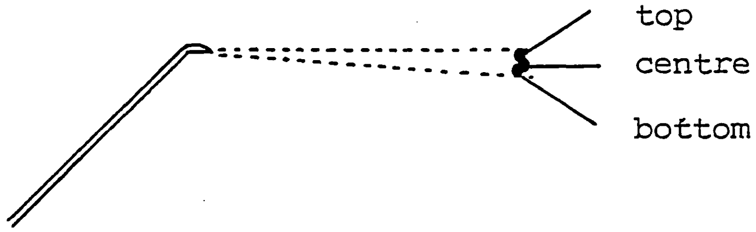


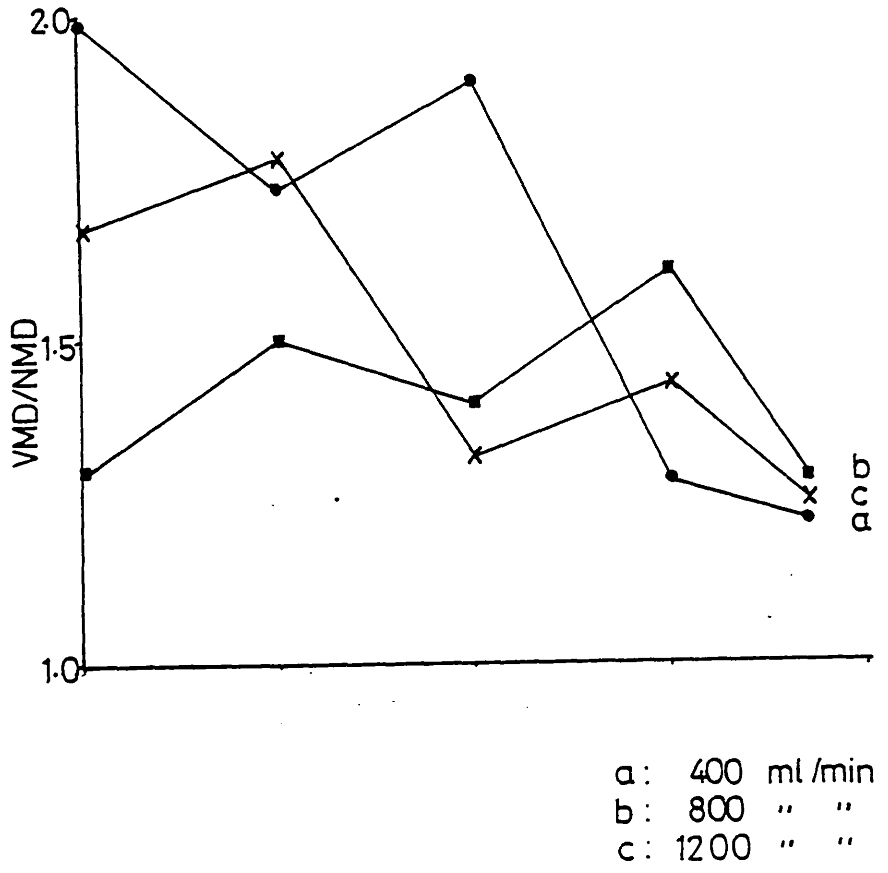
Table 4.2 Effect on Droplet Spectrum of Sampling Different Parts of the Swath



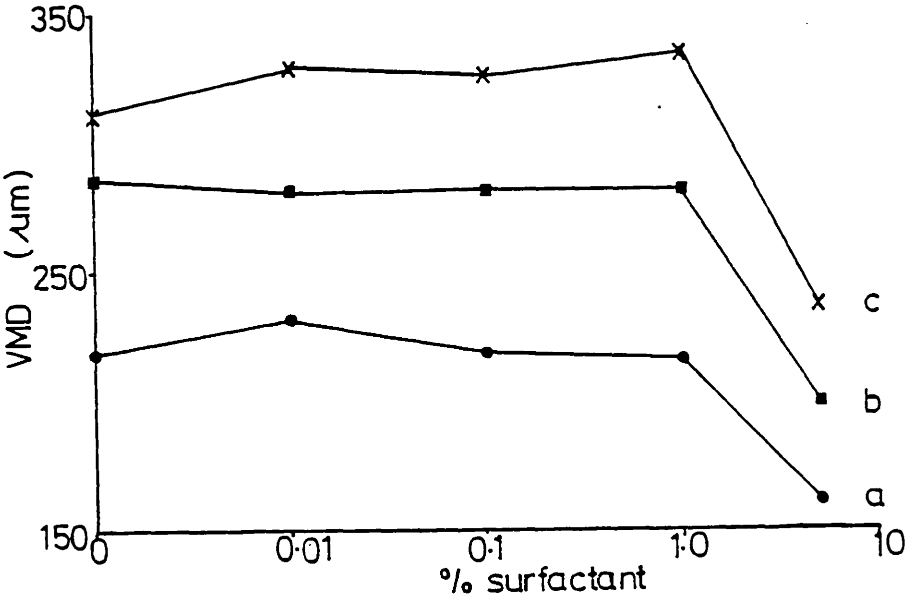
Position in swath	Distance from cup perimeter			
	50 mm		450 mm	
	VMD (µm)	VMD/NMD	VMD (µm)	VMD/NMD
top	259	2.9	291	1.05
centre	268	2.5	286	1.06
bottom	263	3.1	299	1.04

Fig. 4.15 Effect of Surfactant Concentration on Droplet Spectrum at 2000 rpm (3 flow rates onto spinning cup)

a) VMD/NMD



b) VMD



The computer fits the distribution of droplet sizes to a Rosin-Rammler distribution, which does not take into account a bimodal distribution caused by the production of satellite droplets. This is not likely to have a significant effect on the VMD due to the negligable volume of the satellite droplets, but it may affect the NMD by underestimating the number of very small droplets.

4.4.2. Spinning cup characteristics

i) effect of flow rate and rotational speed

Both the flow rate and rotational speed significantly affect the droplet spectrum produced by the spinning cup. At 1000 rpm, increasing the flow rate from 200 ml/min at first reduced and then increased the VMD. At all other rotational speeds tested the VMD increased linearly with flow rate (Fig. 4.16). The VMD declined with increasing rotational speed, but there was an interaction between speed and flow rate, so that changes in flow rate had less effect at high speeds. This was reflected in the shallower gradients of the responses to flow rate at higher rotational speeds.

At low rotational speeds (<2000 rpm) the VMD/NMD ratio remained below 2.0 over the range of flow rates tested, but the ratio increased at higher rotational speeds. The flow rate at which the VMD/NMD ratio rose rapidly became lower as the rotational speed was increased.

A regression of VMD/NMD ratio on VMD showed a slight correlation (r=0.6) when the rotational speed was 2000 rpm at a flow rate of 500 ml/min.

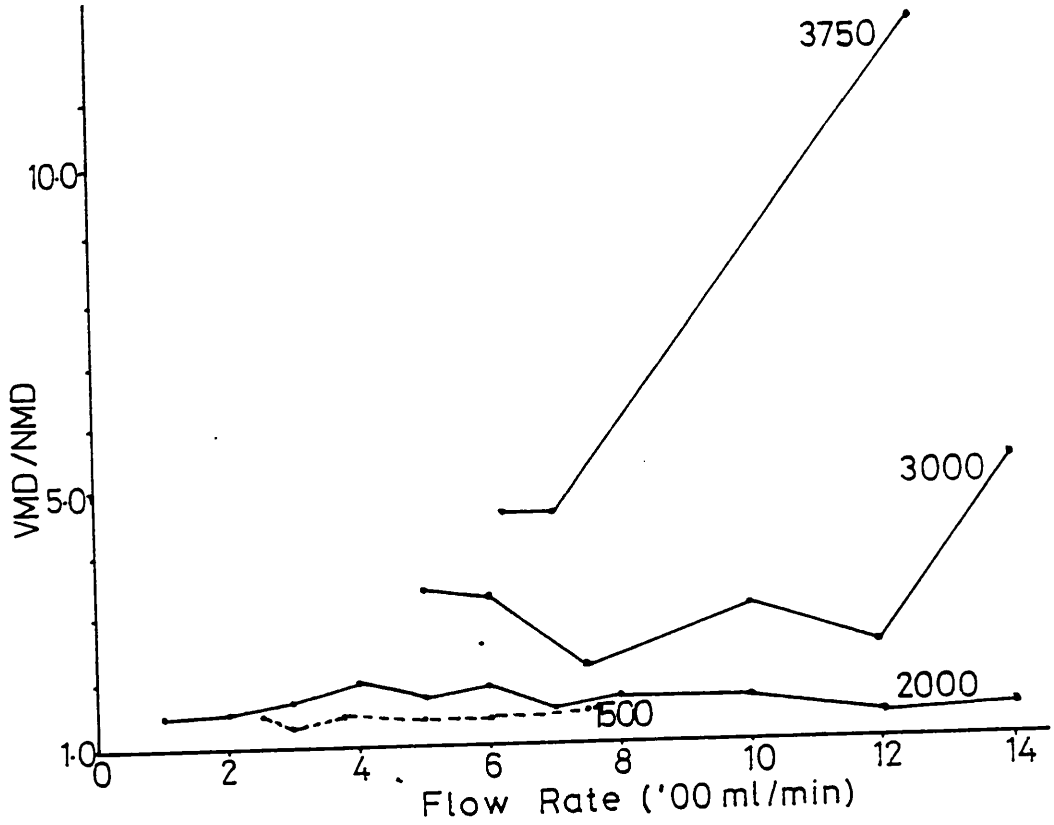
ii) effect of the angle of the spinning cup

The effect of the angle of the spinning cup was investigated, firstly to test any effect on droplet size of the movements of the sprayer in the vertical plane as the operator walks, and, secondly, to check that a similar droplet spectrum is produced when the sprayer is used at 45° and horizontally. A flow of 700 ml/min and a rotational speed of 2000 rpm were used, since this was the most likely combination to be used when spraying in the field.

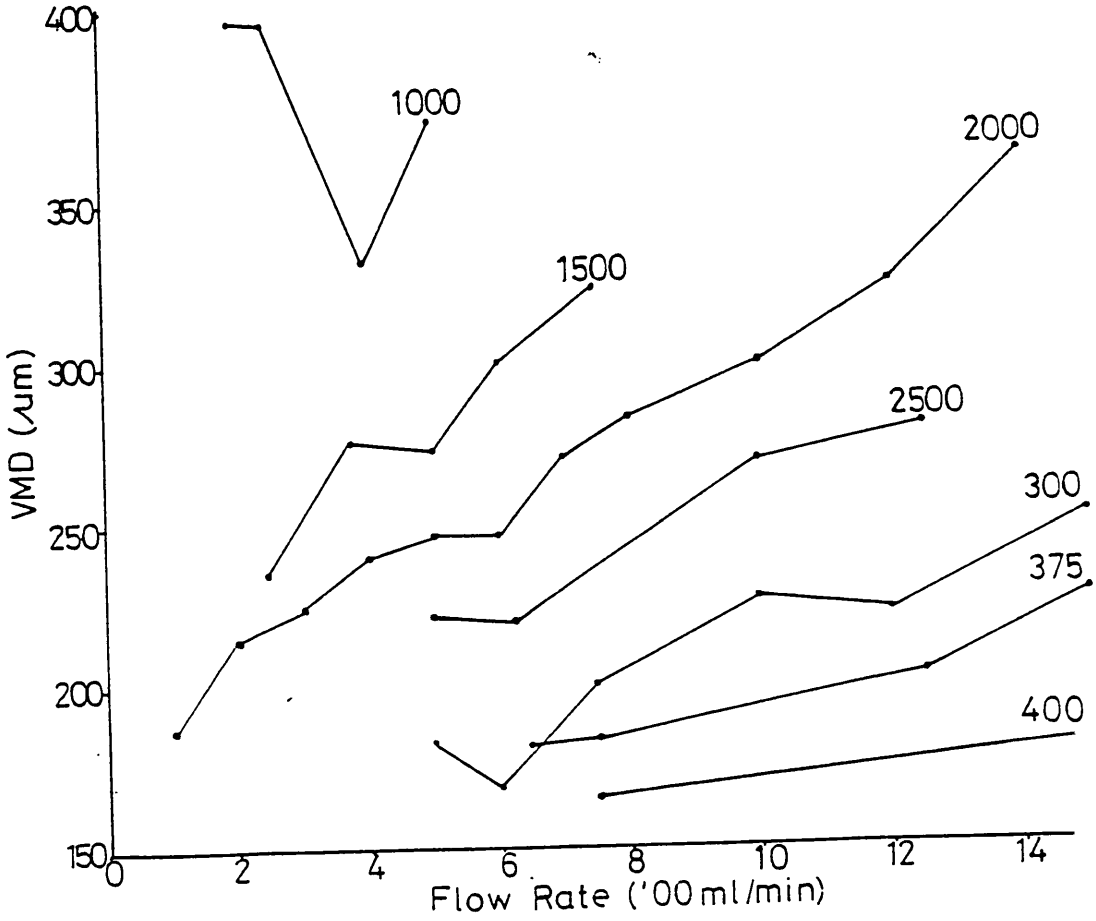
As the angle increased from the horizontal to 60° the VMD fell from 271 µm to 231 µm, but a further increase to 70°

Fig. 4.16 Effect of Flow Rate on Droplet Spectrum at Different Rotational Speeds (rpm)

a) VMD/NMD



b) VMD



caused a sharp rise in VMD to 280 µm (Fig. 4.17). The VMD/NMD ratio rose from 1.5, when the cup was horizontal, to 5.3 at 70°, although at 35° there was a particularly uniform spray with a ratio of 1.4.

iii) discussion

The replication between experiments was such that a ±28 µm confidence interval could be placed on the VMD at 2000 rpm although the VMD/NMD ratio was more variable (Fig 4.18).

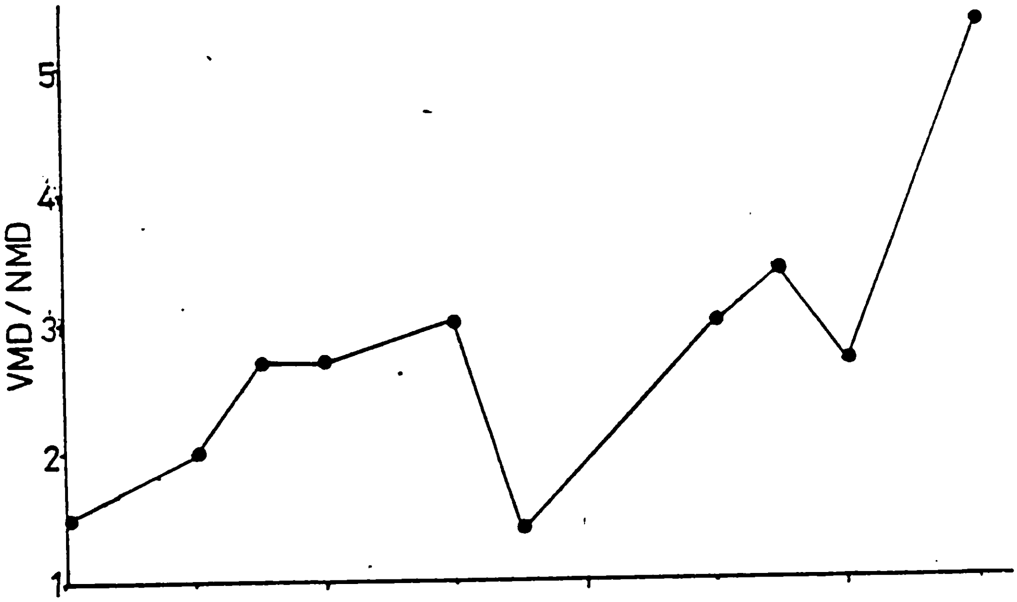
The results from these experiments illustrate two of the modes of disintegration described by Hinze & Milborn (1950). The predominant mode changes with the rotational speed of the cup and with the volume of liquid reaching the edge of the cup. The initial decrease in VMD as flow rate is increased at 1000 rpm, corresponds to a transition phase from direct droplet formation to ligament formation. When only ligaments are produced, further increase in flow rate thickens the ligaments which produce droplets with progressively larger VMD's. At these higher rotational speeds, flow rates lower than those tested would be required for direct droplet formation to occur. The grooves on the spinning cup prevent sheet formation at all the flow rates and rotational speeds tested with the cup held horizontally.

The VMD/NMD ratio at 2000 rpm was below 2.0 for all flow rates, and was nearly within the limit of 1.4 proposed for true CDA spraying (Johnstone, 1978). At 3000 rpm and above, the droplet spectrum became unacceptable at most flow rates, due to a combination of more irregular ligament production, illustrated by Frost & Green (1978), and more irregular breakup of ligaments, caused by vibrations of the cup at high rotational speeds.

The point of initial contact with the liquid fed onto the cup was changed when it was tilted (Fig. 4.19), which affected the position of the area of high liquid release from the cup perimeter. The exact position of these areas is determined by the flow rate and rotational speed (Frost & Green, 1978; Heijne, 1981), as well as the angle of the cup, and this must be reflected in the droplet size of the sector sampled by the laser beam. As the cup was tilted, there was a decline in the volume of liquid reaching that part of the cup producing this sector, which, therefore, contained more

Fig. 4.17 Effect of Angle of Spinning Cup on Droplet Spectrum (2000 rpm; 700 ml/min)

a) VMD/NMD



b) VMD

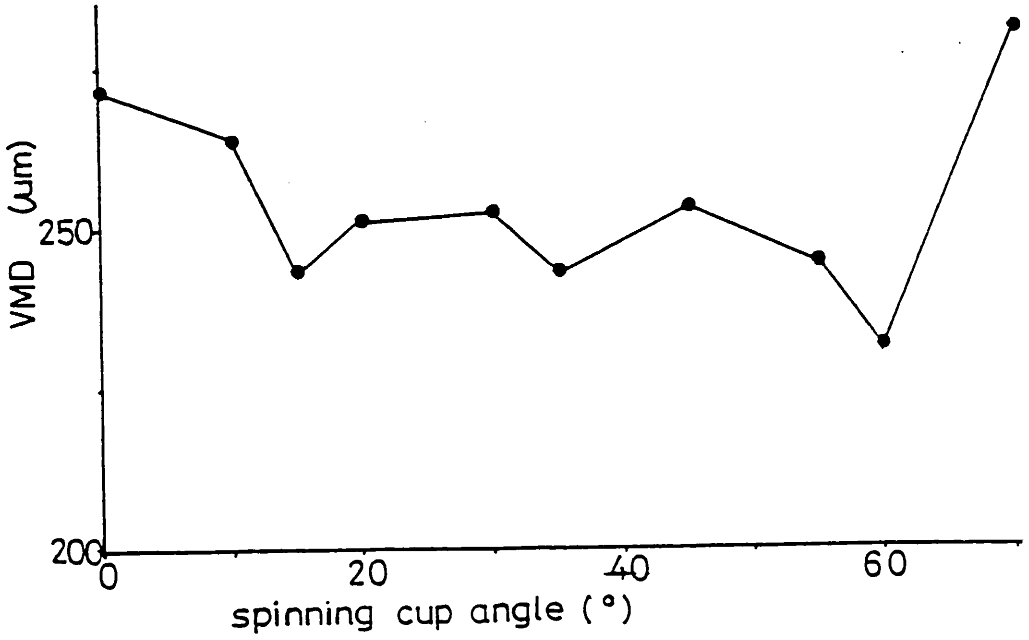
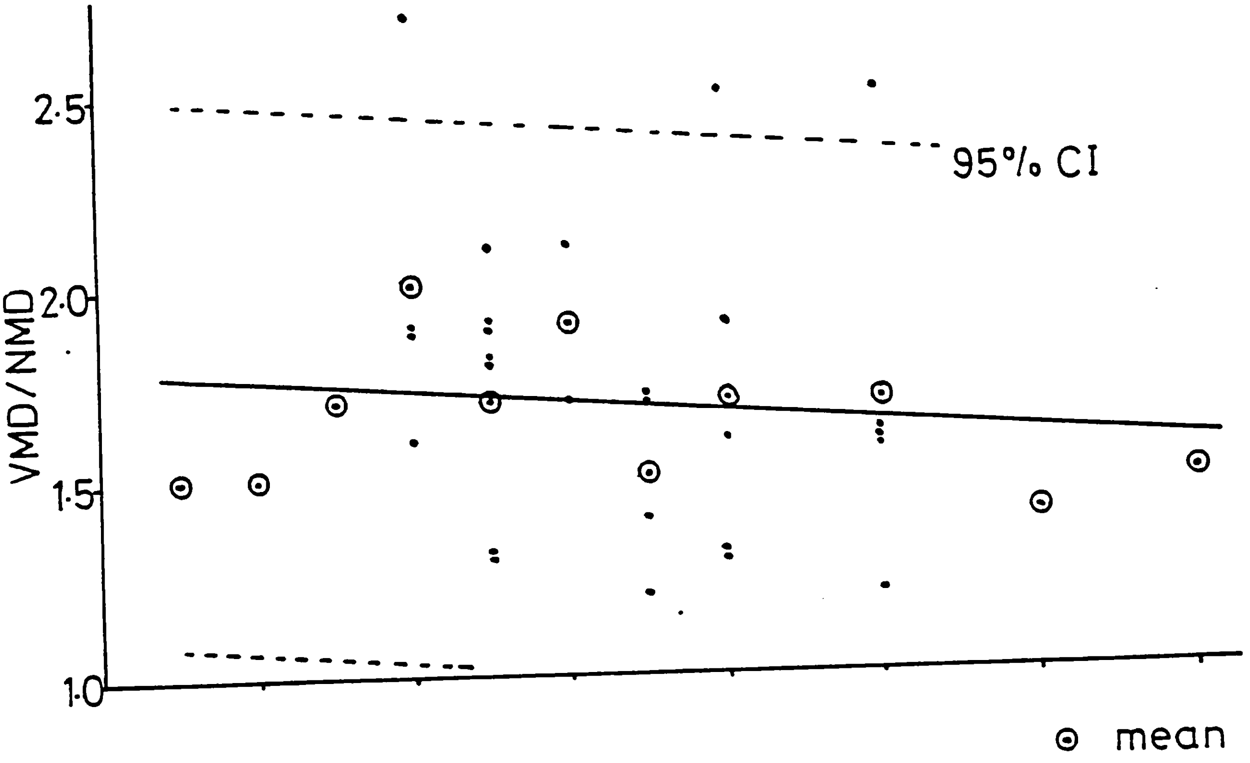


Fig. 4.18 Consistency of Droplet Size Results at 2000 rpm

a) VMD/NMD $y = 1.8 - 1.4x$ $(r = 0.12)$



b) VMD $y = 189 + 0.12x$ $(r = 0.92)$

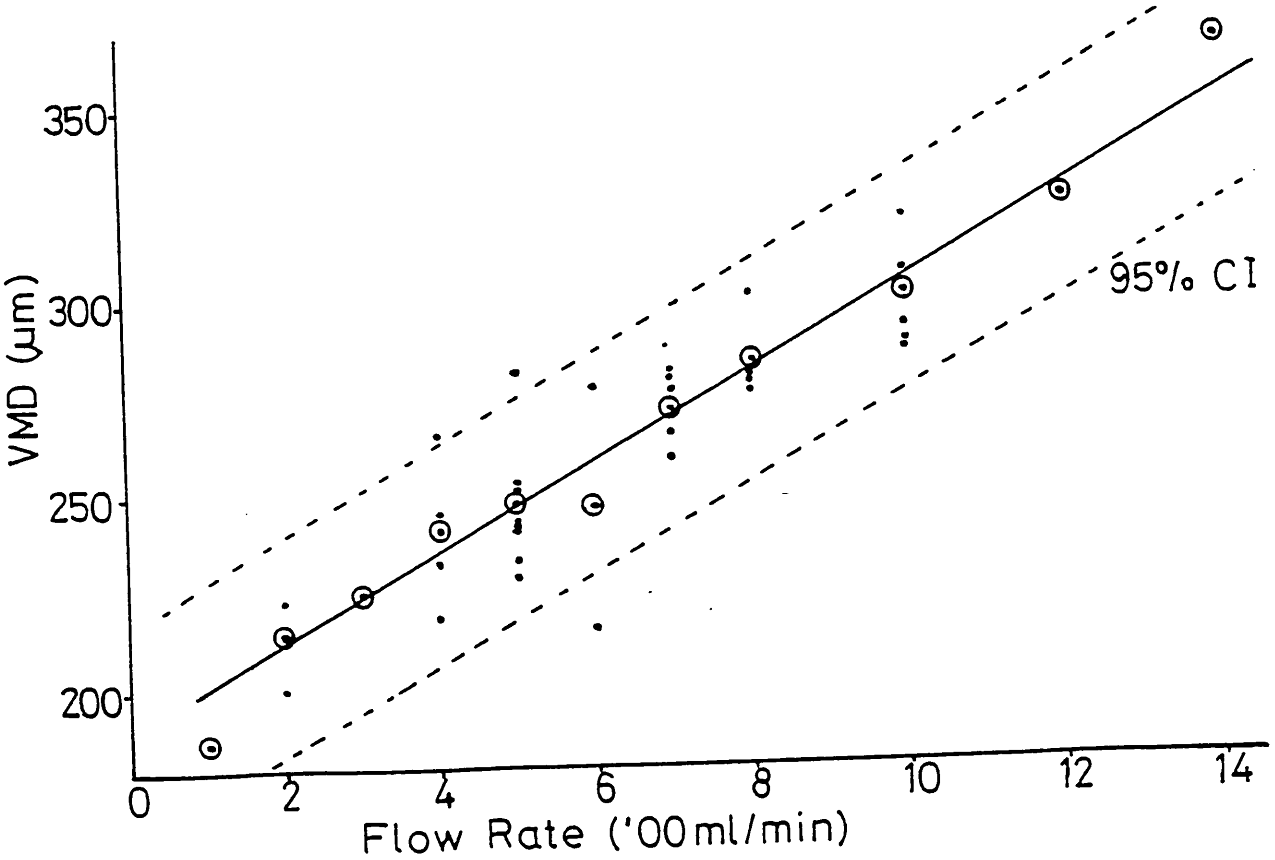
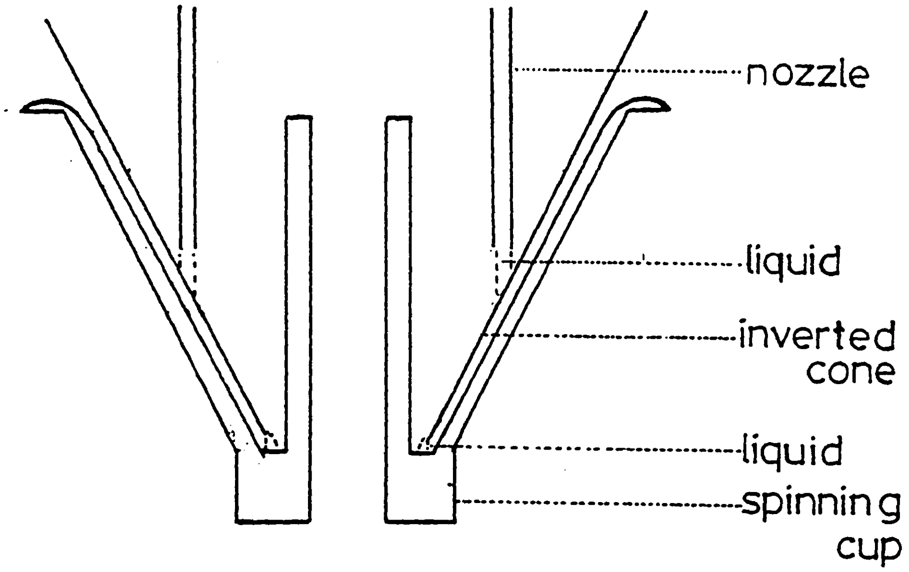
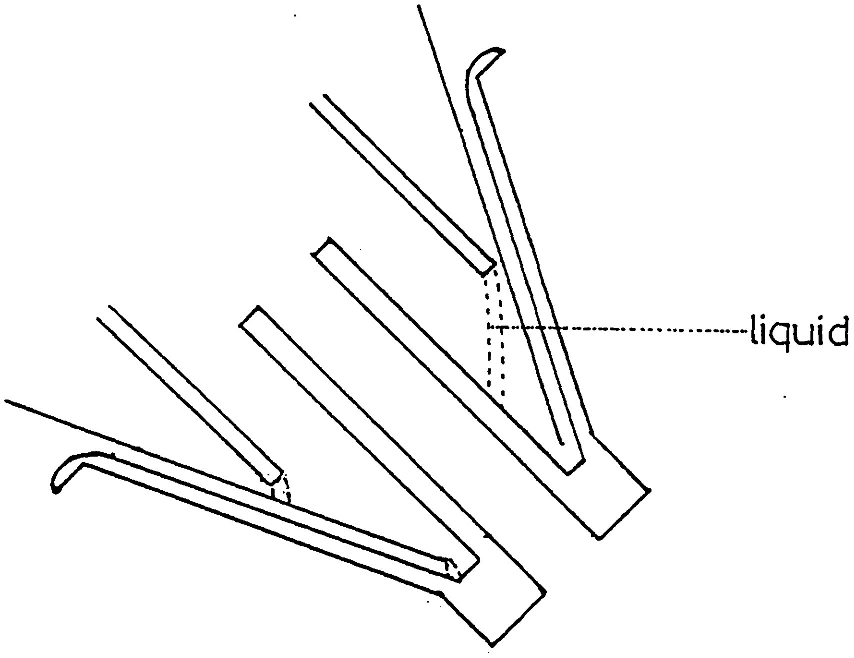


Fig. 4.19 <u>Effect on Feed of Angle of Spinning Cup</u>

a) horizontal



b) angled at 45°



smaller droplets. However, at 70° the angle was so great that the liquid began to flood the lower edge of the cup and more irregular ligament formation occurred.

The results at 2000 rpm are more similar to those of Bode & Butler (1981) than those of other authors (Fig. 4.20). The lower VMD found by Heijne (1981) may be due to shattering of droplets on the shroud, which fitted closely around the spinning cup, although the short focal length lens on the droplet analyser may have underestimated the number of large droplets. In contrast to the other authors, Azopardi (1980) showed little response of the VMD to flow rate, possibly due to the much higher concentration of surfactant in the spray liquid (Table 4.3). However, there is conflicting evidence on the effect on VMD of increasing the surfactant concentration. The present work suggests that there is no effect up to a 1% surfactant concentration, but an increase to 5% significantly decreases the VMD (Fig. 4.15). A decrease in droplet size with increasing surfactant concentration was found by Heijne (1981), but Bode & Butler (1981) found the opposite effect when an unspecified surfactant was added to water in the spray.

4.4.3. Effect of linking rotational speed and flow rate to walking speed

When using the wheelbarrow sprayer, the rotational speed of the cup and the flow of liquid onto it are varied in proportion to the walking speed of the operator, because the spinning cup and the pump are driven from the ground wheel. In the following experiments this effect was simulated on a motor driven cup using flow rates based on the output of a Glen Creston pump. Four ranges of flow rates were used, equivalent to two diameters of pump tubing used either singly, or paired as on the second prototype sprayer (Table 4.4).

i) varying flow rate and rotational speed together

As walking speed increased the VMD fell, following a power progression ($r > 0.93$). Below 0.5 m/s the very low rotational speeds produced large droplets, even with relatively low flow rates onto the cup (Fig. 4.21). Between 0.29 and 0.58 m/s the VMD fell sharply from about 900 µm to below 400 µm, but as the walking speed increased further the VMD declined more slowly.

Fig. 4.20 Comparison of VMDs Obtained by Different Authors at 2000 rpm

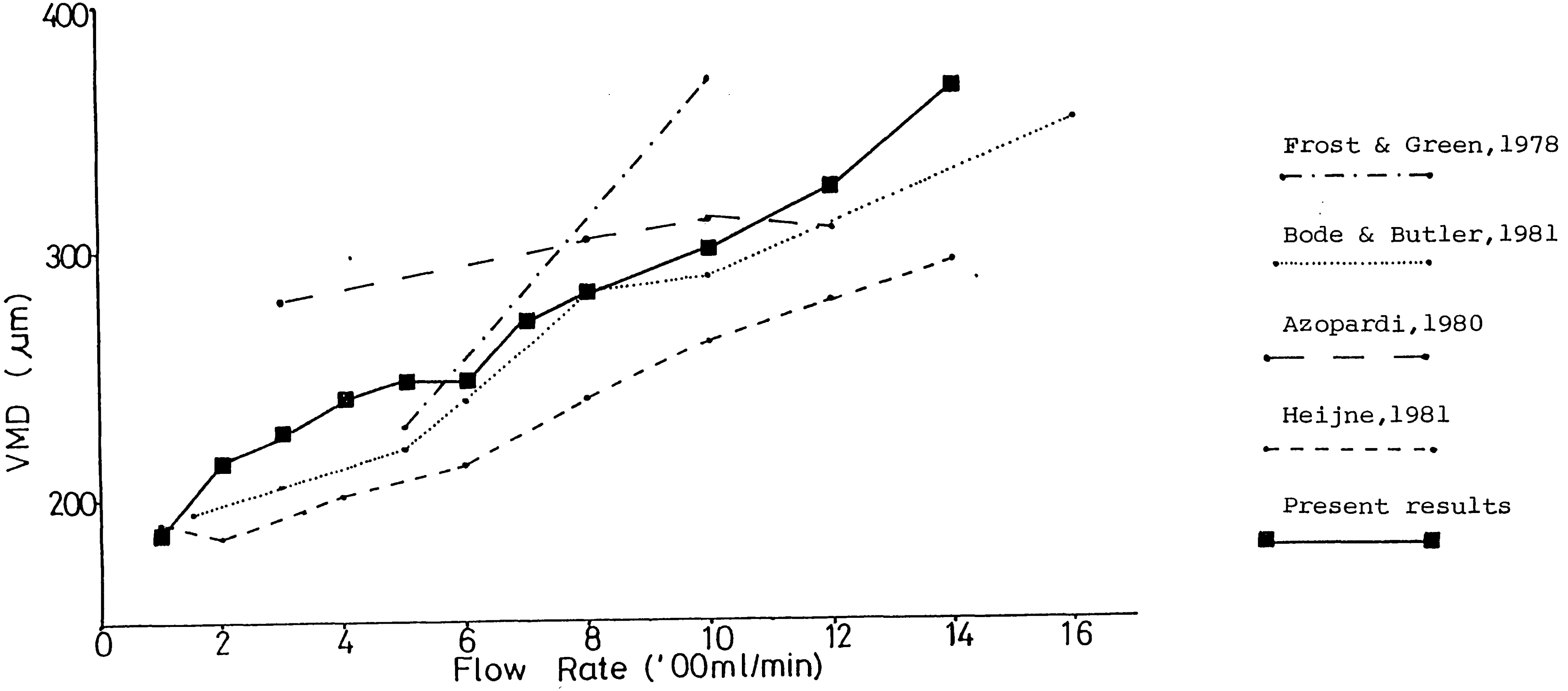


Table 4.3 Experimental Details for Other Authors

Author	Sizing Method	Distance of "Micromax" from Beam (m)	Surfactant+ and Concentration (%)
Azopardi (1980)	Malvern Instruments ST 1800 (1000 mm lens)	0.20	Farmon "Blue" (3.0)
Bode & Butler (1981)	Particle Measuring Systems OAP-2D-G64	-	none (tap water)
Frost & Green (1978)	Flash photography & image analyser	-	Agral (0.1)
Garnett (present results)	Malvern Instruments ST 1800 (800 mm lens)	0.15	Agral (0.1)
Heijne (1981)	Malvern Instruments ST 1800 (300 mm lens)	?	Teepol (0.1)

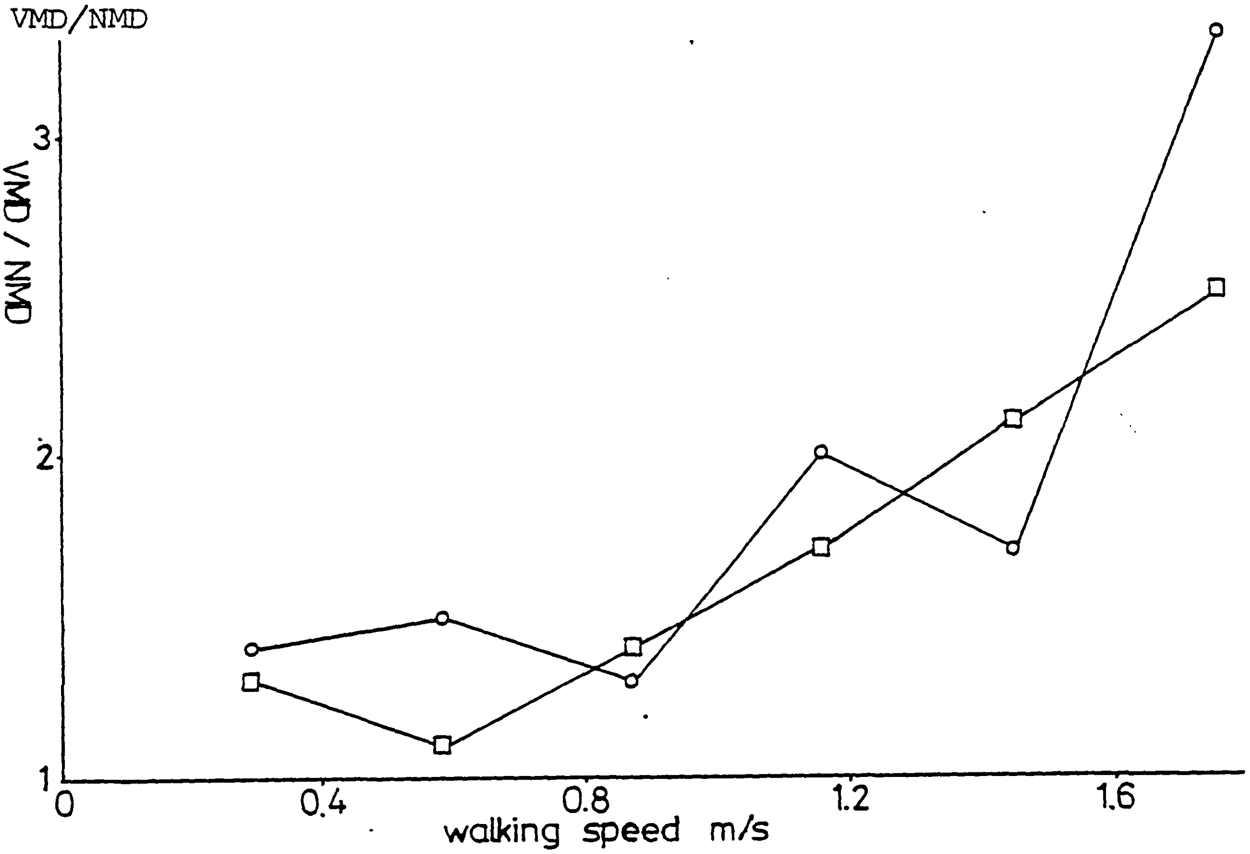
+ non-ionic

Table 4.4 <u>Experimental Details</u>

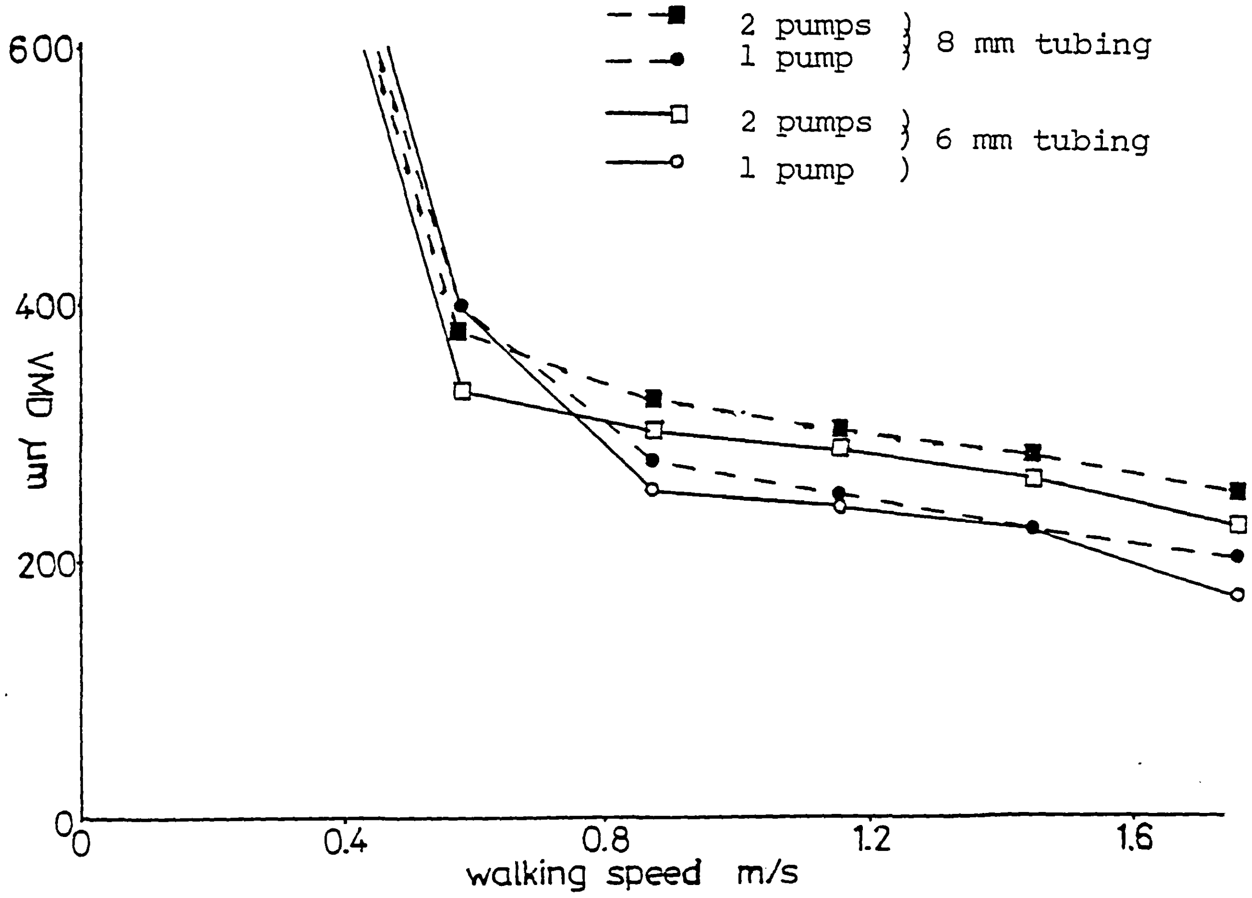
Turns of ground wheel (rpm)	Equivalent walking speed (m/s)	Rotational speed (rpm)	Flow rate (ml/min)			
			8 mm tubing		6 mm tubing	
			X1	X2	X1	X2
30	0.5	1000	215	430	170	340
60	1.0	2000	430	860	340	680
90	1.5	3000	645	1290	510	1020
120	2.0	4000	860	1720	680	1360

Fig. 4.21 Effect on Droplet Size of Varying Flow Rate and Rotational Speed Together: unmounted spinning cup

a) VMD/NMD



b) VMD



The higher flow rates at each walking speed gave VMDs 10-15% larger than at the lower flow rates, except at 0.58 m/s where the lower rates gave the largest VMDs because of the transition from direct droplet formation to ligament formation which occurred at a different walking speed for each flow rate.

The VMD/NMD ratio increased with walking speed. At walking speeds below 1.0 m/s, the ratio was less than 1.5 for all flow rates, and the only notable difference between the flow rates was at 1.76 m/s when the ratio varied between 2.2 and 5.3 depending on the flow rate (Appendix 6).

ii) varying flow rate at a constant rotational speed

There was an almost linear increase in VMD with flow rate as a greater flow was fed onto the spinning cup, at a constant rotational speed (Fig. 4.22). The VMD changed less when the rotational speed remained constant than when the flow rate and rotational speed were varied together. Within the range of walking speeds most likely to be used (0.8-1.5 m/s) the small change in VMD was similar whether flow rate was varied alone or with rotational speed. The VMD/NMD ratios were also similar up to 1.5 m/s, but, when the rotational speed was constant, fewer small droplets were produced at high walking speeds, resulting in a lower VMD/NMD ratio.

iii) effect of varying the range of rotational speeds

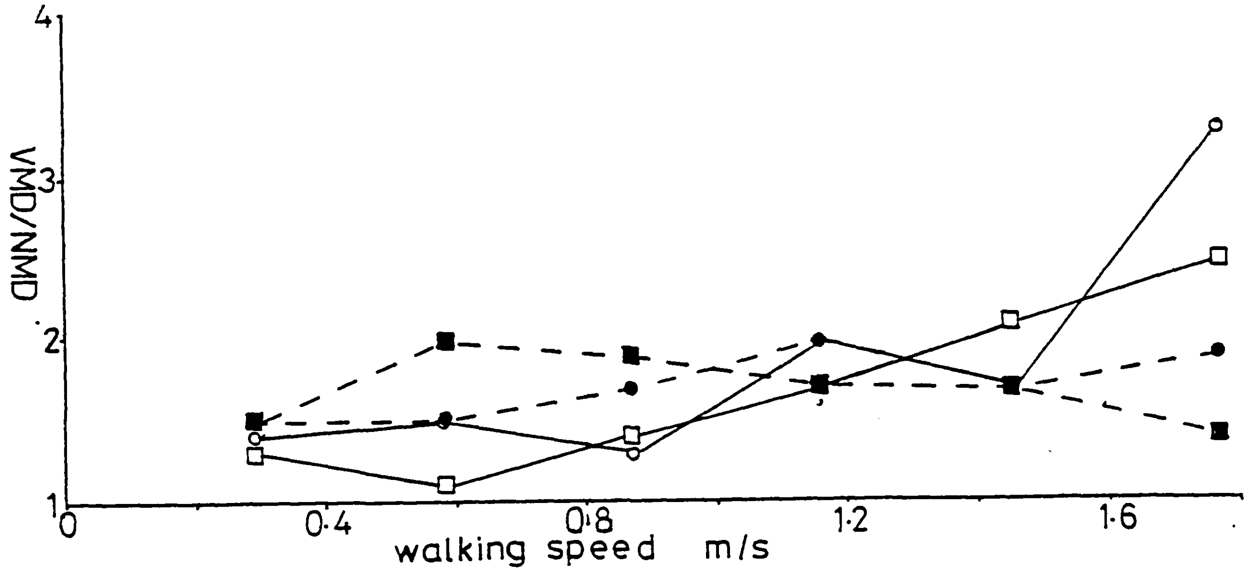
If the diameter of the spindle drive for the cup is changed, then the rate of increase of rotational speed with walking speed will be different. This was simulated by using three cup speed ranges, giving 2000, 2500 or 3000 rpm when walking at 1.0 m/s, i.e. spindle diameters of 9.5, 6.5 and 5.4 mm respectively (see calculations in section 4.1). The response of VMD to flow rate was almost linear at each rotational speed within the range of flows tested, and VMDs of the sprays produced when walking at 1.0 m/s are given in Table 4.5. The VMD/NMD ratio increased sharply with rotational speed at walking speeds over 1.2 m/s (Fig. 4.23), particularly with the high speed ranges.

iv) effect of uniformity of flow

In all the previous experiments the liquid was fed onto the disc by pressure to give a constant flow, but the peristaltic pumps on the sprayer gave a pulsing flow. The

Fig. 4.22 Comparison of Varying Flow Rate Alone or Flow Rate Plus Spinning Cup Speed with Walking Speed.
(6 mm pump tubing)

a) VMD/NMD



b) VMD

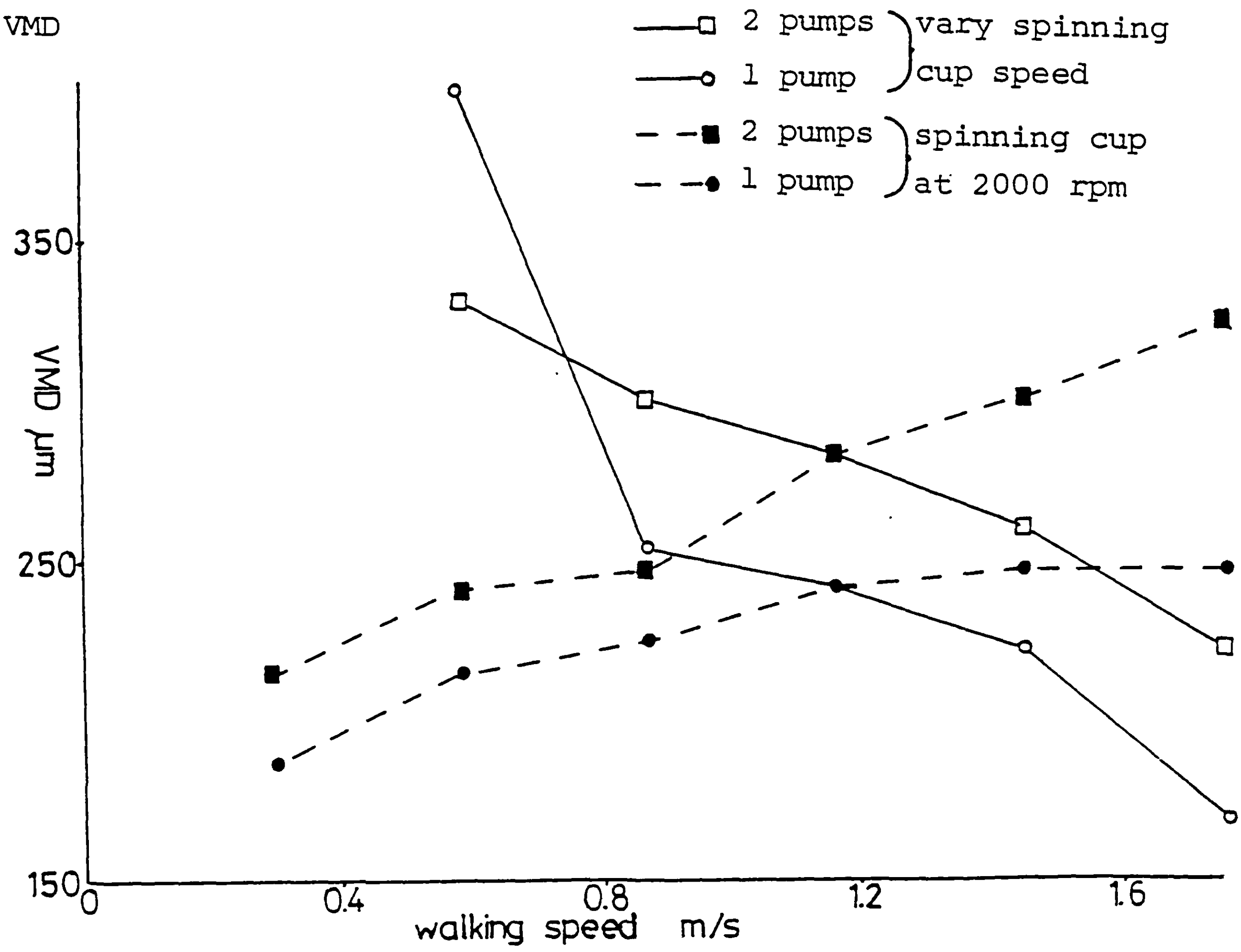
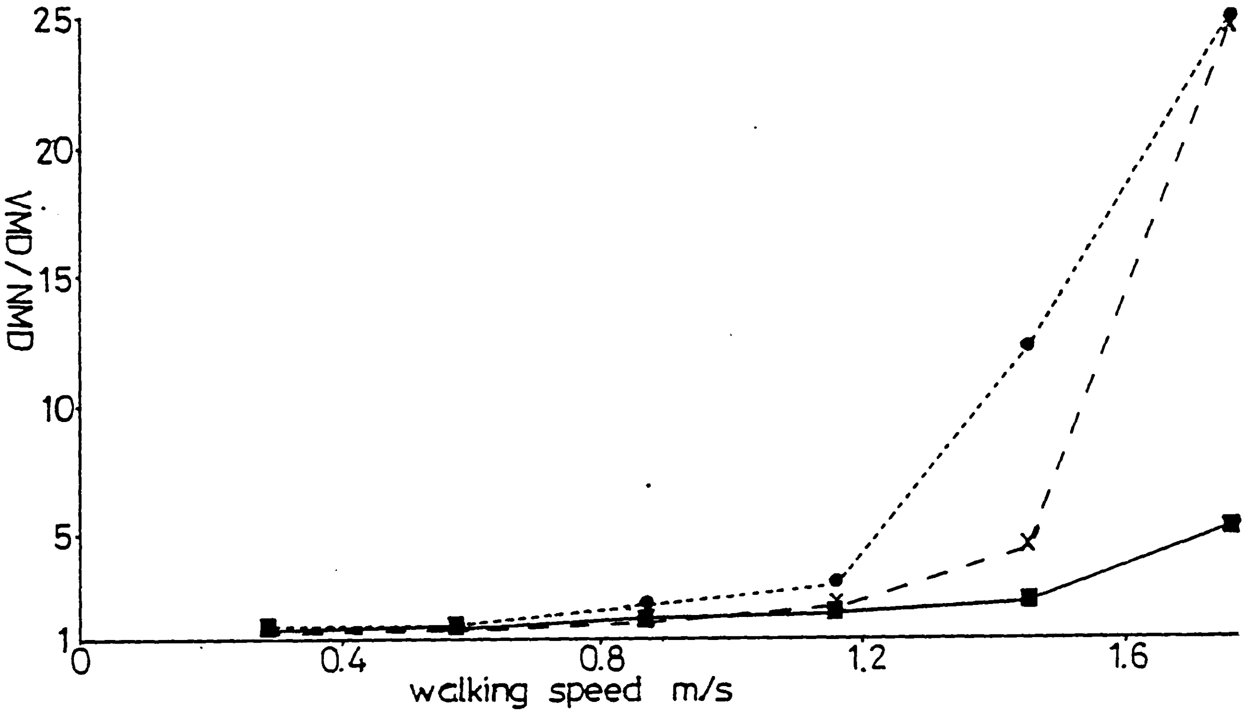


Fig. 4.23 Effect of Friction Drive Diameter on Droplet Production (two pumps, 8 mm tubing)

a) VMD/NMD



b) VMD

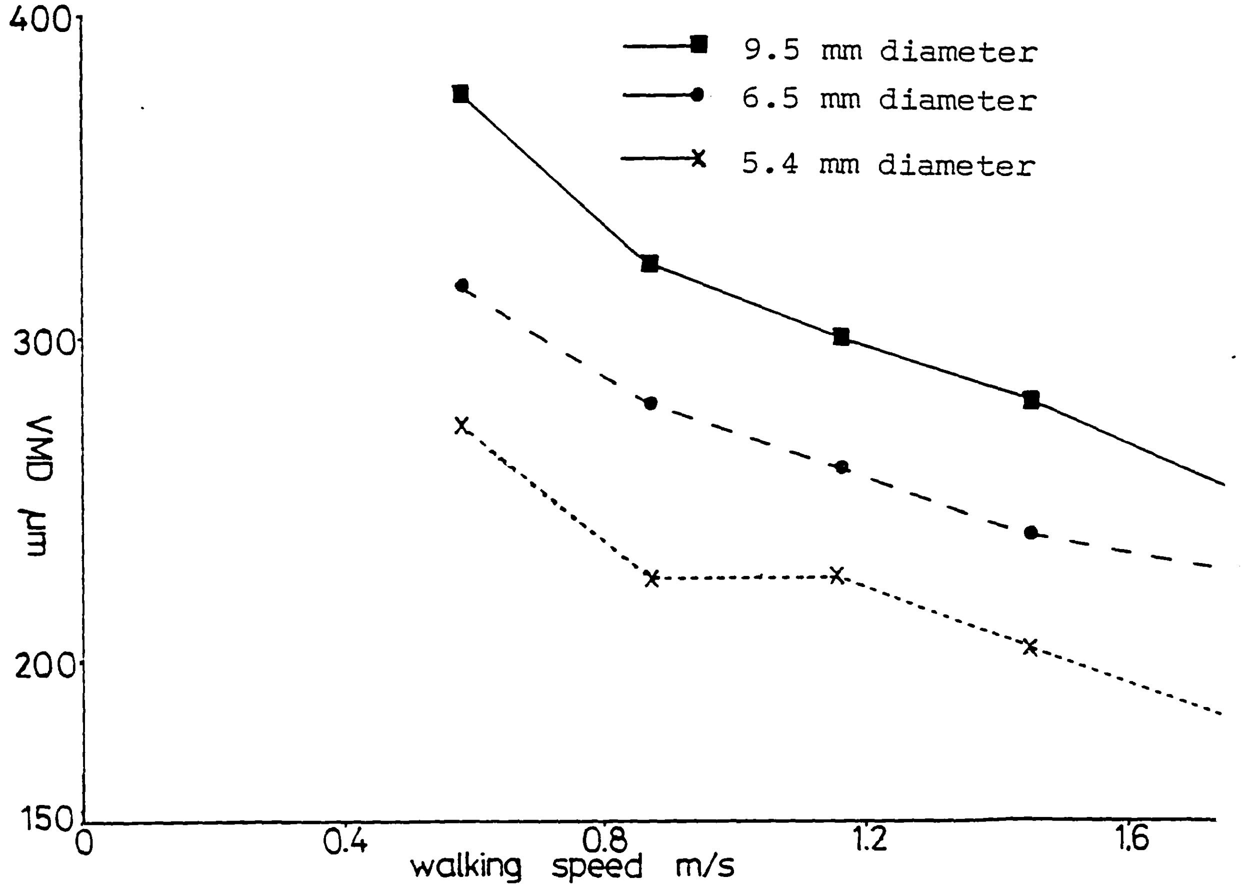


Table 4.5 Effect of Spindle Diameter on VMD

Spindle diameter (mm)	Rotational speed (rpm)	VMD (µm) at 430 ml/min	860 ml/min
9.5	2000	263	312
6.5	2500	231	270
5.4	3000	200	236

Table 4.6 Comparison of Droplet Spectra Produced Using a Pulsing or Uniform Flow

Rotational speed (rpm)	Flow rate (ml/min)	Pulsing flow VMD (µm)	VMD/NMD	Uniform flow VMD (µm)	VMD/NMD
1000	400	489	1.2	484	1.1
1500	640	339	1.5	329	1.6
2000	840	283	2.4	294	2.4
2500	1040	255	5.0	253	2.3
3000	1240	237	8.1	243	6.8

sprays produced from the two types of feed were similar, except at the two highest walking speeds where the pulsing flow gave a less uniform droplet spectrum (Table 4.6).

v) discussion

A non-motorised drive for the sprayer pump and spinning cup requires the power to be taken off the ground wheel, so that the speed of both is directly related to the ground speed.

When the flow rate and rotational speed were increased proportionally, simulating the actual sprayer, the VMD fell following a power progression for all the ranges of flows and speeds tested. When walking at 1 m/s the VMD was larger than would be ideal for post-emergence spray applications. Although it was possible to produce a spray with a lower VMD (200-250 µm) and a reasonably uniform spectrum (VMD/NMD 2.0), the required flow rate range was too low to give the target spray volume of 20 l/ha. With the higher flow rates provided by a pair of pumps, a suitable VMD was given if the spinning cup was rotated faster, but this also gave a poor droplet spectrum with large numbers of small droplets which caused the VMD/NMD ratio to exceed the ideal limit of 1.4. Maintaining a constant rotational speed of the spinning cup would provide a slightly more uniform droplet size over the flow rates tested, but this would be impractical on the sprayer without using an electric power source.

A compromise between the VMD and the spray uniformity is necessary on the wheelbarrow sprayer, because of the limits imposed by the flow rates and rotational speeds. On a new prototype it is recommended that the friction drive spindle should produce a rotational speed of 2250 rpm, giving an adequate droplet spectrum over most walking speeds (Fig. 4.23).

4.4.4. Spray characteristics of the prototype sprayers

On the first prototype sprayer the pump output and the rotational speed of the spinning cup were greater at a given walking speed than on the second prototype which consequently produced a finer spray (Table 4.7). The characteristics of the first pre-production model were similar to those of the second prototype (Oxberry & Seward, 1982).

Table 4.7. Droplet Spectra at 1.0 m/s

	Spinning cup speed (rpm)	Flow rate (ml/min)	VMD (µm)	VMD/NMD
First prototype	1900	760	370	1.7
Second prototype (2 pumps)	1700	720	275	2.4
Second prototype (1 pump)	1700	370	240	1.5

The first prototype produced a less uniform spray with a larger VMD than the second prototype (Fig. 4.24). The differences were too great to be due only to its slightly greater flow rate and spinning cup speed, and may have been because the spray was sampled further from the spinning cup (at 0.45 m). The results of the preliminary experiments suggested that this would give a VMD 20-30 µm larger than sampling at 0.15 m, as for the second prototype, where the spray is less dispersed.

With a single pump feed the responses were similar for the friction driven spinning cup on the second prototype sprayer and a motor driven unit (Fig. 4.25). However, when two pumps were used the results were different. The sprayer gave a steeper fall in VMD and a sharper increase in the VMD/NMD ratio than the motor driven unit (Fig. 4.24). The contrasting responses, compared to the motor driven unit with the two ranges of flow rates may be due to the vibrations of the friction drive causing irregular ligament breakup. This will have a greater effect when high flow rates are used because the ligaments will be longer and more susceptible to vibrations (Hinze & Milborn, 1950).

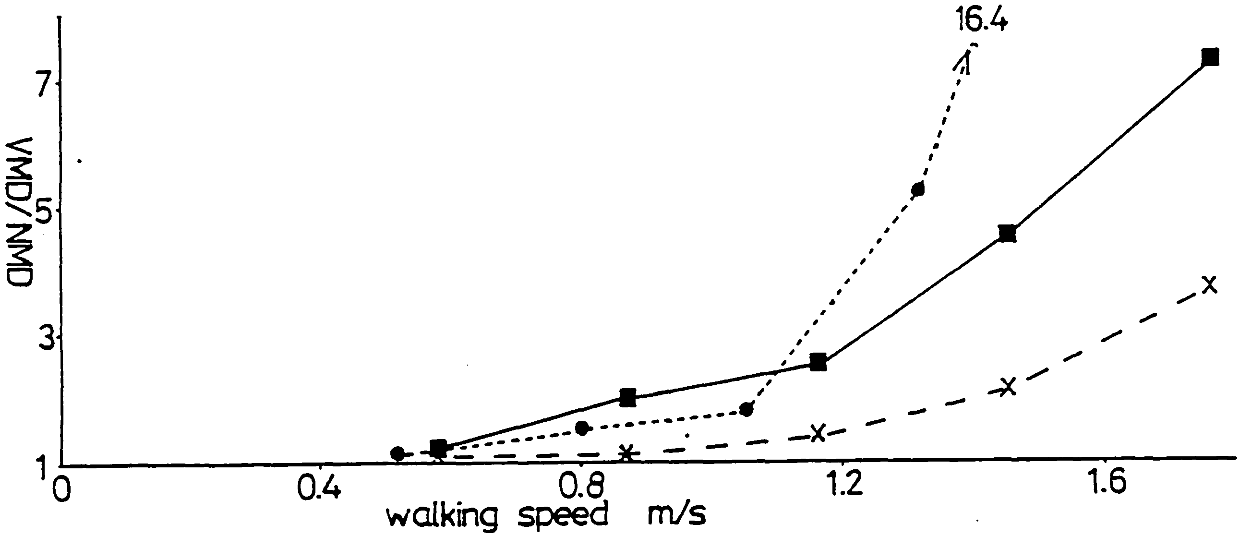
4.4.5. Effect of spray liquid

i) oil based formulation

A 10% v/v oil in water emulsion was compared to a 0.05% surfactant solution using the first prototype. With the

Fig. 4.24 Droplet Production by the Spinning Cup, Driven by Electric Motor or Mounted on the First or Second Prototype Sprayers (2 pumps, 6 mm tubing)

a) VMD/NMD



b) VMD

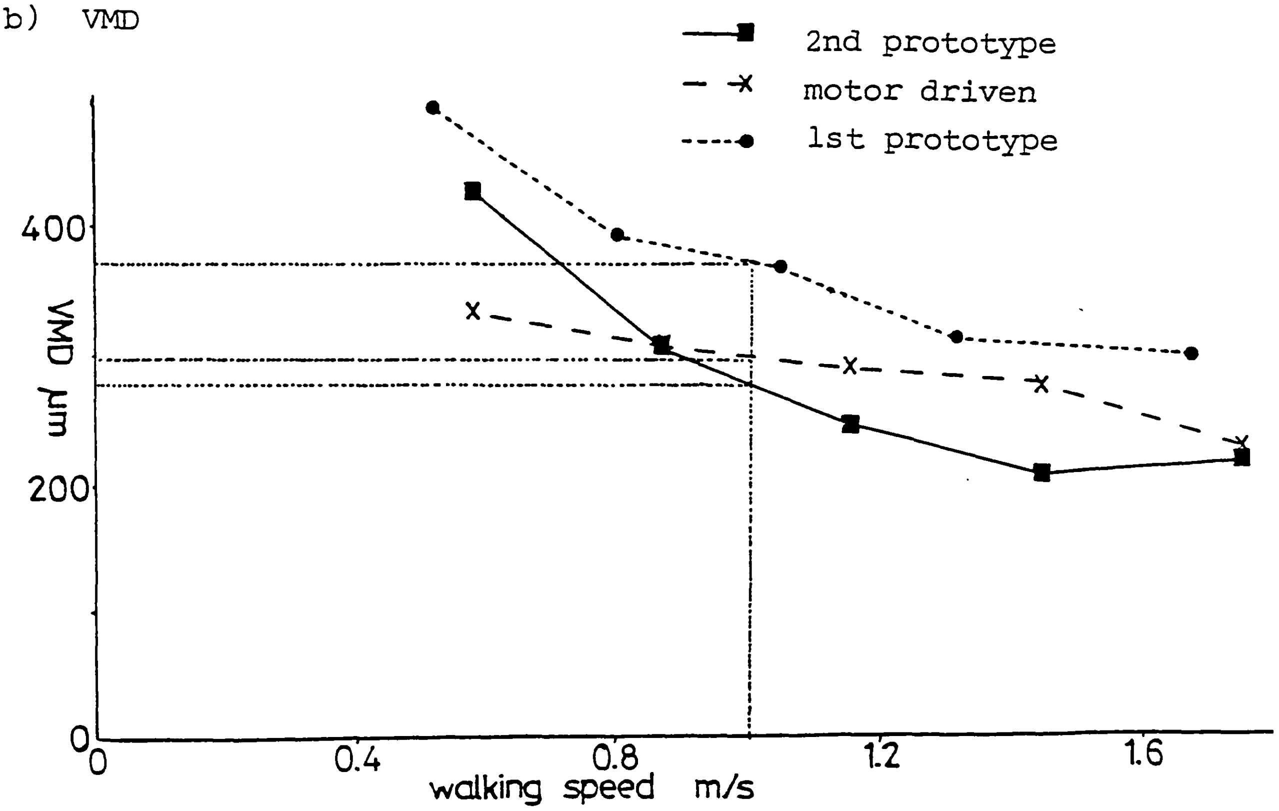
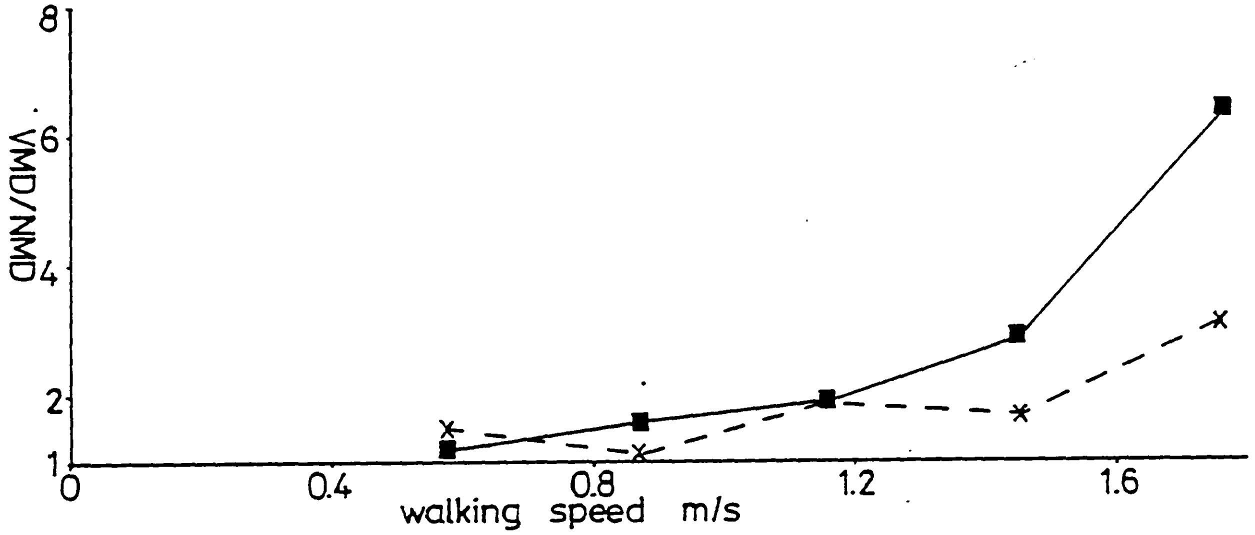
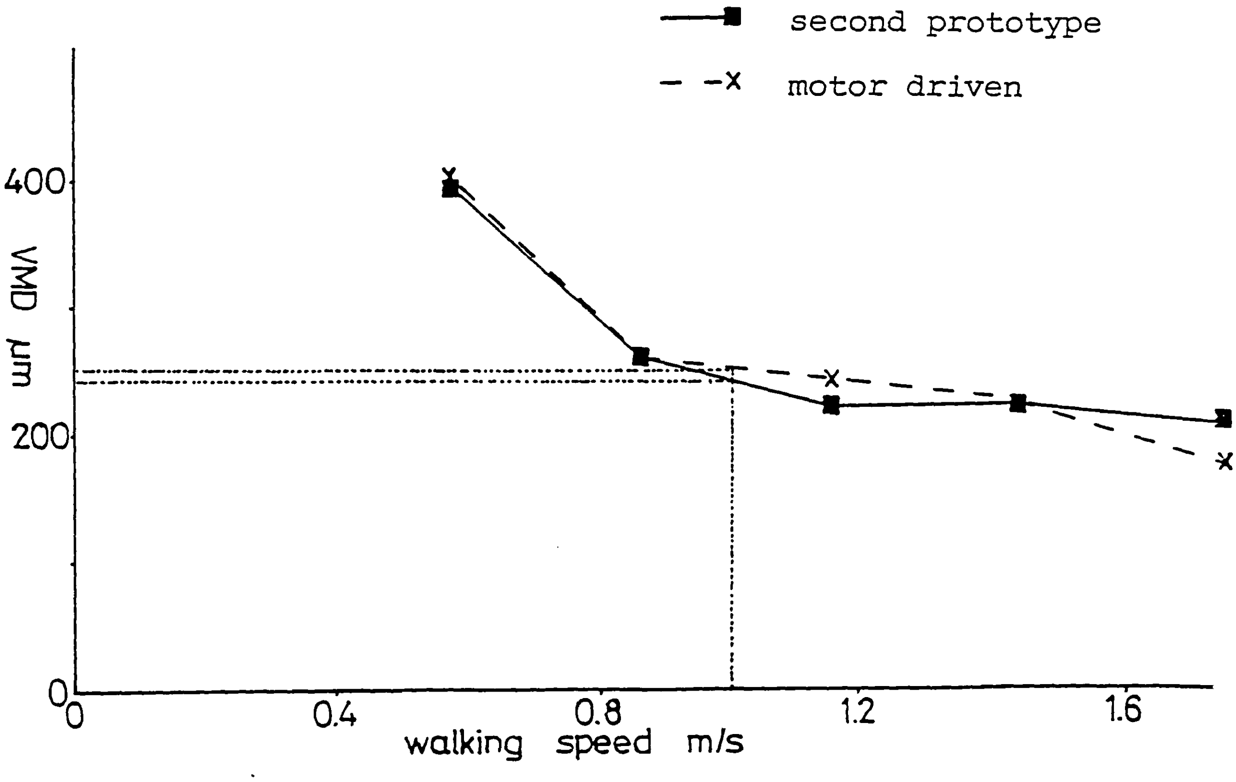


Fig. 4.25 Droplet Production by the Spinning Cup, driven by an Electric Motor or Mounted on the Second Prototype Sprayer. (single pump, 6 mm tubing)

a) VMD/NMD



b) VMD



emulsion, the VMD showed a weaker response to increasing walking speed than with the surfactant solution. At low walking speeds the emulsion gave the smaller droplet size, but it was similar with both formulations at 1.3 and 1.6 m/s (Fig. 4.26). Spray uniformity was similar at low speeds but the oil formulation gave a lower VMD/NMD ratio at faster walking speeds.

ii) three commercial herbicides

Three contrasting commercial herbicides were compared to a 0.1% surfactant solution using the motor-driven unit (Fig. 4.27). At 1000 rpm glyphosate and cyanazine sharply reduced the VMD compared to the surfactant solution. At 2000 rpm the VMD was slightly reduced with glyphosate, but with cyanazine it increased with a 400 ml/min flow and was similar at 800 ml/min. At 3500 rpm there was little effect on the VMD by either material. Chlorthal-dimethyl plus methazole increased the VMD at 2000 rpm compared to the surfactant.

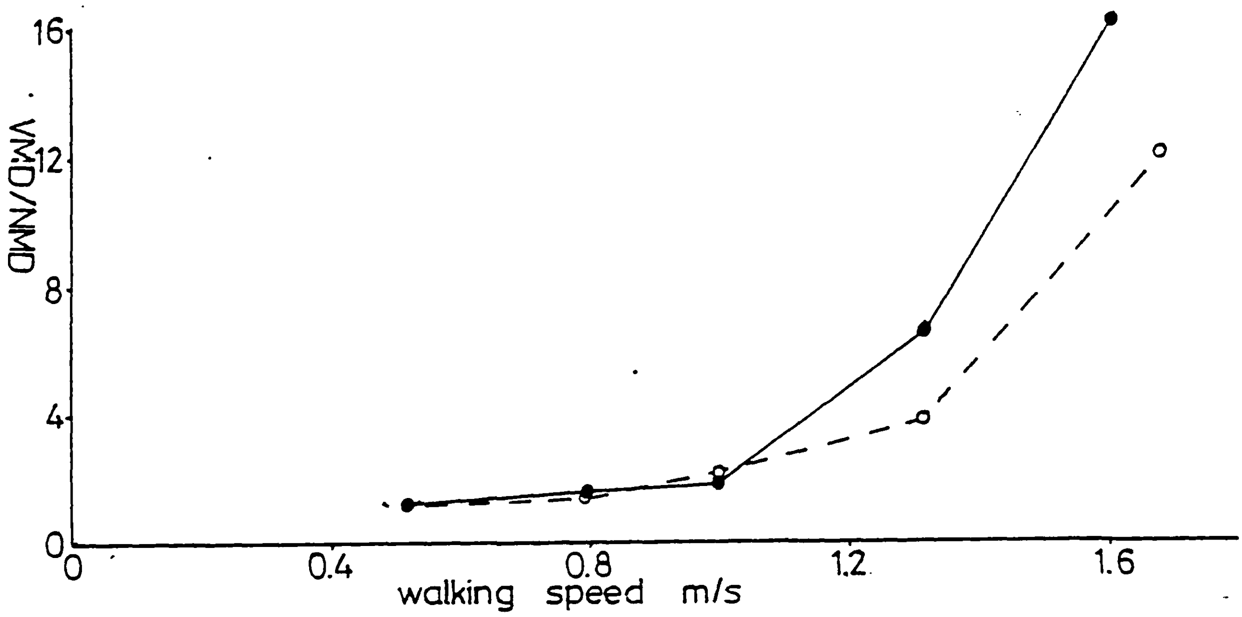
iii) discussion

The properties of the spray liquid influence droplet formation by rotary atomisation, and affect the droplet spectrum of the spray produced. The effect is dependent on the type of formulation of the herbicide (Bode & Butler, 1981; Heijne, 1981). At spinning cup speeds suitable for field spraying, herbicides diluted in water generally produce a similar droplet spectrum to water plus surfactant only, but at low speeds the difference is enhanced due to changes in the point of transition from direct to ligament droplet formation. This was illustrated when glyphosate and cyanazine caused the production of small droplets by ligament formation at a low rotational speed, but direct droplet formation produced larger droplets with the surfactant solution. Herbicide concentrates or oil based formulations, designed to be used in an undiluted form with spinning disc sprayers, tend to increase the VMD of the spray compared to water based materials at the same flow rate (Bode & Butler, 1981; Heijne, 1981).

These results illustrate the problem of interpreting droplet size data measured from the spray of a surfactant solution, used in other experiments.

Fig. 4.26 Effect of Walking Speed and Formulation on Droplet Size : first prototype

a) VMD/NMD



b) VMD

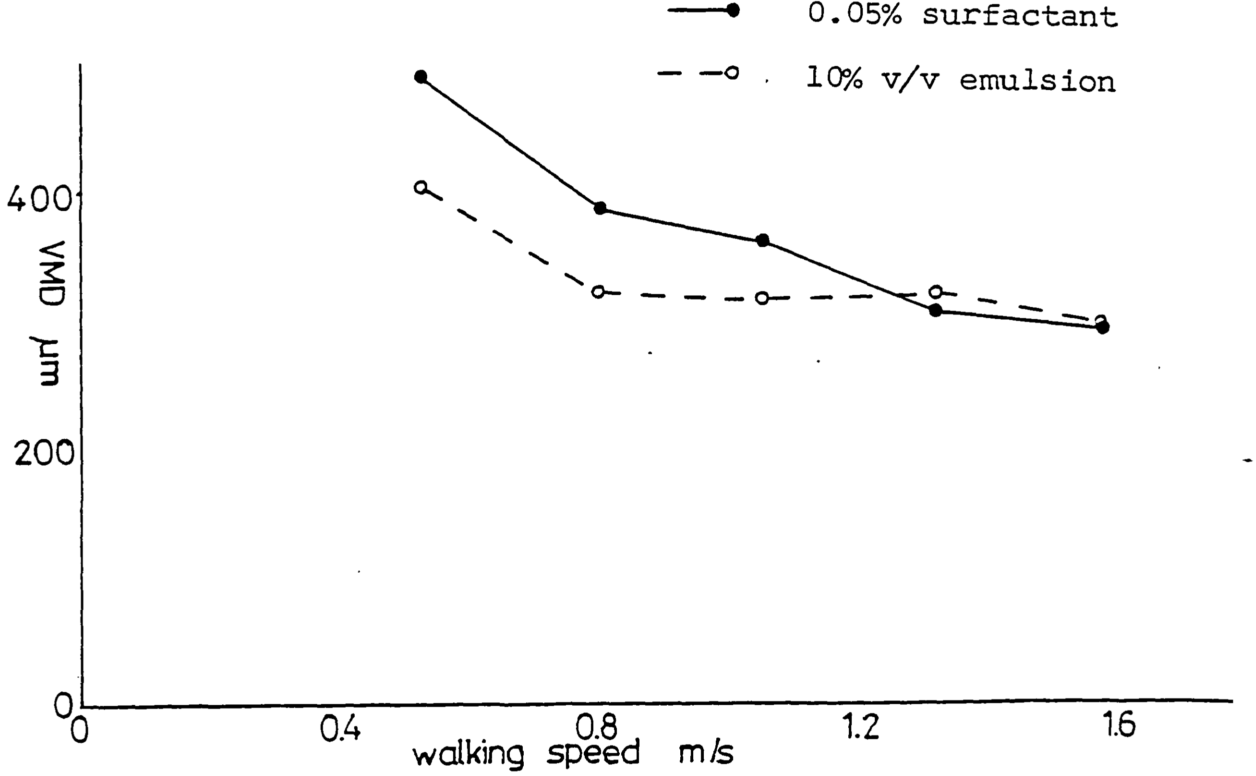
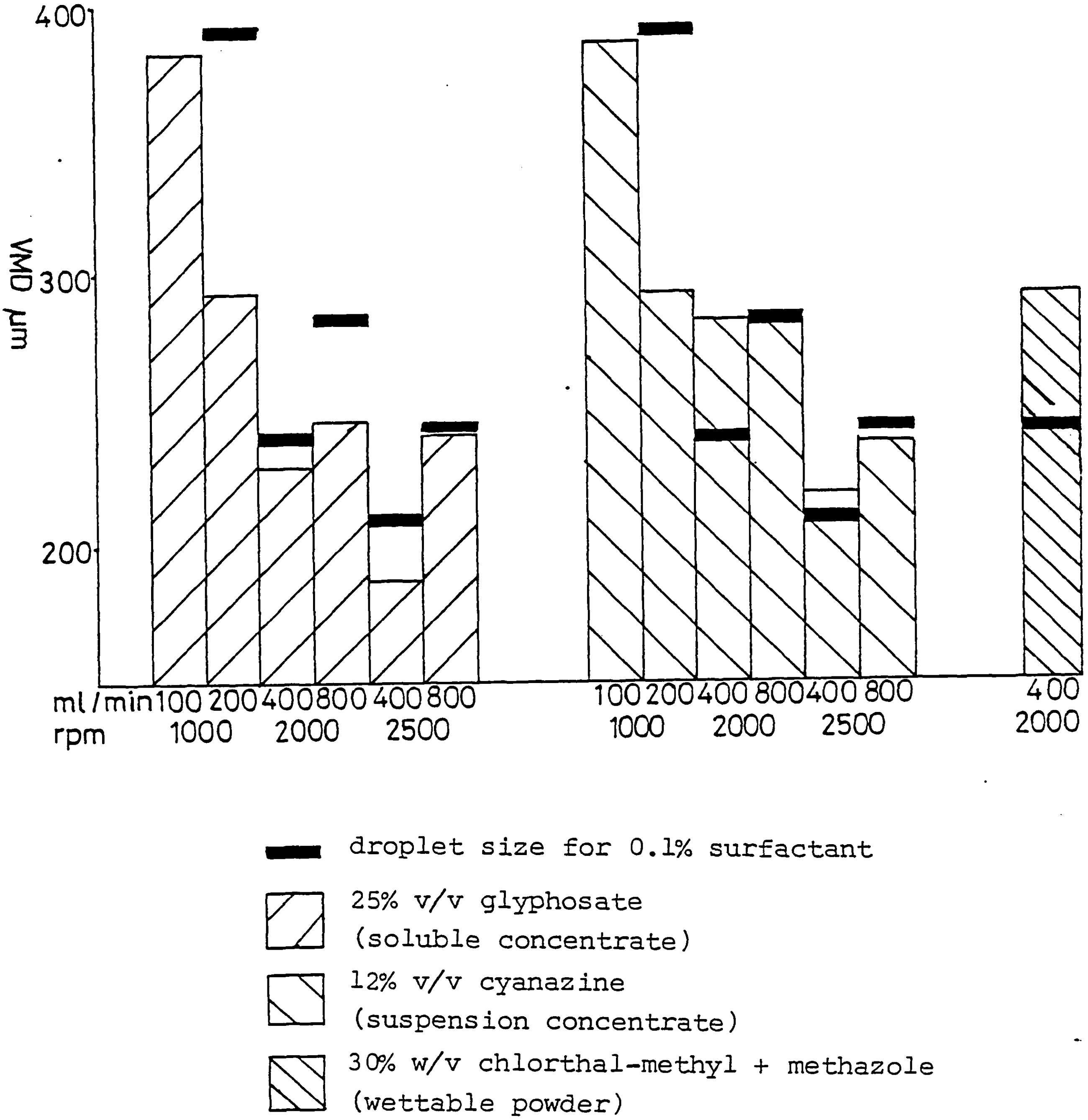


Fig. 4.27 Effect of Three Herbicides on Droplet Size at Different Rotational Speeds and Flow Rates



4.5. The Shroud Design

A shroud mounted around a spinning disc has been used to improve the droplet spectrum of laboratory sprayers (Walton & Prewitt, 1949; Byass & Charlton, 1968), to reduce the drift from a field sprayer (Smith et al, 1970), to remove the peaks from the edges of the spray pattern (Goering et al, 1973; Taylor & Merritt, 1975; Farmery et al, 1976) and to control the swath width (Choudhury & Ogborn, 1979; Nilsson, 1982).

The swath width produced by an unshrouded spinning disc may be altered by varying the height of an angled disc. This does not give accurate swath control, and is not feasible for the wheelbarrow sprayer, since the height of the spinning cup is fixed. If the spinning cup is shrouded, the width of the window through which the spray passes can be varied to change the swath width, and, if the cup is angled, the shroud removes the sector of the spray which is thrown upwards, reducing the potential for drift.

An unshrouded spinning cup produces a more uniform swath than a spinning disc (Heijne, 1981), but the uniformity of the swath from a single cup may be improved either by angling it towards the ground (Choudhury & Ogborn, 1979; Bode & Butler, 1981) or by using a shroud. The latter is most appropriate on a wheelbarrow sprayer, since the spray from an unshrouded cup would contaminate the sprayer framework and the operator.

4.5.1. Shrouds used on prototypes

A similar shroud was used on both prototypes (Figs. 2.3, 2.5). It consisted of a spun alloy base with a large circular hole in the centre, through which the spinning cup fitted. The wall of the top sloped at 45^{o}, so that the droplets flowed down it without shattering. The width of the window through which the spray passed was initially fixed, but sliding shutters were fitted so that it could be varied. The top of the spinning cup was level with the centre of the window, with a 20 mm gap between the peripheral teeth and the shroud wall on the first prototype, and a 25 mm gap on the second.

Liquid was fed onto the spinning cup by two nozzles via an inverted cone which drained into the base of the cup. This reduced the probability of the exact position of the feed onto the cup changing as the sprayer bounced over rough ground.

4.5.2. Theoretical swaths

Theoretical swaths were drawn to examine the effect on the swath of shrouding the cup. A single droplet size was assumed, so that all droplets fell to the ground 1.0 m from the centre of the cup. It was also assumed that droplets leave the cup teeth tangentially, although they actually have some outwards movement imparted to them.

The unshrouded cup gives a "horned" swath (Fig. 4.28), which is cut in half when a 90^{o} swath window is placed centrally in front of it (Fig. 4.29). If the 90^{o} window is moved to 40^{o} off centre (Fig. 4.30), a very uniform swath is produced, centrally to the cup. As the window is widened, maintaining a central swath, the "horns" reappear at the edges of the swath (Fig. 4.31). An equal change in the position of either edge of the window will have a similar effect on the swath (Fig. 4.32).

4.5.3. Spray patterns from a shrouded sprayer

The improvement of swath uniformity using a shroud was investigated using a patternator. The terms used to describe the shroud and the swath are given in Fig. 4.33.

i) position of the window

Droplets leave the shroud almost tangentially, so the window must be offset from the centre (Table 4.8) to give a swath which is equal either side of the shroud (Fig. 4.34). All the following experiments involved the shroud producing a central swath.

ii) effect of feed type and walking speed

A single nozzle feed on to an unshrouded spinning cup may produce an asymmetrical spray pattern because there is a localised release of liquid from the cup, which can be minimised by using four feeds (Heijne, 1978). The shrouded cup was tested using one or two feed nozzles, as four feeds were not considered necessary when the nozzles fed onto a fixed inverted cone draining into the base of the spinning cup.

Fig. 4.28 Swath Produced by Unshrouded Spinning Cup

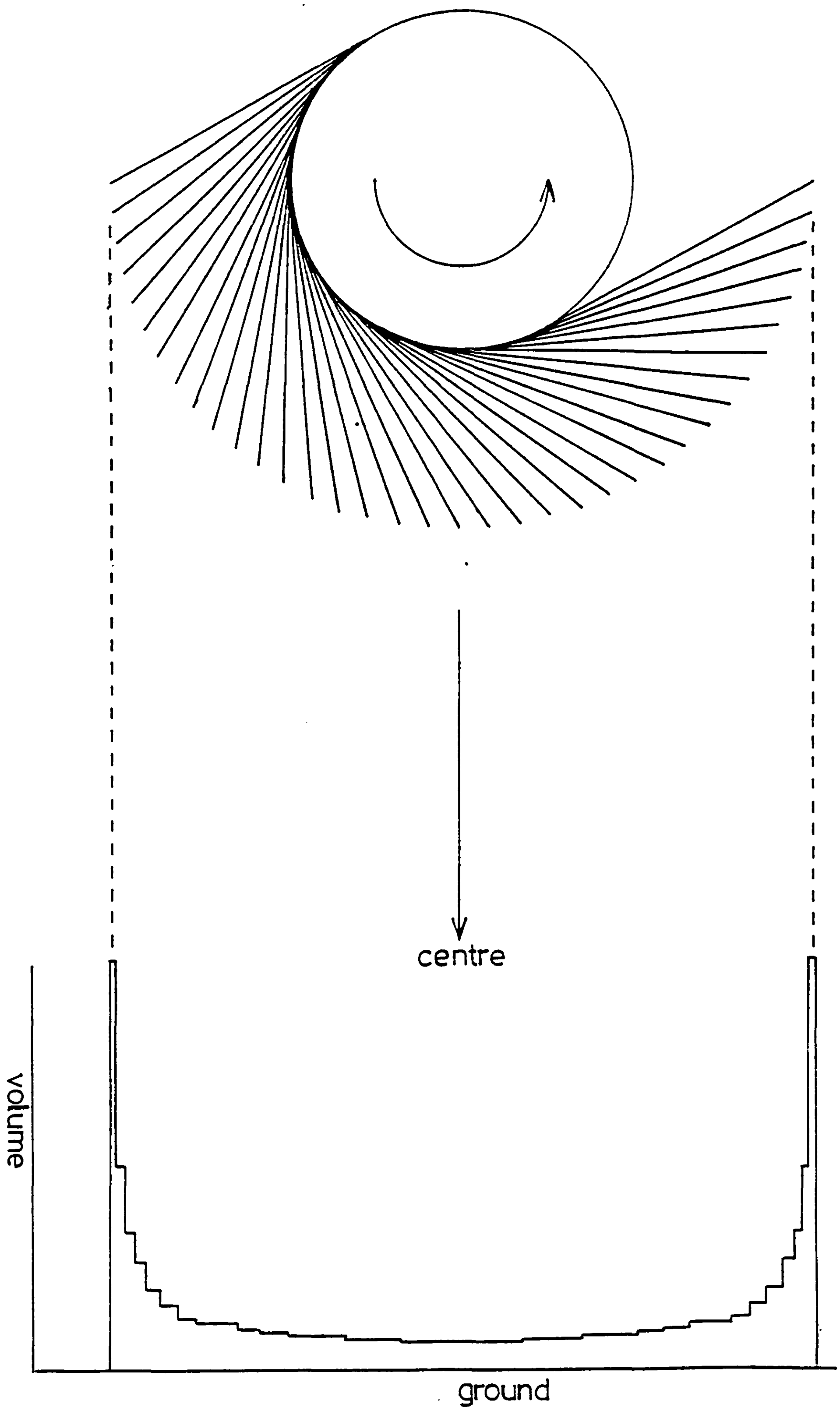


Fig. 4.29 Swath Produced by Shrouded Spinning Cup with Central 90° Window

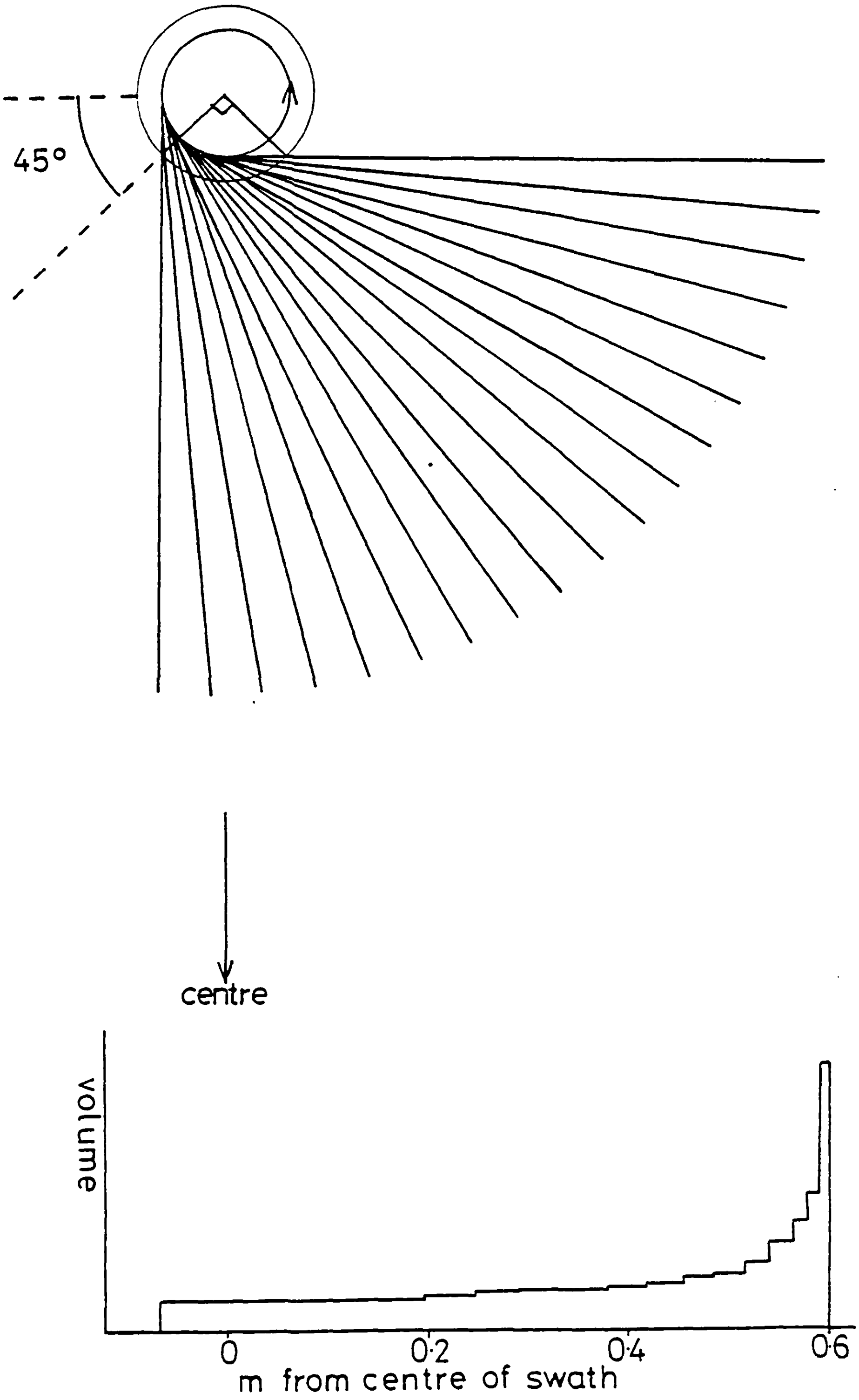


Fig. 4.30 Swath Produced by Shrouded Spinning Cup with Off-centre 90° Window

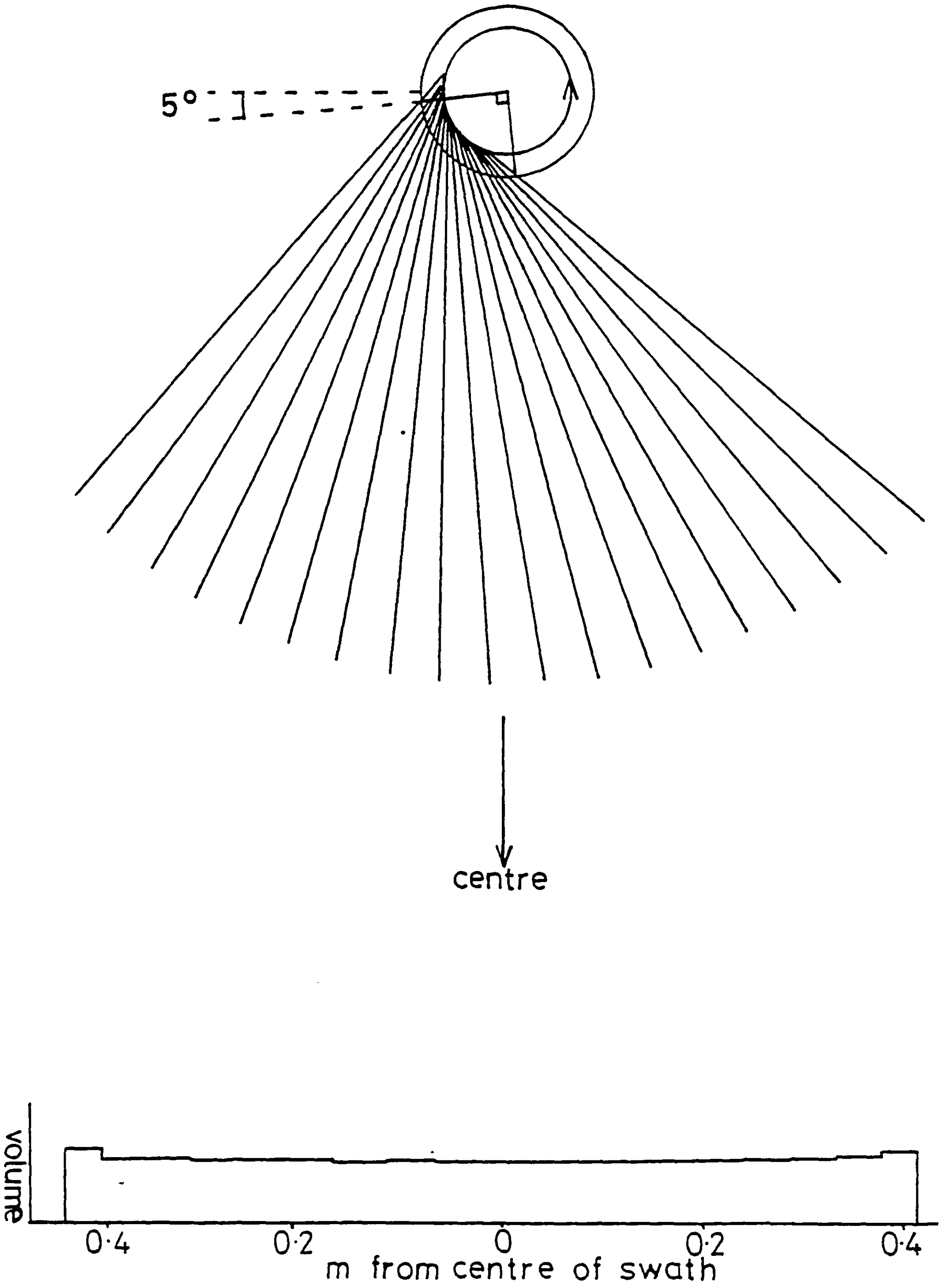


Fig. 4.31 Swath Produced by Shrouded Spinning Cup with Off-centre 145° Window

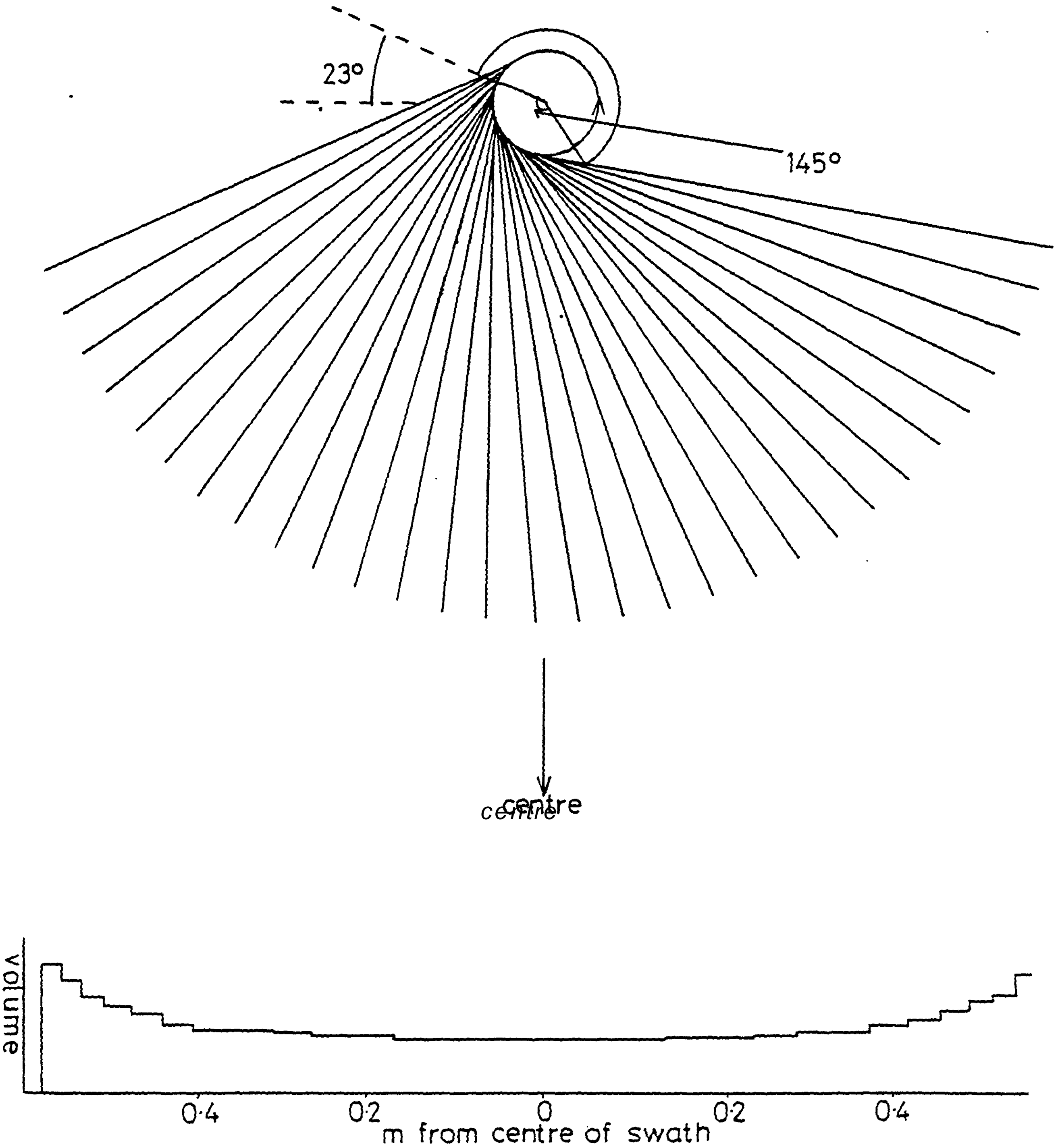
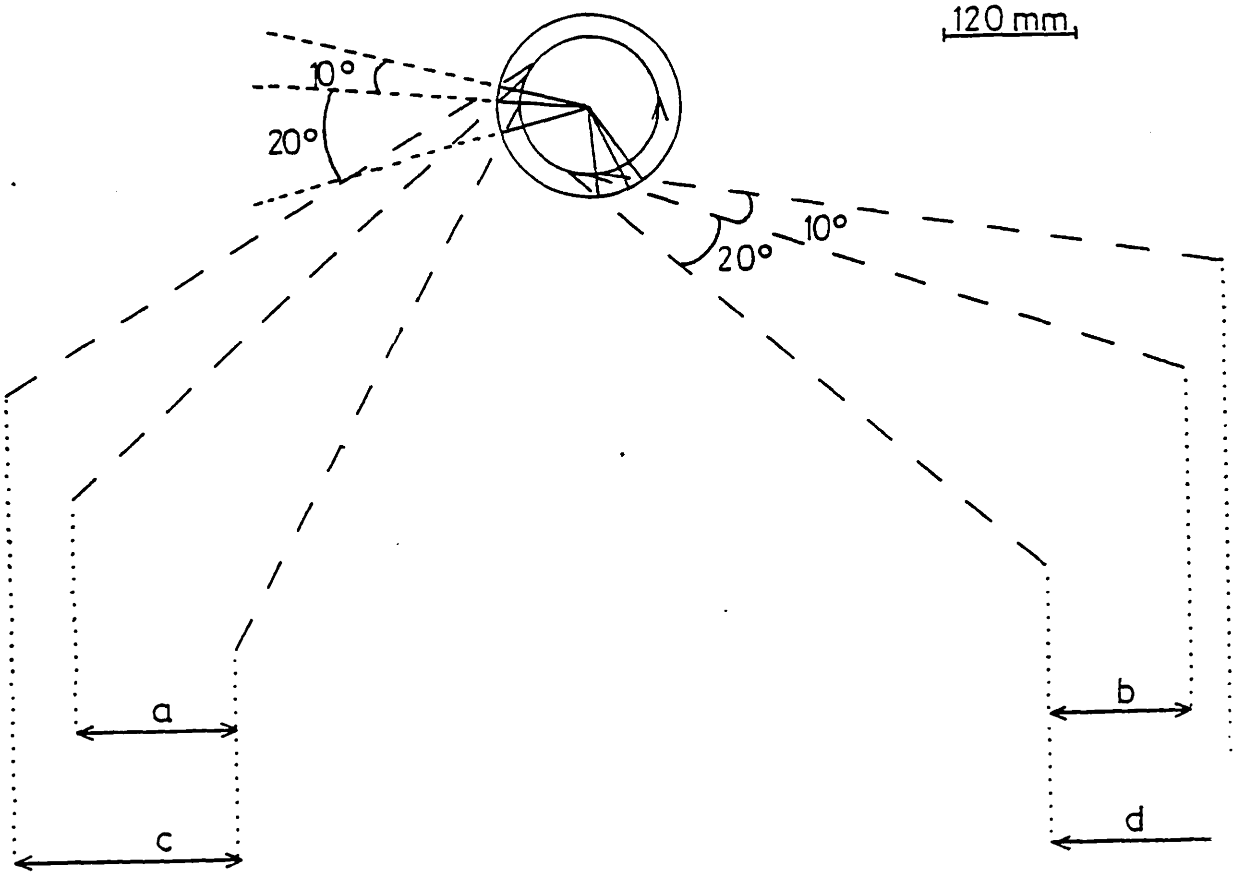


Fig. 4.32 Effect on the Swath of Changing the Position of the Window Edges



a : 20° change in window edge causes 0.15 m increase in swath

b : 20° change in window edge causes 0.13 m increase in swath

c : 30° change in window edge causes 0.21 m increase in swath

d : 30° change in window edge causes 0.16 m increase in swath

Fig. 4.33 Terms Used to Describe the Shroud and the Swath

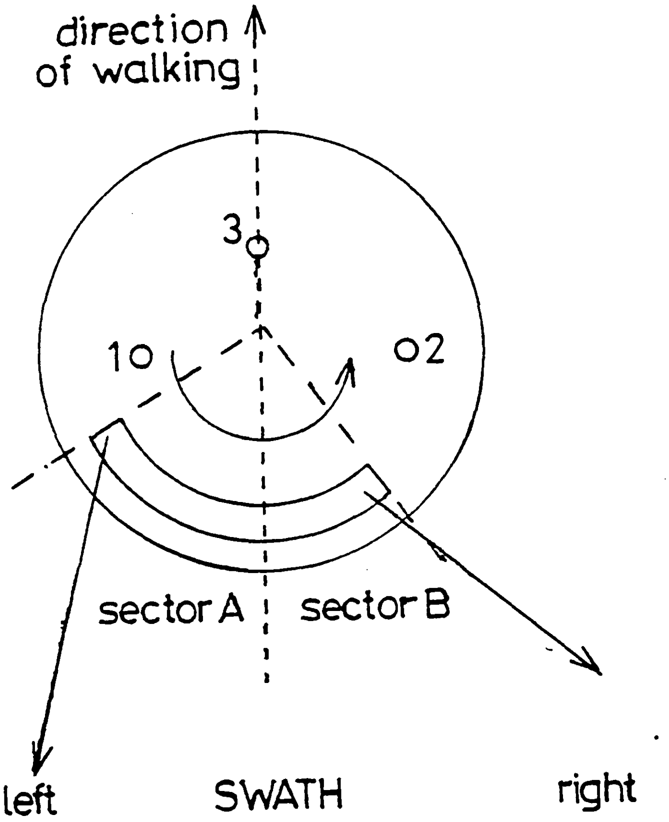
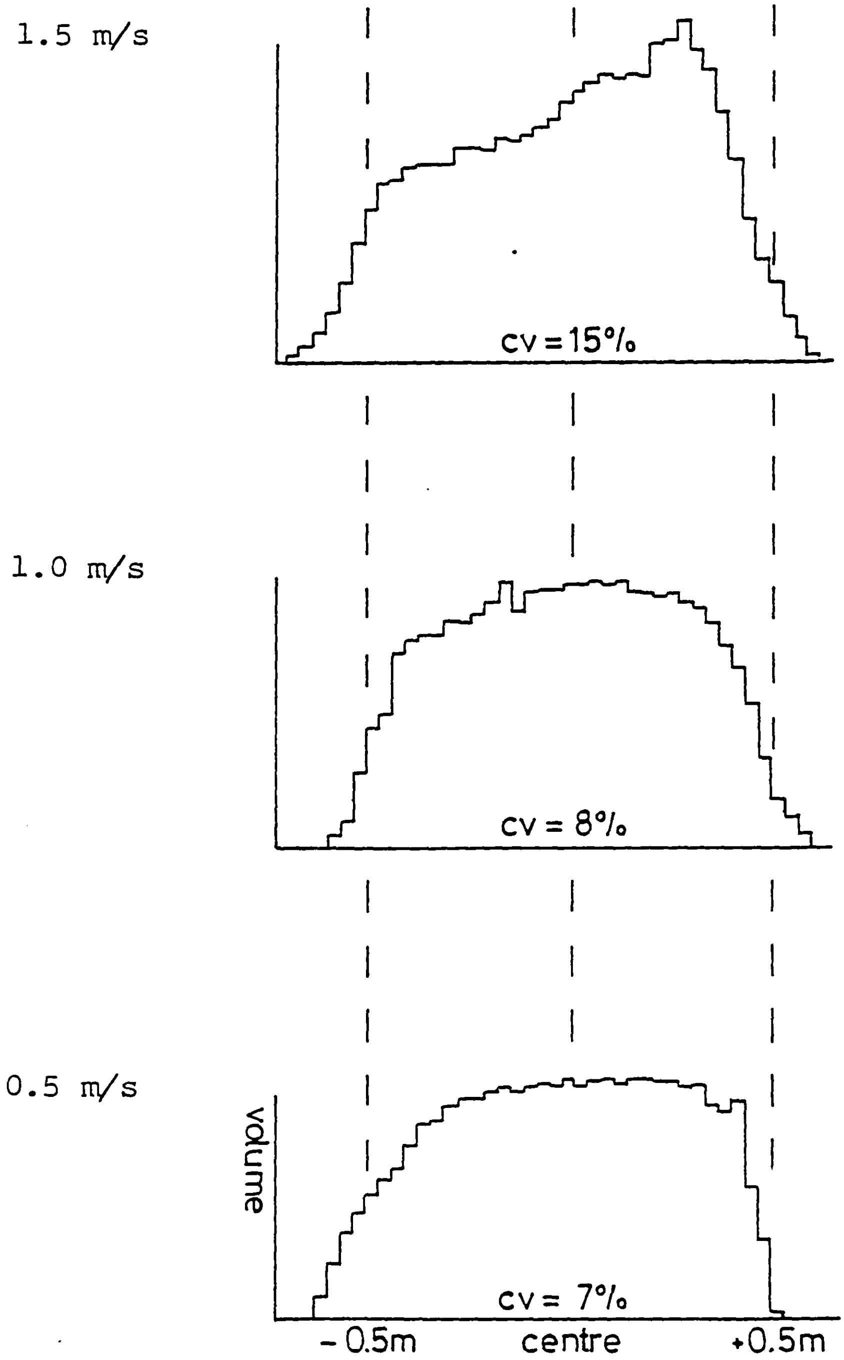


Table 4.8 Window Positions Giving a Central Swath

Total window width (°)	Sector A (°)	Sector B (°)	Ratio A : B
100	85	15	5.7
105	90	15	6.0
110	92	18	5.1
145	120	25	4.8

Fig. 4.34 Effect of Walking Speed on Uniformity of Swath (single feed, 90° window)



The single nozzle feed produced a spray pattern whose symmetry depended on the walking speed (Fig. 4.34). The asymmetry was most severe at a walking speed of 1.5 m/s (flow rate: 540 ml/min; rotational speed: 2800 rpm), but was negligable at 1.0 m/s (360 ml/min; 1900 rpm). A double feed gave a much flatter distribution at all speeds (Fig. 4.35).

The position of the feed had little effect on any of the swath characteristics (Table 4. 9), but the double feed (720 ml/min at 1.0 m/s) gave a slightly wider swath than the single feed (360 ml/min at 1.0 m/s), reflecting the greater momentum of the larger droplets.

The swath width was also dependent on the walking speed. A 13% wider swath was obtained when the speed was increased from 1.0 to 1.5 m/s, for both the 110° and 90° window widths, using two feed nozzles (Table 4.10, Fig. 4.36). The single feed showed a similar trend but with a smaller response. The coefficient of variation of the deposit across the matched swaths was less than 10% for most of the walking speeds.

iii) effect of shroud window width and sprayer angle

The swath width was directly proportional to the width of the shroud window (Fig. 4.37), but changes in the window width had a greater effect when the sprayer was held horizontally rather than angled towards the ground. When the sprayer was horizontal a flat topped pattern was produced unless the window was over 140° wide, when the distribution was "horned", similar to that of unshrouded spinning cups (Fig. 4.38). An angled sprayer produced a more rounded pattern, which was not "horned" at a window width of 145°, but the position of the peak in the distribution was affected by walking speed, reflecting the changes in the position of the area of high liquid release from the spinning cup.

The matched swaths were most uniform when the sprayer was horizontal, with a window width of 110-120° (cv=5%) and the poorest results were at 145° (cv=10%), where "horns" began to appear. The window width had slightly less effect on cv when the sprayer was angled.

iv) discussion

The shroud window must be off-centre to give a swath

Fig. 4.35 Effect of Walking Speed on Uniformity of Swaths (double feed, 110° window)

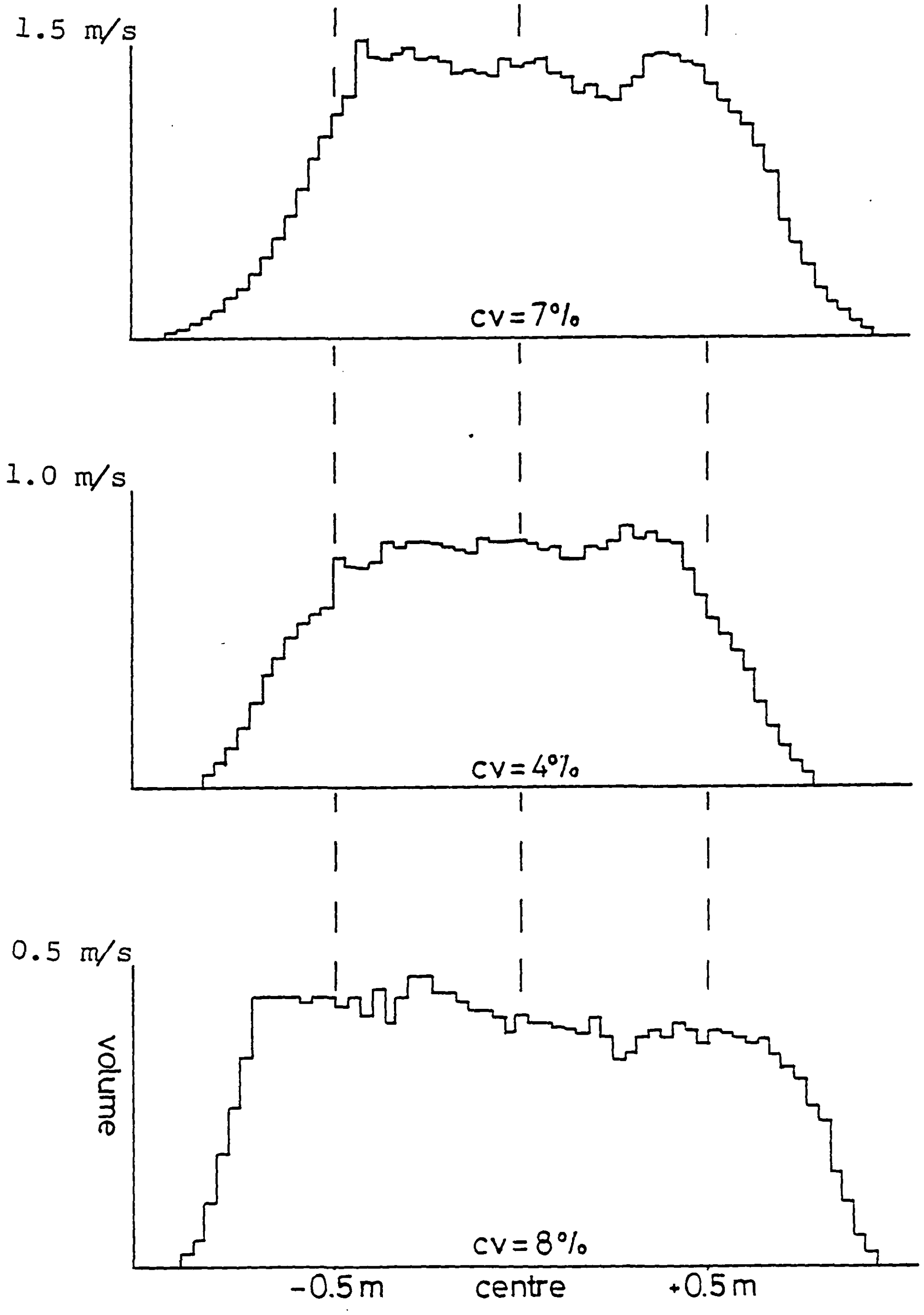


Table 4.9 Effect of Feed Type on Swath Characteristics (at 2000 rpm; 90° window slot)

Feed type	Flow rate = 360 ml/min					Flow rate = 710 ml/min				
	Optimum swath (m)	cv (%)	$\frac{\bar{x}-\text{min}}{x}$ (%)	$\frac{\text{max}-\bar{x}}{x}$ (%)	VMD (µm)	Optimum swath (m)	cv (%)	$\frac{\bar{x}-\text{min}}{x}$ (%)	$\frac{\text{max}-\bar{x}}{x}$ (%)	VMD (µm)
Feed onto cone(1)										
double	0.99	7.5	13	12	324	1.06	6.8	16	17	386
single, central	0.93	7.9	13	17	298	-	-	-	-	-
single, left	0.94	7.6	17	15	-	1.05	5.1	9	11	-
single, right	0.90	8.5	12	19	-	1.04	4.4	8	8	-
Feed without Cone										
double	1.01	6.7	9	23	-	-	-	-	-	-
single, central	0.97	5.2	8	11	330	-	-	-	-	-
central fan nozzle	0.96	5.8	9	13	-	-	-	-	-	-

(1) inverted cone to direct the feed to the base of the spinning cup

Table 4.10 Effect of Walking Speed on Sprayer Swath

	Walking speed (m/s)	Window width (o)	Optimum swath (m)	cv (%)	$\frac{\bar{x}-\text{min}}{x}$ (%)	$\frac{\text{max}-\bar{x}}{x}$ (%)
Double feed	0.5	110	1.09	9.7	21	20
	1.0	110	1.13	4.9	8	8
	1.5	110	1.28	6.6	15	19
Double feed	1.0	90	0.95	10.8	17	21
	1.5	90	1.08	9.9	13	22
Single feed (right)	1.0	90	0.90	8.5	12	19
	1.5	90	0.96	8.4	15	15
Single feed (left)	0.5	90	0.95	6.5	12	17
	1.0	90	0.94	7.6	17	15
	1.5	90	0.95	14.9	25	34
	2.0	90	1.03	9.0	15	20

Fig. 4.36 Effect of Walking Speed on Swath : volume sprayed in 30 minutes. (double feed, 110° window)

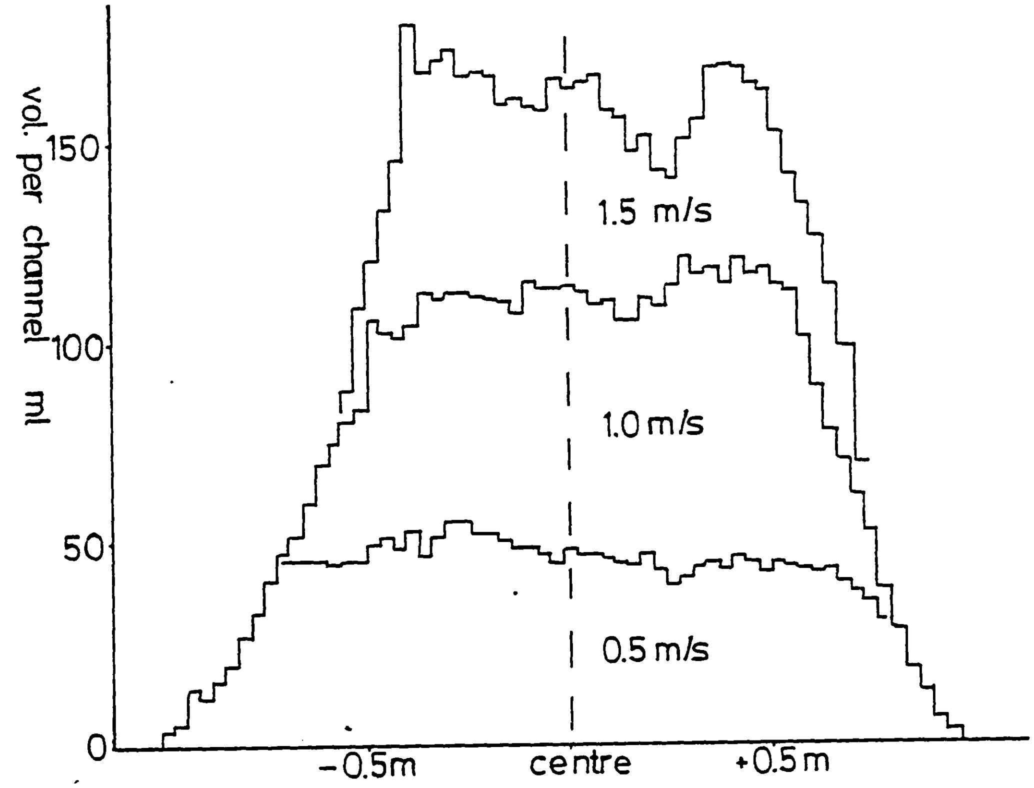


Fig. 4.37 Effect of Shroud Window Width on Swath

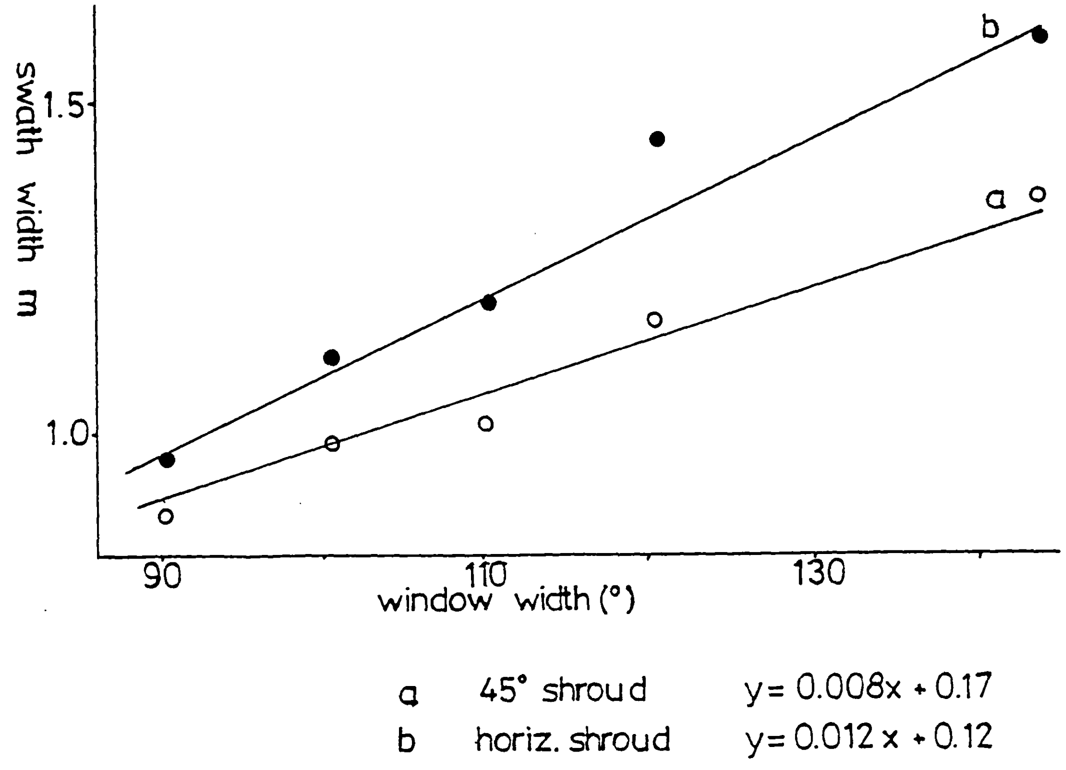


Fig. 4.38 Effect on Swath of Shroud Window Width

a) horizontal sprayer

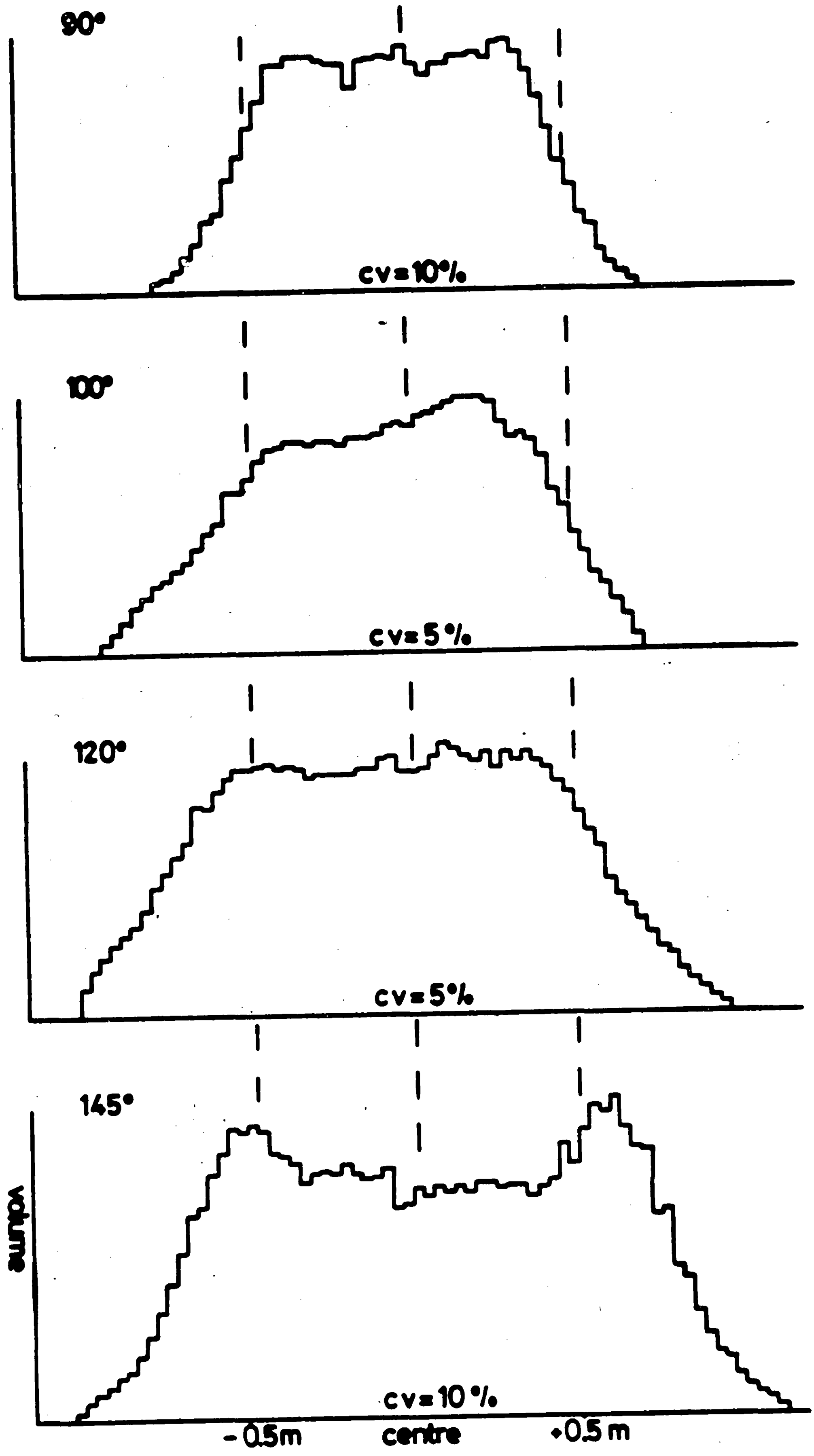
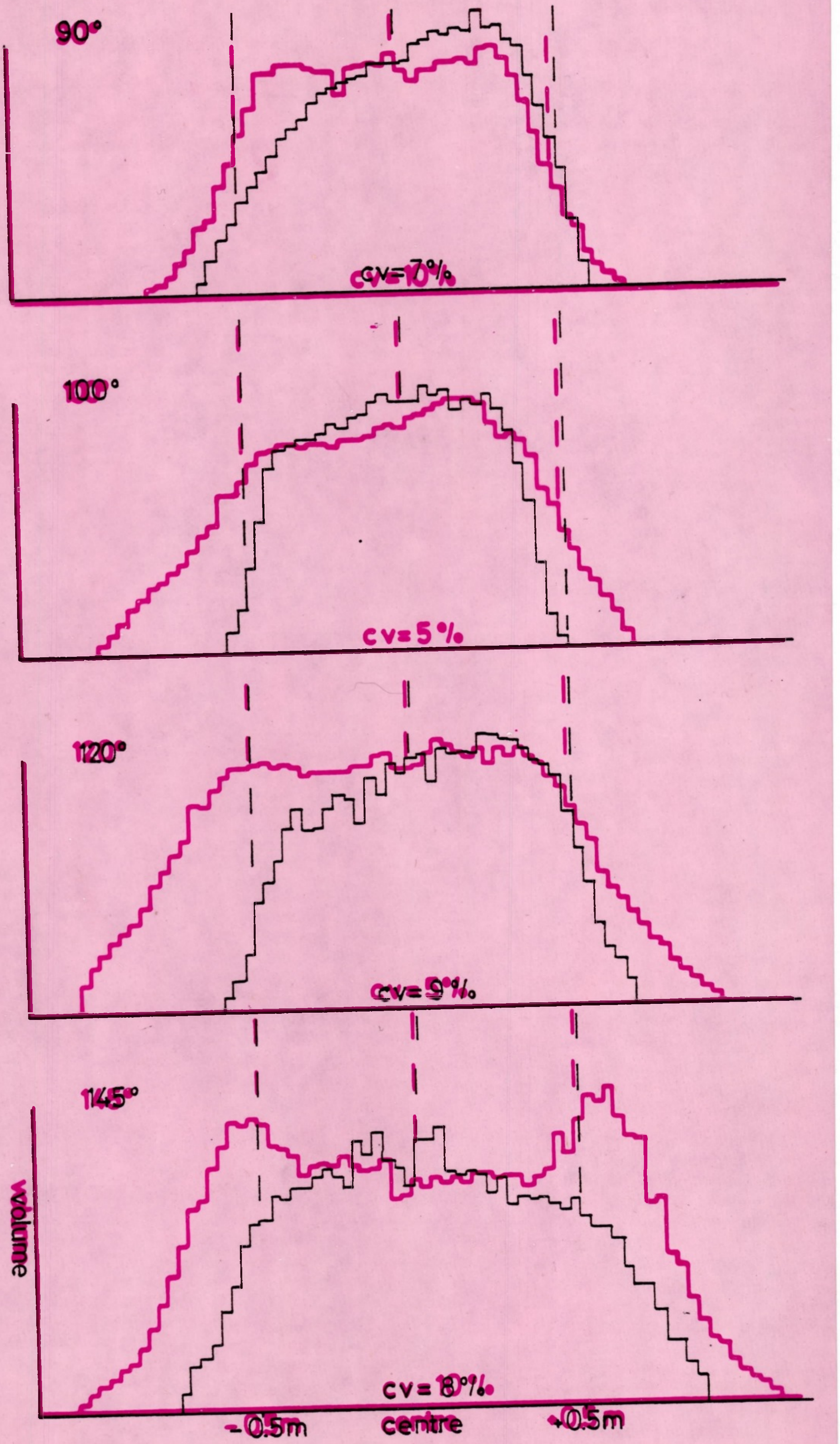


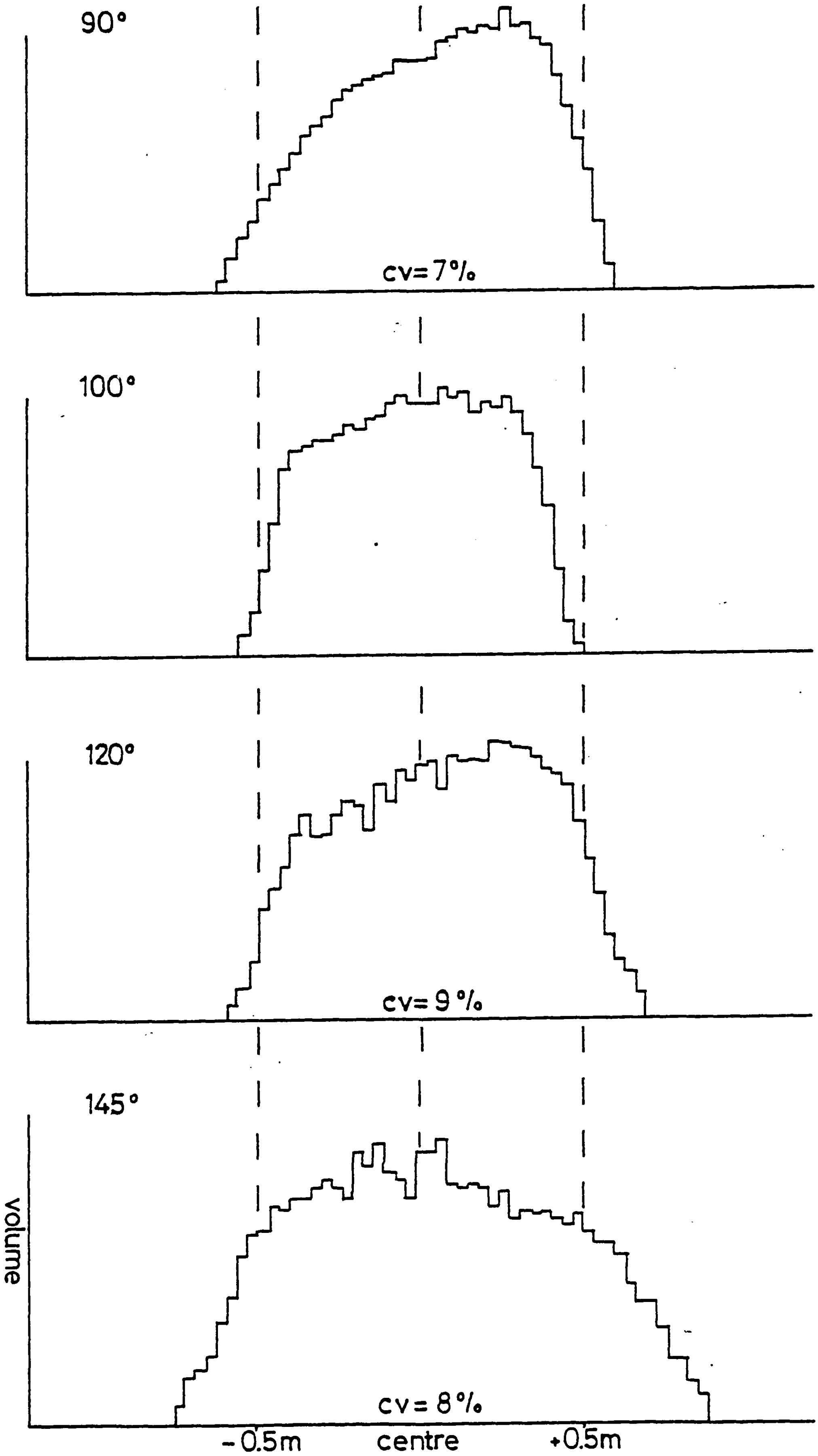
Fig. 4.28 Effect on Swath of Shroud Window Width

b) sprayer angled at 45°

a) horizontal sprayer



b) sprayer angled at 45°



which is equal on both sides of the sprayer, but, in practice, the window is less biased to the left than would be expected from the theoretical drawings. When spray liquid is forced along the grooves of the spinning cup, it gains an outward momentum as well as a tangential momentum, so that the droplets leave the cup with a slight outward trajectory. This causes the swath to be further to the left than expected, and must be corrected by changing the position of the shroud window. This effect is probably the source of inaccuracies in the prediction of the position of the swath produced by a shrouded spinning disc, computed by Goering et al (1973).

Changes in the swath width are likely to be small ($<$15%) within the range of walking speeds likely to be used in the field. This variation would not be important in overall spraying but could be important when inter-row spraying, since the crop could be contaminated by the spray; but the sprayer would normally be angled towards the ground, which greatly reduces the variation in swath width due to walking speed. The swath width for a given shroud window size is related to the momentum of the droplet and its velocity. Similarly, the swath of an unshrouded cup becomes wider as the flow rate increases at a constant rotational speed, but is reduced by increasing the rotational speed with a constant flow rate (Heijne, 1978).

The uniformity of the matched swaths was very good using a two nozzle feed onto the cup, since none of the variables investigated increased the cv over 10%. A horizontal sprayer with a window width of 110-120^{o} gave the best result (cv=5%). This compares to about 20% for an unshrouded cup (Heijne, 1978), although by putting individual cups very close together this may be reduced to 4% (Bode & Butler, 1981). The variation across the swath is within the limits of acceptability (cv=10-15%) set for hydraulic nozzles (Rice & Connolly, 1969; Rice, 1970) and spinning cups (Bode & Butler, 1981), and is better than that measured for most tractor mounted sprayers (Nation, 1968; Combellack et al, 1982). The angle of the shrouded cup affects the cv across the swath less than has been found for an unshrouded cup (Bode & Butler, 1981).

4.5.4. Calibration of the sprayer

The volume of spray which the shroud emitted and retained was measured at several walking speeds with a range of shroud window widths. The application volume was calculated using the optimum swath widths obtained by matching swaths measured on the patternator. The volume should remain constant since the flow onto the spinning cup is directly linked to walking speed.

The quantity of spray leaving the shroud at any one walking speed is directly proportional to the window width (Fig. 4.39). The proportion of the total flow onto the spinning cup which leaves the shroud declines relative to the window width at faster speeds and with wider windows (Table 4.11) resulting in a lower application volume (Table 4.12). With a single nozzle feed onto the spinning cup, the emission from the shroud changed depending on which side the cup was fed, and the sum of the volumes emitted using a left and a right feed was greater than that from the double nozzle feed.

The differences between the results are probably due to the exact position of the area of high liquid release from the spinning cup, relative to the shroud window. This is related to an interaction between flow rate onto the spinning cup and its rotational speed, and so will vary with the walking speed at which the sprayer is used. The area of high liquid release will also depend on the position of the feed onto the spinning cup. A four nozzle feed could allow spray to be produced uniformly around the perimeter of the cup (Heijne, 1978), and should be considered for future prototypes.

4.5.5. Effect of the shroud design on spray characteristics

i) results

The 45° slope of the shroud wall was designed to minimise the shattering of droplets produced by the spinning cup, but observations showed that significant shattering occurred. A spinning cup was arranged in a perspex shroud (Fig. 4.40) so that the spray could be observed using a stroboscope. A fine mist could be seen moving within the shroud and extending out of the shroud window with the main spray cloud. The droplet spectrum of a 30° segment of the swath from each shroud was analysed and compared to that from an unshrouded

Table 4.11 Spray Emission from the Shroud as a Proportion of Total Feed onto Spinning Cup (two feed nozzles)

Window width (°)	Window width (as % of 360°)	% Emitted from shroud at walking speed (m/s): 0.5	1.0	1.5
50	13.9	9.9	9.3	7.9
100	27.8	20.1	19.9	18.2
150	41.7	29.7	29.1	27.5
360	100.0	100.0	100.0	100.0

Table 4.12 Volume of Liquid Applied by Horizontal Sprayer

Window width (°)	Optimum swath (m)	l/ha Applied at walking speed (m/s): 0.5	1.0	1.5
50	0.48	20.8	19.4	17.6
100	1.08	18.8	18.5	18.1
150	1.68	17.9	17.5	17.5

Fig. 4.39 Volume of Liquid Emitted from Shroud (1.0 m/s walking speed)

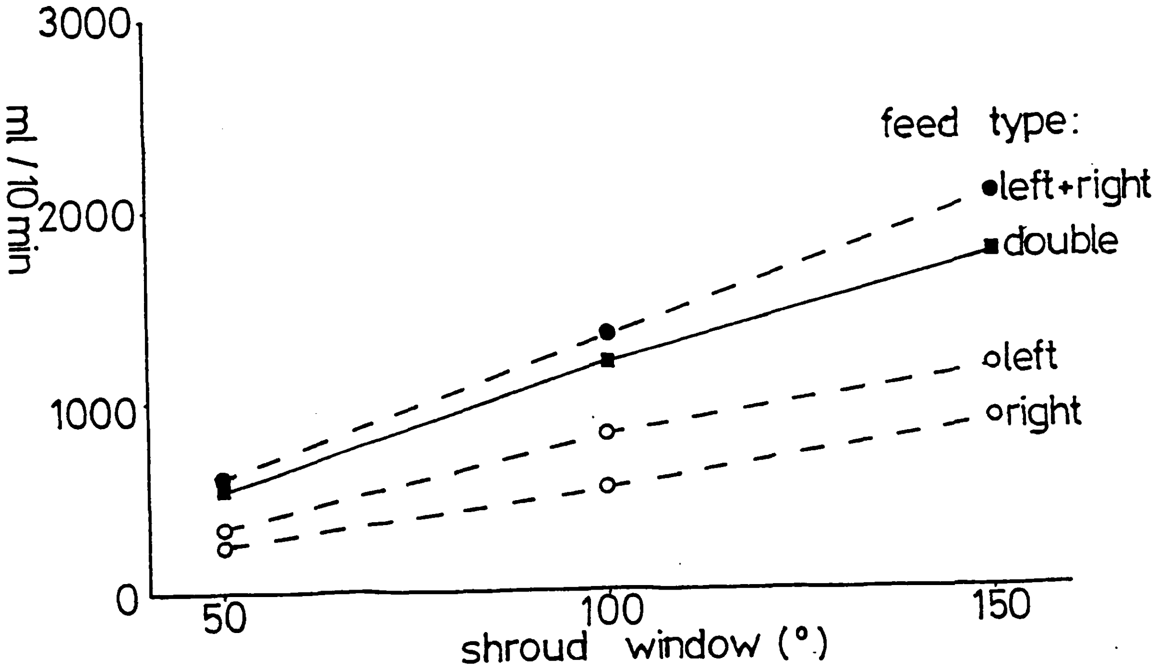
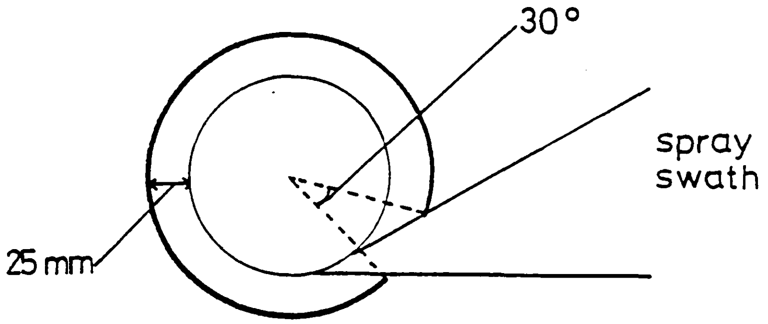
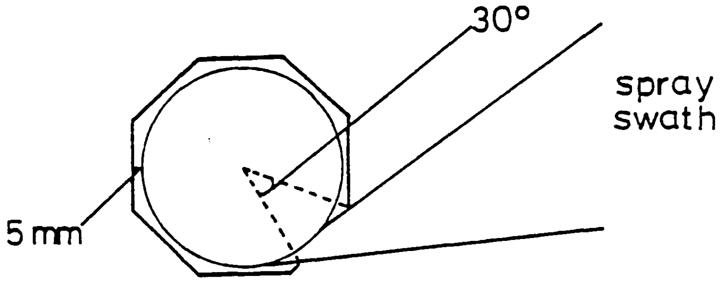


Fig 4.40 Plans of Shrouds

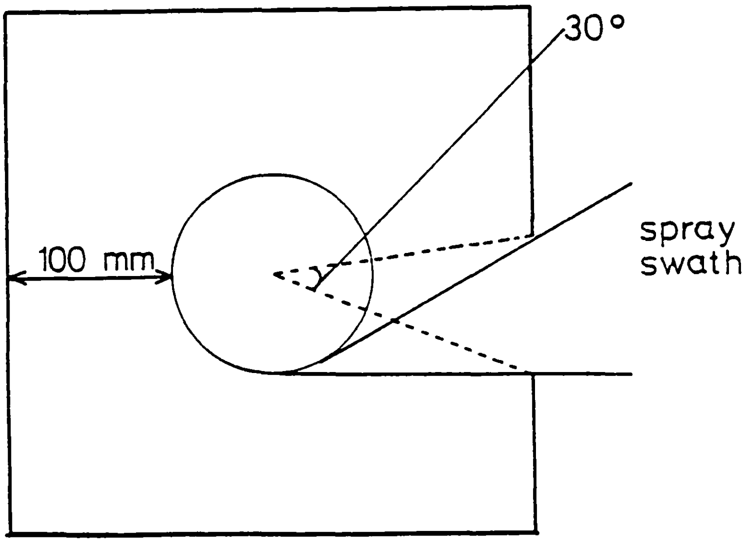
a) sprayer shroud (top & bottom enclosed, ht. = 70mm)



b) perspex shroud (top & bottom enclosed, ht. = 70mm)



c) unshrouded



cup.

The sprayer shroud gave the largest VMD at all flow rates and walking speeds. The lowest VMD was produced by the perspex shroud at all walking speeds with the high flow rate, and at the fastest walking speeds with the low flow rate (Figs. 4.41, 4.42). The unshrouded cup consistently gave the lowest VMD/NMD ratios, while the perspex shroud produced the least uniform spray at high walking speeds.

ii) discussion

The design of the shroud modified the characteristics of the spray produced by the spinning cup. When the cup is surrounded closely by a shroud, droplets shatter on its wall producing a fine spray and the severity of the shattering depends on the momentum of the droplets at impact. This caused the high VMD/NMD ratios when the shroud wall was very close to the cup perimeter, or at fast rotational speeds of the cup. The type of shroud had relatively little effect on the VMD, although the severe droplet shattering which occurred in the perspex shroud at high flow rates slightly reduced the VMD compared to the unshrouded cup.

4.6. Ground Spray Patterns

The distribution of the droplets and of the spray volume on the ground was investigated in more detail than was possible with the patternator. In all the experiments the sprayer was pulled, and, unless stated, it was used horizontally.

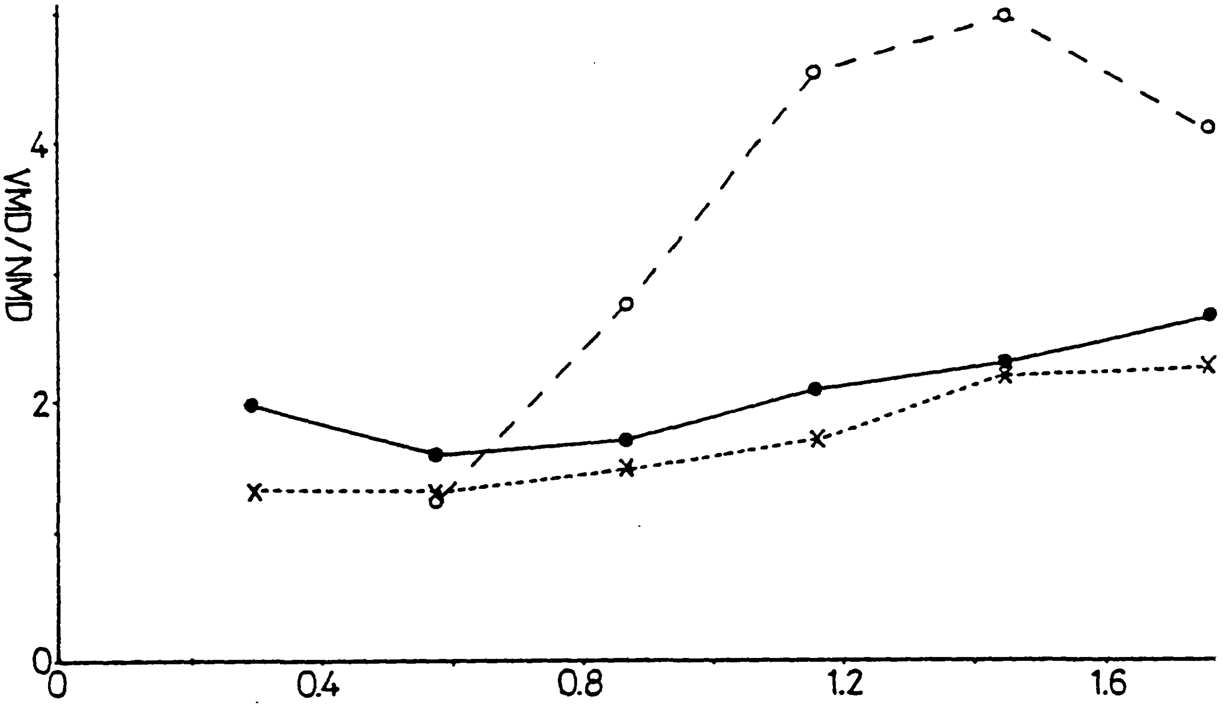
4.6.1. Droplet size distribution across the swath

The patternator experiments showed a flat topped swath, but sampling of dyed sprays suggested that the droplet size varied across this swath. This was tested by counting droplets on magnesium oxide coated slides which had been arranged across the sprayer swath.

The VMD was uniform across the swath, but the NMD was more variable (Fig. 4.43) due to changes in the proportion of small droplets (Fig. 4.44). The very low NMD at the right edge of the swath was due to the low droplet density with a predominance of very small droplets. The droplet spectrum was constant between replicates along the swath (Appendix 9).

Fig. 4.41 Effect of Shroud Design on Droplet Spectrum
(single pump feed)

a) VMD/NMD



b) VMD

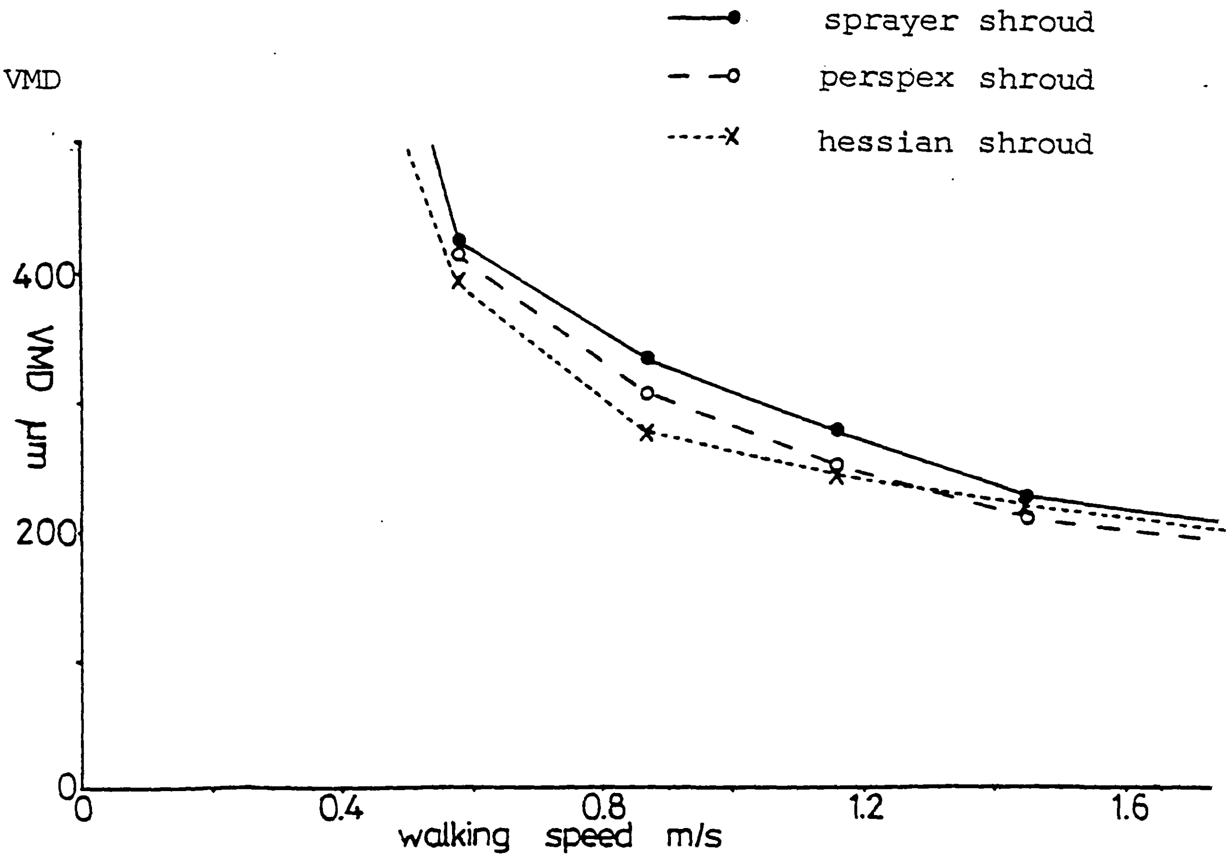
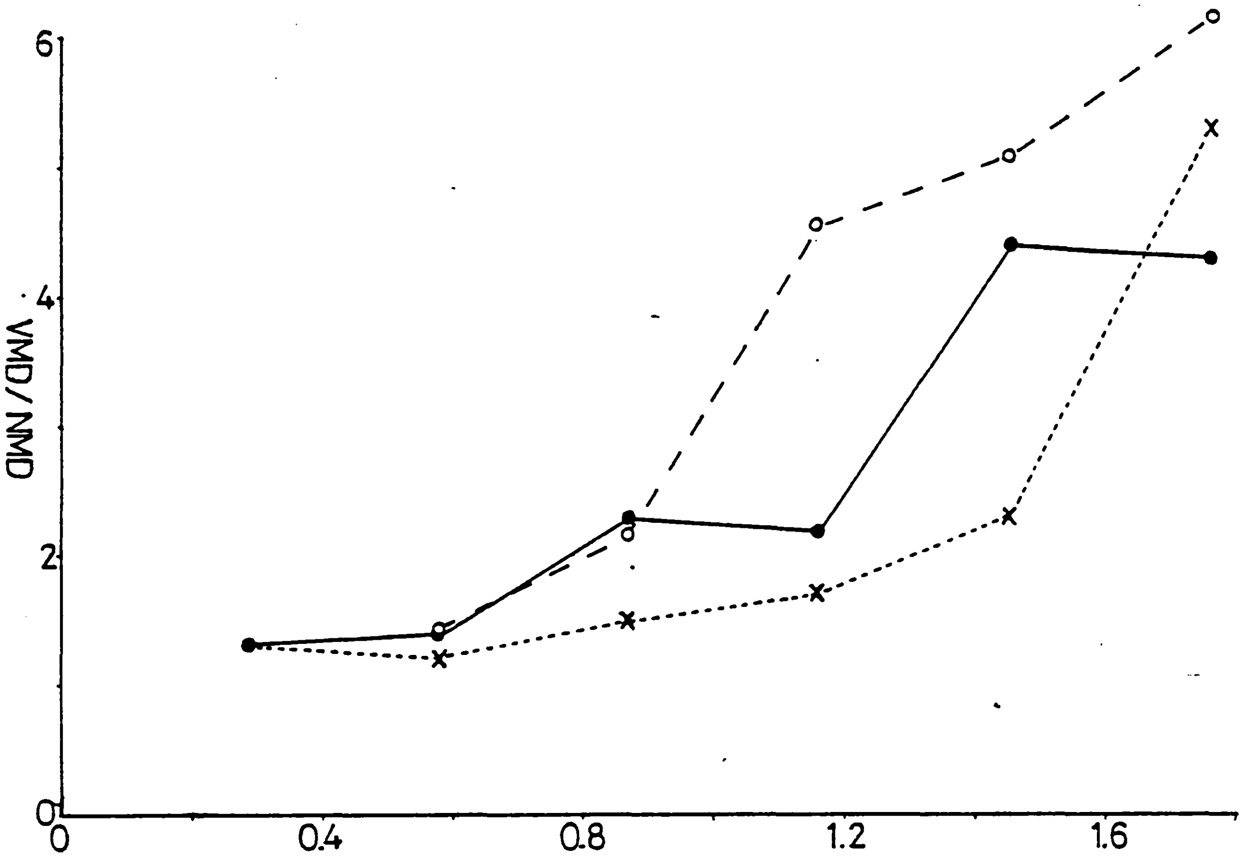


Fig. 4.42 Effect of Shroud Design on Droplet Spectrum
(two pump feed)

a) VMD/NMD



b) VMD

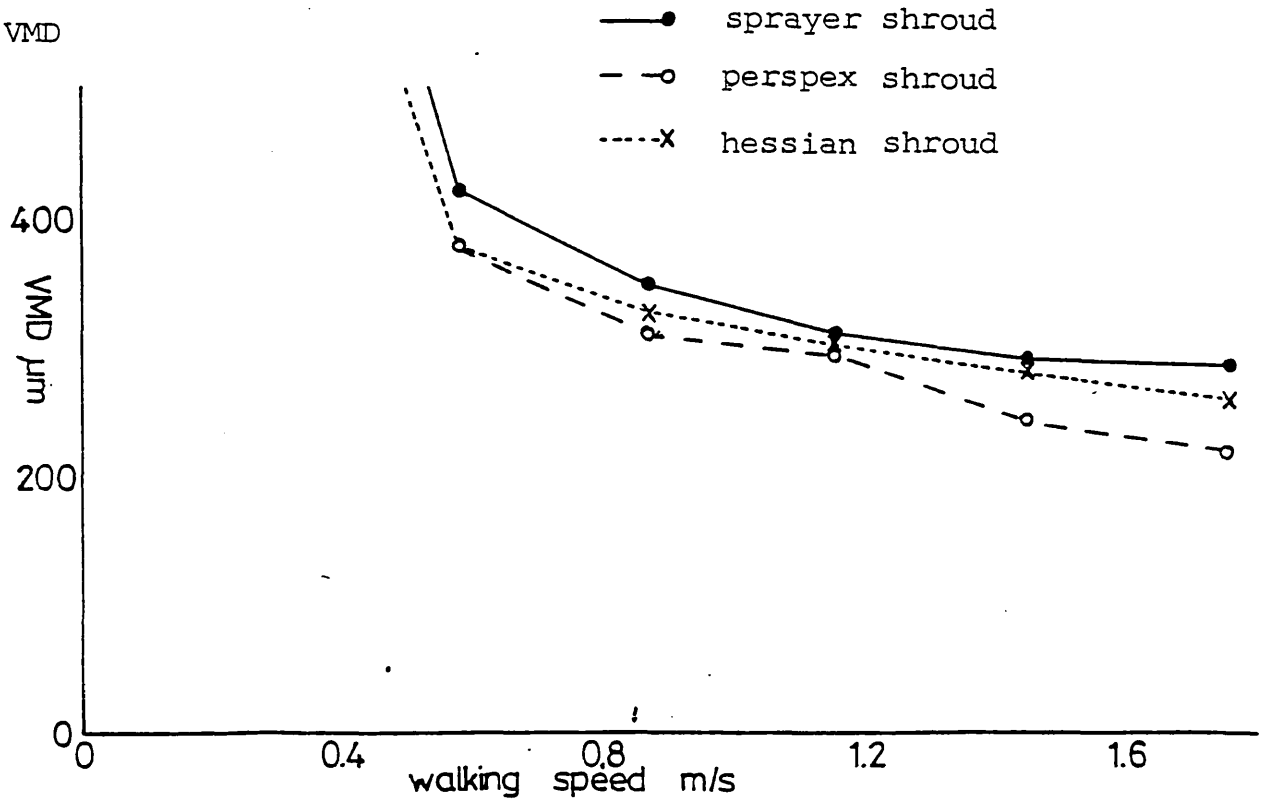
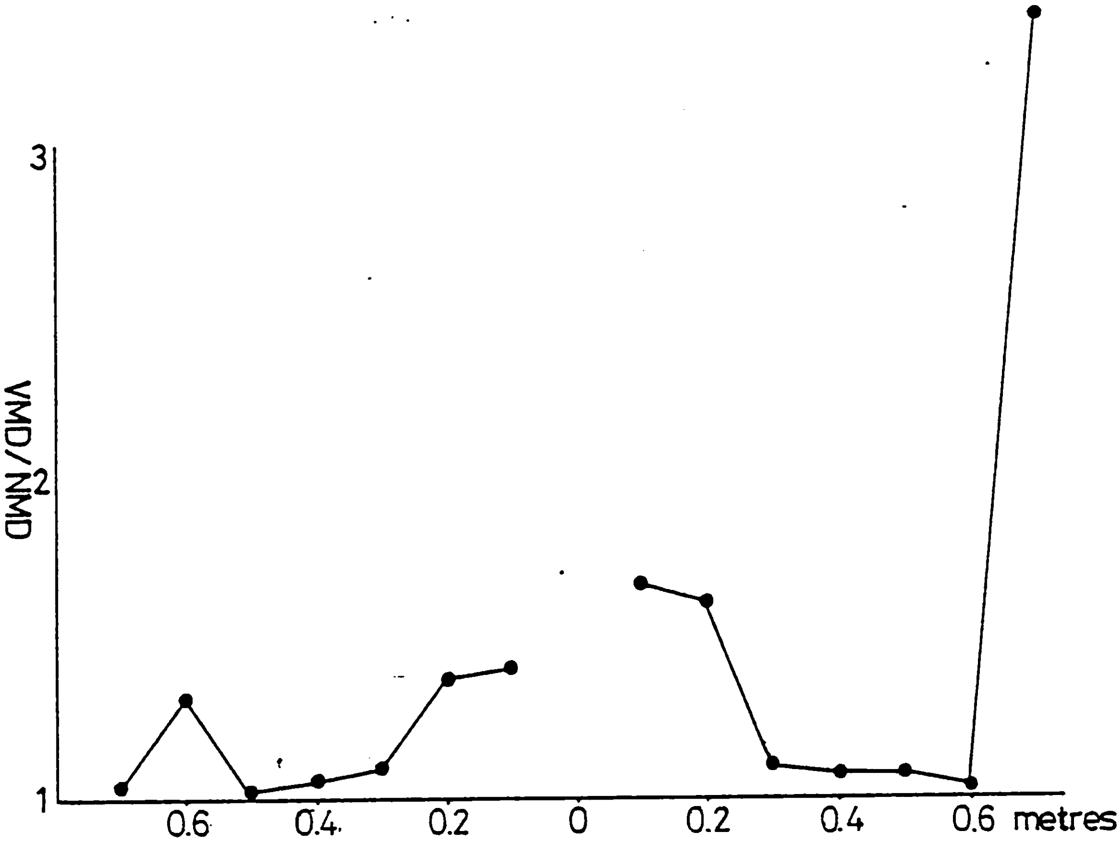


Fig. 4.43 Droplet Spectrum Across the Swath

a) VMD/NMD



b) VMD and NMD

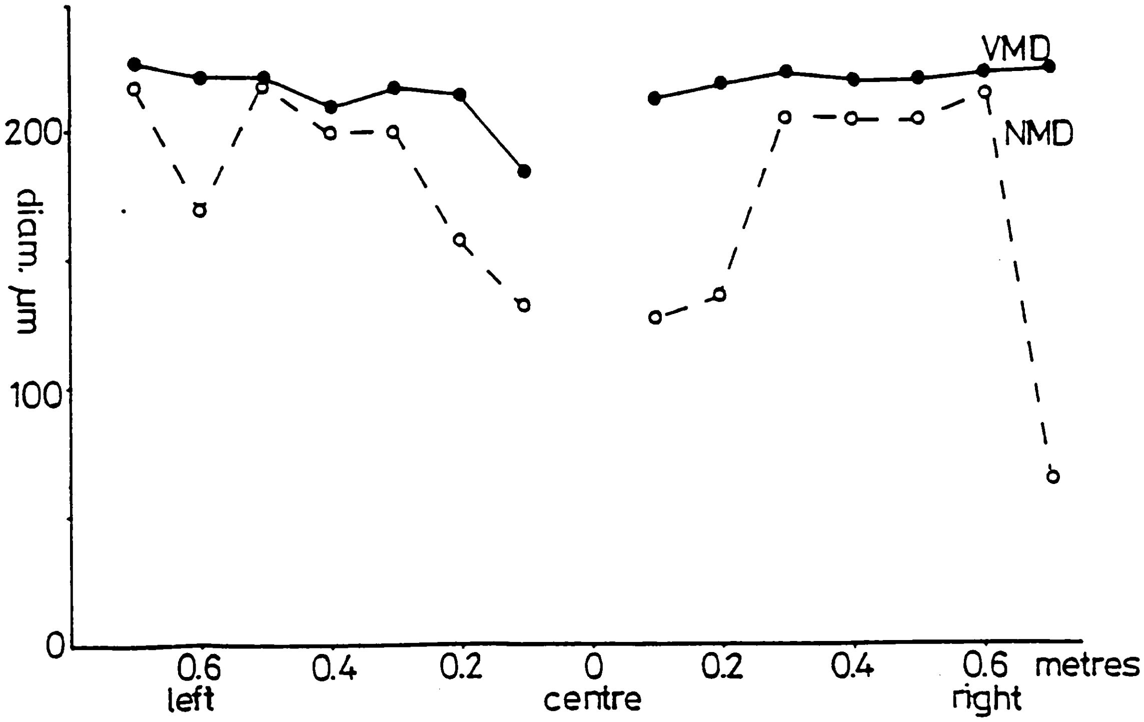


Fig. 4.44 Droplet Density (per 100x100 mm) Across the Swath

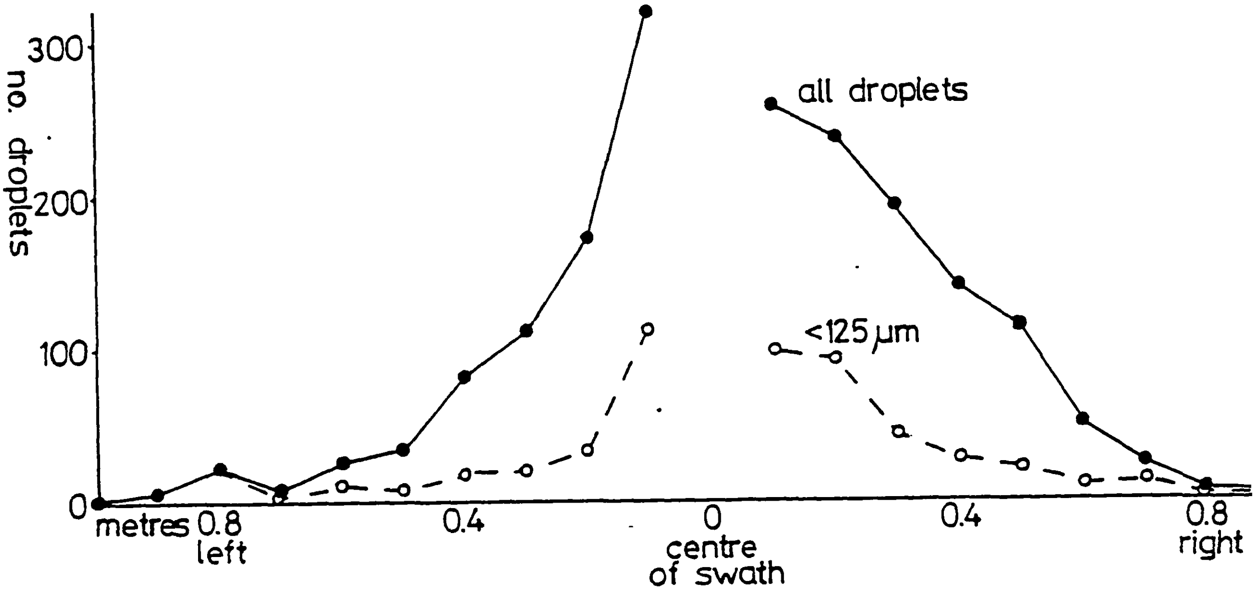
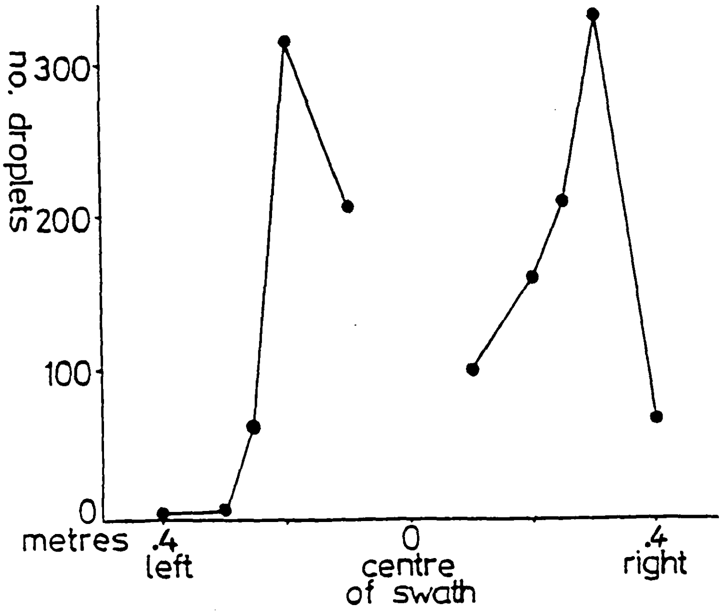


Fig. 4.45 Droplet Density (per 100x100 mm) for the Wheelbarrow Angled at 45° Moving into Swath +



+ adapted from Garnett, 1978

The larger proportion of small droplets at the centre of the swath is due to their low momentum compared to larger ones, which, therefore, travel further. The small droplets at the edge of the swath are probably due to the edge effects of the shroud window, since large droplets hitting the edge of the window shatter into a number of smaller ones. Secondly, there is a flow of liquid along the inside of the shroud which produces droplets when it reaches the edge of the shroud window.

The droplet density distribution when pulling the sprayer contrasted with the results when the sprayer was pushed, particularly when it was angled, When the shroud actually hit the spray which had just been released, producing a "horned" distribution on the ground (Fig. 4.45).

The VMD measured by using magnesium oxide coated slides was lower than that measured by the laser droplet analyser (section 4.4.4.), and the spray was more uniform (Table 4.13). Normally, the slide method would be expected to be less sensitive to small droplets and give a higher VMD than the laser analyser. However, samples were taken across the complete swath using slides, whereas only a sample through the centre of a vertical transect of the swath was intercepted by the laser beam. This part of the swath contains the main volume of the spray, so the laser beam would not have sampled the small droplets at the extremities of a vertical transect through the swath, and, therefore, overestimated the VMD.

Table 4.13 Droplet Size Measured by Two Methods, at 1.0 m/s Walking Speed

	Method	Spinning Cup Speed (rpm)	Flow Rate (ml/min)	VMD (µm)	VMD/NMD
First prototype	MgO (i) slides	1900	760	195	1.3
	laser	1900	760	370	1.7
Second prototype	MgO slides	1700	720	220	1.4
	laser	1700	720	275	2.4

(i) from Garnett (1978)

4.6.2. Volume distribution across and along the swath

The volume reaching the ground along the swath was analysed for variation attributable to the pulsing of the pumps which feed the spinning cup. A fluorescent tracer was included in the spray.

i) across the swath

The distribution of spray across the swath (Fig. 4.46) was similar to that shown by the patternator. The coefficient of variation (cv) was 9-15% for an angled sprayer and 12-25% for the horizontal sprayer. This compared favourably with the 25-44% for the impact nozzle on a knapsack sprayer.

The angled and horizontal sprayers applied a similar volume of liquid per unit area, but it was generally lower than the target volume.

ii) along the swath

The peaks in spray volume, caused by the pulsing of the pumps, were more severe when the sprayer was angled than when horizontal (Fig. 4.47). This was reflected in the generally lower cv of the samples from the horizontal sprayer, although some of those taken from the left side of the horizontal sprayer had a high cv (Table 4.14). The swath produced by the knapsack sprayer was slightly more uniform than that of the wheelbarrow, but the laboratory sprayer gave the most even pattern, with a cv of 10%.

When a 32 mm high bump was incorporated into the track, the spray distribution was affected differently depending on whether the wheelbarrow sprayer was set horizontally or angled (Fig. 4.48). A deeper but shorter trough was produced by the angled sprayer compared to the horizontal sprayer.

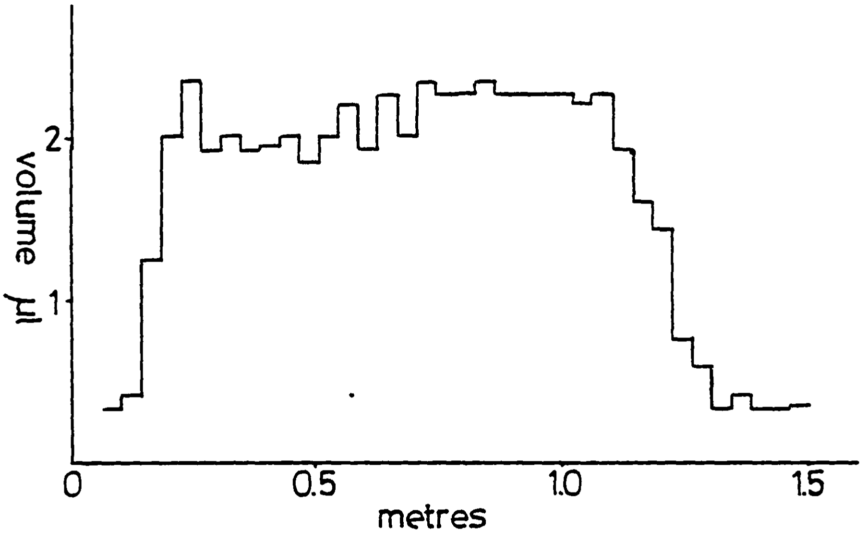
The peaks produced from the pulsing form a regular pattern, which corresponds closely with the distance expected from the number of rollers (Table 4.15). The knapsack sprayer also produced an easily recognisable series of pulses, which was probably due to the manual pumping of the sprayer to maintain its pressure.

iii) effect of pump configuration

Several configurations of the Glen Creston two roller pumps were tested to investigate their effect on the

Fig. 4.46 Samples Across Spray Swath Measured by Fluorescent Tracer (µl/40x40 mm)

a) 45° angled sprayer



b) horizontal sprayer

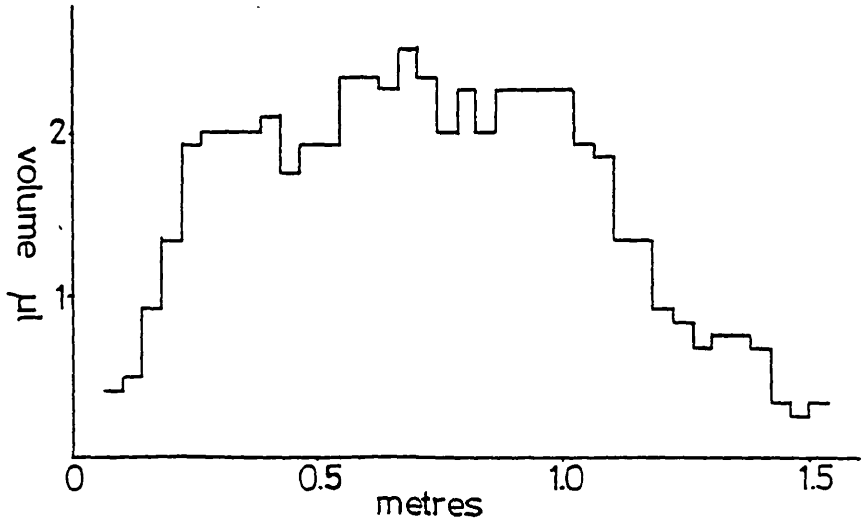
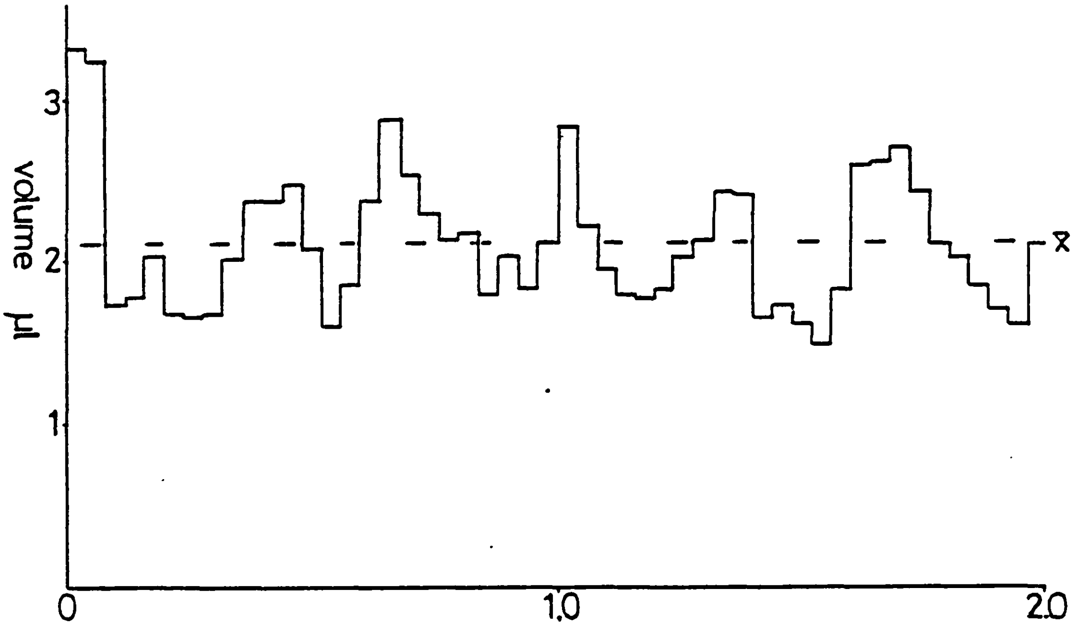


Fig. 4.47 Effect of Sprayer Angle on Ground Spray Distributions Along the Swath (µl/40x40 mm)

a) 45° angled sprayer



b) horizontal sprayer

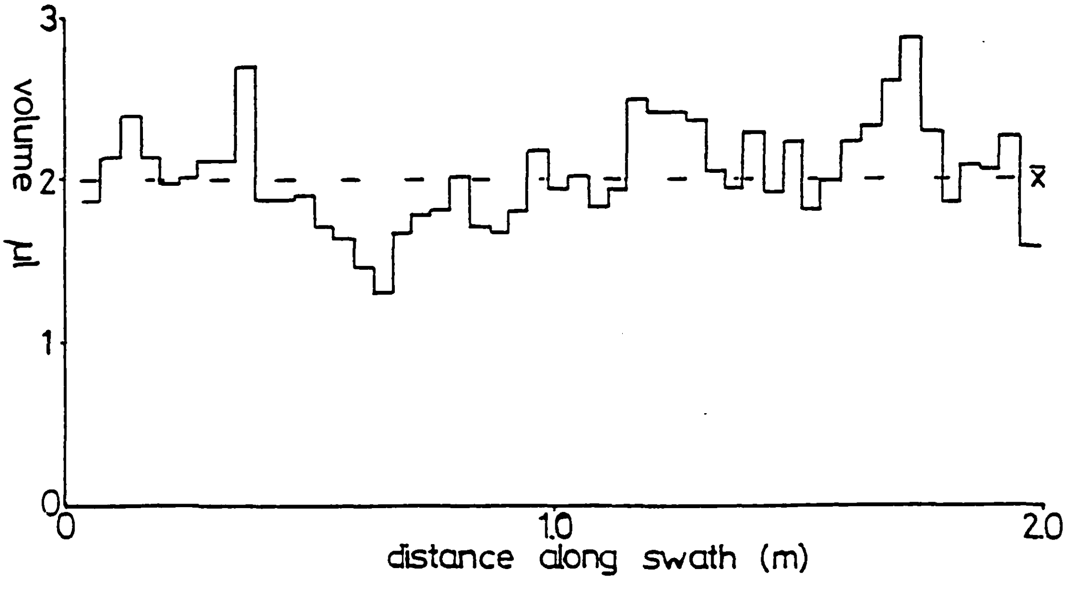


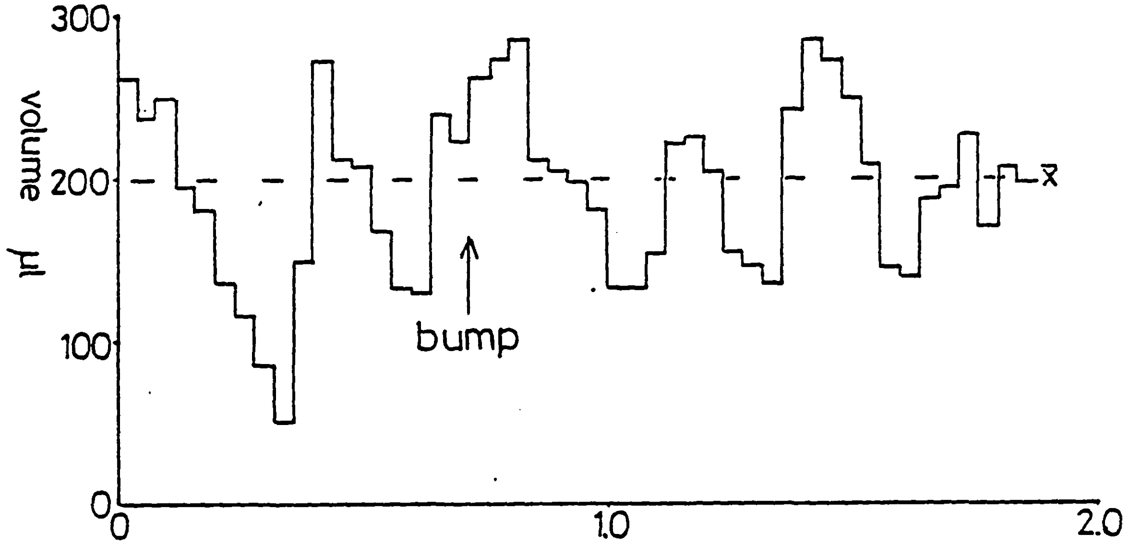
Table 4.14 <u>Swath Characteristics at 1.0 m/s</u>

(mean of 2 - 4 replicates)

Sprayer Type and Target Volume	Across Swath (matched swaths)			Along Swath			
				left		right	
	width (m)	cv (%)	net vol. (l/ha)	cv (%)	net vol. (l/ha)	cv (%)	net vol. (l/ha)
<u>Wheelbarrow</u> at 45^o							
15 l/ha	0.98	11	11.7	28	13.5	21	14.4
15 l/ha, with bump				30	16.6	28	13.2
40 l/ha	0.91	12	34.0	28	36.3	28	38.8
<u>Wheelbarrow</u> horizontal							
15 l/ha	1.22	19	12.6	40	11.8	17	15.7
15 l/ha, with bump				14	14.0	19	12.3
<u>CP3 knapsack</u>, impact nozzle							
300 l/ha	1.34	34	344	17	176	13	246
<u>Spray cabinet</u>, 8001 fan nozzle							
188 l/ha	-	-	-	10	114	-	-

Fig. 4.48 Effect of Bump on Ground Spray Distribution Along the Swath (µl/40x40 mm)

a) 45° angled sprayer



b) horizontal sprayer

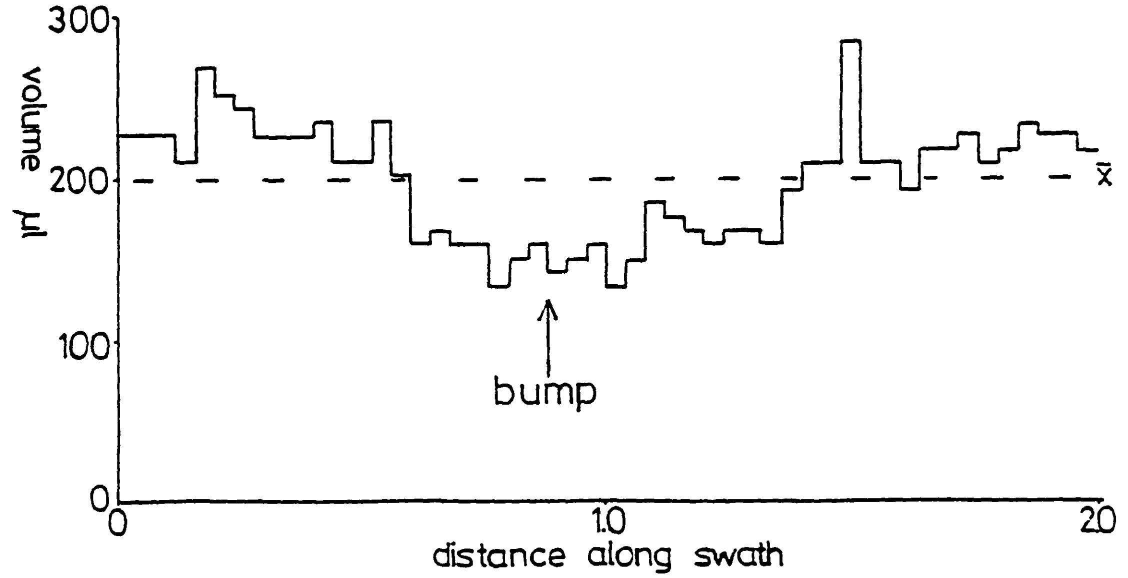


Table 4.15 Longitudinal Spray Patterns to Show Pulsing of Pumps

	Peak to peak distance (m)	Theoretical[(1)] distance
Wheelbarrow sprayer		
3 roller peristaltic pump		
sprayer at 45°	0.32	0.32
sprayer horizontal	no peaks	0.32
2 roller peristaltic pumps		
(x2) sprayer horizontal	0.24	0.24
2 roller peristaltic pump		
(x1) sprayer horizontal	0.49	0.48
CP3 knapsack sprayer	0.55	

(1) wheel circumference = 0.96 m

Table 4.16 Effect of Peristaltic Pump on the Variability of Spray Deposition Along the Swath

Pump configuration	cv (%)
2 pumps in phase	41
2 pumps 60° out of phase	29
2 pumps 90° out of phase	24
right pump only	33
right pump + expansion chamber	36
right pump + expansion chamber + non-return valve	29

variability of the deposition of spray along the swath (Table 4.16). A pair of pumps with their rollers turning in phase produced the poorest distribution (cv=41%), which improved as the pumps were moved out of phase, almost halving the cv to 24% when they were 90° out of phase. A single pump produced a distribution with a cv between these values, but the variation was not reduced by fitting a simple expansion chamber between the pump and the shroud.

iv) discussion

Of the three sprayers tested, only the laboratory sprayer produced a longitudinal spray uniformity within the acceptable limit of variation (cv=10-15%) proposed by Rice & Connolly (1969), Rice (1970) and Bode & Butler (1981), although transverse samples from the wheelbarrow sprayer were acceptable.

The variation across the swath of the wheelbarrow sprayer was within these limits of acceptability, supporting the results of the patternator tests. The horizontal sprayer gave a more uniform swath than the angled sprayer, since its longer spray trajectory smoothed the pulsing of the spray. A pair of pumps, 90° out of phase with each other, minimised the variability along the swath since their combined output was more uniform than that of the pumps in phase. The variation along the swath was significantly greater than has been measured for spinning discs fed with a constant flow of liquid (Taylor & Merritt, 1974).

When the sprayer was pulled horizontally over a bump, the spray was suddenly thrown into the air causing a greater volume of spray to be deposited behind the bump, with less in the region of the bump. This smoothed the effect of the bump compared to an angled sprayer, which concentrated the movement of the spray.

The target spray volume (Table 4.14) had been based on the amount of spray expected to leave the shroud with a given window width. However, the volume of spray actually recovered from the samples was usually equivalent to less than the target volume, because less spray than expected was emitted from the shroud (section 4.5.4.).

4.7. Characteristics of Hydraulic Nozzles

In the biological efficacy tests (section 5.1.), two hydraulic nozzles were compared to the wheelbarrow sprayer. The swath uniformity and droplet spectrum were analysed for both nozzles (Figs. 4.49, 4.50, Table 4.17).

Table 4.17 Uniformity of Matched Swaths of Hydraulic Nozzles

Pressure (kPa)	cv (%) impact nozzle	fan nozzle
70	14	23
105	23	22
140	28	14
210	37	10
280	-	8

i) impact nozzle (red "Polyjet")

There were five peaks in the spray volume across the swath, which were emphasised as the pressure in the spray tank was increased, resulting in a greater cv across the matched swaths. The cv was greater than that for the wheelbarrow swaths. At the pressure used in the biological experiments (100 kPa), a poor droplet spectrum was produced, with a VMD of 282 µm and a VMD/NMD ratio of 10.

ii) fan nozzle (8001)

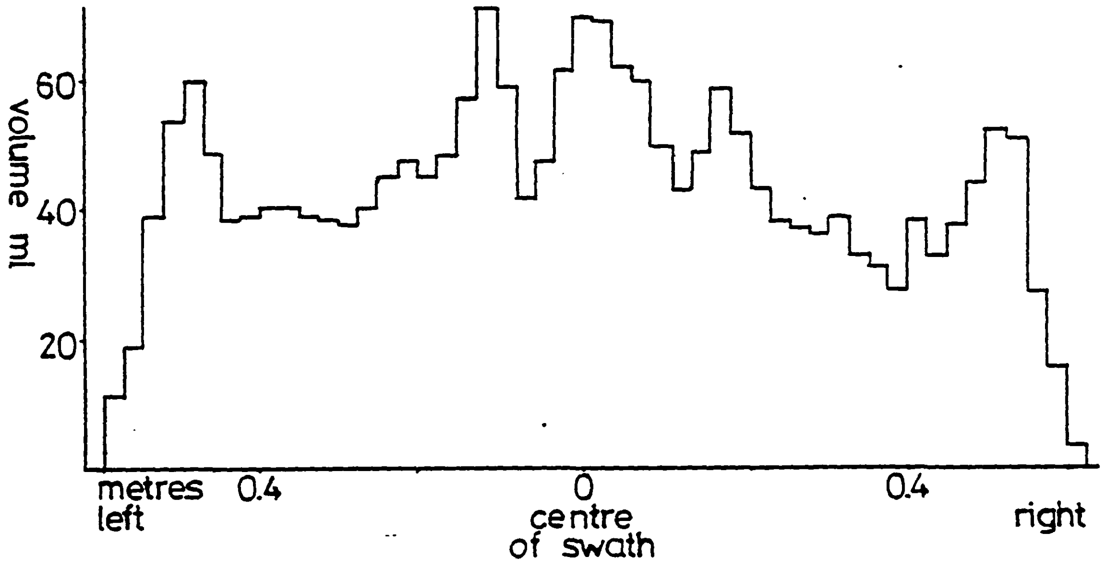
The uniformity of the spray improved as the pressure increased, but high pressures caused the production of a very wide range of droplet sizes. At 200 kPa, the pressure used in the biological experiments, the VMD of the complete spray fan was 161 µm and the VMD/NMD ratio was 47, but the droplet size varies significantly across the fan (Arnold, 1983a).

4.8. The Use of the Sprayer in Botswana

No mechanical faults were experienced with the second prototype during the field trials in Botswana, despite considerable rough treatment. The moving parts were never oiled or cleaned, herbicides were not washed out of the pump after spraying, and it suffered severe knocks during transport and field use.

Fig. 4.49 Spray Patterns from Hydraulic Nozzles

a) impact nozzle (red Polyjet) at 105 kPa,
0.35 m above patternator



b) fan nozzle (8001) at 210 kPa, 0.35 m above patternator

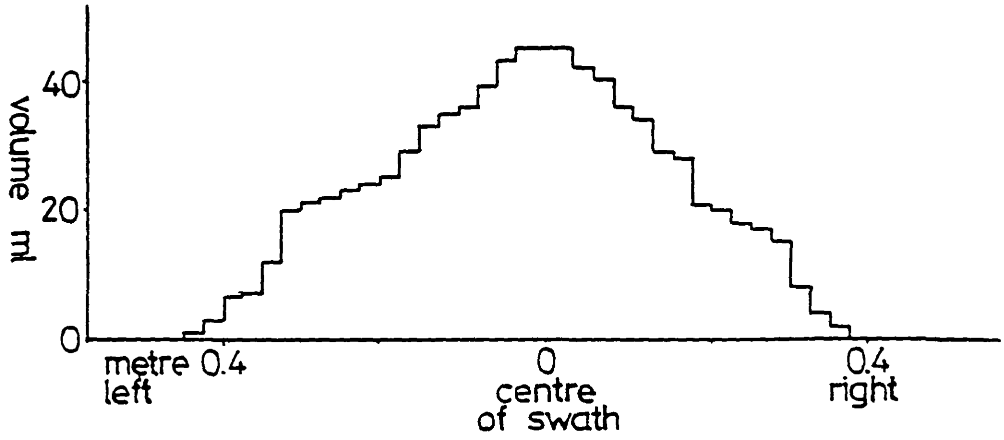
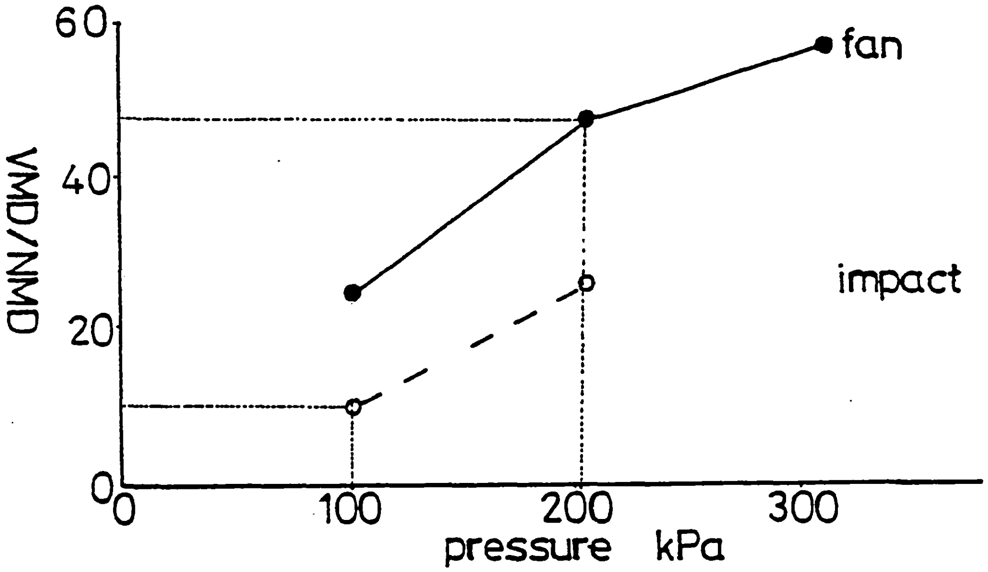
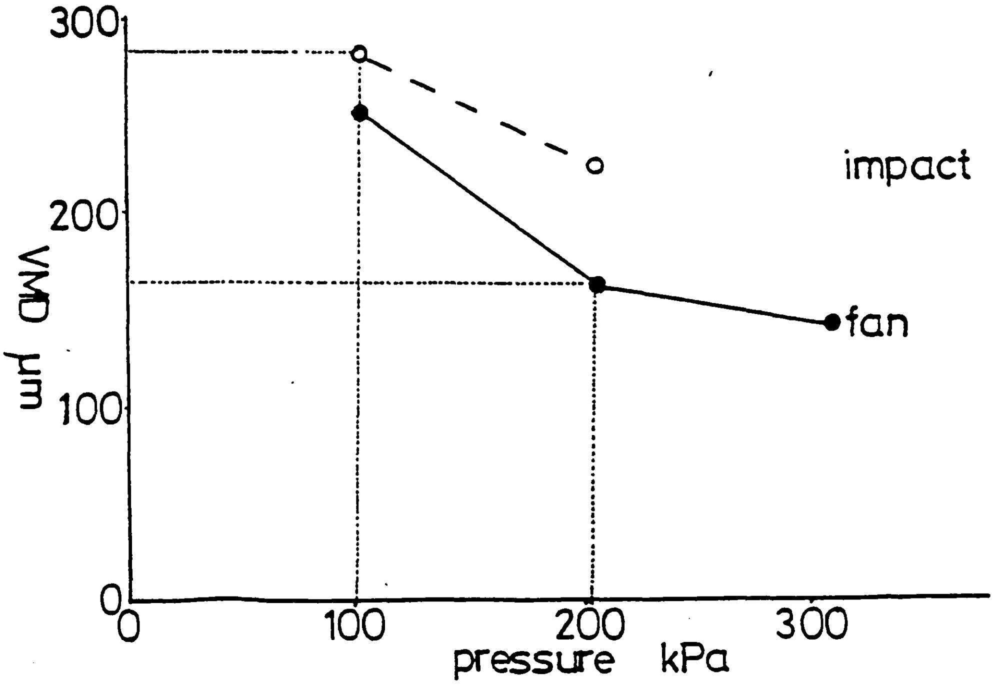


Fig. 4.50 Droplet Spectra from Hydraulic Nozzles

a) VMD/NMD



b) VMD



4.8.1. General use

Several locals operated the wheelbarrow sprayer and commented that it was easier to use than the hand-held spinning disc sprayer or the knapsack sprayer, which was difficult to pump and heavy when filled with spray. Similar comments relating to the use of knapsack sprayers in the tropics have been noted by Lyon (1970) and Matthews (1973). Two operators commented that the wheelbarrow was the easiest to use because of the physical and psychological values of it being on the ground. They appeared much less confident with the lances of the hand-held spinning disc sprayer or the knapsack sprayer, which were held in the air.

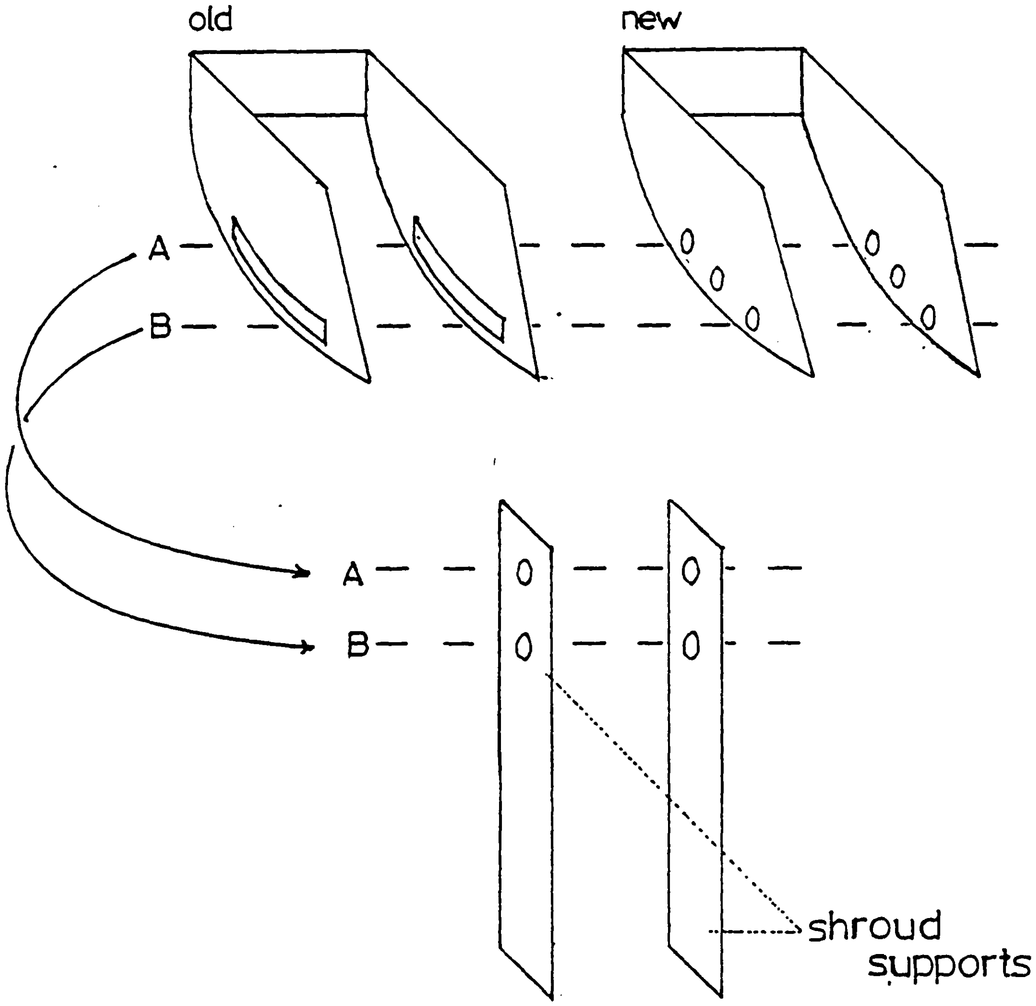
Traction was good on the sandy soils although the wheel sank in up to 40 mm in dry, soft, ploughed soils, and about 50 mm in wet soil, leaving a track which showed where the spray had been applied. Only large clods of soil caused the wheel to lose its grip and, therefore, momentarily stop the pump. This has a negligable effect on the speed of the spinning cup because of the free-wheel mechanism. It was much easier to pull than to push the sprayer and all the operators maintained the sprayer in its correct, upright position, although there have been reports of operators in Nigeria who naturally hold wheelbarrows in a lop-sided manner (Ogborn, 1980).

The average walking speed of the operators was 1.2 m/s. Speeds of 2.0 m/s were difficult to maintain, and at 0.5 m/s the movement of the operator and the sprayer was jerky and irregular due to the slow stepping of the operator and because of his lack of momentum for pulling the sprayer over clods. A slightly longer handle is needed to prevent long-legged operators kicking the wheel as they walk, and an improved attachment of the handle to the framework would allow easy adjustment to spray at predetermined angles (Fig. 4.51).

4.8.2. Spinning cup drive mechanism

The friction drive worked well even when the wheel picked up wet sand on its rim, since its high rotational speed flicked the sand off the wheel. After a heavy rain, a layer of fine, black mud collected between the furrows in one trial. This was picked up by the wheel and the whole drive mechanism

Fig. 4.51 Modification to the Attachment of the Handles to the Sprayer



became blocked. The problem was alleviated by placing an angled scraper against the wheel rim immediately before the friction drive. In addition, a wire brush against the drive spindle would prevent the mud hardening on the spindle and increasing its diameter, which would cause the spinning cup to rotate faster. The bearings in the drive mechanism were apparently unaffected by the dust which collected on the sprayer.

On this prototype, the spring loading of the spindle against the tyre had been decreased compared to that on the first prototype, resulting in less wear on the tyre, and making the machine easier to pull.

4.8.3. Peristaltic pumps

The pair of Glen Creston "WAB pumps" were 90.° out of phase with each other, and fitted with 6 mm silicone rubber tubing. The flow rate was consistently 12% higher than was expected from measurements made in England. This was probably due to the much higher temperatures in Botswana, about 30°C compared to 15-20°C, which affected the elastic properties of the tubing (section 4.2.3). Although the herbicides were never cleaned out of the tubing, they did not appear to affect the silicone rubber. The Glen-Creston pump mechanism was enclosed, which protected it from grit and from vegetation which might have punctured the tubing.

The pumps were fixed to the same shaft, which was turned by a bicycle chain from the ground wheel. The chain showed no evidence of wear, although sand collected on the oil which lubricated it, but the more open type of chain used on the EFSAIP prototype seed planters (EFSAIP, 1978) would probably have a longer life and would be less likely to become entangled in vegetation.

4.8.4. Shrouding

The swaths shown by vegetation sprayed with paraquat, were of a similar width to those expected from the patternator tests (section 4.5.3.).

The shroud was held horizontally for overall herbicide applications, but was angled to 35° when it was necessary to direct the spray to avoid the crop leaves. However, this was unsuccessful since the shroud was too high, and crop phytotoxicity was noted. Simple shields attached loosely to the sprayer framework and resting on skids on the ground (Fig. 2.1f) prevented some of the spray hitting the crop, but the sprayer was difficult to manoeuvre, and some droplets still hit the crop. A more complete plastic shield of the type available for use with knapsack sprayers, would be light enough to mount on the sprayer and would completely enclose the spray swath. A shroud with a variable height could be lowered close to the ground to avoid the crop, but this was not possible using the direct drive system for the spinning cup.

Slow drainage caused liquid to collect in the shroud and to overflow through the shroud window, particularly when the shroud was angled towards the ground, or when the sprayer bounced over rough ground. The slow drainage was caused by air locks in the sump, and could be overcome using an air-bleed. Recycling this liquid back to the tanks agitates the contents, which prevents wettable powder or flowable formulations from settling out. Although the high concentrations of these formulations which would be used with the sprayer are prone to settling out, this was not noted in the field testing.

Considerable pitting of the shroud occurred during the trials programme, presumably due to a reaction between herbicides and the metal alloy. A plastic shroud would be more suitable.

4.8.5. Filling and cleaning the sprayer

The two spray tanks were connected by a hollow axle to allow equilibration of the liquid in them if more was returned from the shroud to one than the other. The system was cumbersome for filling with spray liquid and cleaning after use, which required several litres of water. This could discourage proper cleaning of the sprayer. A single, removable bottle is recommended for future models.

CHAPTER 5 BIOLOGICAL EFFICACY

The wheelbarrow sprayer had successfully been used to control grass weeds in a preliminary experiment (Garnett, 1978) but further work was required to show that weed control was consistently similar to that using standard sprayers. The interpretation of the biological efficacy of a sprayer is complicated by the introduction of another variable, the efficacy of the herbicide, so a range of types of herbicide were tested under different conditions.

5.1. Laboratory and Greenhouse Tests

The activity of six contrasting herbicides was tested, comparing the spinning cup on the wheelbarrow sprayer with an impact nozzle on a knapsack sprayer and, in some experiments, with a fan nozzle in a laboratory spray cabinet. The sprays were applied to radish (Raphanus sativus) and oats (Avena sativa) grown in pots in a greenhouse (section 3.7.)

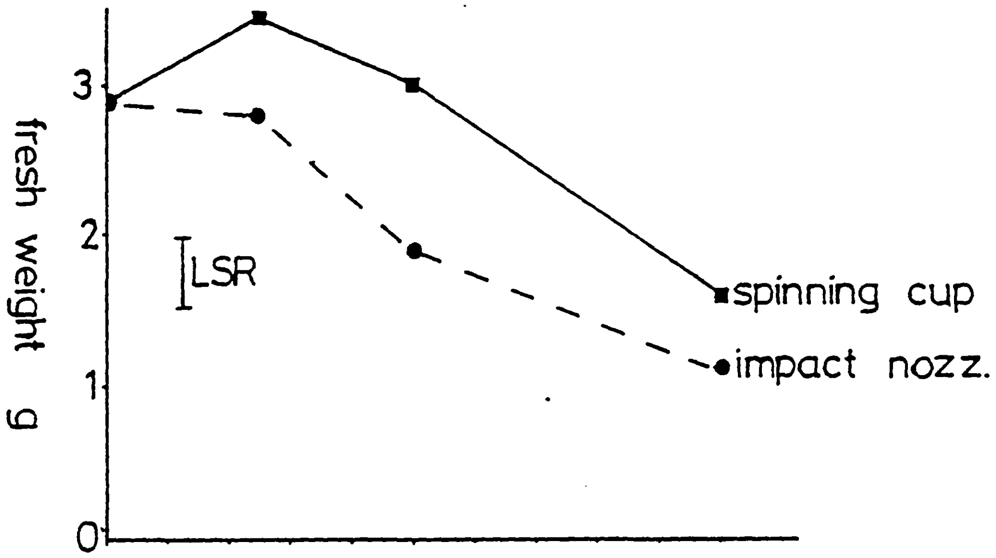
5.1.1. Pre-emergence herbicides

There was a significant dose response with atrazine on both radish and oats, but the spinning cup gave significantly poorer control of both species than the impact nozzle (Fig. 5.1). The phytotoxicity symptoms occurred after plant emergence, with early chlorosis followed by necrosis at the higher doses, but by growth suppression at the lower doses. Radish was slightly more susceptible than oats, and was completely killed by 1000 gai/ha when applied by either of the sprayers.

Pendimethalin had no effect on oats but significantly suppressed the growth of the radishes, with both sprayers giving the same response (Fig. 5.2). Analysis of soil samples taken from the pendimethalin treatments showed that the correct amount of herbicide had been applied (Table 5.1.), and the low level of effect on the plants was probably due to an unsuitable choice of species for use with pendimethalin. Avena spp. are not well controlled by pendimethalin (Kirkland, 1980) and it has poor activity on the Cruciferae (Winfield et al, 1978). Previous screening experiments had shown variable activity on both A.sativa and R.sativus, although the latter was the more susceptible species (Richardson, 1979).

Fig. 5.1 Dose Responses to Atrazine

a) oats



b) radish

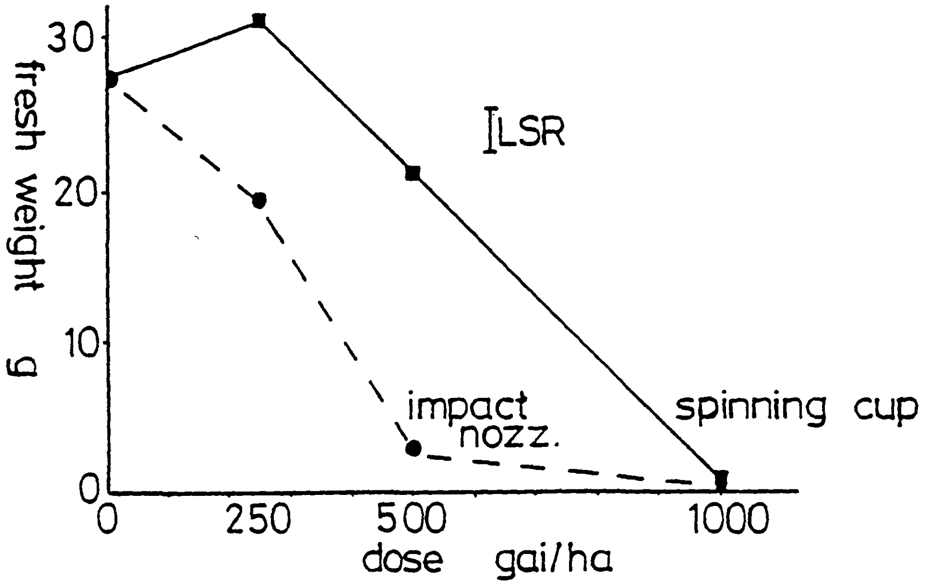
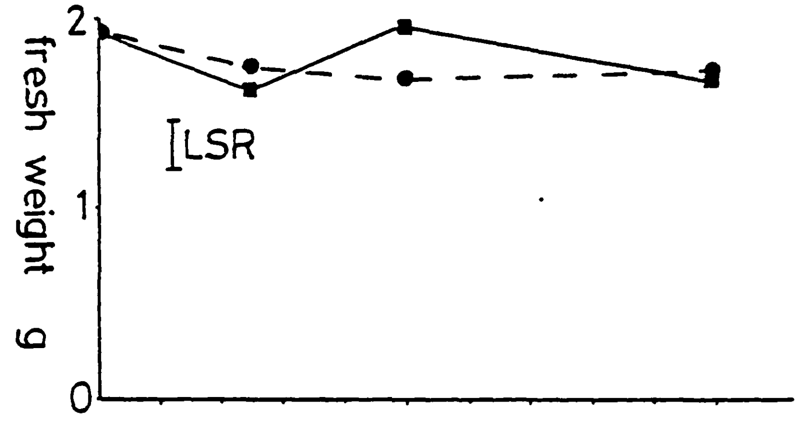


Fig. 5.2 Dose Responses to Pendimethalin

a) oats



b) radish

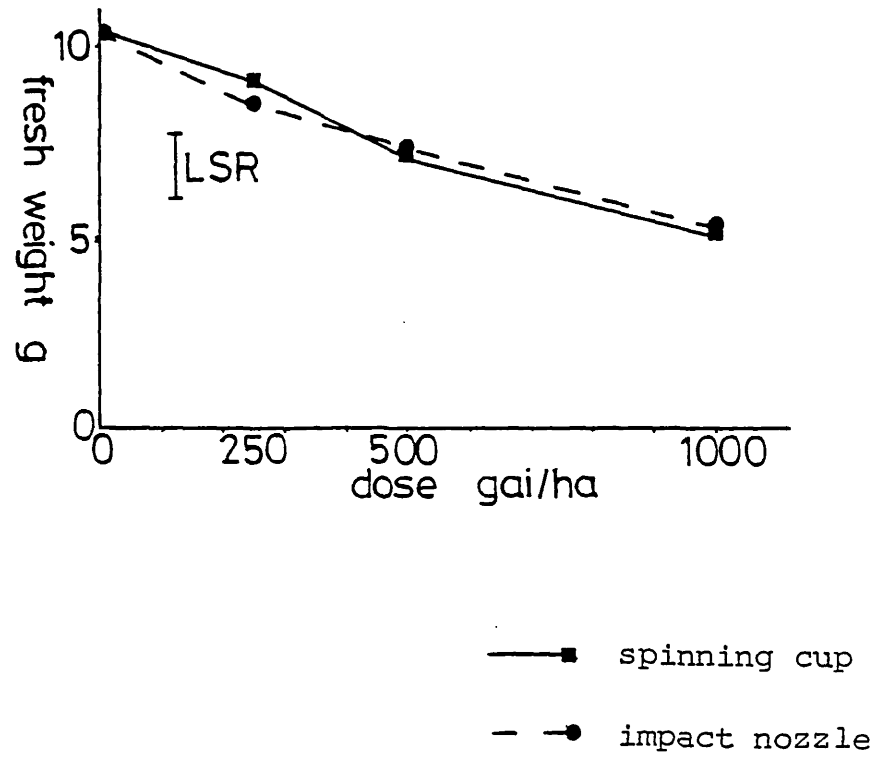


Table 5.1 Soil Residues of Pendimethalin

(Measured at time of harvest)

Treatment (gai/ha)	Measured residue (µgai/g soil)	Residue in sample area (µgai)	Estimated dose applied to sample area (µgai)
0	0	0	0
250	0.84	84	60
500	1.33	133	120
1000	2.81	281	240

5.1.2. Post-emergence herbicides

Three methods were used to assess phytotoxicity. For paraquat, fresh weights best distinguished the observed dose responses (Figs. 5.3-5.5), whereas dry weights masked some differences. The fresh weight : dry weight ratio, sometimes used for herbicides with a desiccant effect, was poorer than fresh weight for distinguishing the slight phytotoxic effects at the lower doses. Similar findings have been discussed by Merritt & Taylor (1978a). With glyphosate there was little difference between the assessment methods (Figs. 5.6-5.7) and, unless stated, the following results and discussion refer to the fresh weights only.

There was a significant dose response to paraquat on both species. The spinning cup gave a significantly better plant kill than the other nozzles, except for the impact nozzle applying 40 gai/ha on radish, which also gave good plant kill. The fan nozzle consistently produced the least effect.

The results with glyphosate were less clear, and significant dose responses were given only by the spinning cup on radish, and by the spinning cup and the impact nozzle on oats. All treatments caused growth suppression only, except for complete kill of the radish by 40 gai/ha applied by the spinning cup. The spinning cup was significantly better than the other nozzles on radish, but gave similar results to the impact nozzle on oats.

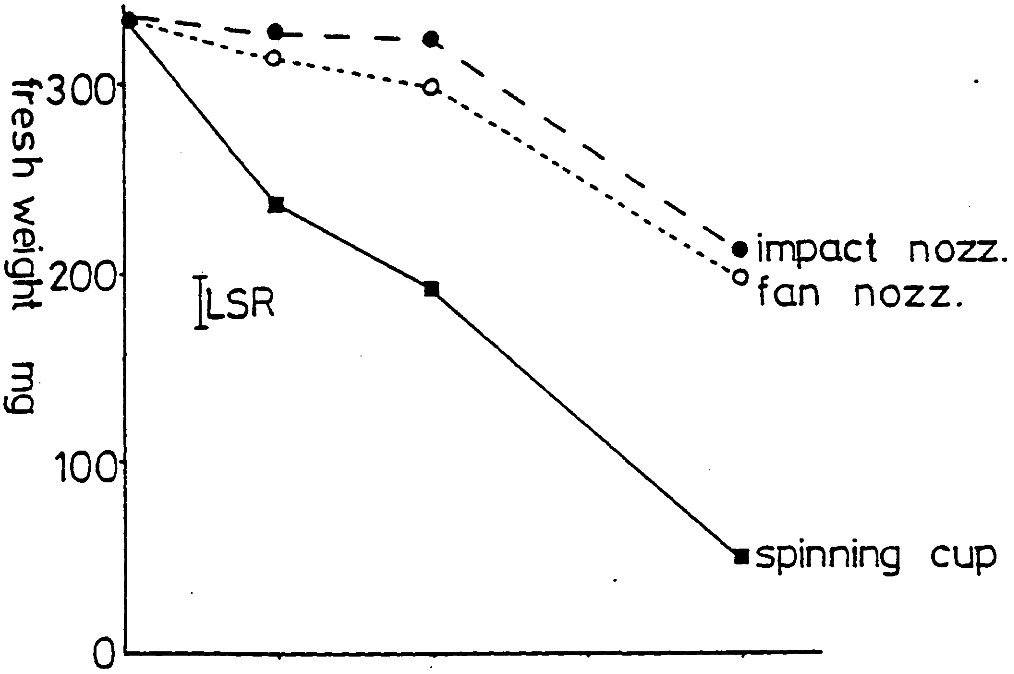
Fresh weights only were used to analyse the results of the 2,4D sprays (Fig. 5.8). The fan jet was not tested in this experiment. The ester formulation of 2,4D gave similar results when sprayed by the spinning cup and the impact nozzle, but the spinning cup had the greater effect with 2,4D amine, although the difference was only significant at 225 or 450 gai/ha. The results from the amine and ester formulations of 2,4D were similar when applied by the spinning cup.

5.1.3. Spray retention

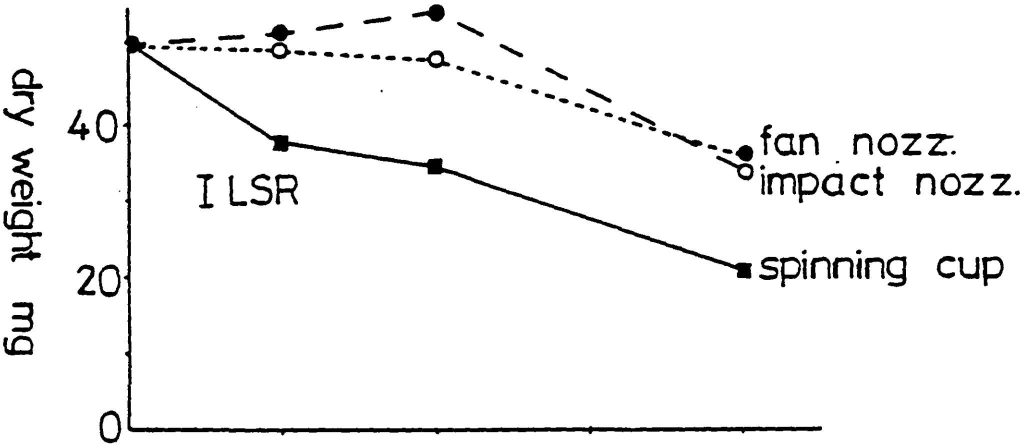
At the same time as the post-emergence herbicides were applied, plants from the same batch were sprayed with a fluorescent dye, so that the retention of spray could be estimated. Oats retained less spray per gram of dry tissue than radish (Fig. 5.9a), and the greatest proportion of the

Fig. 5.3 Dose Response of Oats to Paraquat

a) fresh weight



b) dry weight



c) fresh:dry weight ratio

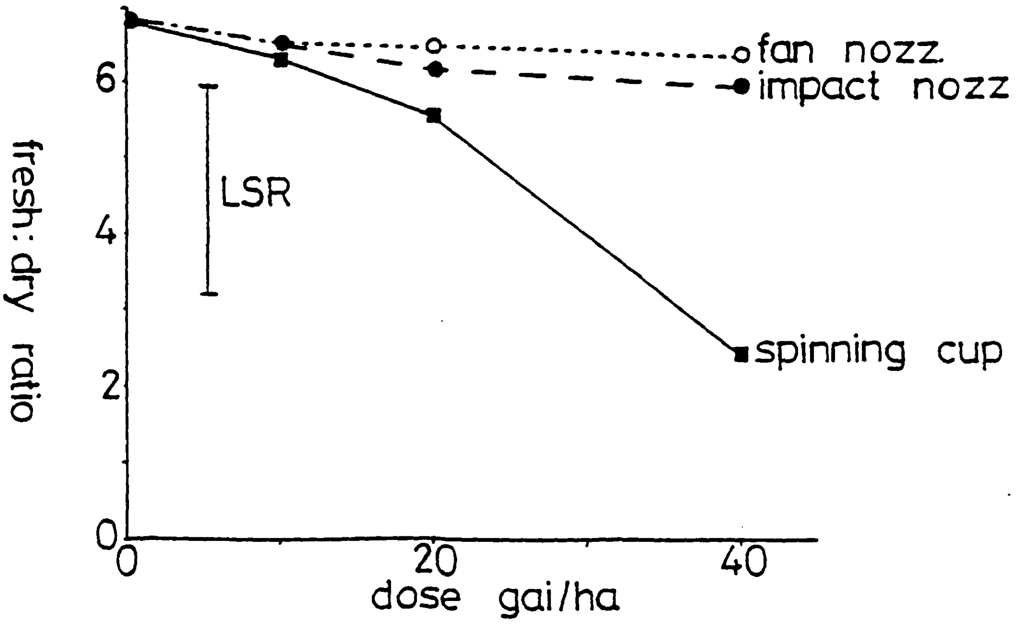
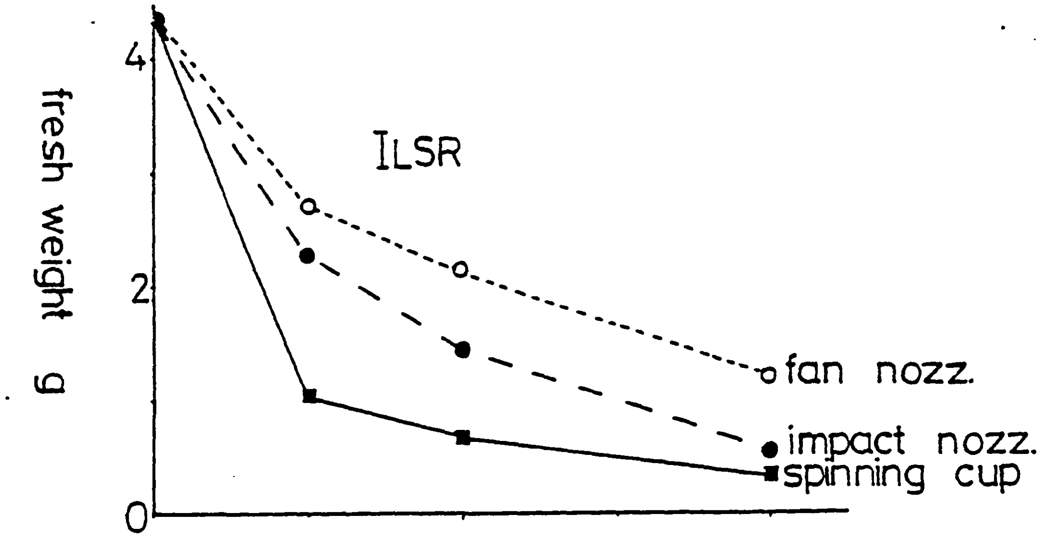
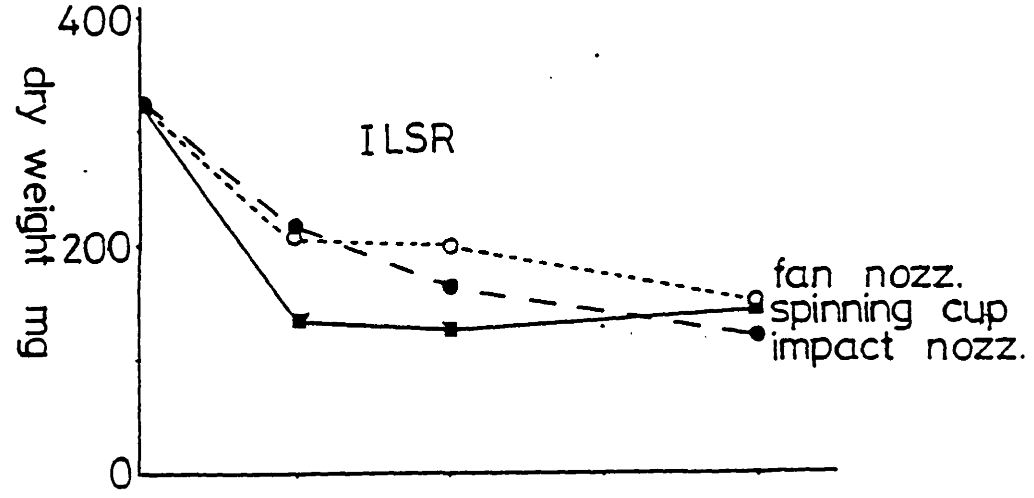


Fig. 5.4 Dose Response of Radish to Paraquat

a) fresh weight



b) dry weight



c) fresh:dry weight ratio

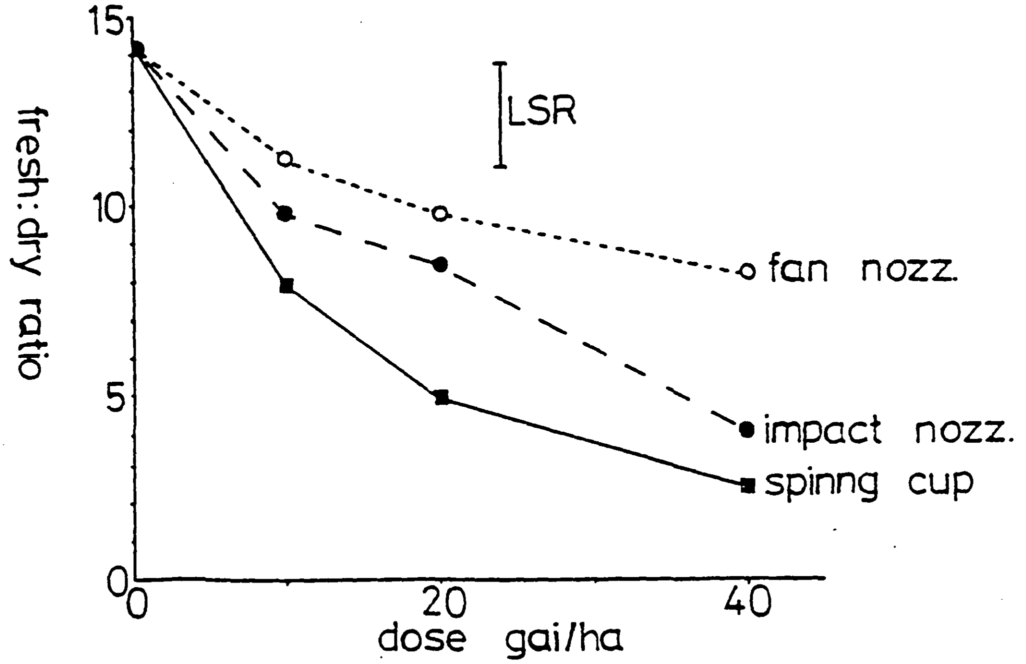


Fig. 5.5 Paraquat Phytotoxicity

a) dose response on radish

b) dose response on oats

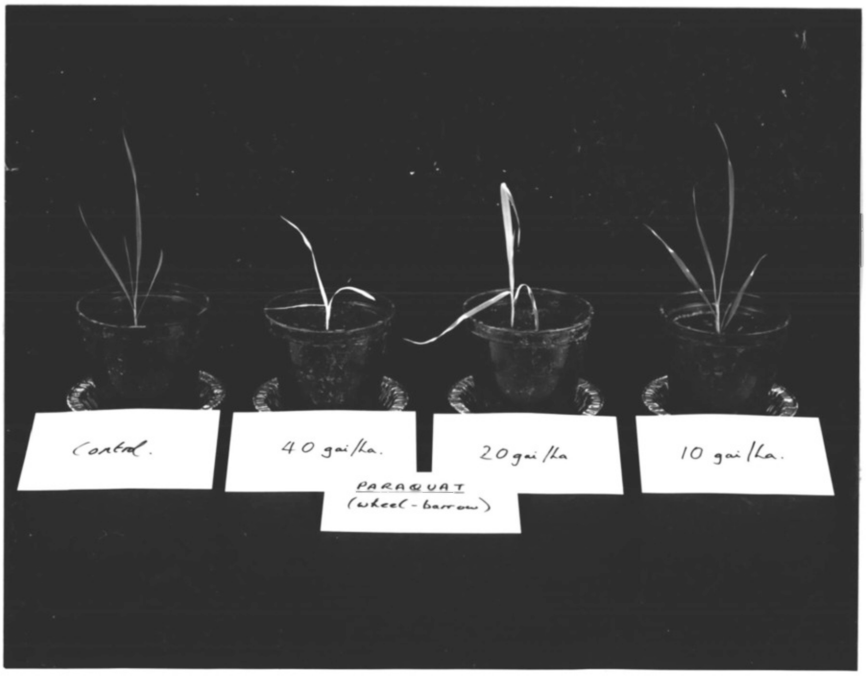
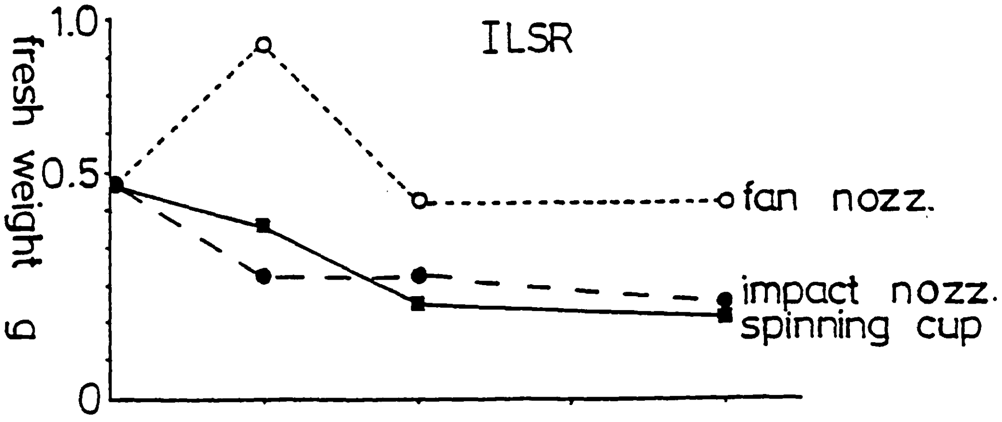
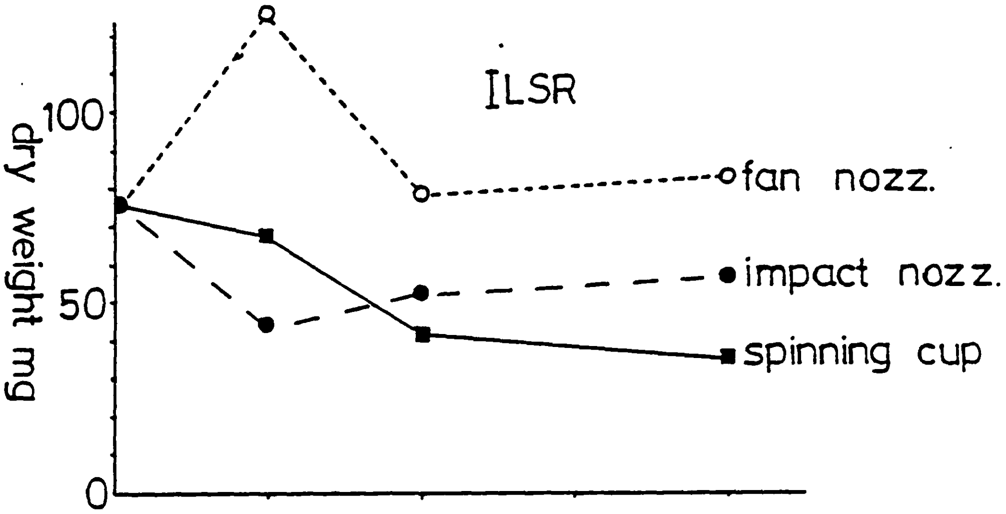


Fig. 5.6 Dose Response of Oats to Glyphosate

a) fresh weight



b) dry weight



c) fresh:dry weight ratio

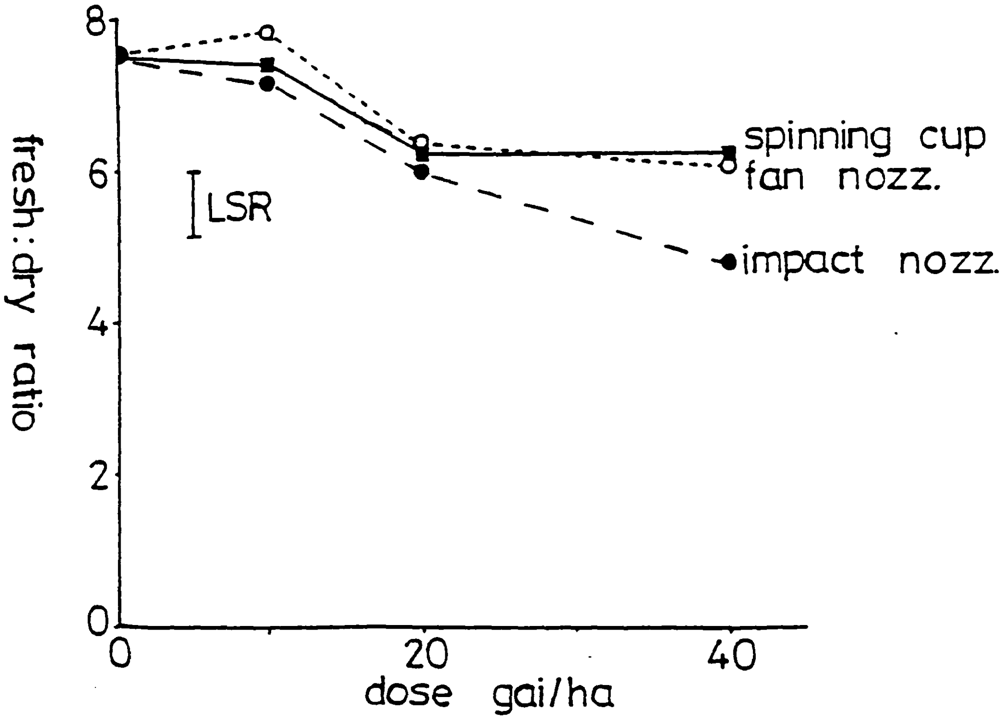
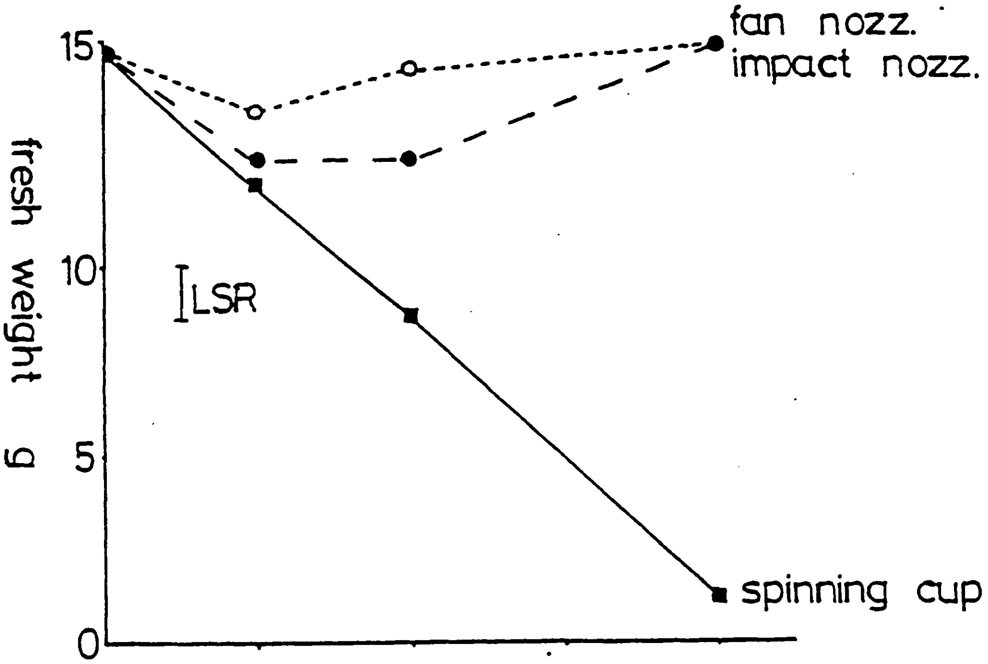
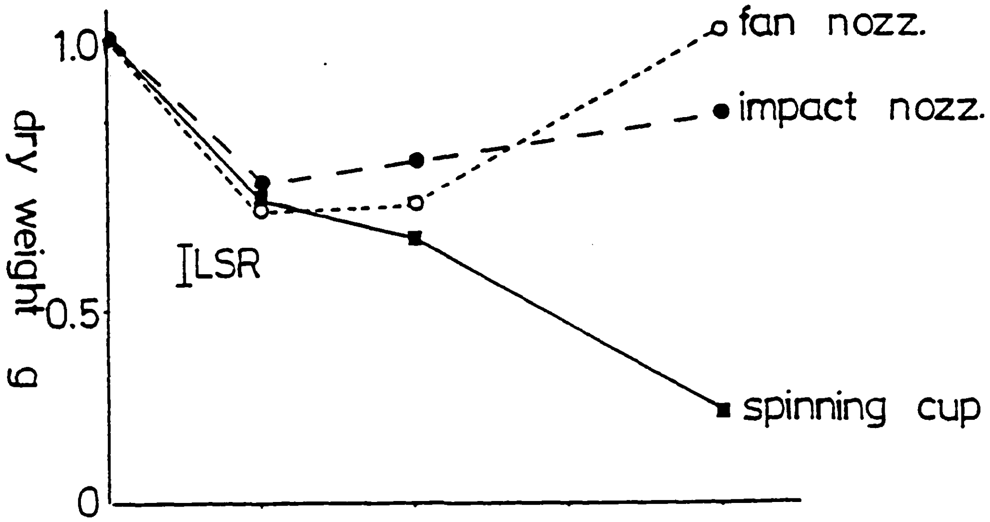


Fig. 5.7 Dose Response of Radish to Glyphosate

a) fresh weight



b) dry weight



c) fresh:dry weight ratio

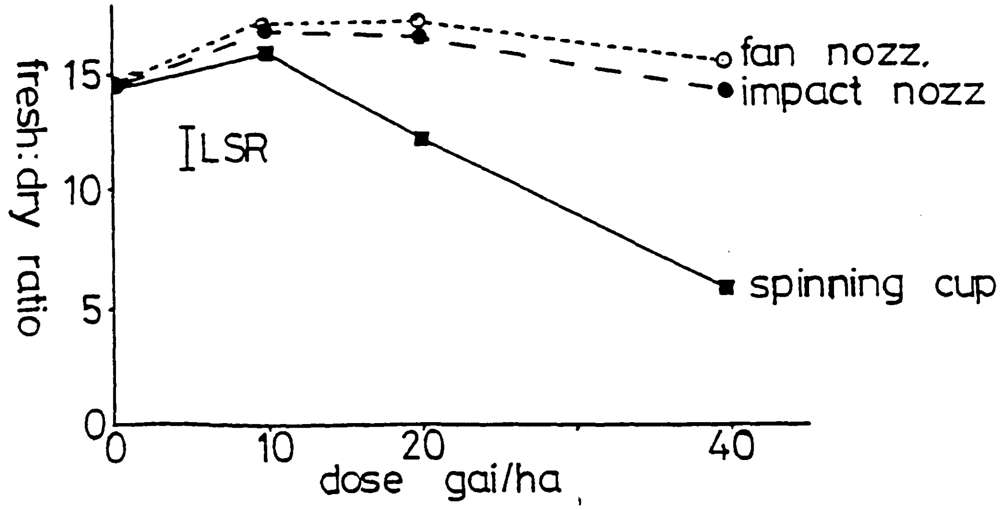
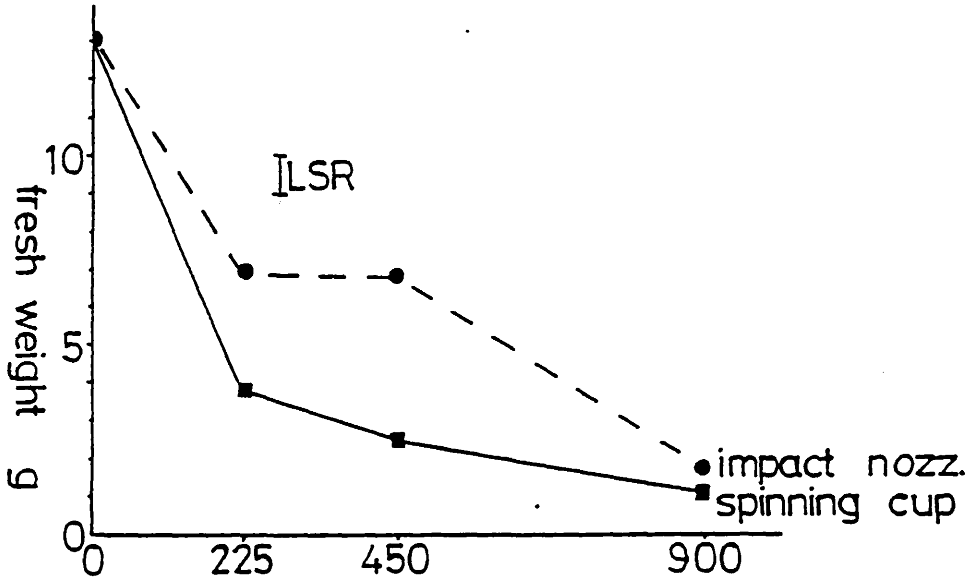


Fig. 5.8 Dose Response of Radish to 2,4D Amine and Ester

a) 2,4D amine



b) 2,4D ester

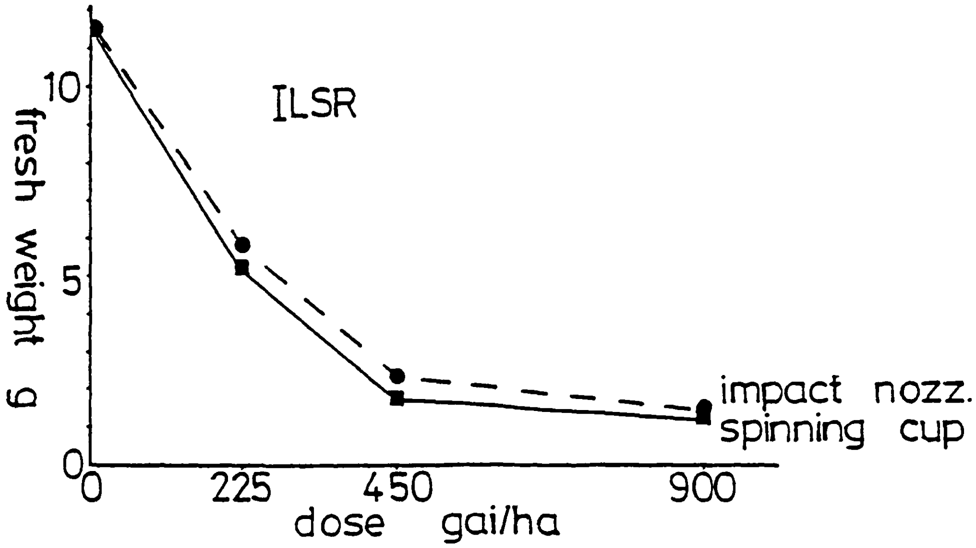
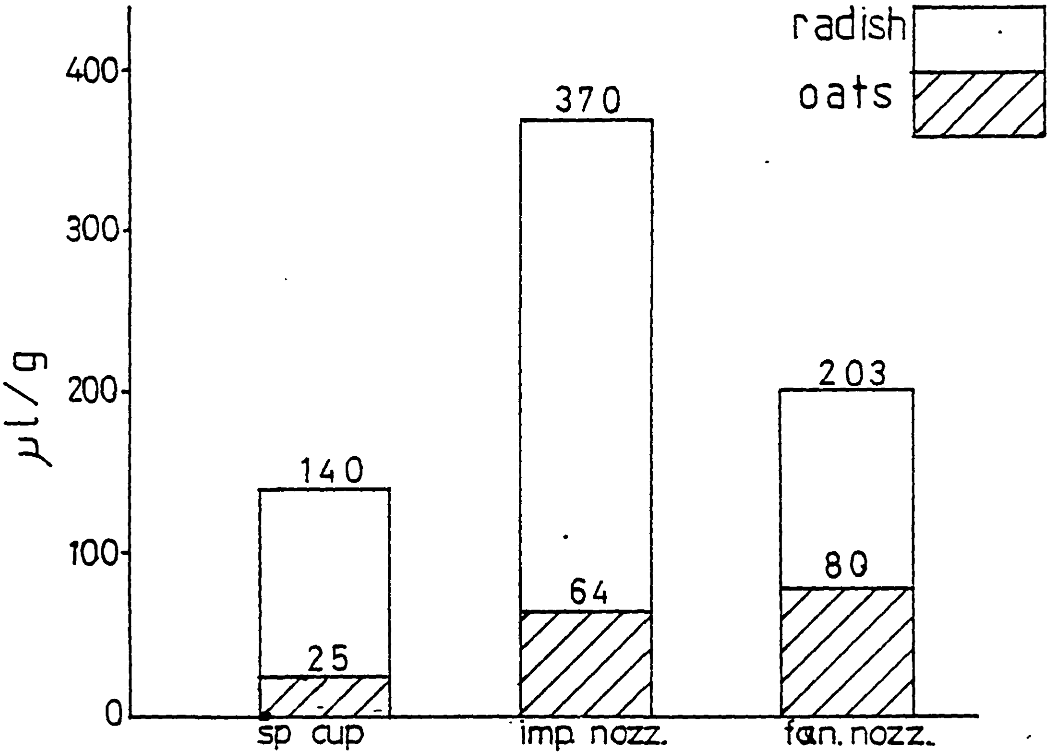
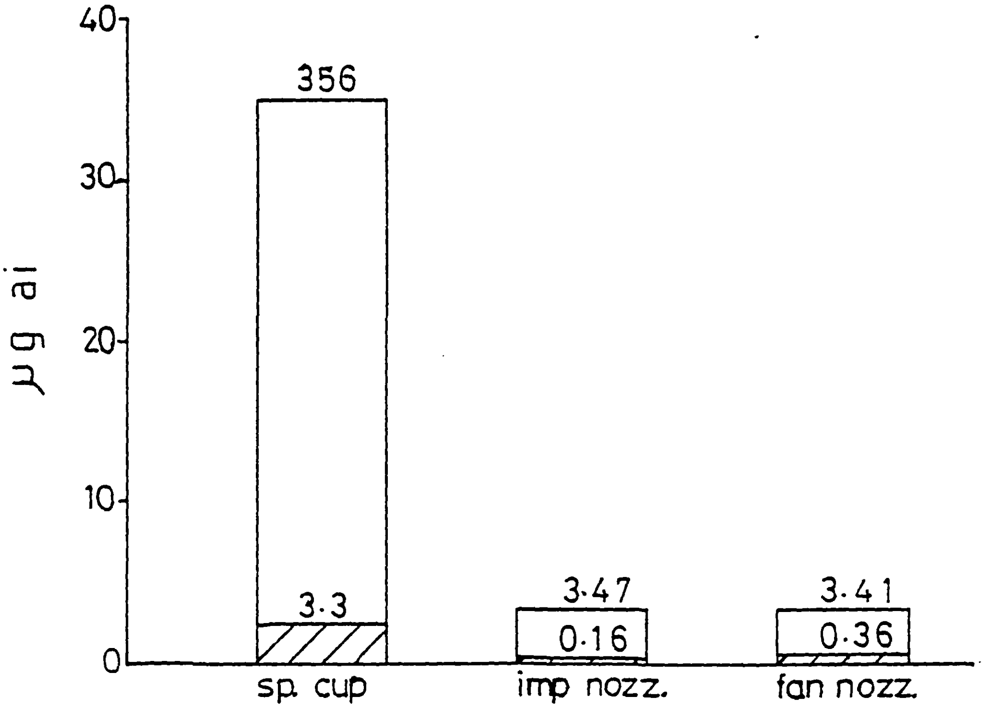


Fig. 5.9 Spray Retention in Paraquat and Glyphosate Experiments

a) µl per g dry weight



b) equivalent active ingredient retained on each plant (900 gai/ha)



spray volume was retained from the spinning cup treatment (Fig. 5.9b). The radish plants used for the 2,4D experiment were larger than those for the paraquat or glyphosate sprays, but retained similar levels of spray per gram of plant tissue from the impact nozzle and less from the spinning cup (Fig. 5.10).

5.1.4. Discussion

The differences between the results using the three sprayers with a range of herbicides (Table 5.2) are due to a complex interaction of spray, herbicide and plant characteristics. While these factors have a relatively small effect on the activity of soil applied herbicides, where results with all sprayers were similar, they are very important in determining the efficacy of foliar acting sprays, the effect of which varied between the sprayers.

i) spray retention

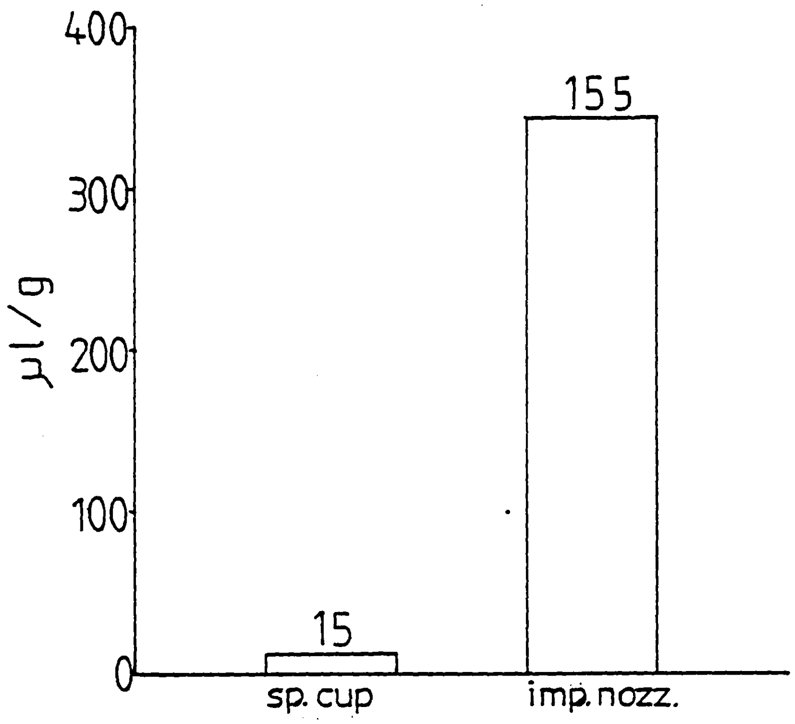
Spray retention is dependent on the characteristics of the spray and the leaf surface, and has been investigated in detail by Brunskill (1956), Blackman *et al* (1958), Holloway (1970) and Merritt (1980). It diminishes with increasing droplet size or more waxy leaf surfaces, and the difference in retention by waxy and less waxy leaved species is greatest with large droplets containing a high concentration of surfactant. However, retention is also affected by the spray volume, and greater proportions of spray are retained at low volumes (Smith, 1946; Blackman *et al*, 1958; Merritt, 1976; Merritt & Taylor, 1978b).

The spray retention on oats in the experiments was similar to that found for similar sized wild oats with conventional sprays (Hibbitt, 1969; Veerasekaran & Catchpole, 1982) and CDA sprays at 200-300 µm (Merritt & Taylor, 1978b). Slightly smaller radishes retained a similar amount of a CDA 250 µm spray, but more of a conventional spray than the larger plants used in the present experiment (Merritt, 1980).

Many of the differences between the sprayers can be explained in terms of spray retention. The oats retained less spray than the radish. This was because the more upright leaves of the oats reduced the angle of incidence of the spray, and their greater waxiness caused a large contact

Fig. 5.10 Spray Retention in 2,4D Experiment (radish)

a) µl spray per g plant dry weight



b) equivalent active ingredient retained on each plant (900 gai/ha)

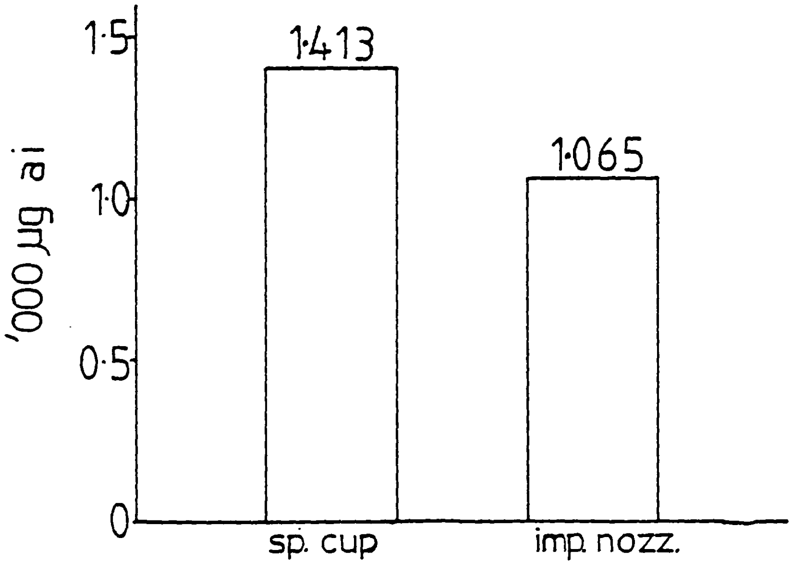


Table 5.2 Summary of Laboratory and Greenhouse Tests

treatment	target dose (gai/ha)	target species	Fresh weight as % of untreated		
			wheelbarrow	impact nozzle	fan nozzle (8001)
glyphosate	40	radish	4	100	100
		oat	38	45	92
paraquat	40	radish	18	29	58
		oat	15	64	60
2,4D ester	900	radish	11	12	-
2,4D amine	900	radish	9	13	-
atrazine	1000	radish	5	3	-
		oat	75	53	
pendimethalin	1000	radish	63	67	-
		oat	87	81	-

angle with the droplets. The greatest amount of spray was retained on the oats from the fan nozzle due to the more efficient retention of the smaller droplets, although it sprayed a lower volume than the impact nozzle (Table 5.3).

Similar results have been found by Lake (1977) and Merritt & Taylor (1978b). As a proportion of the spray volume, the most spray was retained from the spinning cup, because of the improved retention at low spray volumes and the high retention of droplets falling at a low velocity (Lake, 1977), both of which reduce run-off of the spray from the leaf (Merritt, 1980). In contrast, the more horizontal, large, hairy leaves of the radish retained the greatest volume from the impact nozzle, which had a coarser spray than the other nozzles, although the greatest proportion of spray was again caught from the spinning cup. The larger radishes used in the 2,4D experiments, had a lower leaf area (plan view) to weight ratio, so they collected less spray per unit dry weight than the small radishes. The retention of a similar amount of active ingredient by each plant always required a much larger volume of spray to be retained from the hydraulic nozzles than from the spinning cup, due to the different concentration of herbicide in the sprays.

The higher proportion of spray retained from the spinning cup on oats and small radishes compared to other sprays, was illustrated by the significantly greater reduction in plant weight when paraquat or glyphosate was sprayed by the spinning cup. The preferential collection on oats of spray from the fan nozzle compared to the impact nozzle was not, however, reflected in the biological results, in which the fan nozzle was slightly less effective.

The ratio of retention on radish to retention on oats correlated closely with the VMD of each of the sprays, decreasing with smaller droplets, showing their better retention by the oats (Table 5.3.). In the 2,4D experiments, more spray was retained from the fan nozzle than from the spinning cup, although similar amounts of active ingredient were applied to the radishes by both sprayers. This was because of the efficient retention of large droplets by the large, hairy, radish leaves, and was reflected by the similar biological results obtained from the two sprayers.

Table 5.3 Sprayer Characteristics(1) and their Effect on Spray Retention

	Volume (l/ha)	VMD (µm)	VMD/NMD	% Spray in droplets 300 µm by no.,	by vol.	100 µm by no.	by vol.	Differential retention radish:oats(2)
Spinning cup (walking at 1.0 m/s)	10	240	1.7	0.8	9.3	45.3	3.5	15.3
Impact nozzle (100 kPa)	300	281	10	2.8	53.3	76.58	3.9	21.7
Fan nozzle (8001) (200 kPa)	190	161	47	0.1	9.4	94.9	24.6	9.5

(1) from the results in section 4.4.4.

(2) µl spray per gram dry weight radish:
µl spray per gram dry weight oats

Herbicide activity was probably related indirectly to the spray volume and droplet size by their effects on spray retention, rather than by any direct effects. The activity of a number of herbicides has been previously related to droplet size, but the variety of experimental procedures has lead to conflicting results since the effects due to droplet size, spray volume and retention have not always been distinguished. Smith (1946) showed that 2,4D was more effective when applied in large droplets (560 µm) than very small droplets (30 µm), but several authors have shown that activity is improved with smaller droplets, 100 µm giving the best results (Ennis & Williamson, 1963; Hurtt et al, 1969; McKinlay et al, 1972; Vega & Obien, 1963). The increased efficiency of the smaller droplets is probably due to the improved leaf coverage (Behrens, 1957) and more efficient retention, although Mullinson (1953) found that it was the total dose of 2,4D applied to the plant which was important, whether applied as large or small droplets. Richardson (1981) showed that a 2,4D concentration of 10% was better than lower or higher concentrations, but the response to droplet size changed with plant species.

Riepma (1963) and Merritt & Taylor (1978a) found no effect due to droplet size with paraquat, but other authors have shown large droplets, 400-500 µm (Douglas, 1968), or small droplets, 200 µm (Buehring et al, 1973; McKinlay et al, 1974), to be most effective. Glyphosate gave better weed control with a spinning cup producing 240 µm droplets than with 70 µm droplets (Scoresby & Nalewaja, 1981).

ii) other factors

Superimposed on the effects of retention are several complex factors which cannot be analysed unless spray retention is kept constant (Merritt, 1982b).

The high concentration of active ingredient in low volume sprays (<40 l/ha) has reduced the activity of some contact herbicides (Ayres, 1976; Merritt, 1980; Merritt, 1982a) and hormone herbicides (Mullinson, 1953; Richardson, 1982) due to severe local damage to the surface tissues which reduces the net herbicide uptake. Low volume sprays of paraquat may be more active than high volume sprays due to the more rapid penetration of the high concentration of active ingredient into the leaf (McKinlay et al, 1974; Merritt & Taylor, 1978a) but Buehring (1973) suggested low concentrations gave the best results. Glyphosate is also more active at the high concentrations in low volume sprays (Nelson & Becker, 1981; Ambach & Ashford, 1982; Merritt, 1982b).

In practice, a high concentration of herbicide will be associated with a high concentration of surfactant, which also affects herbicide performance (Holly, 1964; Smith et al, 1966). High surfactant concentrations improve glyphosate activity (Sandberg et al, 1978; Jordan, 1981) but do not affect that of paraquat or MCPA (Merritt, 1982b), although surfactants differentially affect the uptake and movement of paraquat in the plant (Bland & Brian, 1975). The herbicide and surfactant concentrations were much higher in these experiments than in the paraquat and glyphosate sprays in the present work, and are unlikely to explain any of the differences in results between the sprayers.

The position on the plant at which the spray is retained may affect herbicide activity. The hairs on the leaves may prevent droplets from contacting the leaf surface (Holly, 1964). This could explain the poor results on radish with the fan nozzle, since the small droplets could have been caught by the hairs on the leaves leading to give good spray retention but poor herbicide uptake in comparison to larger droplets, which would have penetrated the layer of hairs to contact the leaf surface.

The low spray volume from the spinning cup, combined with the low momentum of the droplets ensures that most droplets remain where they land, whereas liquid from the impact nozzle spray could be observed to collect on the radish leaf veins. This could account for the better response to paraquat than to glyphosate using the impact nozzle compared to the spinning cup, since paraquat is most active when applied to leaf veins, while glyphosate is most active when applied to the lamina between the veins (Merritt, 1982b).

5.2. Outdoor Tray Experiments

Winter wheat was grown in trays to provide a length of uniform vegetation on which the biological effects of spray pulsing could be investigated.

5.2.1. Results

The application of 0.1 kgai/ha of paraquat caused only slight phytotoxicity, and there was little variation along the swath in the fresh weights or chlorophyll extracts from the plants (Fig. 5.11). Analysis of the data by TTLV revealed no pattern in the fresh weight data, but indicated some pattern in the chlorophyll data from both the broadcast and directed sprays (Table 5.4.). The scale of pattern was 0.32 m using a horizontal sprayer, slightly greater than the 0.25 m expected from the four pulses per metre produced by the paired Glen Creston pumps.

A higher dose of paraquat (0.15 kgai/ha) had a greater effect on the plants. There was no significant difference between the three walking speeds with the wheelbarrow sprayer and the "Herbi" hand-held spinning disc sprayer (Fig. 5.12), but the wheelbarrow sprayer at 1.0 m/s gave a significantly greater effect than the knapsack sprayer. All the wheelbarrow results showed a marked pattern at a scale of 0.2 to 0.24 m (Fig. 5.13) and the "Herbi" and knapsack sprayer showed a marked pattern at 0.27 m and 0.12 m respectively.

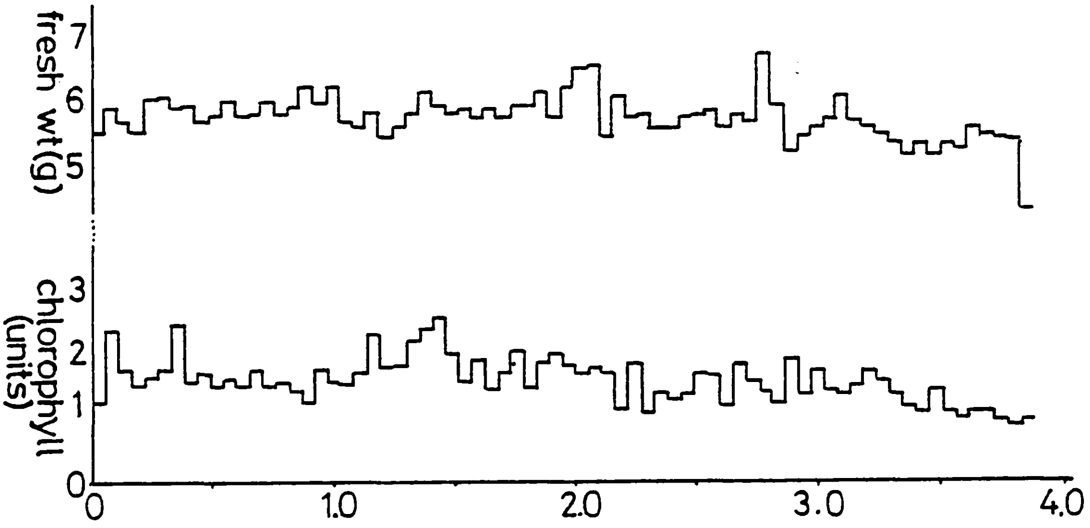
5.2.2. Discussion

There is good evidence that, when using a very low dose of paraquat, the effect of the pulsing of the spray from the wheelbarrow sprayer is reflected in the phytotoxic effects, although these differences could not be seen on the vegetation. The variation along the wheelbarrow swath was not increased by angling the sprayer, as expected from the emphasised pattern shown by fluorescent tracers in section 4.6.2., suggesting that the difference is not significant. Recommended doses of paraquat (0.3 to 1.0 kgai/ha) are unlikely to show visible evidence of pulsing except under difficult conditions. The hand-held spinning disc sprayer and the knapsack sprayer also caused variations along the swath which may have been due to the movement of the sprayer lance as the operator walked, or the action of pumping the knapsack sprayer.

TTLV appears to be a useful theoretical tool to define pattern in sprayed vegetation, but the levels of pattern

Fig. 5.11 Variation in Effect of Paraquat on Winter Wheat Along the Spray Swath, Assessed by Two Methods

a) spinning cup horizontal



b) spinning cup angled at 45°

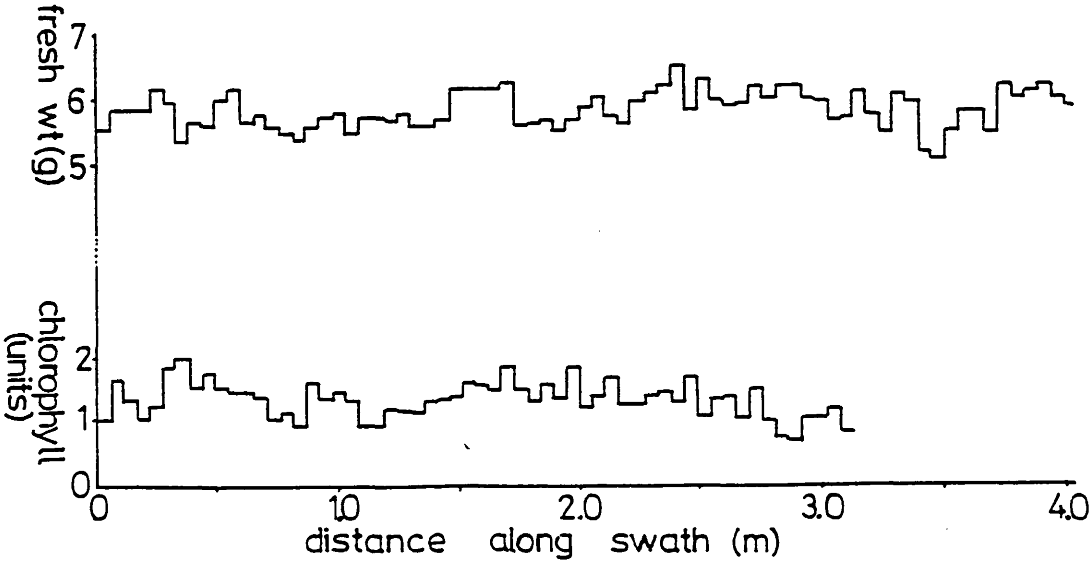


Table 5.4 Effect of Spray Pulsing on the Biological Efficacy of Paraquat (100 gai/ha)

	wheelbarrow (horiz.)	wheelbarrow (angled)	untreated
Fresh Weight:			
g	5.66	5.80	6.01
cv (%)	7	5	7
pattern intensity	0.002	0.003	-
block size (m)	0.20	0.17	-
Chlorophyll Content:			
chlorophyll	1.57	1.83	2.52
cv (%)	23	21	15
pattern intensity	0.177	0.114	-
block size (m)	0.32	0.27	-

Fig. 5.12 Effect of Walking Speed on Paraquat Activity (150 gai/ha)

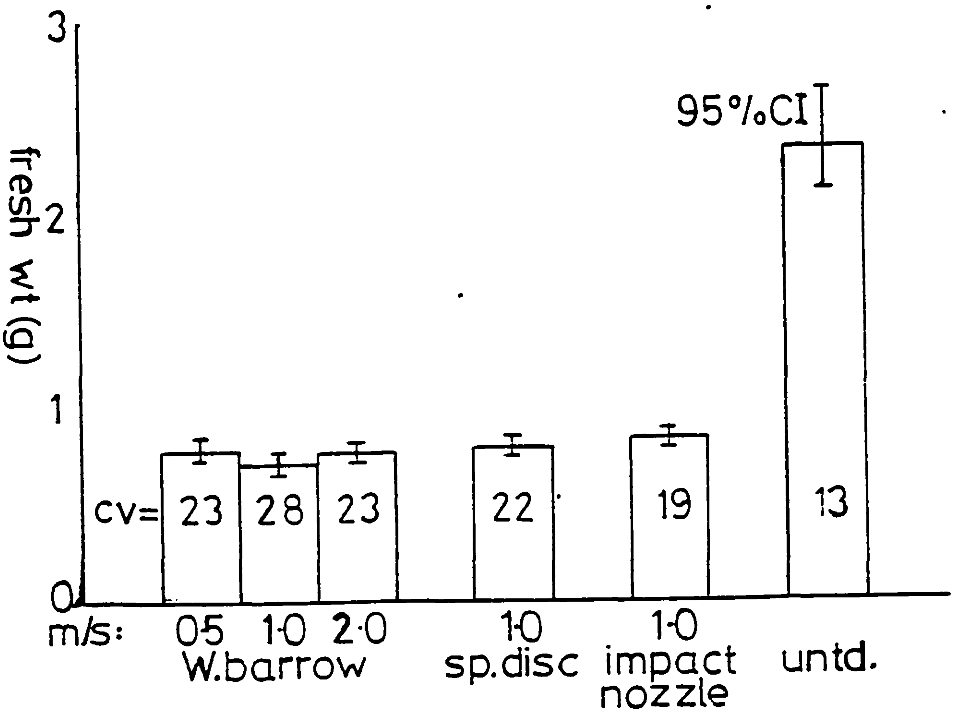
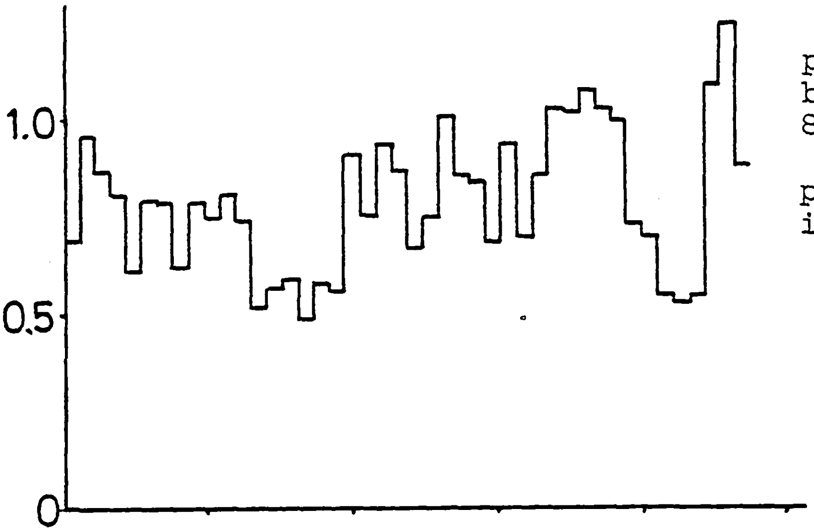


Fig. 5.13 Variation in Effect of Paraquat Along Spray Swath

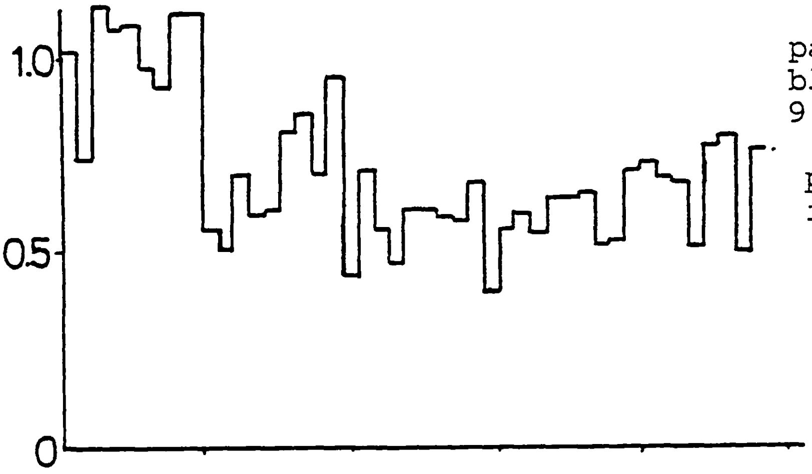
a) spinning cup 0.5 m/s



pattern at
block size
8 = 0. 20 m

pattern
intensity
= 1.22

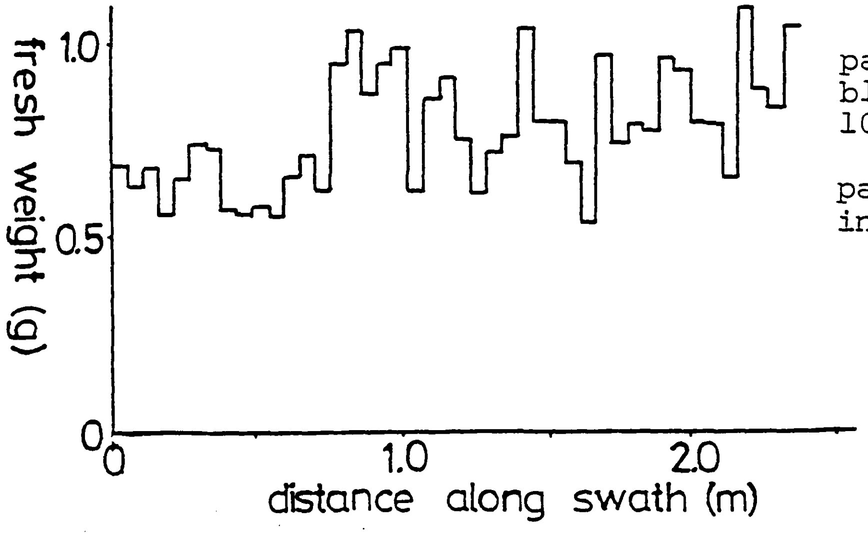
b) spinning cup 1.0 m/s



pattern at
block size
9 = 0.22 m

pattern
intensity
= 1.33

c) spinning cup 2.0 m/s

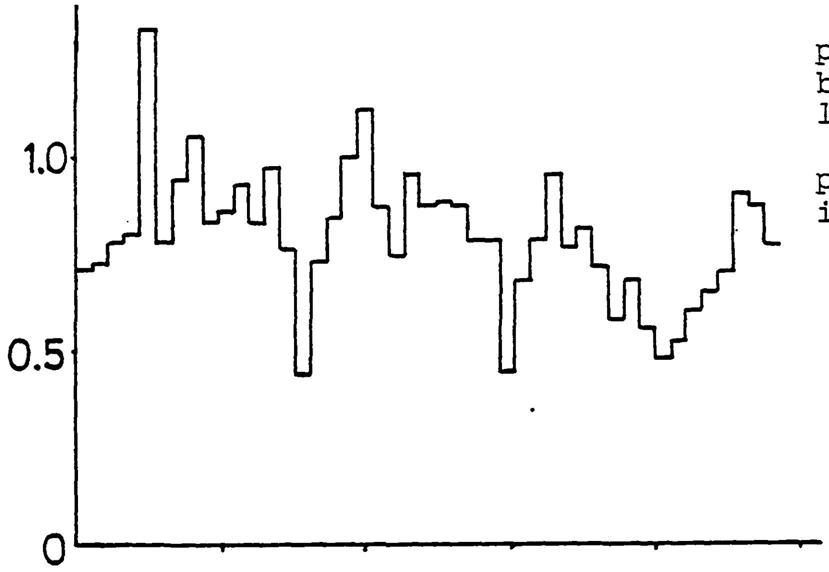


pattern at
block size
10 = 0.24 m

pattern
intensity
= 1.30

Fig. 5.13 cont.

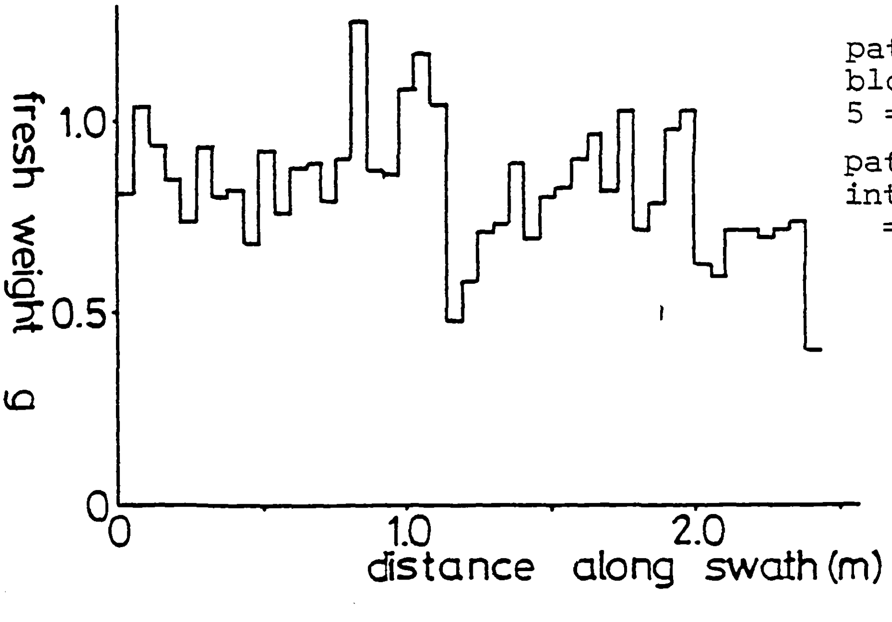
d) hand-held spinning disc 1.0 m/s



pattern at
block size
11 = 0.27 m

pattern
intensity
= 1.22

e) impact nozzle (knapsack) 1.0 m/s



pattern at
block size
5 = 0.12 m

pattern
intensity
= 1.16

discovered in these experiments are probably not of practical significance to controlling weeds. Only when the differences become visible to the eye are they likely to be of importance. Analysis of the spray pattern along the swath would have allowed correlation between the distribution and biological effect. A dye would have to be added to the spray solution since paraquat is absorbed on chromatography paper. The fluorescein used in previous experiments has its emission peak of 514 nm, close to that of paraquat (510 nm), and a dye such as 7-hydroxy-4-methylcoumarin, with an emission peak of 600 nm, would be more suitable (Sharp, 1976).

There was no difference between the effect of the paraquat sprayed at different walking speeds, although these resulted in changes in droplet size. At 0.58 m/s the VMD is 425 µm, falling to 205 µm at 1.45 m/s. Such a difference has given a significant increase in paraquat activity when applied to wheat by a spinning cup (Heijne, 1981).

5.3. Field Trials in the U.K.

5.3.1. Ground spray patterns

Trials were carried out to test for the occurrence of poor weed control attributable to the pulsing of the spray from the wheelbarrow sprayer, and to ensure that swath matching was satisfactory.

i) preliminary experiment (first prototype sprayer)

Both the wheelbarrow and the knapsack sprayers gave good overall weed control using cyanazine + MCPB (1.05 + 0.691 kgai/ha)(Table 5.5). The wheelbarrow gave slightly better control of Chenopodium album than the knapsack sprayer, but Spergula arvensis and volunteer rape were well controlled by both sprayers. The small, waxy cotyledons and leaves of C. album were probably less well covered by the larger droplets of the knapsack sprayer, than by the smaller droplets of the wheelbarrow sprayer. The half rate cyanazine + MCPB gave good control of S. arvensis and volunteer rape only, but the quarter dose caused only transient burning of the weeds.

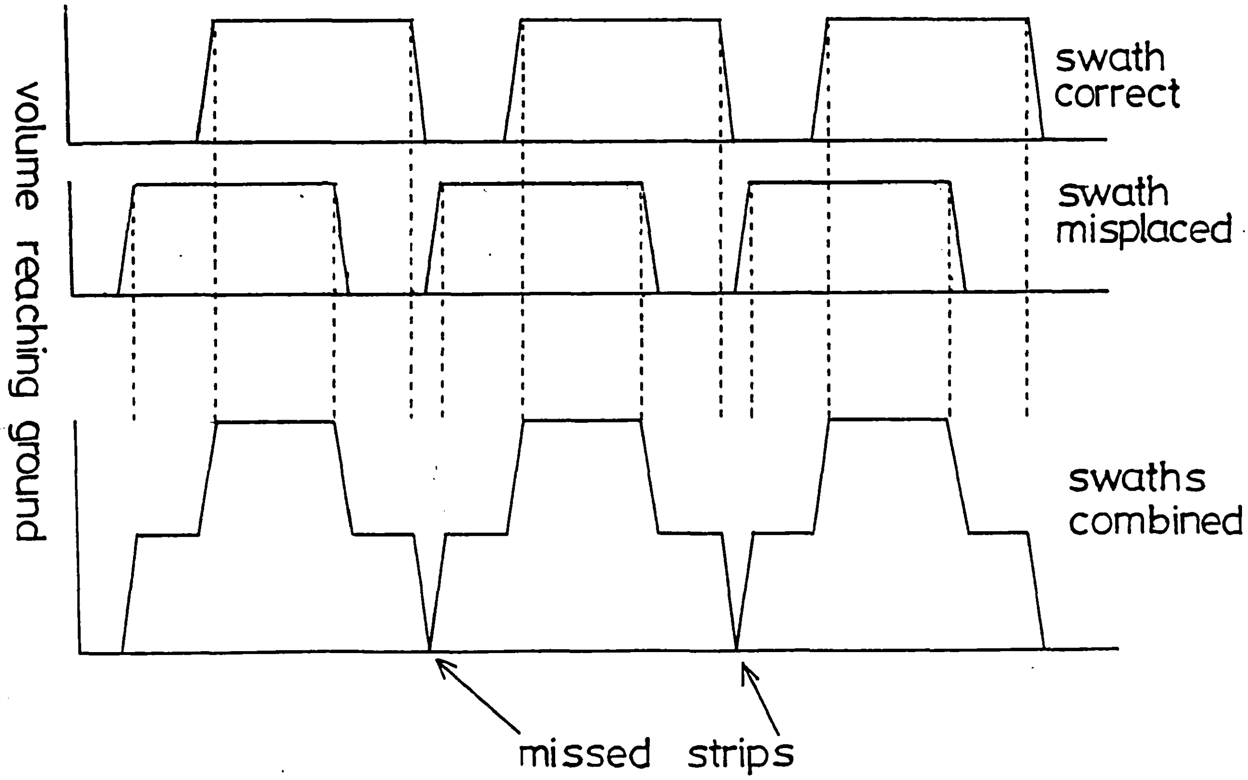
Although there was no evidence of spray pulsing affecting weed control, there were strips of poor weed control illustrating poor swath matching. Laboratory tests on the

Table 5.5 Preliminary Experiment : Weed Control in Peas with Cyanazine + MCPB

Treatment (kgai/ha)	Sperg. arvensis		vol. rape		Cheno. album	
	% Control					
	5•	25•	5•	25•	5•	25•
wheelbarrow:						
1.05 + 0.691	100	98	95	100	70	100
0.525 + 0.345	100	95	100	100	50	70
0.263 + 0.173	40	0	20	0	20	0
knapsack:						
1.05 + 0.691	100	98	100	100	70	90
untreated	0	0	0	0	0	0

• 5 = % burning 5 days after treatment (visual assess.)
•25 = % control 25 days after treatment " "

Fig. 5.14 Cause of Missed Strips with the Wheelbarrow Sprayer



wheelbarrow spray pattern later showed that the swath was not equal either side of the sprayer, which left an underdosed strip (Fig. 5.14). The swaths of the knapsack sprayer were not overlapped and the low volume of spray at the edges of the swath resulted in underdosing.

ii) pre-emergence herbicide

Cyanazine was applied pre-emergence of the crop at half the recommended dose (0.525 kgai/ha), using a knapsack sprayer or the second prototype of the wheelbarrow sprayer, which had been adjusted to improve swath matching. Almost complete weed control was given and only visual assessments were made. Both sprayers left a few narrow strips of weeds where swaths had not been matched, resulting in underdosing, and illustrating the difficulty of walking straight when spraying. These weeds would probably have been killed if a full dose of herbicide had been applied in the main swath. There was no evidence of pulsing except for one narrow band of weeds across one wheelbarrow sprayer swath.

iii) post-emergence herbicide

A half dose of cyanazine (0.525 kgai/ha) was applied by a wheelbarrow sprayer or a knapsack sprayer to a uniform stand of _Spergula arvensis_. At 20 days after treatment, weeds were harvested from transects made along and across the swaths, and the fresh and dry weights of samples from each quadrat were measured. The results were analysed graphically and using TTLV (Fig. 5.15; 5.16; Table 5.6).

The knapsack sprayer gave slightly better weed control at the centre of its swath than at the swath edges, where it was poorer than the wheelbarrow sprayer, which gave uniform weed control. There were a number of peaks in the weight of weeds sampled along the wheelbarrow sprayer swath, averaging a 0.6 m repetition in both transects. TTLV analysis showed a pattern at 1.3 m in one transect and 0.6 m in the other. There was greater variation along the swath of the knapsack sprayer but any possible pattern was at a scale too large to analyse by TTLV with this number of samples. Most of the peaks in plant weight could be correlated visually with lower droplet densities on sampling papers laid adjacent to the transects, but the spray volume along the swaths had not been measured to allow a covariance analysis with the plant weights.

Fig. 5.15 Patterns in Dry Weight of Vegetation Harvested Along the Swath

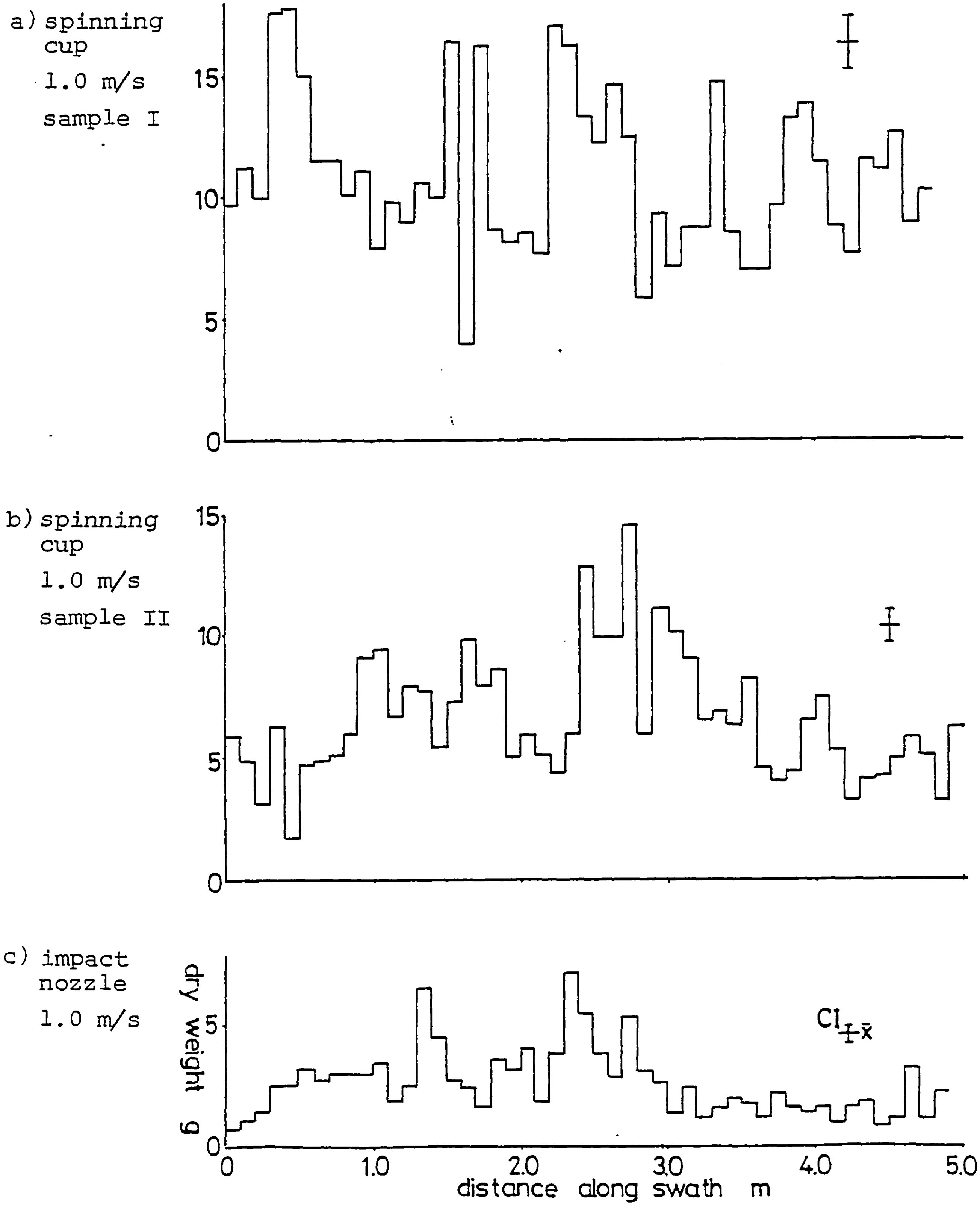
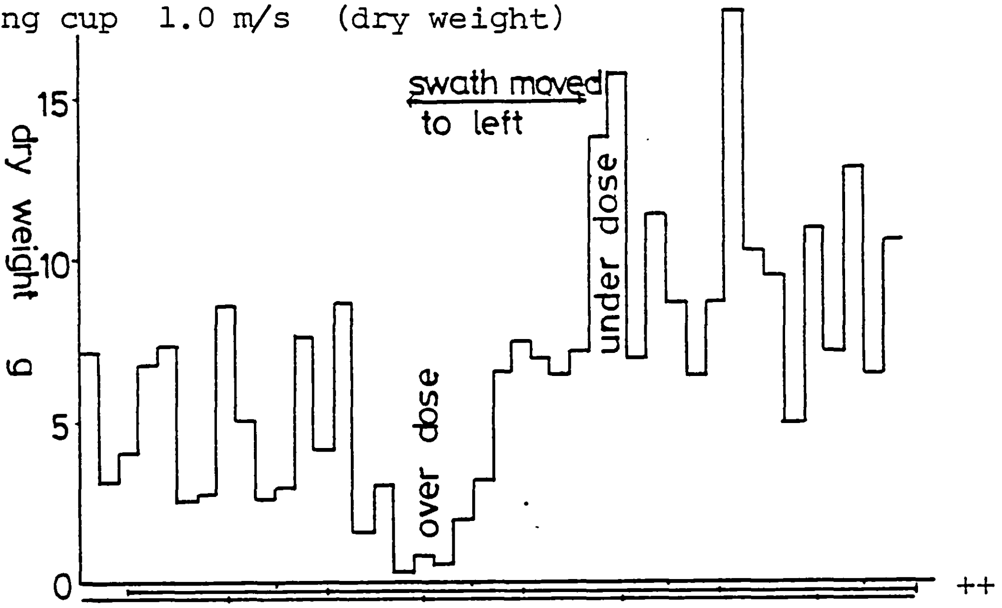
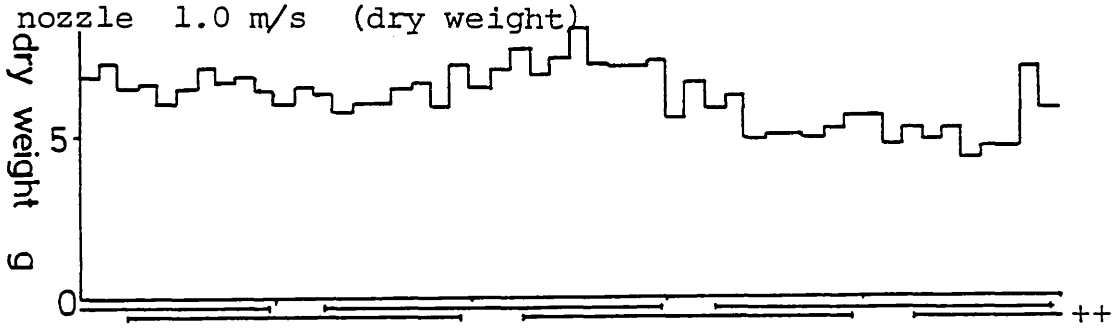


Fig. 5.16 Patterns in Vegetation Harvested Across Several Swaths

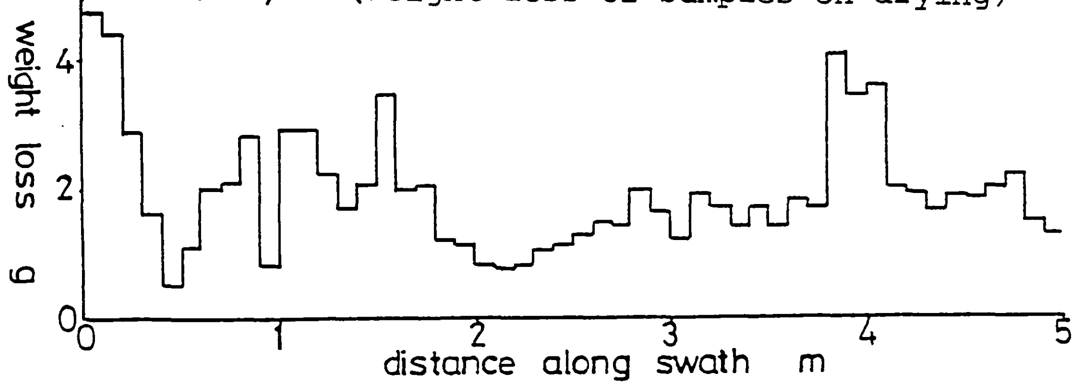
a) spinning cup 1.0 m/s (dry weight)



b) impact nozzle 1.0 m/s (dry weight)



c) impact nozzle 1.0 m/s (weight loss of samples on drying)



++ theoretical positions of swaths

Table 5.6 Swath Pattern Analysis

sprayer	transect	mean dry wt. per quadrat (g)	cv	two-term local variance analysis[+++]	
				peak pattern intensity	block size (m)
wheelbarrow	along swath[+]	10.9	30	0.72	1.3
	along swath[++]	6.6	39	0.15	0.6
	across swath	6.6	61	none	none
knapsack	along swath[++]	2.5	53	2.8	2.0
	across swath	6.4	10	0.74	1.4
untreated		15.7	22	none	none

[+] taken along a length with poor weed control

[++] " " " " " good " "

[+++] see Appendix 11

The result of moving one wheelbarrow sprayer swath to the left of its target course can clearly be seen from the transect across the swaths (Fig. 5.16), which shows areas of under and over dosing. The great variability across all the swaths appears to be due to slightly poorer plant kill on each wheeling, i.e. where alternate swaths meet (Fig. 3.3). The very large overlaps of the knapsack swaths gave a uniform kill of plants across the swaths (Fig. 5.16), although analysis using weight losses highlighted areas of possible under and over dosing, which may correlate with the movement of the swath to the left.

iv) discussion

The cyanazine performed well, even at reduced doses, reflecting the great susceptibility of the weed species (Chapman et al, 1968). However, where spray swaths were poorly matched the resulting dose, one quarter of that recommended, was not sufficient to kill the weeds, and this could be used to observe poor spray distributions in the field.

With the wheelbarrow sprayer shroud adjusted to achieve a 100% swath overlap, the edges of the swaths did not appear to give a full dose of herbicide, although the results of the patternator work suggested that they should (section 4.5). However, this underdosing is slight and not significant compared to incorrect swath matching. There was little evidence of any effects due to the pulsing of the spray, but the results were inconclusive and the effects were less obvious than in the tray experiments (section 5.2). In rough field conditions the exact position of the stream of liquid fed onto the cup is likely to vary, which will cause extra variation in the ground deposit.

The wheelbarrow sprayer produced a more uniform kill along the swath than the knapsack sprayer, but was less uniform across the swaths. Variability along the knapsack sprayer swath was attributed to the variation in spray pressure when pumping, and to changes in the height of the nozzle when the lance moves with the operator walking.

5.3.2. Penetration of the spray into the weed canopy

Spray droplets were counted on the whorls of Spergula arvensis which had been sprayed with cyanazine in the previous experiments. Most droplets from the wheelbarrow sprayer were caught on the top whorls, while the middle whorls retained the most droplets from the knapsack sprayer (Fig. 5.17). The differences between the results of the two experiments reflect the much denser canopy in experiment 1.

The results suggest a more complex situation than that described by Bache (1980), in which the capture of droplets in excess of 150 µm was determined almost entirely by the canopy structure of the vegetation, rather than by foliage dimensions. In comparison to the wheelbarrow sprayer, the impact nozzle on the knapsack produces a large proportion of droplets over 300 µm (Table 5.3) and these have a high velocity because they are produced under pressure. Such droplets hitting the top whorl of the S.arvensis are likely to bounce or flow off its narrow waxy leaves (Brunskill, 1956) either on to lower leaves or through the canopy to the ground. This was illustrated by the lower total number of droplets counted from the knapsack spray despite its higher volume. In contrast, the wheelbarrow droplets are filtered out by the top whorls.

In dense vegetation canopies, species which are at the bottom of the canopy are less likely to be reached by droplets falling under gravity (Ayres, 1978a; Anon 1979b). This emphasizes the need for early herbicide application, before the weeds are large enough to shade each other, and when they are most susceptible to the herbicide.

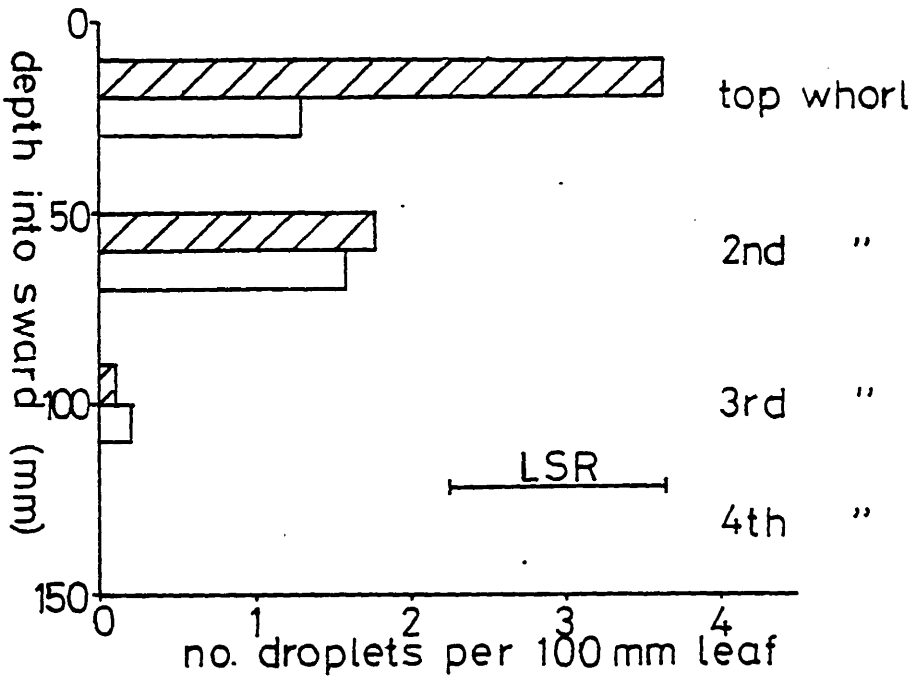
5.3.3. Spraying a ridge crop

A formulated mixture containing equal amounts of trietazine and linuron was sprayed pre-emergence in a ridged crop of potatoes, using the wheelbarrow sprayer and a knapsack sprayer fitted with an impact nozzle. No strips of poor weed control could be observed, so swath matching was assumed to be correct.

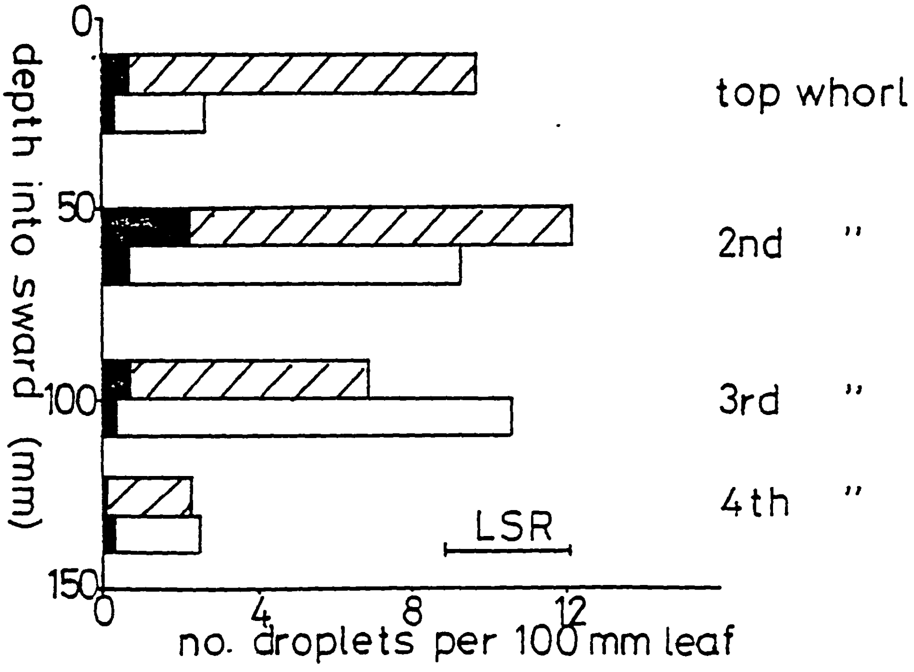
All treatments significantly reduced the weed population compared to the untreated (Fig. 5.18), but there was no significant difference between the sprayers or the doses, except on Polygonum persicaria (Appendix 13), the species least susceptible to the herbicide. Using the wheelbarrow

Fig. 5.17 Spray Penetration into *Spergula arvensis* Sward

a) experiment 1



b) experiment 2



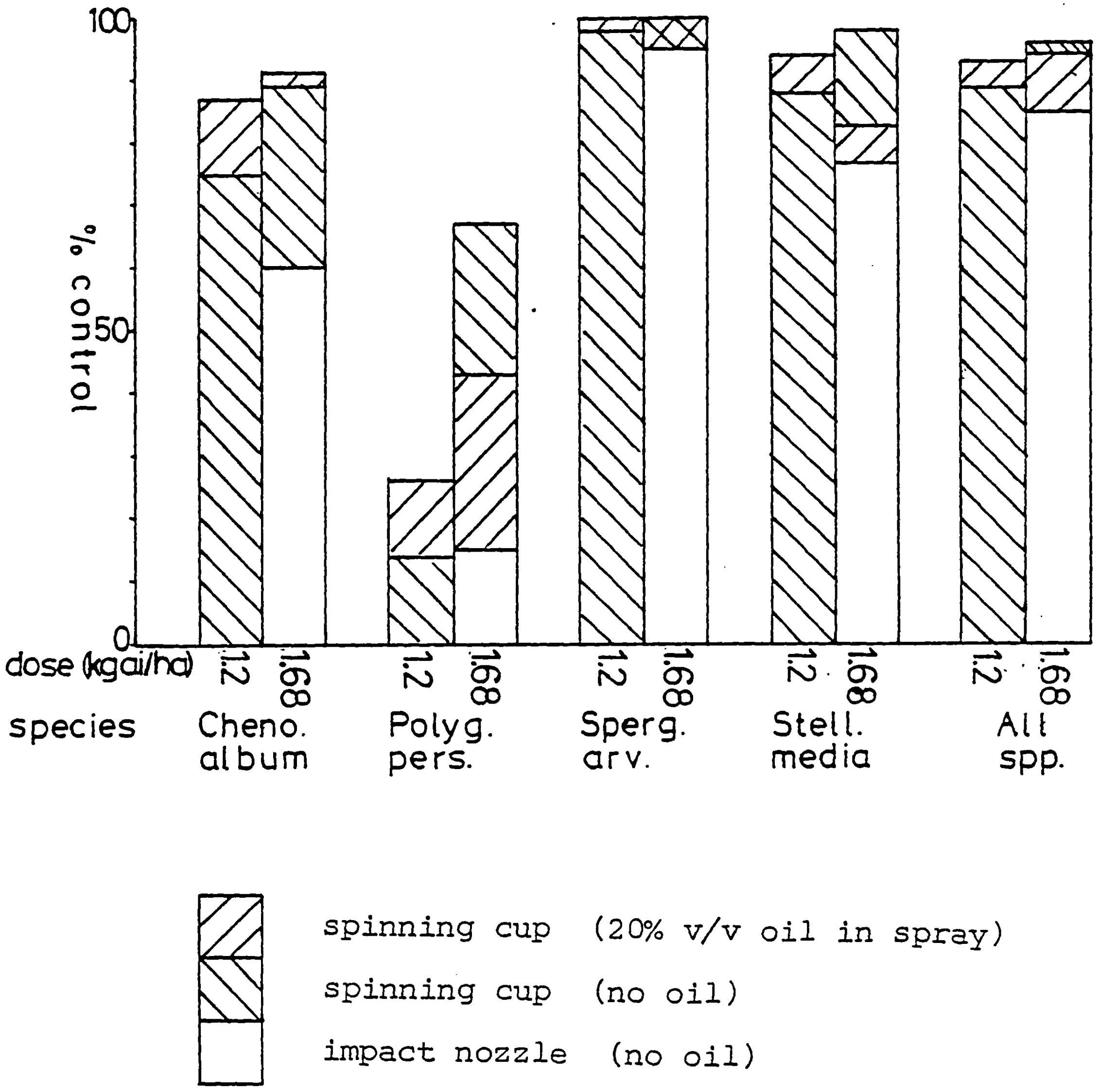
■ No. on lower surface

▨ spinning cup

☐ impact nozzle

Fig. 5.18 Weed Control with Trietazine + Linuron in Potatoes

(significance of differences in Appendix 13)



sprayer, 1.68 kgai/ha of the herbicide mixture controlled P.persicaria, significantly reducing the population compared to 1.20 kgai/ha, but the knapsack sprayer, applying 1.68 kgai/ha, always gave the poorest weed control.

The remainder of the trial field was inter-row cultivated, which left weeds in the crop ridges (Fig. 5.19a). The effect on the crop of the severe competition by the weeds could be seen when the untreated plots were hand-weeded towards the end of the growing season (Fig. 5.19b).

The weed control corresponded to the herbicide manufacturers' recommendations, except that P.persicaria was less well controlled than expected. The addition of a mineral oil to the spray solution may have slightly increased the activity of the herbicide by preventing it from drying out. This would have improved its availability for uptake by germinating weeds during the very dry weather prevailing at the time of the trial. Oil adjuvants have been used commercially to improve the activity of soil acting herbicides by reducing volatilisation, photodecomposition, adsorption and leaching (Anon, 1983d; Barnett, 1983).

5.3.4. Continuation of a preliminary field trial

Following the application of low doses of paraquat and glyphosate to a Holcus mollis sward using the wheelbarrow sprayer at 12.5 l/ha, assessments were made to determine their short term effects (Garnett, 1978). When assessed two weeks after spraying, differences in phytotoxicity were apparent between treatments applied in the morning, afternoon or evening. Paraquat gave the best results when sprayed in the evening, while glyphosate gave better results when applied in the morning or afternoon than in the evening. At least 100 gai/ha of paraquat or 180 gai/ha of glyphosate were required to give acceptable weed control.

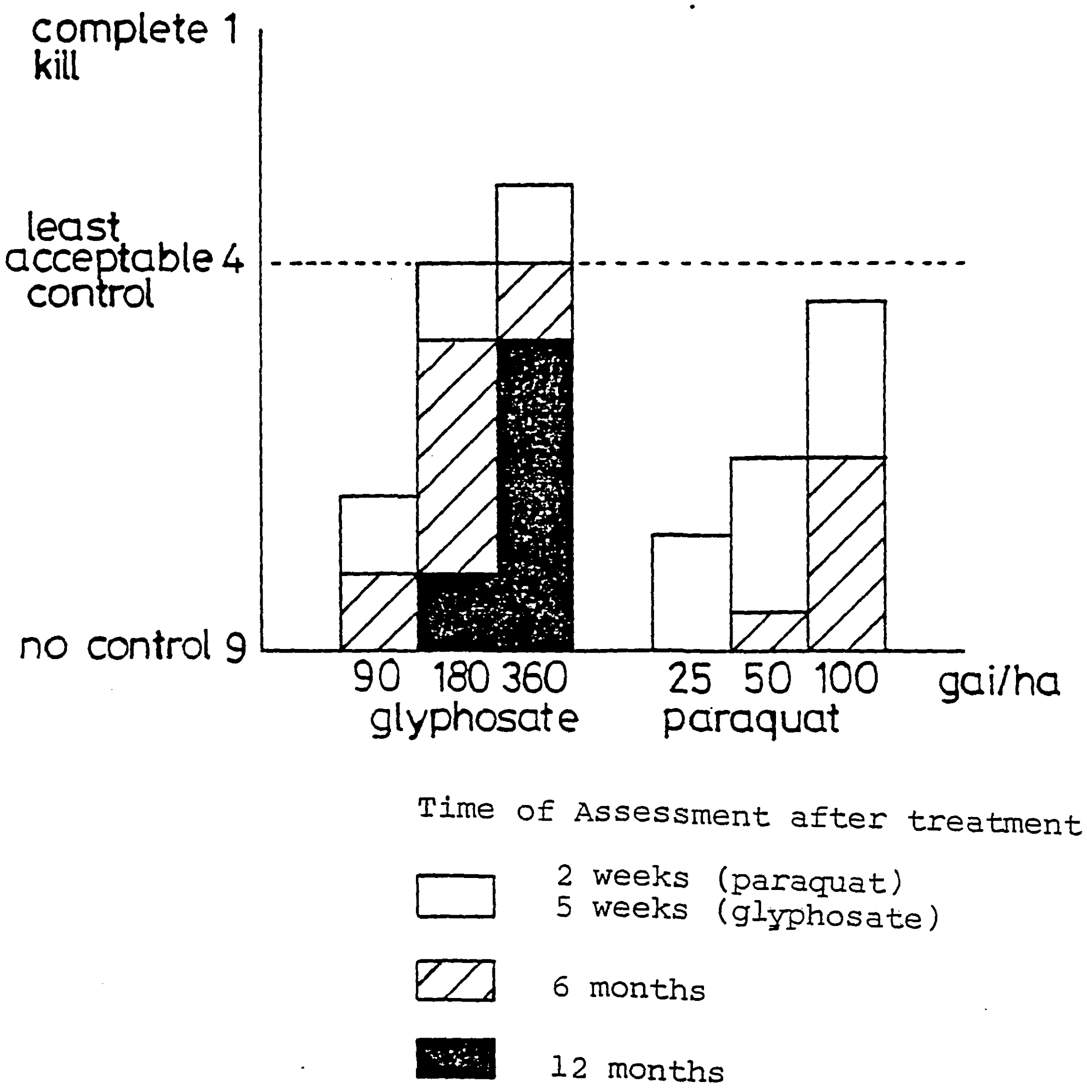
Six months after spraying there were no differences between the results from the three application times, and the results have been combined (Fig. 5.20). The highest glyphosate rate, 360 gai/ha, was only 20% of the manufacturers recommended dose, but continued to give good suppression of H.mollis one year after application, when the grass had

Fig. 5.19 Potato Trial

a) result of inter-row cultivation (untreated behind)

b) result of hand weeding the untreated area (herbicide treated behind)

Fig. 5.20 Control of *Holcus mollis* by Glyphosate and Paraquat: visual assessments using logarithmic 1-9 scale.



completely recovered from the paraquat treatments. This reflects the translocation of glyphosate to the rhizomes where it kills lateral shoots (Sprankle et al, 1975), whereas paraquat is primarily a contact herbicide, although some translocation occurs when it is applied in the dark (Smith & Sagar, 1966).

Glyphosate is more active on perennial grasses when sprayed in the concentrated solution used in low volume spraying with spinning discs, than in high volume hydraulic spraying (Caseley et al, 1976; Bruge & Jean, 1977; Turner & Loader, 1978). It was probably this effect which resulted in the acceptable control of H.mollis using the spinning cup on the wheelbarrow sprayer to apply only 360 gai/ha.

5.4. Botswana Field Trials

A range of experiments was designed to test the wheelbarrow sprayer in a variety of conditions, and to obtain information on the chemical control of weeds in Botswana.

5.4.1. Comparison of sprayers and the effect of walking speed

Direct comparisons were made between the weed control obtained from the wheelbarrow sprayer, a hand-held spinning disc sprayer and a knapsack sprayer fitted with an impact nozzle. Several types of herbicide were sprayed at a range of walking speeds with each sprayer. At all sites there was great variation in weed and crop densities across the trial.

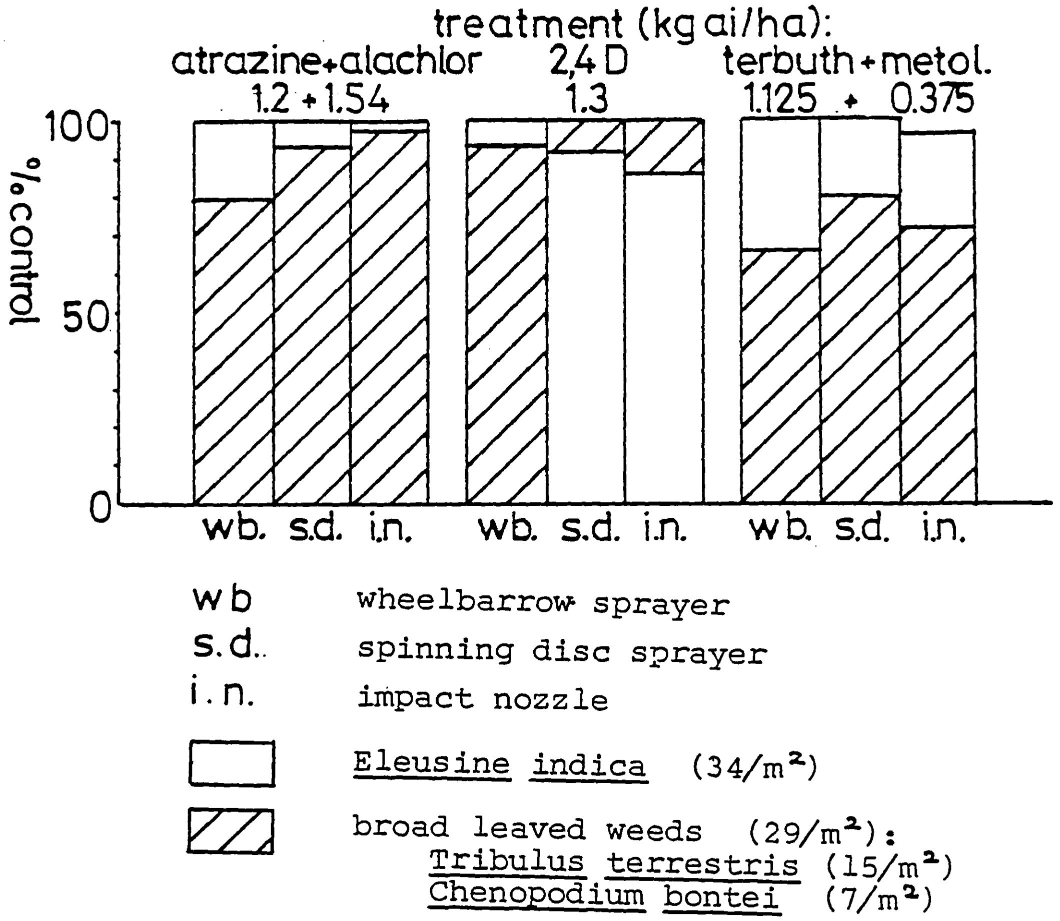
i) pre-emergence herbicides in maize

All combinations of sprayer and herbicide type gave 97-100% control of Eleusine africana, except for 2,4D sprayed with the spinning disc sprayer (92%) or the knapsack sprayer (86%) (Fig. 5.21a). Tribulus terrestris was generally controlled well using either atrazine plus alachlor, or 2,4D alone, but the results were poorest when they were applied using the wheelbarrow sprayer. Terbuthylazine plus metolachlor gave poor control of T.terrestris None of the herbicides affected crop emergence (Appendix 14).

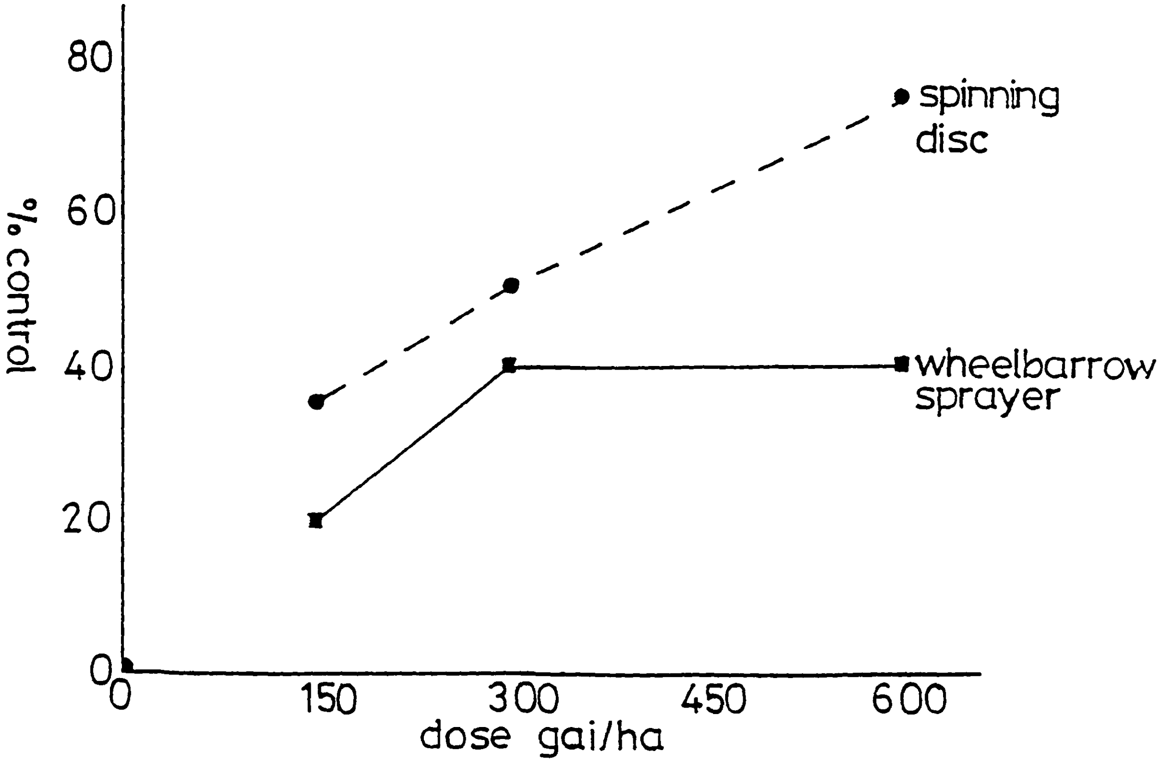
The low weed populations in this trial may have masked any potential treatment differences, but if reduced doses of the herbicides had been used differences might have been enhanced.

Fig. 5.21 Weed Control Comparing Different Sprayers

a) pre-emergence herbicides (35 days after treatment)



b) paraquat (9 days after treatment)
(80% cover of grass weeds)



ii) paraquat applied to fallowed land

The wheelbarrow sprayer and the spinning disc sprayer were compared using low doses of paraquat, chosen to highlight any differences in weed control between the sprayers. In the very windy conditions, a test spray with the knapsack sprayer produced considerable drift, so this was not used for safety reasons. The wind caused noticeable lateral displacement of the swaths from both sprayers, and scorch marks could be seen on plants outside the main swaths, suggesting some droplets had drifted.

No treatment gave acceptable weed control, but the spinning disc sprayer gave much better results than the wheelbarrow sprayer (Fig. 5.21b). There was a greater proportion of local necrotic lesions compared to overall burning of the leaves in plots sprayed using the wheelbarrow sprayer than in plots sprayed with the spinning disc sprayer.

iii) 2,4D applied post-emergence at different walking speeds

The application of 2,4D by the wheelbarrow sprayer gave good control (85-100%) of the three broad-leaved weed species, with similar results when spraying with a horizontal or an angled sprayer (Fig. 5.22). However, the sprayer was found to be overdosing by 12% when the spray volume was checked.

The wheelbarrow sprayer gave better control than the knapsack and spinning disc sprayers, of the weeds less susceptible to 2,4D (Amaranthus thunbergii and Tribulus terrestris), but all the sprayers gave similar control (96-100%) of the most susceptible species, Chenopodium bontei. The grass weed, Eleusine africana, was unaffected by 2,4D.

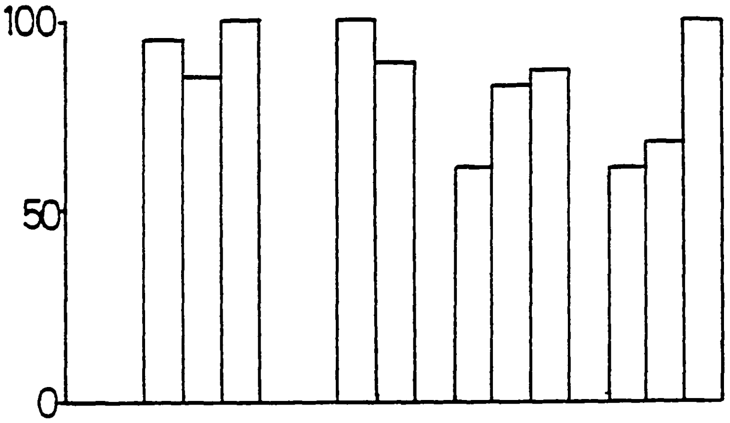
Although there were differences in the control of A. thunbergii and T. terrestris using all the sprayers at the three walking speeds there was no trend for one speed to give consistently better results than the others.

iv) pre-emergence herbicides at different walking speeds

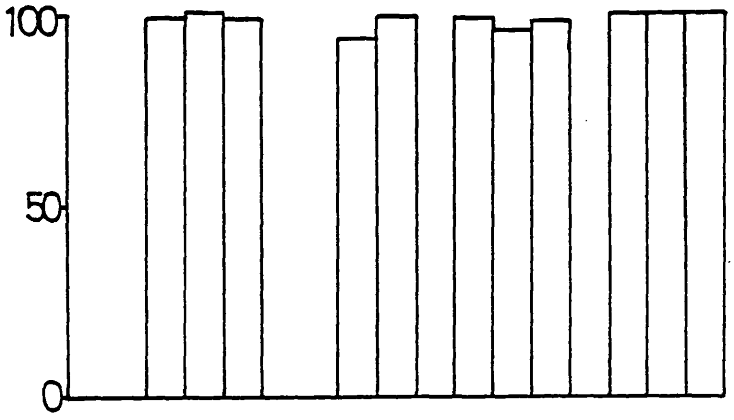
Metolachlor was applied pre-emergence of sunflower using the wheelbarrow sprayer at three walking speeds (Table 5.7). Metolachlor is primarily a grass herbicide, but the weed spectrum consisted mainly of broad-leaved species, which should have illustrated any potential differences between the

Fig. 5.22 <u>Effect of 2,4D amine (1.1 kgai/ha) Applied Post-Emergence Using Three Sprayers</u>

a) *Amaranthus thunbergii* $(18/m^2)$



b) *Chenopodium bontei* $(71/m^2)$



c) *Tribulus terrestris* (40% cover)

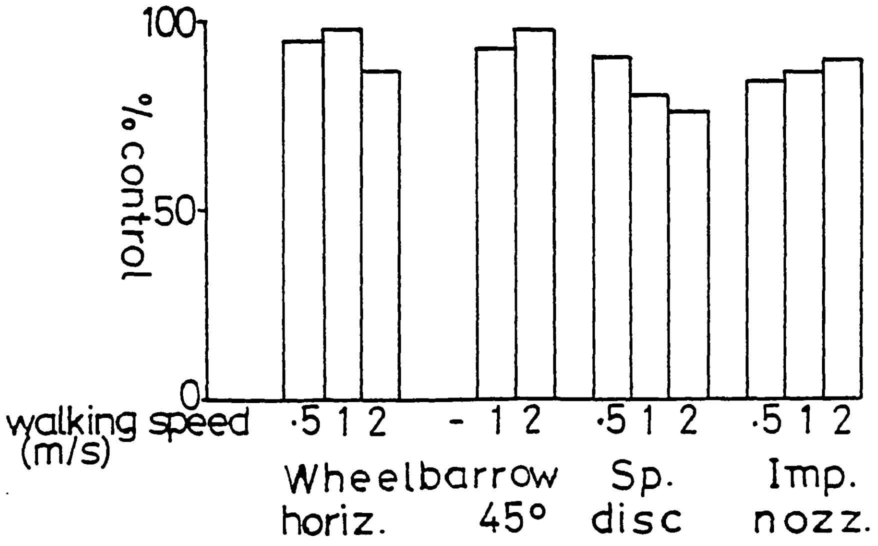


Table 5.7 Effect of Walking Speed with the Wheelbarrow Sprayer on the Activity of Metolachlor (1.1 kgai/ha) 20 Days after Treatment.

	% control			untreated	LSR
walking speed (m/s)	0.5	1.0	2.0	no./m^2	
Eleusine africana	94	69	96	10	4
all dicotyledenous species:	32	32	50	342	178
Chenopodium bontei	55	71	79	31	26
Portulaca oleracea	16	15	6	263	66
Tribulus terrestris	0	0	0	39	14
no. crop plants /m. of row	62	65	62	52	21

treatments. The dry period of eleven days after spraying probably reduced the activity of this soil acting herbicide, and the very heavy rain which followed may have leached the chemical through the sandy soil, away from the germinating weeds.

There was no significant difference between the treatments and the untreated for any broad-leaved species, and no trend in relation to walking speed. The grass species Eleusine africana was controlled well (>90%) except at 1.0 m/s, but this was not significantly different from the others due to the variable weed population across the trial site.

The use of pre-emergence herbicides appeared to aid crop establishment, since there were consistently more sunflower plants in treated plots than untreated plots. The difference was not statistically significant, but might be expected during a long, dry period when water is the main limiting factor for crop growth.

v) discussion

Spraying with the wheelbarrow sprayer controlled the weeds at least as well as the hand-held spinning disc sprayer and the knapsack sprayer when using pre-emergence herbicides or foliar applied 2,4D amine. These results agree with those of other authors, reviewed in section 2.3.

The walking speed of the operator did not affect the weed control given by the wheelbarrow sprayer. Although the application rate remains constant when the walking speed changes, the droplet size varies from a VMD of 500 μm at 0.5 m/s, to 220 μm at 1.8 m/s. Such changes are unlikely to affect the activity of soil applied herbicides, since, provided the herbicide is evenly distributed over the soil, the droplet size and density have little effect on its activity (Addala, 1982).

Foliar applications of 2,4D may be most active when applied as small droplets which are well retained by the leaves and which cover them well (Behrens, 1957). This would apply particularly to very waxy species such as Tribulus terrestris. However, the dense but shallow canopy of weeds in this experiment (Fig. 5.23a) probably collected sufficient droplets of all sizes to give the similar weed control at all

Fig. 5.23 Botswana Field Trials

a) Site used in 2,4D experiments (sections 5.4.1iii & 5.4.4iii) Photograph shows dose response to 2,4D sprayed early in the morning in experiment 5.4.4iii

1.1 0.55 0.27

dose kgai/ha

b) Wheelbarrow sprayer in tall grass (experiment 5.4.1ii)

walking speeds.

The hand-held spinning disc sprayer gave better results with the contact herbicide, paraquat, than the wheelbarrow sprayer. This was because spray from the wheelbarrow sprayer can cover weeds up to 0.3 m tall, but the vegetation in the trial was up to 0.5 m tall (Fig. 5.23b). The spinning disc sprayer could be held above these weeds. The overall weed control was poorer than expected, for several possible reasons. The large volume of vegetation was probably not well covered by the low volumes of spray used (500-1000 l/ha is recommended) but good cover is especially important for contact materials (section 2.3). In the bright sunlight of the tropics paraquat kills the plant tissue very rapidly, resulting in poorer overall activity than in dull conditions (Headford, 1970) since the herbicide is not translocated within the plant (Smith & Sagar, 1966). There was a visible layer of dust on the weed leaves, which has been shown to adsorb the paraquat, reducing its activity (Damanakis et al, 1970). Paraquat activity has also been shown to be reduced at low relative humidities, particularly below 80%, since there is less uptake and movement within the plant (Brian, 1966).

5.4.2. Directed spraying using the wheelbarrow

The sprayer was angled towards the ground for inter-row spraying in growing crops. In preliminary tests spraying dye, it was noticed that the spray hit the drooping leaves of maize and sorghum, so a shield was mounted on the sprayer which brushed the leaves away from the spray. The angled sprayer was not compared to the horizontal sprayer in these experiments because of potential crop damage with the latter.

i) 2,4D in maize

There was very little effect due to 2,4D on the weeds in this trial (Appendix 15a). This may have been due to their large size at spraying, or because most of the weeds present were not on the label recommendations and may not have been susceptible to 2,4D at 1.1 kgai/ha.

ii) paraquat in sorghum

There was unacceptable control of most weeds present but there was a dose response, with 0.6 kgai/ha giving 50% burning and 0.3 kgai/ha only 20% (Appendix 15b). Tribulus terrestris, Amaranthus thunbergii, Datura ferox and Eleusine africana showed burning symptoms where they had been hit by the spray, but parts of the plant were too tall to be covered by the spray. There was no damage to the crop except for a few small burn marks on the lowest parts of the leaves.

iii) paraquat in sunflower

The sprays were applied when the sunflowers had an average of 6 leaves per plant, when the weeds in this trial were all less than 0.1 m tall. Paraquat at 0.6 kgai/ha gave very good control of those weeds present at spraying, but there was a subsequent germination of Chenopodium bontei and Ipomoea sp. which caused the level of weed control to appear poorer (Table 5.8). In spite of the shield, many crop plants were hit by the paraquat, which caused a 61% reduction in crop stand.

iv) discussion

Herbicides can be applied in susceptible crops by spraying only the inter-row areas. Paraquat is recommended for post-emergence weed control in maize if it is directed to avoid the crop by fitting a shield on a knapsack sprayer lance, or by using a tractor mounted boom sprayer, with the nozzles mounted either on drop arms or on a skid assembly close to the ground (Richards, 1973). Small farmers in Columbia apply paraquat post-emergence in maize, using a shielded knapsack sprayer (Doll, 1976). Controlling a heavy weed infestation in this way significantly increased the maize yield, although there was considerable phytotoxicity on the lower leaves of the crop (Hill et al, 1973). In South Africa post-emergence applications of 2,4D are recommended using these methods in sorghum and maize, at growth stages which are otherwise susceptible to the herbicide. Such applications are useful to control weeds which are tolerant of herbicides applied early in the life of the crop, or to control weeds which germinate when the activity of a residual herbicide has run out. However, inter-row weed control should not be used alone, since it can result in much lower crop yields than overall control (Fowler, 1981).

The wheelbarrow sprayer must be angled towards the ground to avoid the spray spreading into the crop, but shields were

Table 5.8 Spraying v Hand Weeding in Sunflower : crop damage and weed control 7 days after treatment

	% ground cover in untreated	% weed control herbicide[+]	hand-hoe
Chenopodium bontei	3	84	69
Ipomoea sp.	6	81	72
Portulaca oleracea	35	98	90
Tribulus terrestris	39	99	92
all dicot. species	100	97	89
crop (% killed)	-	61	6

[+] wheelbarrow sprayer (angled) applied paraquat at 0.6 kgai/ha

Notes: i) treatments were made 14 days after sowing, when 75% of the crop had between 4-6 leaves.

ii) all the plots were smothered by weeds at harvest time.

necessary to prevent spraying some of the crop leaves. The shields worked well in ridged crops but in an unridged crop it proved difficult to walk straight and considerable amounts of spray hit the crop. This technique of spraying needs further development before it can be safely recommended.

5.4.3. Comparison of chemical weed control and hand-hoeing

Two trials compared the weed control by herbicides sprayed using the wheelbarrow sprayer with that by hand-hoeing. Hoeing removed small weeds which are often missed by farm labourers.

i) atrazine versus hand-hoe in maize

There was a low weed population at this trial. Post-emergence applications of atrazine at 1.2 kgai/ha poorly controlled Ipomoea sp. and Tribulus terrestris, but gave very good control of Chenopodium bontei (Fig. 5.24). The addition of 0.5% v/v surfactant did not improve the activity of the atrazine. Hand-hoeing 30 days after sowing, on the day of spraying, removed some of the large plants of Ipomoea sp. and T. terrestris, which were little affected by atrazine, but stimulated a germination of these species, and, particularly, C. bontei. Atrazine reduced the number of small Eleusine africana plants, but mature plants were not affected. In contrast, hand-hoeing stimulated a greater germination of E. africana, but controlled most of the mature plants although some re-rooted.

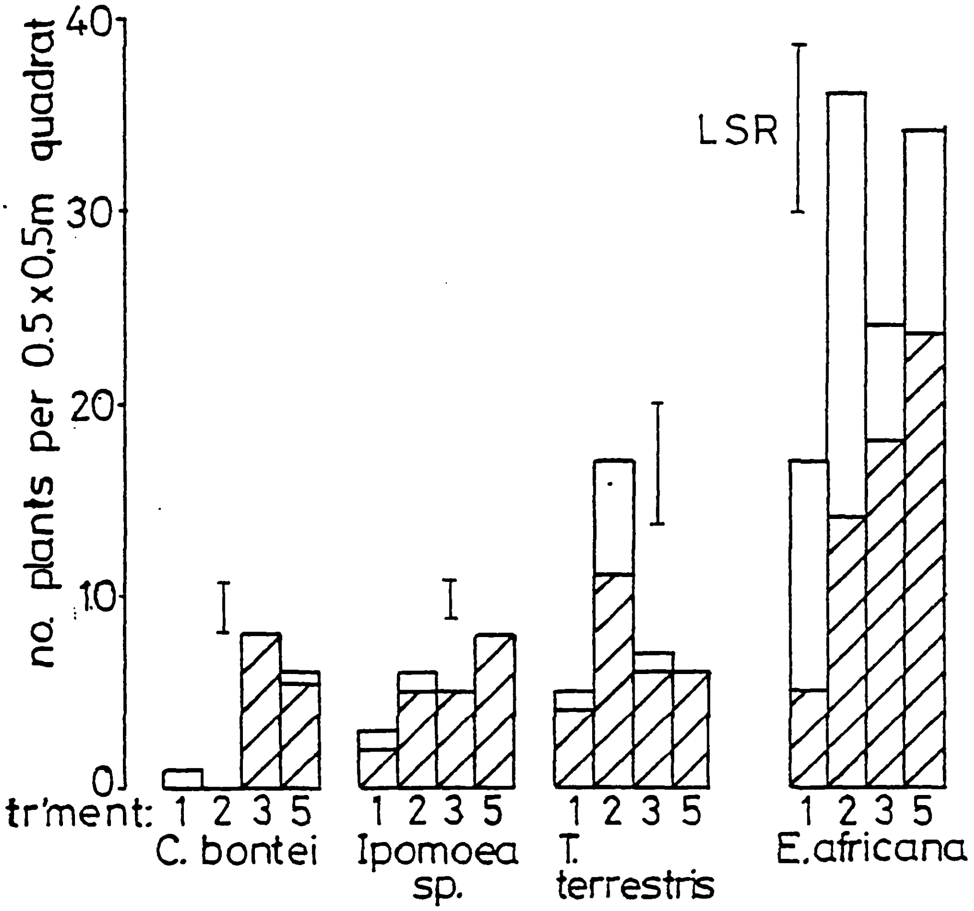
The highest yield of threshed grain resulted from hand-hoeing 50 days after drilling. This was significantly greater than the yield from untreated or the atrazine plus surfactant, but it was similar to that from hoeing at 30 days or from atrazine alone.

ii) paraquat versus hand-hoe in sunflower

A comparison of a directed spray of paraquat with hand-hoeing showed similar levels of control by both methods (Table 5.8). Large plants of Tribulus terrestris and Portulaca oleracea survived the hoeing, probably because of a period of rain following hoeing, which allowed them to re-root. The germination of Chenopodium bontei and Ipomoea sp. was stimulated by hoeing resulting in reduced control. Paraquat severely damaged the crop because the shields on the wheelbarrow sprayer were not successful, but hand-hoeing

Fig. 5.24 Chemical Weed Control Compared to Hand-Hoeing in Maize

a) weed control

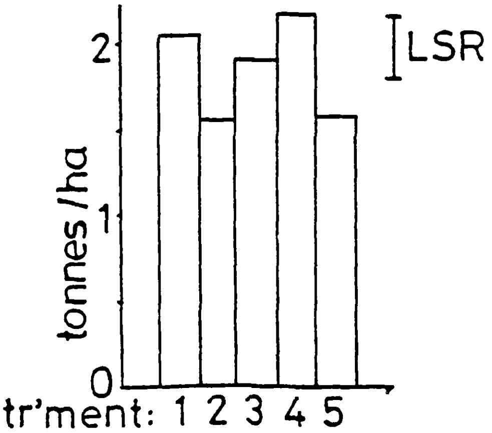


Key:

☐ mature plants
▨ small plants

1 atrazine (1.2 kgai/ha)
2 atrazine (1.2 kgai/ha) + surfactant (0.5%)
3 hand-hoe (30 days)
4 hand-hoe (50 days)
5 untreated

b) yield response



caused only a 6% reduction in crop stand.

iii) discussion

Hand-hoeing is the standard weed control practice on small farms in most regions of the tropics. The surface of the soil is broken by hoeing which may stimulate a flush of weed germination, but if the surface is not broken, as when using a herbicide, penetration of the rain into the soil is reduced, which may severely restrict crop growth under very dry conditions such as those prevailing in Botswana. This capping on the soil surface forms a physical barrier to crop emergence (Meikle, 1973).

In these trials herbicides and hand-hoeing gave similar results, and neither proved very effective against well established weeds, although more timely operations when they were smaller, would probably have been successful. The significant yield increase from removing the low weed population demonstrated the severe competition which can occur between the weeds and the crop, particularly under dry conditions.

Hand-hoeing is often used as the standard treatment on herbicide trials in the tropics, and, in general, comparisons show that correctly chosen herbicides can be at least as effective as hand-hoeing in terms of weed control and crop yield (e.g. Carson, 1979; Upadhyay et al, 1979; Akobundu, 1980c; Choudhary & Lagoke, 1981). In the tropics, rapid growth of weeds requires that a pre-emergence herbicide may have to be followed by a post-emergence herbicide or by hand weeding, in the same way that with traditional weed control several hand weedings may be necessary during the season (Choudhary & Lagoke, 1981; Lagoke et al, 1981).

Pre-emergence herbicides require timely rainfall after application and a reasonably uniform seed-bed for optimum activity. These conditions are not always fulfilled, so pre-emergence herbicides are unlikely to completely replace traditional weed control methods (Ogborn, 1978b). They remove weeds during the early growth of the crop which is most susceptible to competition (Nieto et al, 1968; Kasasian & Seeyave, 1969), and their residual activity reduces the population later in the season to a level which would require only a single, rapid hand-hoeing. In areas where the crop is thinned after emergence, such as parts of Nigeria (Ogborn, 1976) and Cameroons (Atayi & Knipscheer, 1980), the weeding and thinning operations could be combined. Hand weeding following a herbicide should be regarded as an integral part of the weed control programme for small-holder farmers (Parker & Fryer, 1975), particularly since it also prevents the build up of resistant weeds, and makes harvesting easier (Carson, 1979). Reduced doses of herbicides could be the basis of a combined programme of hand-hoeing and herbicide use. It would be cheaper than either method alone, and would significantly reduce the labour requirement compared to hand-hoeing, while lowering the chance of crop damage due to the herbicide (Versteeg & Maldonado, 1978; Carson, 1979; Ebner, 1982).

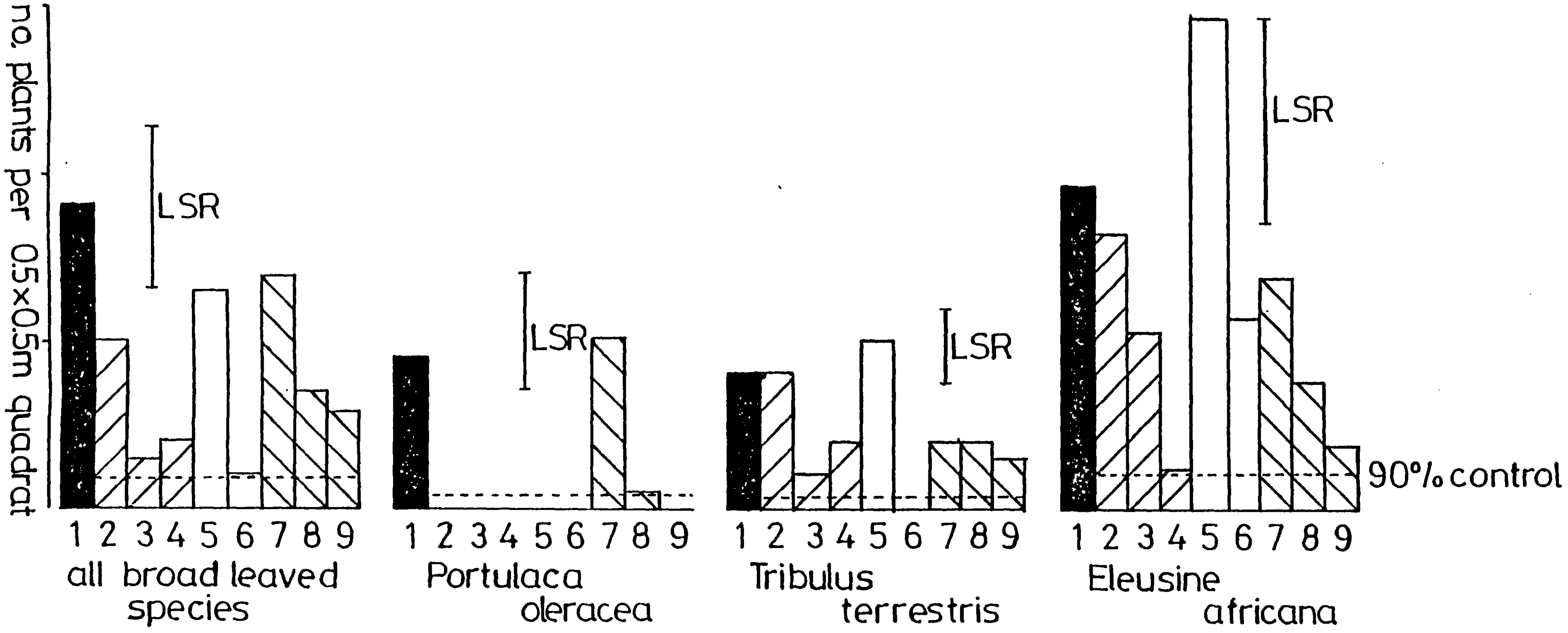
5.4.4. Other experiments

i) dose responses of early post-emergence herbicides in maize

Atrazine, 2,4D, and a formulated mixture of terbuthylazine and metolachlor were sprayed overall, early post-emergence of maize. Another treatment using the formulated mixture with extra metolachlor was band sprayed to avoid crop damage. Spraying was preceded by heavy rain.

No treatment gave over 90% control of Eleusine africana or all broad-leaved weeds, which included some tolerant species (Fig. 5.25). The standard dose of atrazine (1.68 kgai/ha) was required to control E. africana (88%), but a lower dose of 1.20 kgai/ha gave reasonable control (83%) of broad-leaved species. The dose of 2,4D could not be reduced below that recommended (1.3 kgai/ha) without loss of activity against Tribulus terrestris, although Portulaca oleracea was controlled. The recommended dose of the formulated mixture of terbuthylazine plus metolachlor (1.125 + 0.375 kgai/ha) was not acceptable for grass or broad-leaved weed control, but the addition of a further 0.36 kgai/ha of metolachlor improved the control of E. africana from 61 to 80% with little effect on broad-leaved species. Only the atrazine (1.68 kgai/ha) and the dose of the metolachlor mixture with extra metolachlor, reduced the weed population significantly below that of the

Fig. 5.25 Dose Response to Early Post Emergence Herbicides



Treatments (kgai/ha):

1 untreated

2 atrazine 0.8
3 " 1.20
4 " . . . .1.68+

5 2,4D 0.8
6 " . . . . . 1.3+

7 metolachlor + terbuthylazine 0.25 + 0.75
8 " " 0.375 + 1.125+
9 " " 0.735 + 1.125+

+ recommended doses

untreated, due to the great variability of the distribution of the weeds in this trial.

ii) effect of 2,4D on sorghum

2,4D is known to damage certain varieties of sorghum more than others (Marshall & Nel, 1981), and in South Africa it is only recommended in sorghum beyond 0.15-0.25 m high if drop arms are used on the sprayer. In Botswana severe crop damage has been reported in sorghum due to 2,4D (Mazhani, 1978) but crop growth stages at spraying were not reported.

2,4D was tested on a local cultivar, Segaolane, and an improved cultivar, Savannah 5. The crop was not uniform and the growth stage at spraying varied from stage 4 to 6, using the scale of Vanderlip & Reeves (1972), i.e. from 0.3 m high to the beginning of flowering. Although this was well beyond the recommended spray timing, the recommended dose of 2,4D (1.3 kgai/ha) caused no damage or distortion to either cultivar up to 7 weeks after spraying.

The full dose of 2,4D (1.3 kgai/ha) gave acceptable control of Chenopodium bontei and other broad-leaved species, and 0.65 kgai/ha significantly reduced the number of weeds compared to the control (Fig. 5.26).

iii) effect of the time of day at spraying on 2,4D activity

The strong sun in the tropics causes many plants to wilt during the day, and in many pinnately leaved species, e.g. Tribulus terrestris, the leaves fold to avoid the sun. Early in the morning, when many of the other trials were sprayed, the leaves were fully turgid and were often covered in dew, but spraying later in the day could affect the results. To investigate this, 2,4D was sprayed at three times of day, at the start of a period of four days without rain or cloud. On the day of spraying, the temperature reached 33°C, and the mid-day relative humidity was 32%.

The differences between the times of application became more marked when the dose of 2,4D was reduced below that recommended (Figs 5.23a,27). The poorest results were given by spraying in the evening, when weed control was not acceptable, even using the full dose (1.1 kgai/ha). The morning and mid-day sprays gave similar results with 1.1 kgai/ha but the

Fig. 5.26 Dose Responses of Weeds to Post-Emergence Applications of 2,4D

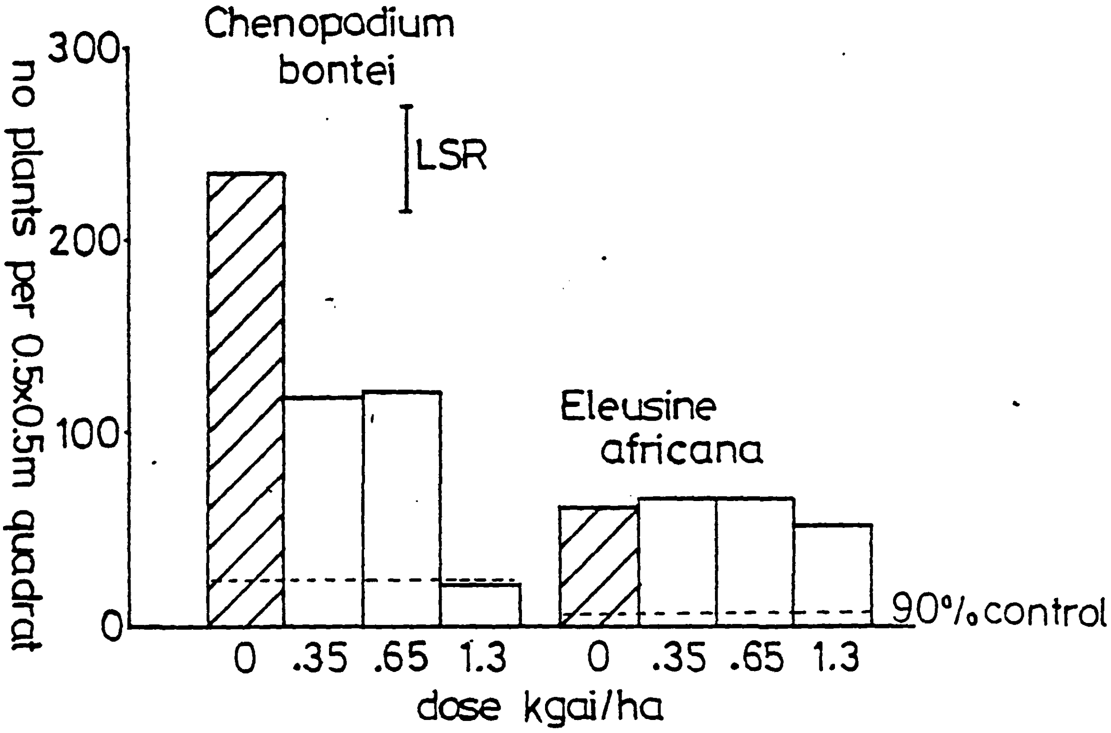
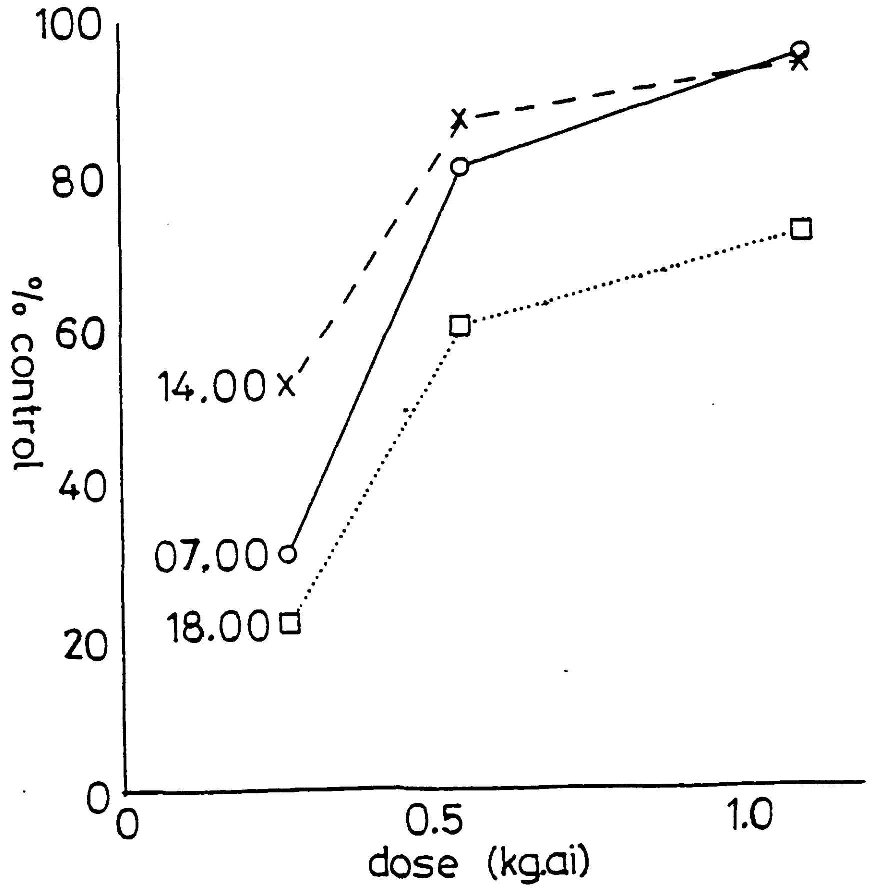


Table 5.9 Dose Response to 2,4D and the Time of Spraying

2,4D dose (kgai/ha)	Time (hrs)	% Kill after 15 days Amaranthus thunbergii	Chenopodium bontei	Tribulus terrestris
1.10	7.00	86	97	98
	14.00	89	99	97
	18.00	36	94	86
0.55	7.00	86	93	82
	14.00	67	91	85
	18.00	21	90	70
0.27	7.00	66	70	22
	14.00	0	41	51
	18.00	8	30	28
untreated (no./m^2)		5	109	(40)$^+$

$^+$ percentage ground cover

Fig. 5.27 Effect of Time of Day of Spraying on 2,4D Activity (all broad-leaved weeds)



mid-day spray was the poorer when the dose was reduced.

Chenopodium bontei was acceptably controlled by the half dose of 2,4D (0.55 kgai/ha), but the full dose was needed to control *Amaranthus thunbergii* and *Tribulus terrestris* (Table 5.9).

iv) discussion

It was not possible to reduce the doses of herbicides below those recommended, and these were not always fully effective due to the adverse weather conditions.

This particularly applies to soil acting herbicides which are rain dependent since they must be in solution for absorption into the plant. When atrazine or alachlor were sprayed immediately after 15 mm of rain the weight of weed growth was over 50% less than when the spray was applied eight days before the rain (Shetty & Krantz, 1978). In semi-arid regions crops are normally planted in the rains, which would be a convenient time to apply the herbicide (Sharman, 1970; Shetty & Krantz, 1978). By giving the farmer a specific time for spraying, the chance of crop damage by application at a susceptible growth stage is reduced, and a soil acting herbicide will be activated by the prevailing moist conditions. It is also easier to introduce a new technique if it can be associated with an existing production factor such as drilling (Deuse, 1978).

In sandy soils, as in Botswana, severe capping is common and herbicides lying on this surface may be washed by rain which is unable to penetrate the soil. Herbicides move more rapidly through sandy soils than clay soils, so if the rain does penetrate a sandy soil, it may carry the herbicide to the germinating crop, causing damage, and it may leach the herbicide below the level of the germinating weed seeds, rendering it ineffective. Leaching of atrazine was faster when rain was concentrated in a short period in a tropical storm, than when it was spread over a longer period (Ogbakoba, 1978).

There was evidence in the trials that 2,4D efficacy is reduced if it is sprayed when the weeds are wilted. The activity of laboratory applications of 2,4D triethylamine salt was reduced under conditions of moisture stress as a result of restricted movement within the plants, although the uptake into the leaf was not reduced (Pallas & Williams, 1962). Other translocated herbicides, including asulam, dalapon and glyphosate were less active at low relative humidities due to reduced absorption and translocation (Hammerton, 1968; Chase & Appleby, 1979; Veerasekaran, 1980). The uptake may also be reduced in dry conditions by the more rapid evaporation of the spray from the leaf surface, and the closure of the stomata.

5.4.5. Suitability of herbicides for small farms in Botswana

The weed spectrum on the research farm where trials were carried out was different from that on local farms. A brief survey was made of weeds occurring at the end of December in fields sown at the end of November (Appendix 16), to relate the trials results to local farm conditions. Grass weeds were less common on the local farms than on the more intensively cropped research farm. Some broad-leaved weeds were common on the research farm but rare elsewhere (Chenopodium bontei, Portulaca oleracea, Tribulus terrestris). Amaranthus thunbergii and Ipomoea sp. were more common on the local farms. A list of weeds which occur in this area throughout the season was given by EFSAIP (1977).

Although most of the herbicides in the field trials were used on only a few weed species, the table of susceptibilities shows the importance of herbicide mixtures for controlling both broad leaved and grass weeds (Appendix 17). The susceptibilities were similar to those on the South African label recommendations for the herbicides (Appendix 18). Since there were relatively few grass weeds on local farms mixtures may not be required in the short term, but intensification of cropping, and the use of herbicides selectively killing broad-leaved weeds are likely to increase the grass weed problem. Atrazine or metolachlor used alone can lead to the proliferation of grass or broad-leaved weeds respectively, but a mixture of the two is complementary and controls both types (Akobundu, 1979; Lagoke et al, 1981). Such mixtures are in common use in South Africa, and have been tested on small farms in Zambia (Vernon, 1980). They could be used in Botswana to control most of the weeds observed, but pre-emergence herbicides are likely to prove unreliable due to the very irregular rainfall.

No crop phytotoxicity symptoms were observed in the trials when the herbicides were used correctly, and the application of atrazine to maize did not reduce yield. In contrast, a screening experiment in Botswana showed crop damage due to herbicides (Mazhani, 1978) but the results were very variable. Further testing must be undertaken before any recommendations can be made.

Considerable risks are involved in the use of herbicides in Botswana, and these make their widespread adoption unlikely in the near future. The average returns from crops are very low: in sorghum in 1977 and 1978 the gross margin varied from [+]P7/ha to P23/ha on traditional methods and from P24/ha to P68/ha on improved farming (EFSAIP, 1977; 1978). These figures do not include the cost of weed control, which is carried out by female family labour.. In 1979 atrazine cost P6/ha, and the atrazine/metolachlor mixture cost P16/ha at South African prices. The economical advantage of herbicides, therefore, looks very poor, particularly considering that crop failure is likely once every six years due to drought (Anon, 1978), and that the use of herbicides would not necessarily increase the crop yields.

[+] 1 Pula = c.£0.8

CHAPTER 6 DISCUSSION

Spraying systems have changed little this century, but, despite their effectiveness, new ideas and changes in the economics of agriculture have encouraged research into improving application techniques.

The use of herbicides has increased rapidly during the past 15 years, particularly in comparison with insecticides (Table 6.1). However, relatively little herbicide is used in developing countries although the use of insecticides is considerable (Table 6.2), particularly in cotton. A similar contrast can be seen in Africa between the little herbicide used in maize, primarily a subsistence crop, and the greater use in sugar cane, primarily a commercial plantation crop (Table 6.3). In the future the pesticide market is expected to expand more rapidly in developing countries than in other sectors (Anon, 1983c).

The requirements in a sprayer for tropical small-holder farmers are similar to those for farmers in developed countries. The spray must be effective and economical, and the sprayer should be simple to use but reliable. The differences between the two groups of farmers are embodied in their definitions of each of these factors, which must be considered when designing sprayers.

Research in to application methods for developed agriculture has centred on improving their cost effectiveness by three approaches. The logistics of spraying has been improved by using lower spray volumes and faster speeds (Elliott, 1980), allowing more timely application. However, lower volumes require optimal retention by the target in order to maintain activity, and this can be gained by manipulating the physical characteristics of the spray (Merritt, 1980). Advanced electronic monitoring and control systems have recently become available to ensure correct dose rates and spray characteristics (Allan, 1980). Conventional hydraulic nozzles are still used almost universally, inspite of new technologies such as spinning discs, since they have proved cheap, reliable and flexible in use.

The main impetus to new developments in application

Table 6.1 World Pesticide Usage, 1957-1982
(value in billion U.S. Dollars)

	1957[+]		1977[+]		1982[++]	
	value	%	value	%	value	%
herbicides	0.22	13	3.51	46	5.25	39
insecticides	0.97	57	2.63	34	4.35	33
fungicides	0.43	25	1.20	16	2.92	22
others	0.09	5	0.34	4	0.78	6
total	1.71		7.68		13.3	

sources: [+] Robinson, D. (1978) adjusted to 1977 values
[++] Anon (1983c) 1982 values

Table 6.2 Pesticide Usage in Developed and Developing Countries (1979)

	%total usage	
	developed countries	developing countries
herbicides	80	20
insecticides	60	40
fungicides	85	15
total	75	25

Source: Anon (1980e)

Table 6.3 Herbicide Use in Maize and Sugar Cane

	% of cropped area treated			
	maize		sugar cane	
	1972	1979	1972	1979
U.S.A.	85	88	-	-
Latin America	35[+]	25[+]	45[++]	90
Africa[+++]	2	11	44	50
Asia			6	10

[+] excluding Argentina
[++] Central America only
[+++] excluding South Africa
Source: Ebner (1980)

techniques has come from less developed countries (Matthews, 1981b) where other factors are important, such as the small size of farms, very low incomes, poor water supply and negligible technological infrastructure. The development of sprayers for tropical small-holder farmers aims to introduce an appropriate new technology, in contrast to developed agriculture, where new spraying techniques can only be successful by replacing old ones. Potential sources of error in spraying must be minimised by careful research, design and development reflecting the difficult conditions.

6.1. Efficacy and Advantages of the Wheelbarrow Sprayer

The wheelbarrow sprayer was designed within the constraints relating to herbicide application by tropical small-holder farmers, who require a simple but robust sprayer, with which it is difficult to apply the incorrect dose of the herbicide.

i) low volume

Many authors consider the high volumes associated with conventional sprayers to have limited the use of herbicides in the tropics due to the difficulties in collecting sufficient water, especially at the start of the cropping season when water levels in streams and boreholes are low (e.g. Renault, 1972; Ogborn, 1975; Hildebrand, 1979; Deat, 1981; Hammerton, 1981; Matthews, 1981a). Even in areas where water is not considered limiting low spray volumes can greatly increase the work rate compared to conventional volumes, so that sprays can be timed more accurately in relation to weed growth or crop stage, and when the weather is favourable.

The wheelbarrow sprayer applies 20 l/ha on a single swath, or 40 l/ha when the swaths are completely overlapped. These volumes have generally given better results using spinning atomisers than either lower or higher volumes, although contact herbicides tend to perform better at 40 l/ha than 20 l/ha (Merritt & Taylor, 1977; Ayres, 1978a; Bailey _et al_, 1978a, 1978b; Robinson, 1978; Phillips _et al_, 1980). When the spray volume is reduced, the greater concentration of herbicide needed to maintain the required dose may result in a more viscous spray liquid. This can block the very narrow restrictors of the hydraulic nozzles used for these volumes, particularly when wettable powders or flowable formulations are used, or if there is silt suspended in the water. The restrictors on gravity fed spinning disc sprayers (normally 0.8-2.0 mm) are less likely to become blocked. On the wheelbarrow sprayer, the narrowest constriction is 3 mm in the feed nozzles to the spinning cup, which should allow the passage of any particles likely to be in the spray liquid.

ii) ground metering

The output of the peristaltic pumps is closely related to the ground wheel speed, so an almost constant application volume is possible for any walking speed of the operator and there is no need to calibrate the sprayer. Wheel slippage could cause under dosing but has rarely been encountered in field use, due to the low resistance to ground wheel movement. Knapsack and hand-held spinning disc sprayers have proved almost impossible to calibrate without supervision, and inaccurate dosing results from changes in the walking speed of the operator (Doll, 1976; Vernon, 1980; Fowler, 1981; Pickin _et al_, 1981). Unsatisfactory weed control was obtained by farmers on Manaoag because an average of 57% of the recommended dose was applied at 50% of the recommended volume using knapsack sprayers (Navarez & Moody, 1980).

Although the flow of liquid onto the spinning cup increases linearly with walking speed within the range of speeds likely to be encountered, the effective application volume falls slightly at high speeds due to an edge effect with the shroud window. This has not been reflected in biological results. The peristaltic pump causes the spray to pulse, but this has not affected weed control when using full doses of herbicides. The pulsing is less than that from a hydraulic peristaltic pump sprayer, the Norman-King sprayer, which has given acceptable results (Fowler, 1981).

iii) no batteries

The need for up to 8 batteries to power a hand-held spinning disc sprayer is a constraint to the acceptance of CDA spraying in the tropics (Matthews, 1981a). Apart from the cost, they are not always available when required and often have a short service life.

The spinning cup is driven by friction off the ground wheel, obviating the need for batteries. The rotational speed increases linearly with walking speed and a free-wheel mechanism is incorporated into the drive spindle so that the speed is little affected by wheel slip. Soil particles can build up on the drive spindle increasing the spinning cup speed, and in wet conditions the mechanism may become completely blocked.

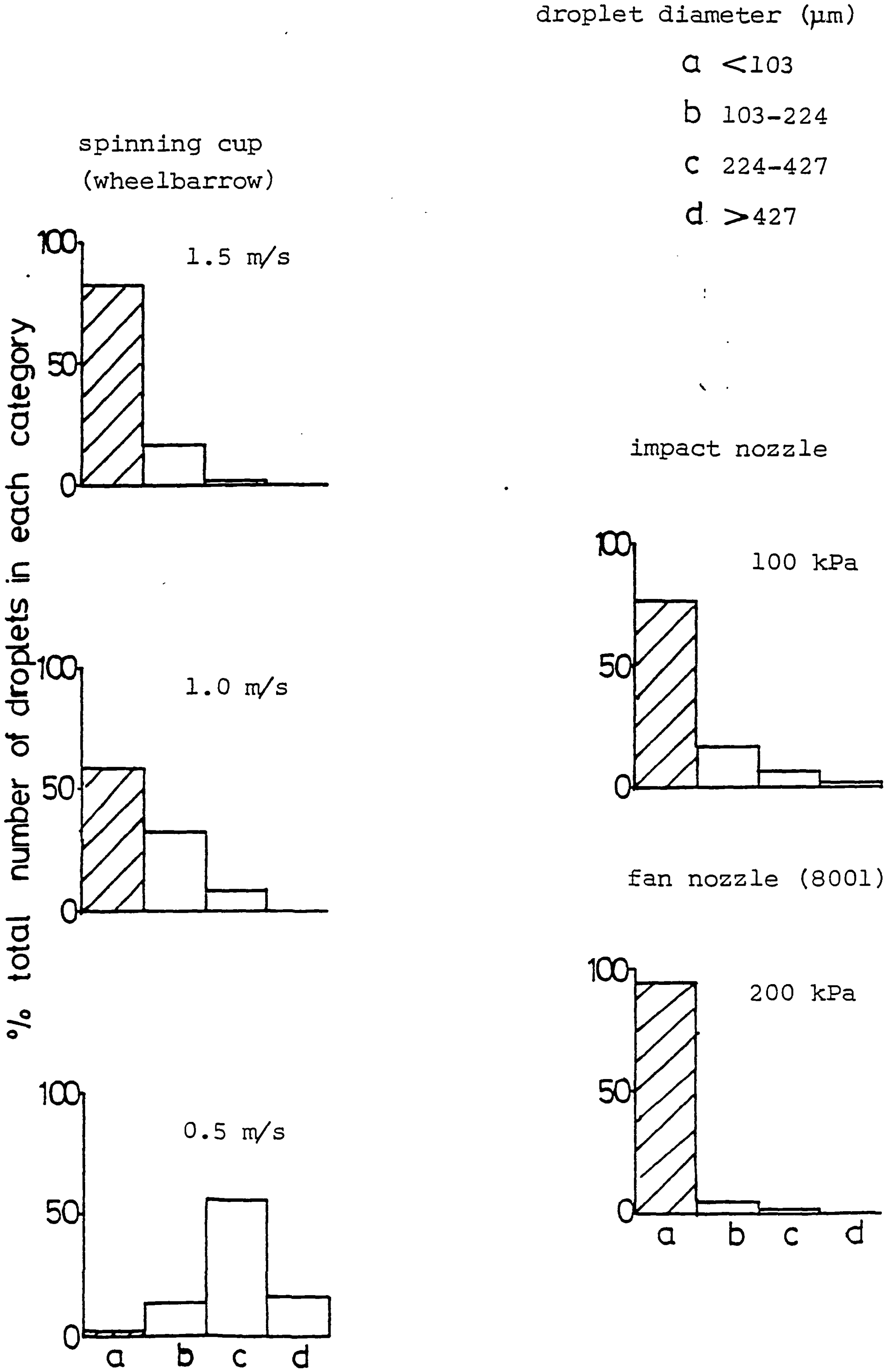
The combined effect of changes in rotational speed and flow rate causes the droplet spectrum to vary with walking speed. Below 0.5 m/s very large droplets are produced, but the VMD falls almost exponentially as the walking speed increases, from 500 µm at 0.5 m/s, to 275 µm at 1.0 m/s and 215 µm at 1.8 m/s. This change was never reflected in the effects of herbicides which were consistently similar at all walking speeds. This is expected for soil applied herbicides, whose efficacy is not greatly affected by droplet size and density (Addala, 1982), but foliage applied herbicides may show a response to droplet size when applied using a spinning disc (Phillips et al, 1980; Bailey et al, 1982a). This response is probably dependent on the spray volume (Merritt & Taylor, 1977; Ayres, 1982), and may not have been significant in the volumes applied by the wheelbarrow sprayer, which would have given adequate cover of the foliage to maintain herbicide activity at all walking speeds tested.

The spinning cup on future prototypes should rotate faster so that a spray with a lower VMD is produced. Fewer large droplets would be produced at low walking speeds, reducing the potential wastage of spray by poor retention (Brunskill, 1957; Lake, 1977), but there would be more droplets susceptible to drift (Fig. 6.1). The potential value of a reduction in the VMD is shown by the slight improvement in the activity of isoproturon or ioxynil + bromoxynil + CMPP when applied by spinning disc at 150 µm compared to 250 µm (Ayres, 1980; Bailey et al, 1982a; Robinson, 1982).

iv) minimise drift

Droplets of very small diameter possess lower terminal velocities than larger droplets, and take longer to reach their target. While airborne they are susceptible to air movements which can carry very small droplets great distances

Fig. 6.1 Percentage of Droplets by Number in Given Size Categories



from the target area of the spray swath (Maybank et al, 1974; Bouse et al, 1976; Matthews, 1979). Droplets less than 100 µm in diameter are most susceptible to drift (Edwards & Ripper, 1953; Courshee, 1969), and the susceptibility is increased because they evaporate more rapidly than larger droplets.

The wheelbarrow sprayer produces fewer droplets less than 100 µm in diameter than conventional nozzles, although the number is increased at fast walking speeds (Fig. 6.1). When the spray is projected horizontally from the spinning cup, the droplets are airborne longer than those from vertical hydraulic nozzles, but this does not increase the risk of drift compared to hydraulic nozzles because of the low number of small droplets (Maybank et al, 1980; Erickson & Duke, 1981).

The complete swath can be displaced by a strong wind when spraying horizontally. The displacement is 0.2-0.7 m per 1.0 m/s of wind speed with a spray of a VMD of 250 µm (Table 6.4).

Table 6.4 Lateral Displacement of CDA Sprays by Cross-wind (VMD=250 µm)

Atomiser	Author	Cross-wind speed (m/s)	Lateral displacement (m)
spinning cup	Erickson & Duke (1981)	4.4-6.7	1.5
spinning disc	Ciba-Geigy (1981)	1.0-2.0	0.7
" "	Taylor & Merritt (1975)	2.7-3.6	1.0
" "	" "	3.6-5.4	1.0-3.0

When the spinning cup is angled, the spray is airborne for a shorter time and the displacement of the swath by the wind is reduced (Smith et al, 1970). This is useful when inter-row spraying to minimize the chance of spray hitting the crop. The greater momentum of directed droplets may also improve spray penetration into weed canopies. This could be important in dense vegetation where weed control has been reduced by poor penetration when using horizontal spinning discs (Ayres, 1978a; Anon, 1979b).

v) adjustable swath width

The shroud around the spinning cup improves the swath uniformity and allows the swath width to be increased to 1.5 m by changing the width of the window. The width of the swath produced by hand-held sprayers can be changed by adjusting the nozzle height, but this is susceptible to the operator's movements. The shroud is maintained at a uniform height by the wheelbarrow sprayer so the swath width is constant for a particular shroud window setting. The swath can be adjusted to allow directed, inter-row spraying of herbicides which are not tolerated by the crop or a component of a mixed crop. Expensive herbicides can be band sprayed within the crop row leaving inter-row weeds which are more easily hand-hoed.

Individual swaths up to 1.5 m wide show good uniformity, and properly matched swaths gave a coefficient of variance (cv) below 10%. This compares favourably with other sprayers. An unshrouded, horizontal spinning cup gave spray patterns with a cv between 13-26% depending on the flow rate and rotational speed (Heijne, 1978), while the swaths from a shrouded cup had a similar range (Nilsson, 1982). A horizontal spinning disc produced a less uniform swath (Johnstone _et al_, 1977), which was improved by tilting the disc at 60° (Ciba-Geigy, 1980), or by shrouding (Taylor _et al_, 1976). Impact and fan nozzles produced matched swaths with a cv of 8-37%, confirming the results of Holly (1956) and Combellack _et al_ (1982). The swath width and uniformity of spray patterns from hydraulic nozzles were dependent on nozzle height and pressure which are difficult to maintain with knapsack sprayers.

vi) manoeuvrability

The second prototype was considered to be of the maximum allowable weight (Table 6.5). A heavy wheelbarrow sprayer is difficult to manoeuvre in the field, particularly in ridge crops, but some weight is required to aid traction and minimise wheel slippage.

It is easier to pull the sprayer than to push it. When a machine is pushed the action forces it towards the ground, so that the power requirement is affected by the ground conditions and the physique of the operator (Anon, 1980f). This problem is largely avoided by pulling the machine. No difficulties were encountered in the U.K. or by the Botswanan operators, who commented that the sprayer was easier to use than knapsack sprayers. Further tests are required on heavy soils and mulches, and in the wet conditions which are likely to occur at the time of post-emergence spraying. It is likely to be as tiring to use on wet, heavy soils as a knapsack sprayer, but the heavier Norman-King sprayer has been used successfully by farmers under these conditions (Fowler, 1981).

Table 6.5 Sprayer Weights

Sprayer		Tank vol. (l)	Weight (kg) empty	 full
wheelbarrow sprayer		5.5	13.7	19.2
knapsack:	"CP3"	18.0	6.2	24.2
	"CP15"	15.0	3.7	18.7
hand-held spinning-disc:				
	"Herbi"	2.5	3.5	6.0
	"Handy"	5.0	3.0	8.0

When the wheelbarrow sprayer is pulled the spray is directed away from the operator so he does not walk through the spray or the treated area. It is particularly important to avoid contamination when using low volume sprays with a high concentration of active ingredient.

vii) easy to maintain

The sprayer is robust and requires virtually no maintenance since it has few moving parts. The shroud protects the spinning cup from hitting vegetation which could damage the peripheral teeth and cause poor droplet formation. The pump tubing is enclosed to reduce the chance of puncturing, and the silicone tubing will withstand at least 400 hours of use. The tubing should be washed after each use, but it apparently survives soaking in many common herbicides although this must reduce its durability.

Applications of oil or grease should be applied periodically to the spinning cup bearings. This is unlikely to be carried out in the field but the mechanism survived two months of use in Botswana without treatment.

Hand-held spinning disc sprayers require routine servicing by trained personnel because of corrosion of the motor and electrical contacts. This is rarely carried out on small farms (Parker & Vernon, 1982). Maintenance of hydraulic sprayers is infrequent except when nozzles or filters become blocked.

6.2. Disadvantages of the Wheelbarrow Sprayer

The wheelbarrow has several disadvantages, most of which are common to wheelbarrow hydraulic sprayers.

The sprayer is likely to cost about £100 in the U.K. (Anon, 1983a), which is considerably more than most knapsack sprayers or hand-held spinning disc sprayers (Table 6.6). Another wheelbarrow sprayer, the Norman-King, shows promise for use by small-holder farmers in Swaziland in spite of its cost, which is compensated for by its simplicity and reliability (Fowler, 1981). The cost will be spread over several years of use, possibly reducing its net cost compared to hand-held spinning disc sprayers which were considered to have a life of only two years in Zambia (Parker & Vernon, 1982).

Knapsack sprayers can be used to apply a wide variety of pesticides, but wheelbarrow sprayers are more restricted in their use because they normally cannot be raised in height to spray insecticides or fungicides over crop foliage, or herbicides to tall weeds. However, there was a possibility in Botswana of using the sprayer to apply insecticides to the foliage of cowpeas to control aphids (*Aphis craccivora*). There are a few soil applied insecticides available in liquid formulations, e.g. chlorfenvinphos, which could be applied through the wheelbarrow sprayer.

It was difficult to transport the Norman-King wheelbarrow sprayer over long distances (Fowler, 1981) and this is also likely with the wheelbarrow sprayer. Many small farms are comprised of fields several kilometres apart (Ruthenberg, 1980) so transport of the sprayer about the

Table 6.6 Guide to Recommended Retail Prices of Sprayers

Type	Manufacturer	Model	Tank Vol. (l)	Retail Prices$^+$	
				S.Africa 1980 (R)	U.K. 1983 (£)
knapsack (hydraulic)	Allman	Polypack	18	-	63.50
	Berthoud	Cosmos	18	-	52.00
	Cooper Pegler	CP3	20	75.00	57.00
		CP15	15	50.00	41.40
	Spraygen	375	17	-	55.00
	Triomf	Carpi	-	48.00	-
ground-actuated (hydraulic)	Triomf	Norman-King	25	84.00	-
hand-held spinning disc	Berthoud	H2	-	-	39.00
	Micron	Herbi	-	64.00	43.50
	Tecnoma	T5	-	-	40.00
	Turbair	Weeder	-	-	35.00

$^+$ These prices vary considerably between countries farm would be difficult. The mobility would be improved if an attachment could be designed to allow the sprayer to be pulled behind a bicycle.

The output of the sprayer is susceptible to large fluctuations in temperature. If the sprayer recommendations are based on the spray produced at a typical temperature, the fluctuations should not greatly affect the dose applied.

In wet conditions the wheel picks up mud which can block the drive mechanism, and the sprayer is difficult to pull when the soil is soft.

6.3. Recommendations for Modifications to the Second Prototype

There were limitations to the design of the second prototype sprayer, and the following improvements are recommended.

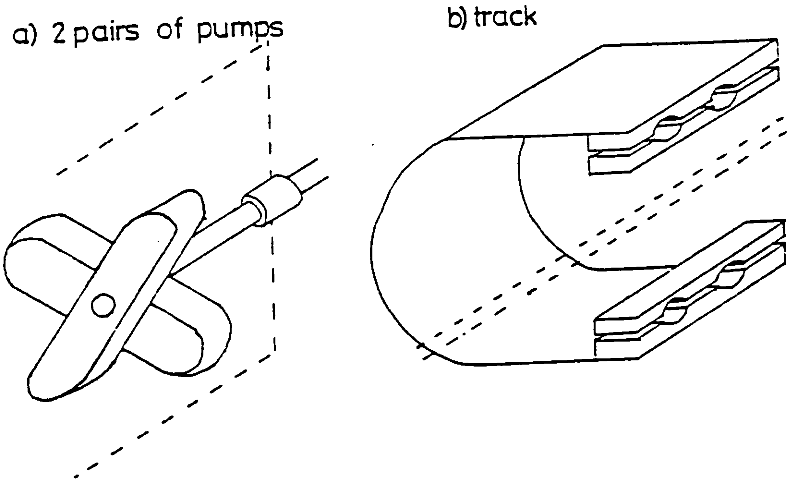
i) pump

The two peristaltic pumps were expensive laboratory instruments which should be replaced by a single, purpose made pump. The pump could be composed of a moulded plastic or metal track, within which rotate two pairs of rollers, 90° out of phase (Fig. 6.2). The tubing should be clamped firmly but be easily accessible for renewal. The open sides of the pump should be enclosed by removable plates to minimize damage to the tubing. The pump is most easily mounted on the ground wheel axle.

ii) shroud

A single plastic moulding could replace the present spun metal shroud, consisting of a base and a lid. The base of the shroud should slope away from the operator to ensure that liquid drains rapidly to the sump when the sprayer is used horizontally (Fig. 6.3a). When spraying, liquid caught by the shroud runs along the inner wall and the flow disintegrates to form irregularly sized droplets at the edge of the window. This can be prevented by flanges at the edges of the window (Fig. 6.3b).

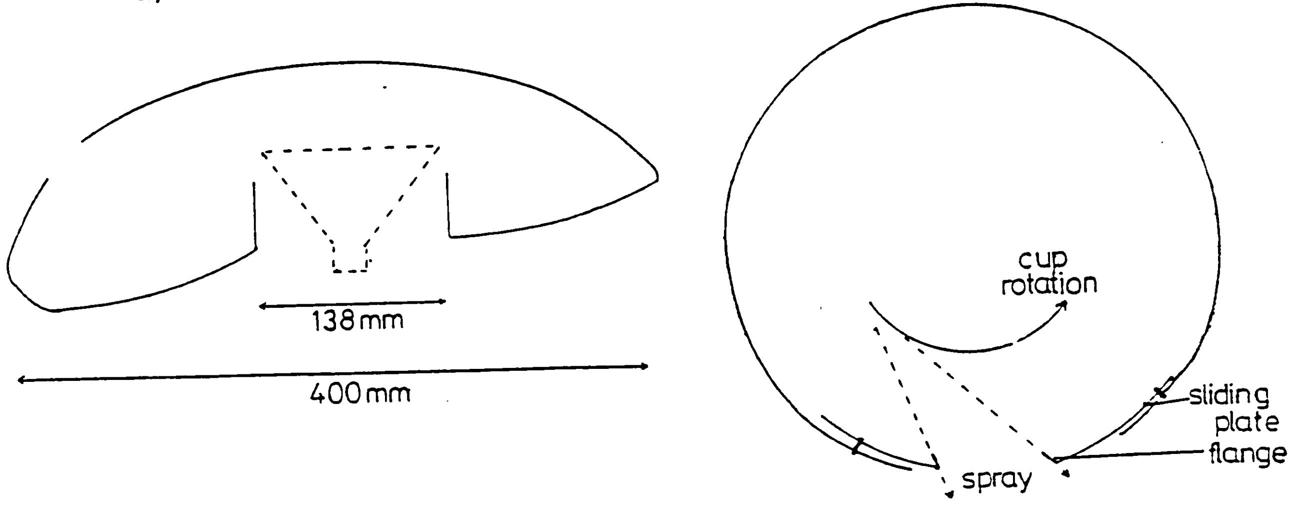
The window width should be adjustable to a limited number of positions, perhaps two options allowing overall or inter-row spraying. The choice of widths could be fig 6.2 New pump design



a) 2 pairs of pumps

b) track

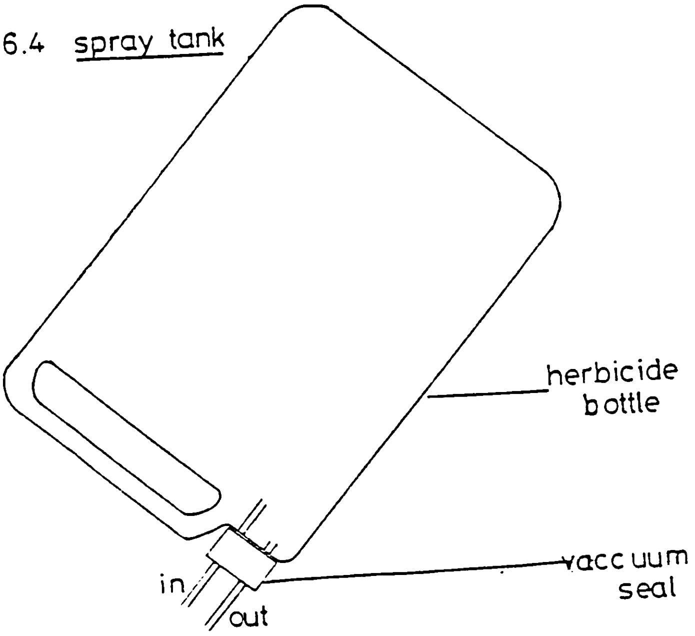
fig 6.3 New shroud



a) vertical section

b) horizontal section

Fig 6.4 spray tank



determined locally at the assembly factory.

The drainage from the shroud was inadequate on the second prototype. An air-bleed incorporated in the return system aided the drainage, but alternatively, the spray could be sucked back by the tank itself (Fig. 6.4). As liquid is drawn out of an airtight container a negative pressure will suck back liquid from the shroud.

iii) spinning cup mounting and axle

There is no need for the reversible drive mechanism which was used on the second prototype for experimental purposes. A similar spring loaded friction drive is recommended, but the mounting can be simplified.

A smaller diameter drive spindle (8 mm) should be used to increase the rotational speed of the cup to slightly over 2000 rpm when walking at 1.0 m/s. If the flow rate of 700 ml/min at 1.0 m/s was maintained this would produce a spray with a lower VMD, without producing too many very small droplets. A plastic sleeve over the central core of the spindle might reduce some of the vibrations which affect droplet production at fast walking speeds.

There should be a scraper in front of the drive mechanism to remove any mud which collects on the ground wheel. A stiff nylon brush held against the drive spindle might prevent the build up of mud.

iv) spray tank

A single tank should replace the two tanks. A 5 l or 10 l tank should be mounted on a platform in front of the wheel so that the liquid can drain quickly from the shroud. It should be easily removable for filling and cleaning. If the "suck back" system is to be used, then a watertight cap should be fitted to ensure a complete seal.

v) framework

Folding handles are necessary to reduce the bulk of the sprayer, and, therefore, minimize the freight charges if the machine is to be imported. The handles should be 1.2 m long to prevent tall operators from kicking the sprayer while they are walking and there should be a simple adjustment from horizontal to angled spraying (Fig. 4.51). There is probably no need for accurate adjustments to allow for the height of individual operators, but this should be checked in the field.

Tests should be made on the use of skids to balance the sprayer, and of shields to prevent spray from hitting the crop during inter-row spraying.

6.4. Alternative Methods of Application

Several new sprayers have recently become available. The "Birky"knapsack sprayer uses an air pump to drive a spinning disc; an acoustic warning device and an over-speed governor help to regulate the disc speed. There is no need for batteries, but the problems of correct dosing remain.

The "Electrodyn" electrostatic sprayer has been used successfully for the experimental application of herbicides (Parham, 1982). It is simple and cheap to use but requires special oil formulations of pesticides (Coffee, 1979, 1980), and is unlikely to become available for herbicide application for several years.

Rope-wick applicators are used for the selective application of herbicides to tall weeds in susceptible crops. On small farms in the tropics they could prove useful for the application of glyphosate, but considerable development work is required before they could be introduced (Davison & Parker, 1983).

6.5. Weed Control : Comparison with Other Sprayers

The biological efficacy of herbicides sprayed by hand-held spinning disc or knapsack sprayers has been compared by few authors, and most comparisons between CDA and conventional spraying have involved tractor mounted sprayers or small plot precision sprayers. These do not relate directly to the use of hand-held sprayers in the field since there are fewer variables involved. Although sprayers are unlikely to perform well in the field if they do not give good results in ideal conditions, the true performance of hand-held sprayers can only be assessed when a number of farmers have used them for at least a season. The trials summarised in Table 6.7 have recently been followed by widespread testing with farmers in a number of countries to provide more extensive information (Imminck, 1982).

Table 6.7 Summary of Sprayer Comparisons

	Wheelbarrow results compared to:					
	knapsack sprayer			hand-held spinning disc		
	+	=	-	+	=	-
Pre-emergence:						
atrazine			L			
atrazine + alachlor	B					
cyanazine	F					
2,4D amine	B				B	
metolachlor + terbuthylazine	B			B		
pendimethalin		L				
trietazine + linuron	F					
Post-emergence:						
cyanazine ± MCPB		F				
2,4D amine	B(x2)			B(x2)		
2,4D ester		L				
glyphosate	L					
paraquat		F,L				B

\+ better

= equal

\- poorer

L = laboratory result

F = field trial (U.K.) result

B = field trial (Botswana) result

The wheelbarrow sprayer controlled weeds at least as well as the standard sprayers in 17 of the 19 comparisons carried out in the laboratory and the field. This agrees with the results of other authors which have shown that soil applied and translocated herbicides usually perform similarly in low or conventional volume spraying (e.g. Barzee & Stroube, 1972; Merritt & Taylor, 1977; Turner & Loader, 1980; Robinson, 1982). Contact herbicides (e.g. bentazone, bromoxynil, dinoterb, ioxynil, MSMA) were not tested in the present work but are less reliable when sprayed at low volumes (Merritt & Taylor, 1977; Ayres & Merritt, 1978; Robinson, 1978). Small holder farmers are likely to use fewer contact herbicides than other types. However, ioxynil is used in sugar cane plantations, and bentazone and MSMA have been suggested for use in direct sown rice and cotton respectively in Nigeria (Akobundu, 1978b; Ogborn, 1978b; Akobundu, 1979). Bentazone may also be suitable for use in groundnuts (Lagoke et al, 1981).

6.6. Factors Contributing to the Acceptance of New Technology

A traditional small-holder farmer aims to ensure the survival of his family by minimising the risk of crop failure (Miller, 1982). There is a very low non-labour input to growing his crops (Haswell, 1972) and any capital investment adds to the potential problems of crop failure. Changes which increase the risks must have striking advantages before they are accepted by the farmers (Haswell, 1974; Farrington, 1977; Ryan & Binswanger, 1979; Conklin et al, 1982).

There are social, cultural and psychological barriers to changes in traditional practices and beliefs (Beaumont, 1977; Onyemelukwe, 1979). This was illustrated by the poor response to requests for Nigerian farmers to grow sole crop cowpeas, since this conflicted with the traditional beliefs that cowpeas would not grow well when planted alone (Hayes & Raheja, 1977). The barriers are often made more severe by land tenure systems (Johnston, 1964; Todaro, 1981) and political instability (Forsythe, 1981), which reduce the desire to invest resources.

The main incentive for adopting new methods appears to be a greater financial return for a lower risk. The increase in returns required for adoption is said to be from two (Deuse, 1978; Nachtigal, 1981) to five (Wijewardene, 1978b) times the initial investment, but changes may not be economical unless the standard of crop production is also improved (Farrington, 1977; Hayes & Raheja, 1977). Sometimes new cropping methods require the use of herbicides. For example, the introduction of direct seeding of rice has required the use of herbicides to allow the crop to become established (de Datta, 1972; Anon, 1976b). However, the profitable sale of surplus crops, which is basic to increased investment, first requires the improvement of the transport and marketing systems (Haswell, 1974; Onyemelukwe, 1979).

The financial cost is particularly important with the introduction of herbicides to replace, or partially replace, hand-weeding. Many farmers do not recognise the yield reductions caused by weeds (Parker & Fryer, 1975; Kasasian, 1978; Nachtigal, 1981), and the use of herbicides does not always increase the crop yield compared to hand-weeding (Conklin _et al_, 1982; Parker & Vernon, 1982). The cost of using herbicides is likely to be too great for them to be attractive to most traditional small-holder farmers (Miller _et al_, 1980), when the high cost of herbicides and sprayers is compared to the often low labour costs and the low sale value of food crops, e.g. in Botswana (Garforth, 1979), Tanzania (Miller & Burrill, 1980) and Zaire (Terman & Hart, 1977). If there is no alternative employment to compensate for the cost of the herbicide the farmer may prefer to hand-weed his crops (Doll _et al_, 1977). However, where there is a labour shortage, or labour demands high wages, not only will the herbicide reduce his reliance on paid labour and reduce costs, but also it will allow him to gain other employment or to improve and expand his own crops. It is these "opportunity costs" which are considered when deciding between hiring labour or herbicide use (Akobundu, 1980a). For example, the weed control method selected for rice in the Phillipines reflected the relative cost of labour and the availability of labour and capital, rather than the technical advantages of one method over another (Moody & de Datta, 1980). The substitution of capital for labour causes a greater dependence on the often unstable market economy for purchased inputs and products for sale, introducing another type of risk.

Weed control measures are undertaken at a time of year when the financial resources of a small-farmer are very low (Nachtigal, 1981) and they usually need credit to purchase inputs. This is often difficult to obtain (Beaumont, 1977; Beets, 1979) which may limit the spread of new techniques. With this low financial strength, the farmers are a great risk to distributors selling the inputs, particularly considering the low, seasonal turnover. This may result in poor availability of the inputs, lowering the chance of adoption (Capinpin, 1975; Deuse, 1978; Hildebrand, 1979; Atayi & Knipscheer, 1980; Parker & Vernon, 1982). Credit schemes can help the introduction of new technology (Terman & Hart, 1977; Prior & McPhillips, 1980) but they are difficult to organise successfully (Capinpin, 1975; Aebi, 1976).

6.7. Introduction of New Technology

Recent thoughts on the development and introduction of new techniques for small-holder farmers are reviewed by EFSAIP (1977), Beets (1979), Hildebrand (1979) and Zandstra (1980). In summary, there may be considered to be four stages:

i) descriptive
Examine the traditional farming system in agronomic, social and economic terms to recommend areas for improvement.

ii) design
Thorough evaluation of a range of technologies on experimental stations and trials farms.

iii) testing
Evaluation of a small number of techniques by the farmers under supervision, to determine the potential for adoption of the techniques.

iv) extension
The technique which best achieved the objectives is passed on to farmers on a wide scale.

The wheelbarrow sprayer has been developed to the design stage in this project.

The adoption of herbicides may be aided by associating their application timing with a crop production factor which is already familiar, such as sowing (Sharman, 1970; Shetty & Krantz, 1978) or fertilising (Ogborn, 1975, 1977; Zahran & Ibrahim, 1975). Considerable education is necessary in the prevention of weeds and timing of weed control, as well as the new concepts of herbicide use: dose, selectivity, pre- and post-emergence, residual and foliar activity, toxicity etc. (Haswell, 1972; Doll, 1976). Only 60% of farmers using herbicides in Mindanao were aware that some herbicides were selective. 13% were aware that some were applied pre-emergence and others post-emergence (Navarez & Moody, 1980). This ignorance can be a source of many practical problems such as the use of an inappropriate herbicide or the wrong dose leading to crop damage or poor weed control which may inhibit the acceptance of herbicides (Capinpin, 1975; Ebner, 1982).

A simple, graphic presentation of information to farmer groups is useful to communicate concepts and techniques (Vicenzi, 1979), particularly if it is associated with a well organised system of demonstration plots (Sprague, 1970). Governments often ensure that there is a strong advisory component in any package deal for the supply of chemicals by a company, to overcome the ineffectiveness of some government extension agencies (MacPherson, 1980). The distributors of machinery and pesticides are important in disseminating information. They were of equal importance to extension workers in introducing 2,4D to Colombian farmers (Rogers & Meyhan, 1965), and the adoption of paraquat and 2,4D in Orissa State, India was related to the accessibility of a distributor rather than to the proximity of a demonstration site (Lewis & Watson, 1972). However, agricultural distributors are less widespread in Africa than in Asia or Latin America, and more must become established before herbicides can be widely used.

6.8. Considerations for the Use of the Wheelbarrow Sprayer

The recommendation of a few, well researched herbicides with a simple but reliable method of application will overcome some of the problems of the introduction of herbicides (Adam, 1976; Parker, 1976; Prior & McPhillips, 1980). The wheelbarrow sprayer is designed to be used in areas with few trained personnel so the spraying programme should be as simple and self-explanatory as possible.

6.8.1. Swath matching

There is little emphasis on correct swath matching in the manufacturers' instructions for using knapsack or spinning disc sprayers. The nozzles of the sprayers are susceptible to movements of the operator, causing variations in the position and the width of the swath. The wheelbarrow sprayer runs on the ground so the swath is must less susceptible to these movements, improving the accuracy of spraying. Field tests showed that the effective swath width was consistently slightly less than that calculated from patternator tests. This must be taken into account in the final recommendations.

An acceptably even ground cover can be obtained easily when the crop rows are visible to guide the operator, provided the correct swath width is chosen and a 100% overlap is used. When the 100% overlap is used the lowest dose applied when the swaths are not correctly matched will be 50% of the target, and the highest will be 150% of the target. In pre-emergence spraying the crop rows are likely to be less visible, but the planted row of seeds has proved an adequate marker (Fowler, 1981). If a suitable herbicide is available, such as atrazine for maize, spraying may be delayed until the crop rows are just visible. This is necessary when the seeds have been harrowed in (Fowler, 1981).

In no-till farming stubble remaining from the previous season is visible and the operator can follow the crop inter-rows when spraying a broad-spectrum herbicide to prepare for drilling. When establishing the first crop it is necessary to use a marker system. A series of posts at either end of the field is useful, but a system of ropes stretched across the field improves the accuracy of the spraying (Wijewardene, 1981). The rope system has been used successfully by farmers practising the Lima cropping system in Zambia (Prior & McPhillips, 1980).

An alternative to placing markers in the field is to incorporate a marking system in the sprayer design. An arm from the wheelbarrow sprayer could be used to leave a mark in the soil where the next wheeling should occur. At the end of each run across the field the arm would be switched to the other side of the sprayer, and when not in use the arm could be easily folded against the handles. This system may not provide a sufficiently visible mark in some conditions, but the increased cost of the sprayer could be offset by the savings in accurately applied herbicides.

6.8.2. Choice of herbicides

The choice of herbicides for use with the wheelbarrow sprayer is an important factor in determining its success. Unfortunately there is a great lack of experience with herbicides in many tropical crops, and the susceptibilities of many tropical weeds are unknown. Suggestions for herbicides have recently been made for a number of tropical small farm crops, including cassava (Akobundu, 1980c), cotton (Carson, 1979; Choudhary, 1980), cowpea (Akobundu, 1982; Lagoke et al, 1982), groundnuts (Lagoke et al, 1981), tropical legumes (Moody, 1978b), pearl millet (Choudhary & Lagoke, 1981), rice (Anon, 1976b) and sorghum (Parker, 1979; Shetty, 1979). There are recommendations and reviews available for some areas, including the Caribbean (Hammerton, 1981), Nigeria (Ogborn, 1976; Akobundu, 1979), South Africa (Hattingh & Swanepoel, 1978), Swaziland (Anon, 1975b) and Zimbabwe (Anon, 1974). Yet there are many crops for which there is still a need for more herbicide screening, even for widely grown crops such as sorghum (Parker, 1979).

The efficacy and crop safety of herbicides must be tested locally before they can be recommended, because of the variations in weed spectrum, cultivars, climate and soil conditions. A crop:weed selectivity ratio of 5:1 for the herbicide for all crops grown by the small-holder farmer has been suggested as necessary (Ogborn, 1969), but this is impractical and a two-fold safety limit should be acceptable. Unless the herbicides are consistently active and safe they are unlikely to be accepted by small farmers. Few herbicides will control a broad spectrum of weeds without damaging some of the components of a mixed crop (Moody, 1978a), but several have been considered suitable for particular mixtures

(Appendix 19). Low doses of herbicides are tolerated by more crops than are full doses, and they could give adequate weed control in mixed crops although additional hand-weeding may be necessary (Akobundu, 1978b; Ebner, 1982). Combinations of herbicides are often required to control the wide range of weed species present and may allow the use of safer, reduced doses of the components (Akobundu, 1978b). Broad-leaved weed herbicides used alone will allow grass weeds to develop rapidly, and competition with the crop may be as severe as without any herbicide. Care must be taken that residual herbicides do not persist and affect the following crop. A low dose of atrazine in combination with metolachlor did not affect a following crop of cowpeas, whereas a full dose caused damage (Olunga & Akobundu, 1978).

Herbicides with low volatility are likely to be the simplest to use. Volatile residual herbicides must be incorporated into the soil which would be difficult under small farm conditions. Volatile herbicides, particularly ester formulations of hormone herbicides, are susceptible to vapour drift which may damage neighbouring crops (Combellack, 1982).

The safety aspects of pesticide use by small-holder farmers in the tropics are reviewed by Bull (1982). Considerable education is required to minimise the number of accidents. Although herbicides are not usually toxic if used according to the recommendations, these may not be fully understood and hot, humid conditions are not conducive to wearing chemical proof clothing. Gloves, footwear and washing facilities are all essentials which are not always available. Some manufacturers' literature illustrates barefooted knapsack operators walking through the spray swath, but the wheelbarrow sprayer is inherently safer than most hand-held sprayers since the atomiser is well behind the operator. Residues in food crops may cause problems when there are only one or two staple foods (Kasasian, 1971). The herbicide should be suitably packed for storage in hot, humid conditions and contamination of drinking water, or storing food in used containers should be avoided. The prevention of the misuse of pesticides requires the cooperation of the manufacturers, their distributors and governments.

The cost of the herbicide is an important factor. In Asia 2,4D was adopted for rice because it was much cheaper than newer chemicals (Birowo, 1977). Parker (1976) considered that it was important to develop new recommendations for the cheaper, off-patent herbicides, but care must be taken with recommendations to ensure that they do not give disappointing results. Low doses of herbicides, backed up by hand weeding, could reduce the costs of both herbicides and labour (Versteeg & Maldonado, 1978; Ebner, 1982; van Hoogstraten & Fine, 1982), while optimising the use of labour and using a dose which is safer to the crop.

6.8.3. Herbicide packaging and availability

A few ready to use herbicide formulations are available for hand-held spinning disc sprayers applying less than 10 l/ha. The small size of the market probably does not warrant the development of many special formulations, and the pack size required for the wheelbarrow sprayer which applies 20 l/ha would be prohibitively expensive.

Many herbicides are presently sold in quantities which cover a larger area than a small-holder farmer is likely to spray. These large packs are costly, and the herbicide remaining after use could degrade before it is used in the following season and could be a safety hazard if stored on the farm. Smaller packs are now being introduced by some companies for sale to small-holder farmers, e.g. glyphosate, pendimethalin. Pre-packed herbicides, containing the correct dose for the area covered by one spray tank, reduce the errors in dosing and provide the herbicide in an appropriate pack size. They have been used successfully in the introduction of insecticides to small-holder cotton growers (Tunstall & Matthews, 1965; Matthews, 1981b) and of herbicides to farmers in Swaziland (Fowler, 1981), but this system has inherent disadvantages when using pre-emergence herbicides, since the dose may vary with soil type. Ogborn (1983) suggested that all herbicides should be supplied to small-holders from a central service station where they would be diluted ready for use, but this would require a high level of supervision to ensure correct dilution and labelling, and reformulation would not be popular with the manufacturers (Parker, 1983). However, centralised mixing has a number of managerial advantages. It has been used in sugar cane plantations in South Africa (Boast, 1975) and could be applicable to farmers in settlement schemes where the problems of transport and organisation might be less severe than in other areas.

6.8.4. Instructions for using the wheelbarrow sprayer

Simple pictograms with titles illustrating the correct use of the sprayer should be printed on the spray tank:

i) add chemical to small amount of water in spray tank; operator wearing gloves.
ii) top up with water to the mark on the tank.
iii) pull the sprayer to commence spraying.
iv) walk up inter-rows, or, mark out field with ropes if these are not visible.
v) push sprayer when not spraying.
vi) clean sprayer after use by filling with water and walking.
vii) result of spraying: dying vegetation / clean crop.

Herbicide packages should also illustrate the use of their contents. If a single herbicide is introduced the instructions can be very simple as with the Norman-King sprayer in Swaziland (Fowler, 1981), but when other chemicals become available more comprehensive instructions are required:

i) crop or crop mixtures in which the herbicide can be used (colour coding or pictograms).
ii) illustration of crop at correct stage for spraying.
iii) indication of the area the pack should cover, e.g. the number of paces required to spray it.
iv) protective clothing required.
v) mixing the herbicide.
vi) spraying.
vii) storage of the herbicide, e.g. full pack on shelf away from people or livestock; destroy the empty pack.
viii) colour codes or pictograms illustrating specific problems with the chemical.
ix) hand-hoe weeds appearing later in the season.

Labelling should be in the local language and supplemented with pictograms for less literate farmers. A set of 16 pictograms covering safety recommendations has been designed for use anywhere in the world. They are preferred to colour codes which can be interpreted differently in different regions (Anon, 1983b).

6.8.5. Integrated weed control

The introduction of herbicides is not a complete answer to weed control problems. The high doses which are required to control difficult weeds may not have an adequate crop safety margin, and some weed species are tolerant of specific herbicides, particularly since climatic effects may reduce herbicide activity. Herbicides should be complemented by other factors which can be manipulated to suppress or control the weeds.

Education should be the basis of a weed control programme: sow clean seed; prevent weeds from producing seeds; maintain multiple cropping and suitable crop rotations where appropriate; sow the crop into a clean seedbed; timely weed control. Cultivations are an important method of weed control. In Botswana autumn ploughing gives better weed control and improves soil moisture conditions compared to traditional spring ploughing, but it is a major change to the farming method and requires considerable education for its introduction (EFSAIP, 1978).

There is potential for improving the competitiveness of crops, although farmers traditionally grow the more competitive of the crops available locally. Some new varieties of cassava branch more profusely and are more competitive than tall, non-branching local varieties (Akobundu, 1980c) and similar differences can be exploited in other crops e.g. cowpea and soyabean (Nangju, 1978). A denser plant spacing increases the competitive ability of the crop, but the costs and benefits must be investigated; although dense planting of rice reduced the effect of weeds it also had a lower cost:benefit ratio compared to a wider spacing with hand or chemical weeding (Kim & Moody, 1980). Mulches suppress weed growth and are used in traditional systems (Conklin _et al_, 1982) and in no-till farming (Wijewardene, 1981).

More efficient weed control may have wider effects than expected. Weeds are important in reducing erosion, and may be used as food for humans and animals. The removal of weeds from the growing crop for animal fodder offsets part of the cost of weeding but the result is late weed removal (Navarez & Moody, 1980; Walter, 1982). In semi-arid areas it may be necessary to cultivate even in the absence of weeds to break the cap which forms on sandy soils. This aids crop emergence and seedling establishment, and reduces the run-off of heavy rain (Meikle, 1973).

6.9. Potential Markets

The sprayer is aimed at small-holder farmers for whom the use of herbicides would improve their returns through savings on labour or better yields. It is suitable where the use of larger equipment is not feasible because of the size or inaccessibility of fields, or because of the costs involved. Unfortunately there have recently been large increases in prices of herbicides in some regions, e.g. Caribbean (Hammerton, 1981), Costa Rica (Miller, 1982), which will obviously affect the potential use of the wheelbarrow sprayer.

i) areas with labour bottlenecks

Small farmers in areas where labour is expensive or scarce could benefit from herbicides by improving yields due to better timing of weed control than is possible by hand-hoeing. The farmer would have more time available to increase the area he crops and to allow more timely planting of other crops. Other possible benefits could be to free children for education and to allow farmers more time for non-agricultural pursuits. Although the use of herbicides is commonly suggested for these regions (Haswell, 1972; Ogborn, 1977; Moody, 1978b; Carson, 1979; Akobundu, 1980a; Miller & Burrill, 1980) very little is used by small farmers (section 1.3). The wheelbarrow sprayer could make herbicide use a more practical proposition because of its simplicity compared to other sprayers.

ii) terrace agriculture

Terraces reduce erosion on cultivated slopes. On the steepest land only manual labour is possible, so that farmers can only progress beyond subsistence if they grow and market high value crops, as in the Malaysian highlands (Seth, 1977), and there are many examples of difficult terraces being abandoned because of poor returns due to low yields, the cost and availability of labour, and the inaccessibility of markets, e.g. Madeira, Seychelles, Yemen (Bell, 1981). Minimum cultivation would reduce the labour input, but the terraces are unsuitable for using tractors since they are inaccessible and may be only one metre wide (Seth, 1977). The wheelbarrow sprayer is an ideal size and the low water requirement minimises the need to carry water up steep slopes. Paraquat is already used in terraces in Malaysia (Seth, 1977) and herbicides have been suggested as useful for terrace farming in the Caribbean (Kasasian, 1964; Hammerton, 1974).

iii) no-till farming

Both the previous groups of farmers may find no-till techniques useful for reducing the labour input for crops, and to suppress weeds and reduce soil erosion (Wijewardene, 1978b). No-till is used in Central America where hand-cut weeds are left as a mulch into which the crop is planted, but trials suggest that mulch production using herbicides could be more economical (Conklin _et al_, 1982). Similar investigations have been made in West Africa (Ndahi, 1982) and a programme has been developed using a pre-plant broad spectrum herbicide (paraquat or glyphosate) to produce a mulch. A mixture of paraquat and a residual herbicide is applied after planting to maintain weed control through the season (Wijewardene, 1981; Akobundu, 1983). The time and labour required is greatly reduced so that double cropping may be feasible in some regions (Parker, 1976; Shetty, 1979). Live mulches using a legume cover crop to smother the weeds and supply nitrogen are being investigated, but they are most effective if a growth regulator is sprayed onto the legume to allow the crop to grow without excessive competition (Akobundu, 1980b). The wheelbarrow sprayer is suitable for all these systems.

iv) small plantations

Small plantations provide a potentially large market for the wheelbarrow sprayer since they involve cash crops. Money or credit may be available for the purchase of inputs, and as labour costs rise herbicides become more economical.

In West Africa most produce from tree or plantation crops is derived from small farms, where herbicides are likely to be used in the near future (Komolafe, 1978), for example in pineapple (Py, 1981) and rubber (de Vernou, 1981). In East Africa a large proportion of tea, coffee and cotton is produced by small farmers, who have used fertilisers for several years and many of whom possess knapsacks for applying insecticides (Senga, 1976). Few herbicides are used but labour is becoming more expensive and the use of herbicides by these farmers is likely in the near future (Hinga & Heyer, 1976; Miller & Burrill, 1980).

Herbicide use in small plantations in South East Asia is becoming economical (Alif, 1977). Several rubber plantations in Indonesia now use a double headed spinning disc sprayer to apply paraquat or glyphosate around trees, saving 40% on labour costs (Turner & Jollands, 1983). Interest has been shown in the use of the wheelbarrow sprayer in sugar cane plantations in Mauritius (Unmole, 1982).

v) settlement schemes

In many parts of the world governments encourage the intensification of small-holder agriculture in specially designated settlement schemes. These usually have marketing facilities, technical advisers and credit and inputs are available (Senga, 1976; Barlow, 1983). This basic infrastructure could allow a relatively easy introduction of the wheelbarrow sprayer.

vi) European markets

There are a number of potential uses for the wheelbarrow sprayer in Europe. Many horticultural units presently use knapsack sprayers, but the wheelbarrow sprayer might be easier to use for the application of soil or foliage applied pesticides in many crops (Anon, 1983a).

Hand-held spinning disc sprayers have advantages compared to heavy knapsack sprayers in amenity turf spraying (Rees, 1980) but the wheelbarrow sprayer would also aid accurate dosing. However, the need for very accurate swath matching to prevent damage on fine turf has been overcome by a new ground-metered hydraulic sprayer (the "Walkover") which marks its swath to allow accurate matching.

Weed control on pavements is commonly carried out by workmen using knapsack sprayers. The same work could be done easily and more accurately by the wheelbarrow sprayer, with the shroud adjusted to direct the spray at the kerb. Some interest has been shown in such uses.

vii) other uses

Several sprayer units could be attached to a tool bar pulled by a tractor or oxen. This overcomes the incorrect dosing of herbicides due to the irregular movement of oxen (Sharman, 1970). Band spraying would also be possible, and a shrouded spinning cup has been used in this way in sugar beet (Nilsson, 1982).

6.10. Logistics and Economics

The wheelbarrow sprayer will probably cost about £100 per unit, so it must have advantages to the small holder farmers which cover the extra cost compared to the hand-hoeing or knapsack sprayers and hand-held spinning disc sprayers (Table 6.6). A number of factors are involved in an assessment of the costs of spraying and hand-hoeing.

6.10.1. Work rate

The work rate for the wheelbarrow sprayer is compared to other sprayers (Table 6.8) using calculations based on the Baltin formula (Baltin, 1959). These figures give the minimum time for spraying and it is probably realistic to double them to allow for rests, which gives figures similar to the 4-5 hrs/ha suggested for spraying with a hand-held spinning disc sprayer (Wijewardene, 1978b, 1979). The spray volume greatly affects the work rate since a high spray volume requires many refills of the spray tank. In the tropics the water source is often a considerable distance from the field, which further reduces the proportion of time actually spent spraying (Fig. 6.5) and can lead to less timely spray applications. The advantage of low volume spraying can be clearly seen in East Africa, where up to 5 hrs per day can be spent carrying water for domestic use alone (Harrison, 1980). In practice high volume spraying requires two labourers, one spraying and one ferrying water (Akobundu, 1980a), so the wheelbarrow sprayer could save the cost of the assistant.

Table 6.8 <u>Time Spent Spraying One Hectare</u> (overall application)

	Wheelbarrow[i]	"Herbi"	Conventional[i] Knapsack	VLV Knapsack
Spray Tank Size (l)	10	2.5	20	20
Spray Volume (l/ha)	20	10	200	60
Swath Width (m)	1.5	1.2	1.5	1.2
<u>Time</u> (hrs/ha):				
Ferrying Time[ii]	0.06	0.06	0.56	0.17
Mixing Time (no. of refills)[iii]	0.1 (2)	0.2 (4)	1.0 (10)	0.3 (3)
Spraying Time @ 1.0 m/s	1.85	2.31	1.85	2.31
Total Time[iv]	2.01	2.57	3.41	2.78
Hectares Sprayed per Hour	0.5	0.39	0.29	0.36

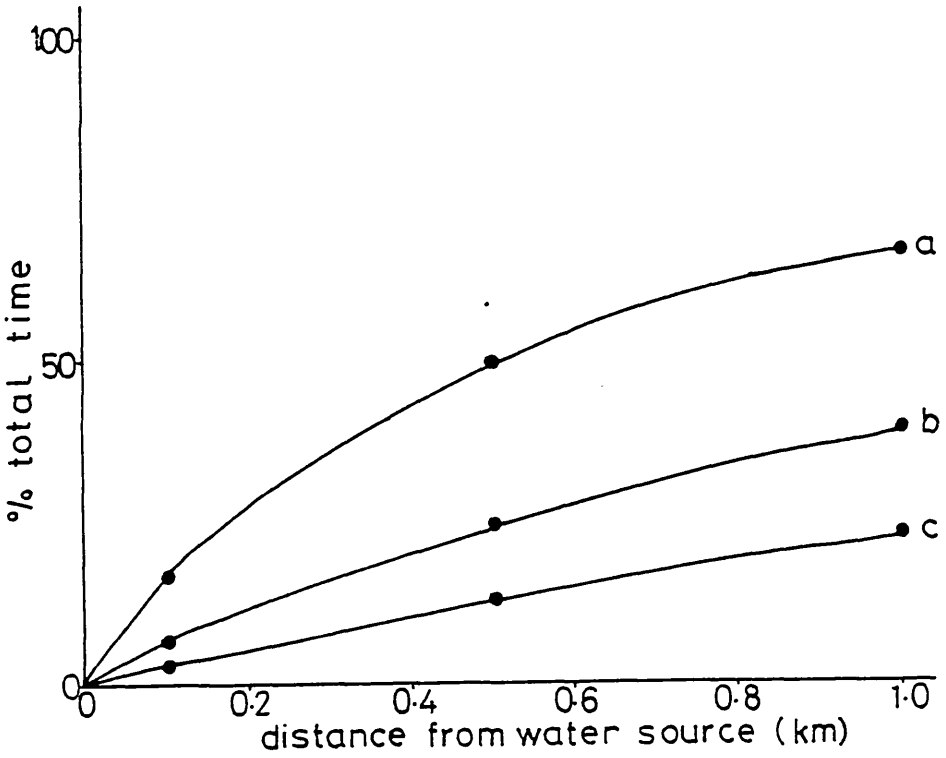
[i] : using 100% overlap, the effective swath is 0.75 m and total time is 3.91 hrs/ha.

[ii] : carry 20 l per trip from water source 0.1 km from field, walking at 1.0 m/sec.

[iii] : wheelbarrow and "Herbi" = 0.05 hrs to fill. Knapaack = 0.1 hrs to fill.

[iv] : add on cleaning out time of about 0.1 hr per day.

Fig. 6.5 Proportion of Total Spraying Time Occupied by Ferrying Water



a conventional knapsack (200 l/ha)

b VLV knapsack (60 l/ha)

c wheelbarrow (20 l/ha)

Similar problems arise in the U.K. where 37% of farmers spent over half their time filling their sprayer, and 29% occupied over a fifth of their time travelling between the field and the water source (Rutherford, 1976). The overall work rate was less than 0.4 ha/hr/metre of boom for 72% of the farmers, which is comparable to work rates with hand-held sprayers.

The walking speed affects the work rate of all sprayers. The walking speed of operators using the wheelbarrow was 1.2 m/s when spraying field trials in Botswana. Observations in Nigeria also suggested a natural walking speed of 1.2 m/s when pushing another wheelbarrow sprayer, but some operators approached 2.0 m/s over short distances (Choudhury & Ogborn, 1977).

6.10.2. Costs

The calculation of the costs and benefits of spraying herbicides depends on a number of factors, particularly since economic costs are difficult to relate to subsistence farming.

i) labour costs

The wages of hired labour vary greatly between regions and between seasons, and it is best to take the wages at the peak weeding time when comparing herbicides with hand-weeding. Wages vary greatly between individual farmers (Farrington, 1977), particularly when they are paid partly in food (Navarez & Moody, 1980), and official wage rates can be very different from those actually paid (Binswanger & Shetty, 1977).

The cost of family labour is more difficult to assess. In Nigeria Hayes & Raheja (1977) assumed family labour could directly substitute for hired labour and therefore commanded the same remuneration, but in Malawi the effective cost of family labour was lower than hired labour due to the lack of opportunity for alternative labour (Farrington, 1977). The cost of family labour may be defined by multiplying the hired wage rate by the probability of finding a job on a given day (Binswanger & Shetty, 1977).

ii) length of working day

The term "man-day" is commonly used as a measure of labour input, but this requires further definition. In Africa a working day is usually 5-6 hours, while in Asia and Latin America it is 7-8 hours (Ruthenberg, 1980). Weighting coefficients have been made to convert woman or child labour into man-hours, but such conversions become irrelevant when the men are employed in urban areas away from the farm.

iii) equipment costs

The effective costs of the equipment and herbicides depends not only on manufacturing costs, but also on whether they are imported, the cost of credit, the level of government taxes or subsidies and the type of ownership. A small farmer is unlikely to afford a sprayer unless he has a significant area of cash crops.

Joint ownership by a cooperative would spread the cost over more individuals and over a greater area, and bulk buying of herbicides would further reduce costs. However, the joint ownership of an ox-drawn tool-bar in India was rejected due to the complications of long term ownership and the managerial abilities required to ensure the implement was in the right place at the optimum time (Doherty, 1980). The high cost of the machine precluded individual ownership and renting or contracting by entrepreneurs was considered the best method of introduction. This is common practice with tractor hire in Nigeria, but requires institutional support to be successful (Morris, 1983). In Swaziland the Norman-King sprayer is purchased by cooperatives who rent out to individuals at a small fee which penalises the farmer who takes but does not use the sprayer (Fowler, 1981). Many Phillipine farmers borrow sprayers belonging to neighbours or friends (Navarez & Moody, 1980), while contract spraying occurs in small-farm regions of Mexico (Haswell, 1972).

The price of the wheelbarrow sprayer must cover the considerable costs involved in the production of plastic mouldings for the shroud and the pump, as well as component and assembly costs. Local production is feasible, but centralised production of the plastic components would be most economic, so they will have to be imported for local assembly.

iv) sale of produce

The price which can be obtained for the produce can vary considerably depending on government pricing structures, supply and demand, and accessibility to markets.

6.10.3. Cost effectiveness

It was not considered relevant to carry out a cost: benefit analysis for using the wheelbarrow sprayer due to the difficulty of defining costs without a specific survey. The wheelbarrow sprayer is likely to be cost effective where herbicide use has been shown to be economical.

Herbicide use has been considered cost effective in maize in Costa Rica (Conklin et al, 1982, Miller, 1982), Ghana (Carson, 1978), southern Mexico (Haswell, 1972), Nigeria (Akobundu, 1980a); cotton in Nigeria (Ogborn, 1978b) and Sudan (Jennings & Drennan, 1979); mixed cropping in Indonesia (Ebner, 1982); sorghum, sunflower and cowpea in Peru (Versteeg & Maldonado, 1978); no-till rice production in Sri Lanka (Wijewardene, 1981); soybean in Thailand (Moody, 1978b) and various plantation crops (Alif, 1977; Komolafe, 1978; Miller & Burrill, 1980). However, the calculation of cost efectiveness depends partly on the number of hand-weedings which the herbicides replace (Moody, 1978b; Versteeg & Maldonado, 1978; Akobundu, 1980c) and, in some cases, on the assumption that hand-weeding would not be timely and yield would be lost.

Herbicides were not considered economical in maize in Zambia in spite of an 80% reduction in the labour input, since the labour demand for the second crop, cotton, contributed more to the labour peak (Parker & Vernon, 1982). The very low labour costs in India made hand weeding more economical than herbicides in sorghum and groundnuts (Davies & Shetty, 1981), and they were not considered economical on small farms in Zimbabwe (Mayo, 1981), north east Brazil and El Salvador (Miller et al, 1980) for similar reasons. Although Birowo (1977) considered that weed control was traditionally poor in the Phillipines and herbicides could complement hand labour in raising food production, they were uneconomical in upland rice (Sabio et al, 1980).

6.11. Conclusion

The wheelbarrow sprayer has recently been developed into a commercial pre-production prototype which has been tested around the world. The results have been promising and the sprayer may be test marketed in 1983. Few modifications have been made to the second prototype, but certain recommendations for changes have been followed (Oxberry & Seward, 1982). The final design will be based on experience with the pre-production prototype.

SUMMARY

1) Small-holder farmers form a large proportion of the population of most developing countries, and produce most of the locally grown food. Unfortunately they do not produce sufficient to feed the increasing urban populations, although there is potential for a greater output. The area cultivated by a farmer can be limited by the area which he can weed adequately, but additional labour for hand-weeding is scarce or expensive in many regions. The use of herbicides could ease the labour bottleneck and possibly increase the farm output.

2) Very little herbicide is used by tropical small-holder farmers, although use is increasing where cash crops are grown. Simple but reliable application methods are vital if herbicides are to be introduced, but conventional knapsack sprayers and hand-held spinning disc sprayers have disadvantages which have restricted their use.

3) Following a review of application techniques, a sprayer was designed in the form of a wheelbarrow to overcome several of these disadvantages. A spinning cup allowed the use of a low spray volume (20 l/ha). The liquid feed onto the cup was related to walking speed since it was supplied by a pair of peristaltic pumps driven by the ground wheel. This allowed a constant spray volume of 20 l/ha to be applied over a range of walking speeds. The spinning cup was shrouded to produce a uniform, adjustable spray swath and liquid caught by the shroud was recycled to the spray tank. The spinning cup was rotated by a friction drive from the ground wheel. The angle of the spinning cup could be adjusted for overall or band spraying.

4) The flow rate of liquid onto the spinning cup and the rotational speed of the cup both increase linearly with walking speed. The VMD of the spray decreased rapidly as the walking increased to 0.6 m/s, but more slowly as the walking speed increased further. The VMD/NMD ratio was fairly constant up to 1.2 m/s, but then increased rapidly. When walking at 1.0 m/s the characteristics of

the second prototype were:

spinning cup speed	1700 rpm
flow on to spinning cup	720 ml/min
droplet spectrum: VMD	275 µm
VMD/NMD	2.4

The droplet spectrum was measured using a laser analyser.

5) The pattern along and across the swath was examined using a patternator and fluorescent dyes. The transverse section of the swath was more uniform than that from an unshrouded spinning cup and when adjacent swaths were matched the coefficient of variation (cv) ranged from 5-10% (patternator results) or 9-25% (fluorescent tracers). The pulsing of the output from the peristaltic pumps produced regular peaks along the swath (cv=14-40%). To give a central swath the shroud window must be positioned slightly off-centre.

6) In laboratory comparisons between the spinning cup on the wheelbarrow sprayer, an impact nozzle and a fan nozzle, all three gave similar kill of radish and oats using pendimethalin and 2,4D amine or ester. The wheelbarrow sprayer was superior with paraquat and glyphosate but poorer than the impact nozzle with atrazine. The results of post-emergence applications were related to spray retention by the plants.

7) The sprayer gave similar weed control at all walking speeds, although the droplet spectrum changed. The pulsing of the spray could not be detected in terms of weed control unless a very low dose of a herbicide was applied.

8) In field trials in Botswana the wheelbarrow consistently gave better weed control than an impact nozzle on a knapsack sprayer, and the results were equal to or better than a hand-held spinning disc sprayer except when applying paraquat.

9) Several trials were carried out to investigate various aspects of herbicide use in Botswana. Pre-emergence herbicides were unreliable due to the irregular rainfall, while the activity of 2,4D was greater early in the morning than during the day.

10) The wheelbarrow sprayer attained most of the objectives of the project, but it is likely to be expensive and more restricted in use than knapsack sprayers. Recommendations were made for modifications to the second prototype, including a cheaper pump, an improved shroud and a simplified mounting for the spinning cup.

11) The system for using the sprayer should be carefully researched for each region where it is to be introduced, so that the weed control is reliable and acceptable without harming the crop. Further investigations must be made into inter-row spraying before it can be safely recommended.

12) The sprayer is most likely to be used on small-holder farms where the cost of availability of labour severely limits hand weeding, particularly in terrace agriculture, small plantations and settlement schemes. It is also suitable for horticultural or amenity spraying. The wheelbarrow sprayer has recently been developed commercially.

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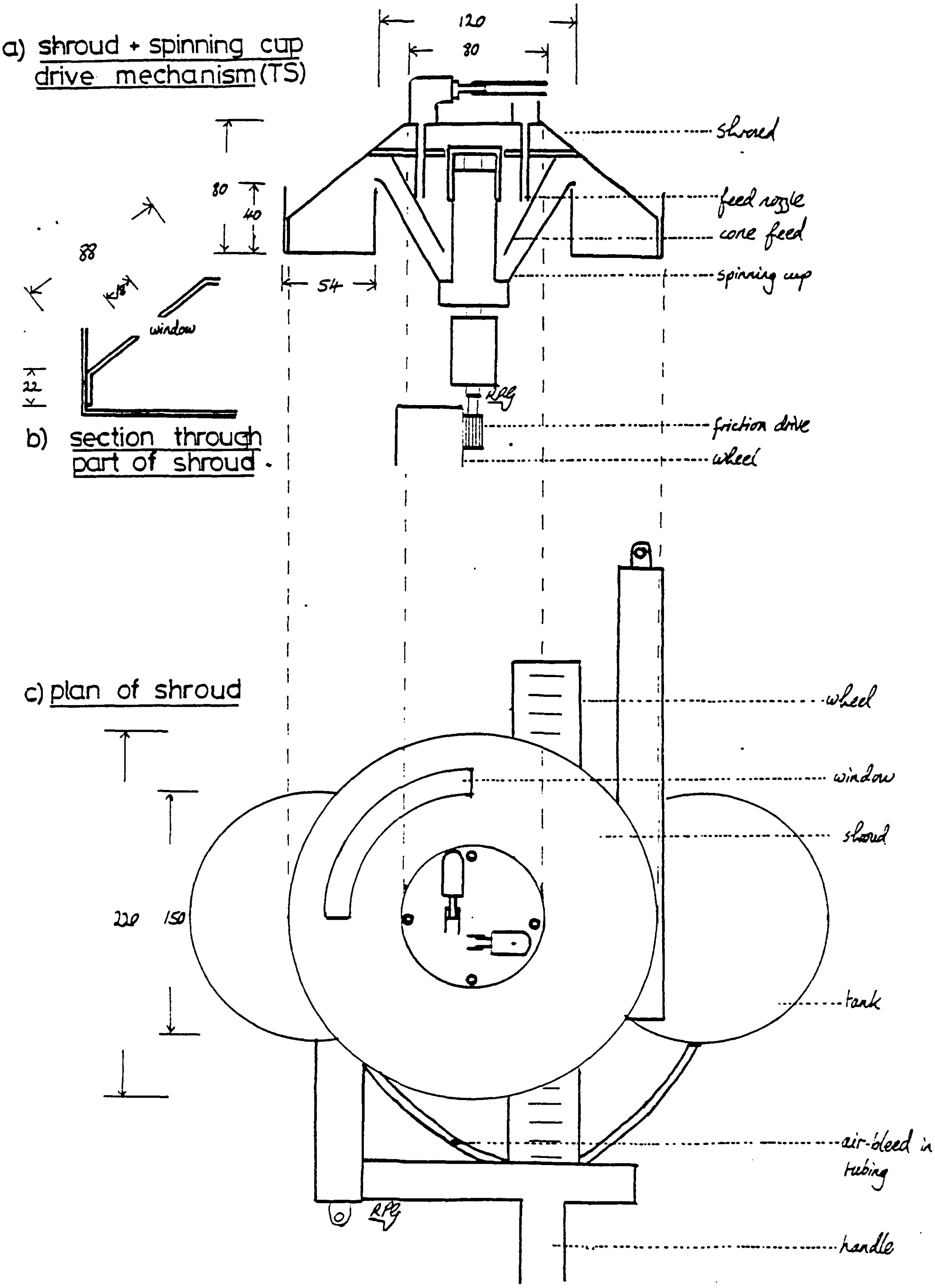
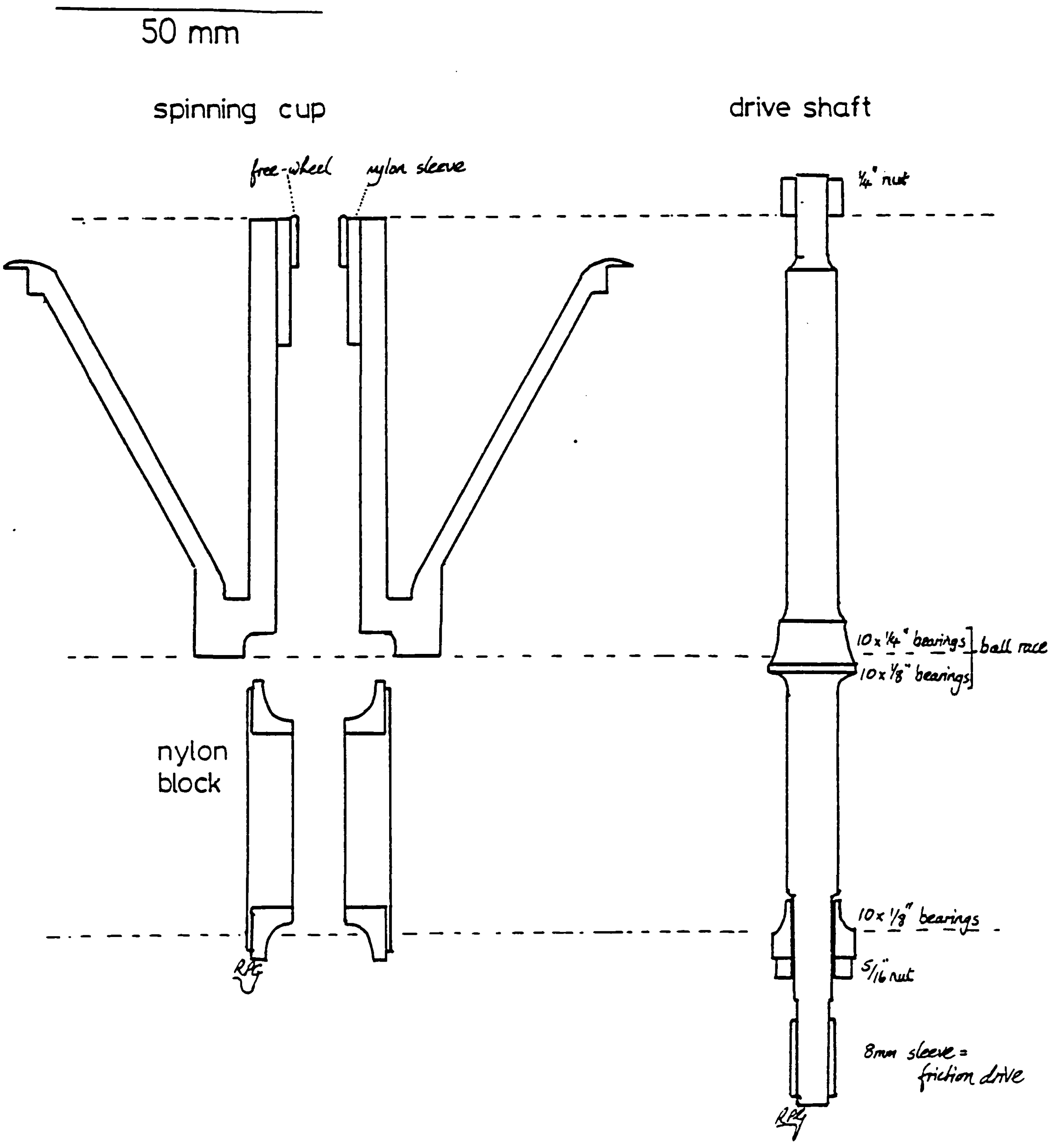
INDEX TO APPENDICES

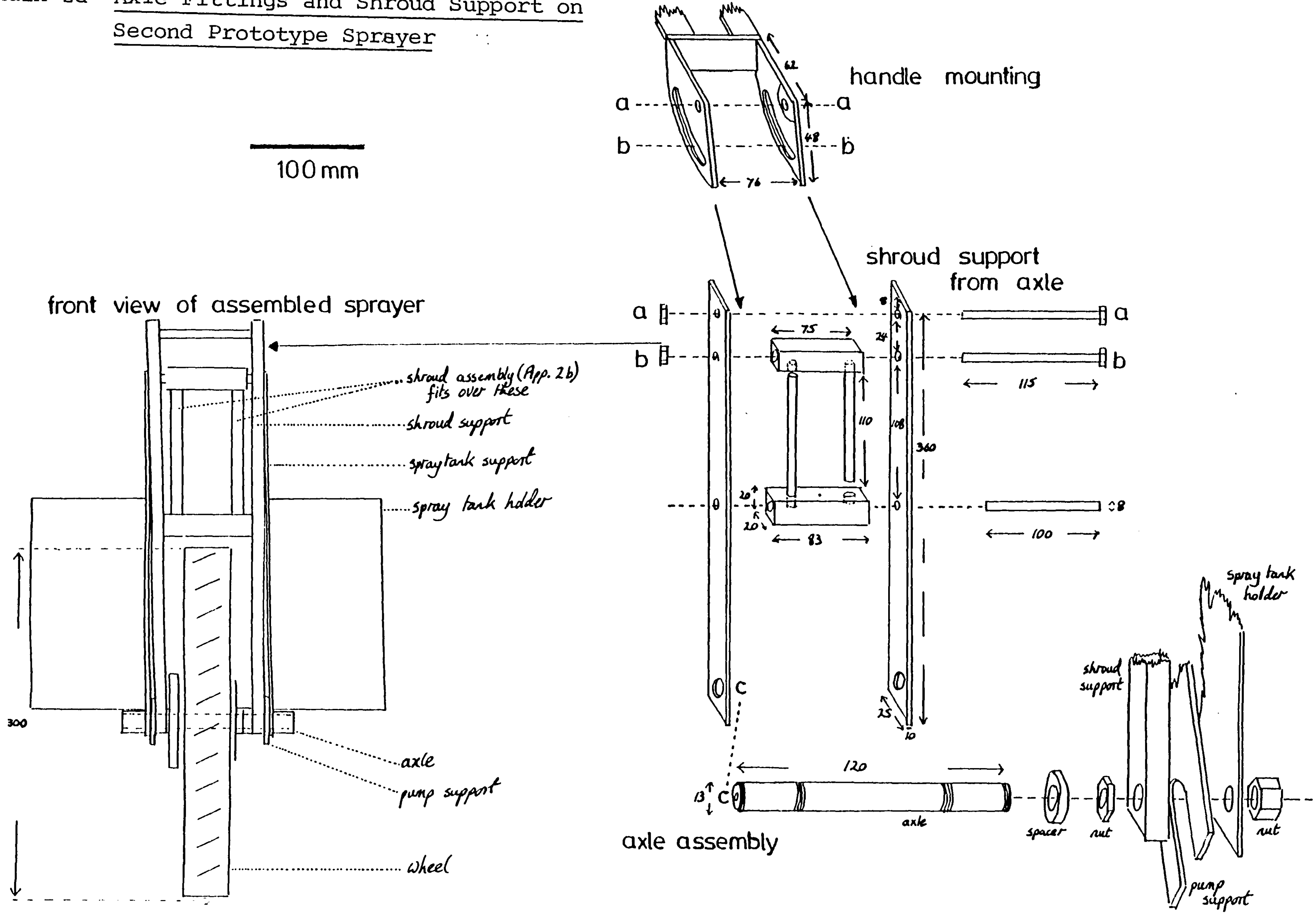
Appendix 1a Shroud and Drive on First Prototype Sprayer (mm)



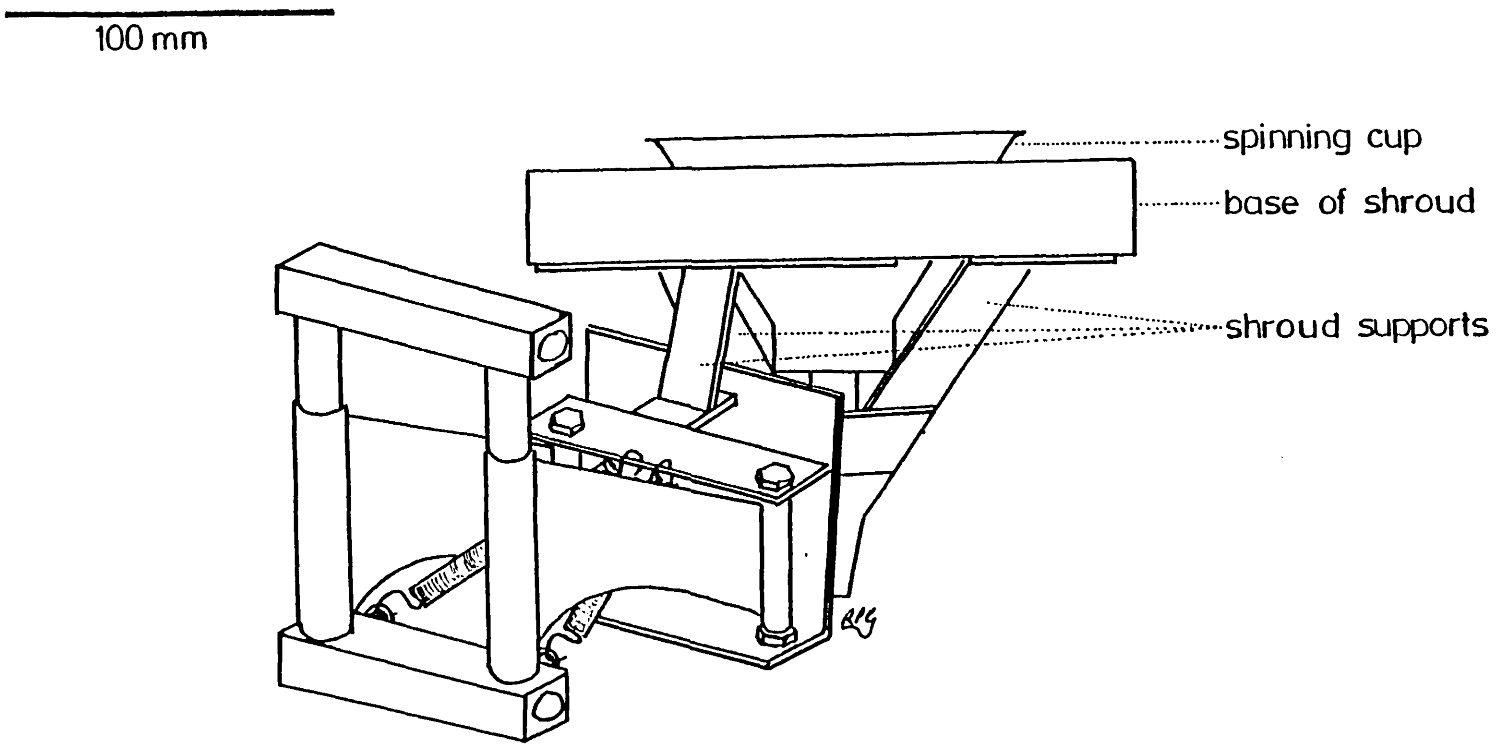
Appendix 1b <u>T.S. of Components of Spinning Cup Drive on First Prototype Sprayer</u>



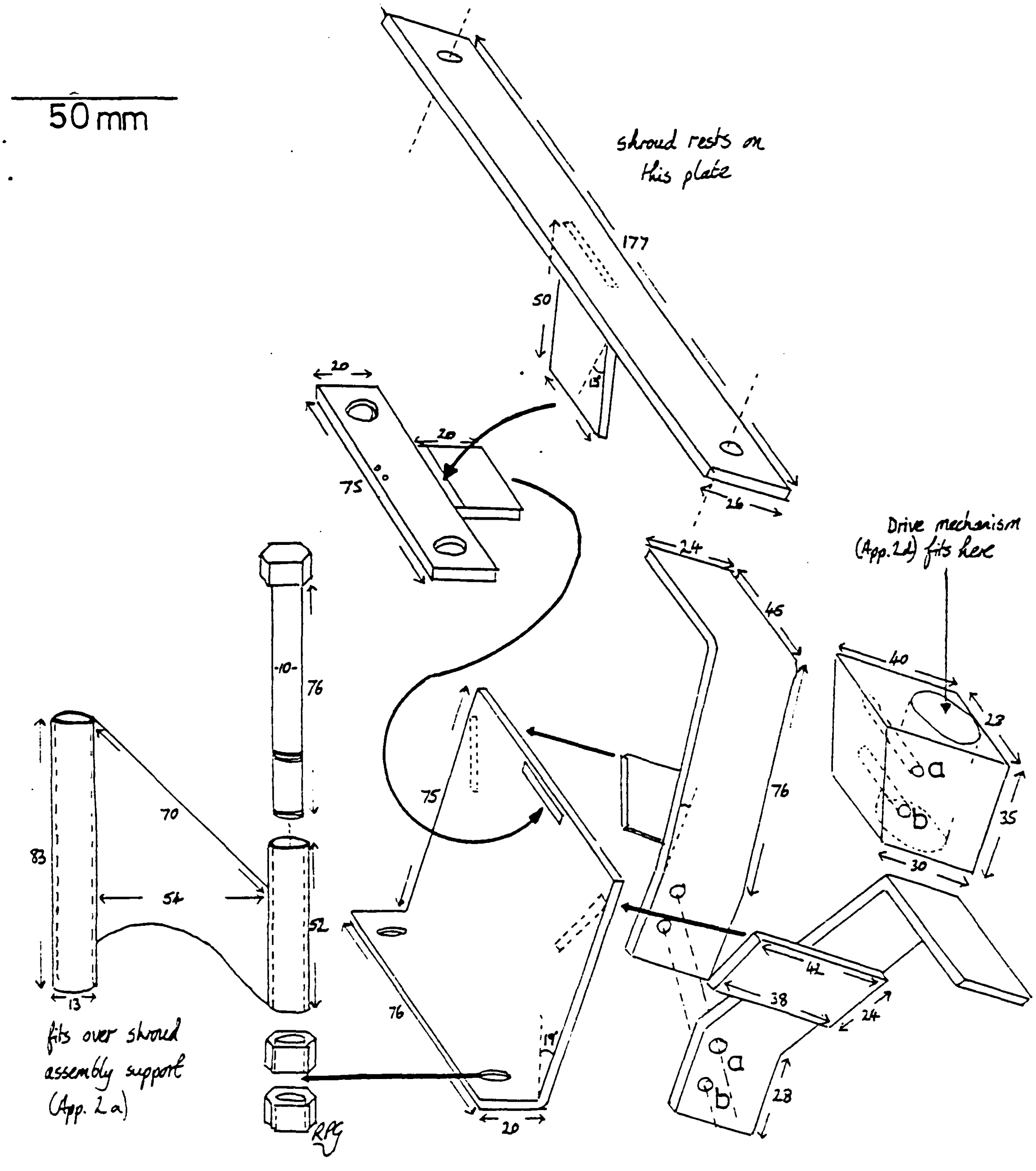
Appendix 2a Axle Fittings and Shroud Support on Second Prototype Sprayer



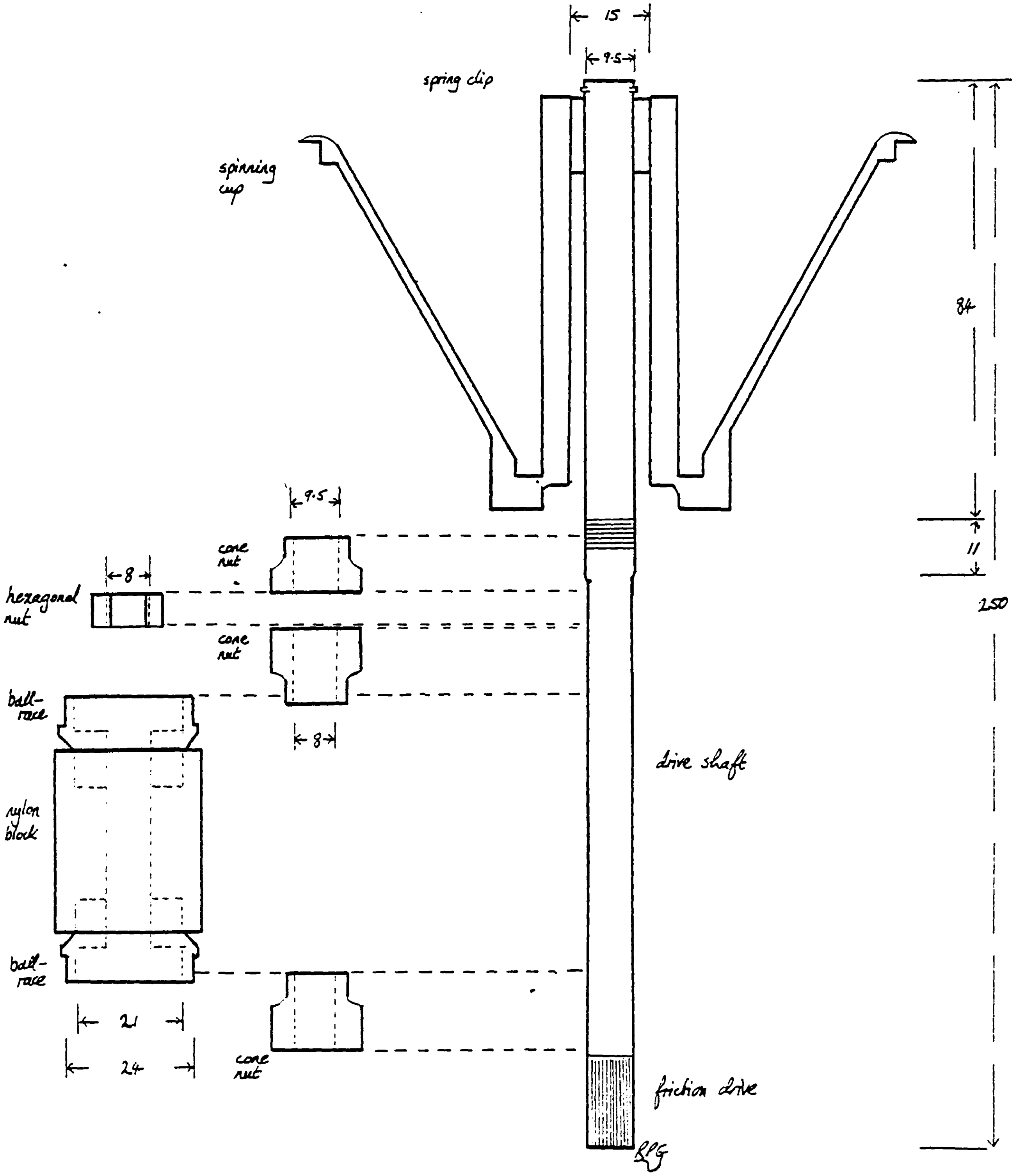
Appendix 2b Complete Drive Shaft and Shroud Assembly on Second Prototype Sprayer



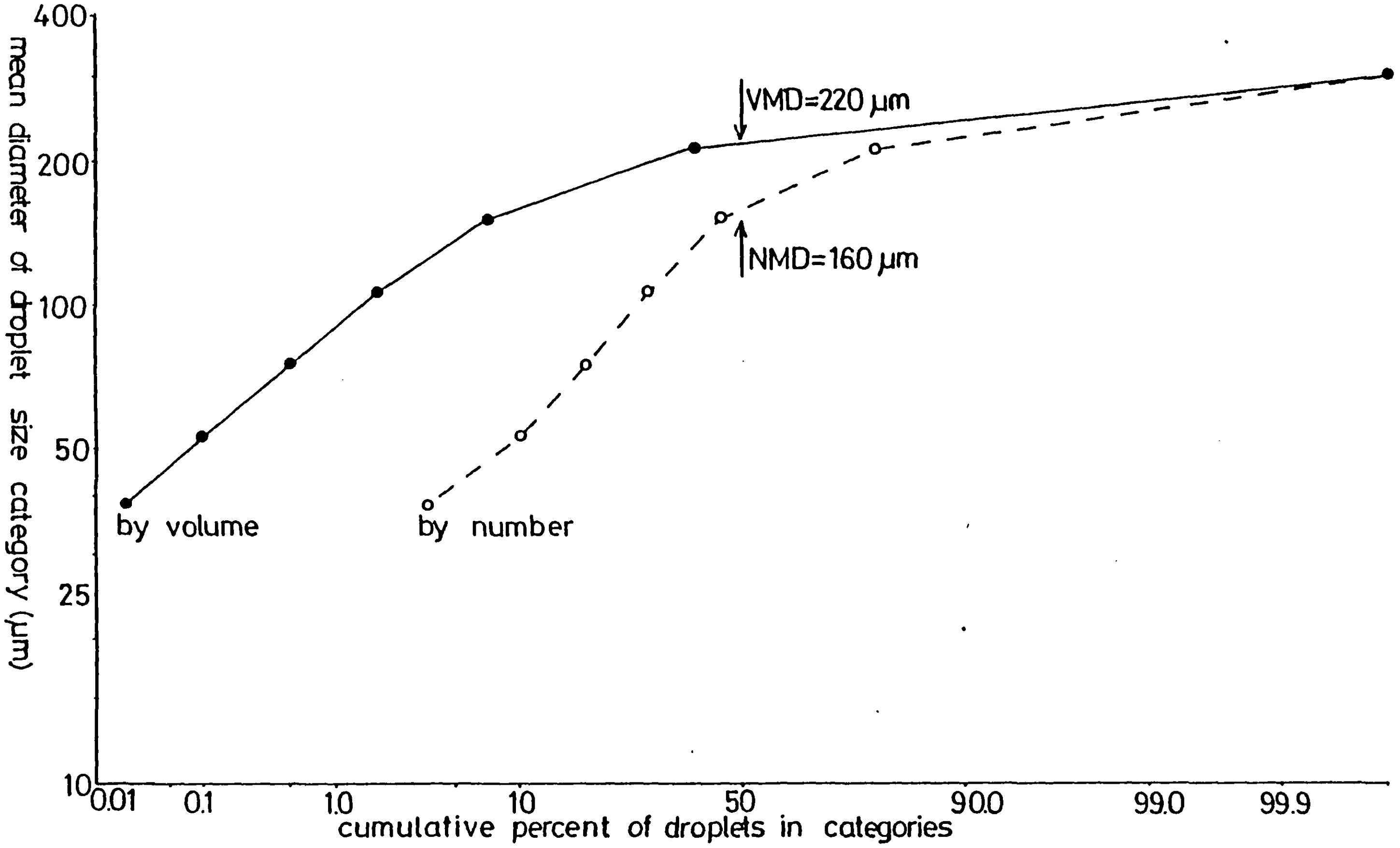
Appendix 2c Drive Shaft and Shroud Mounting on Second Prototype Sprayer



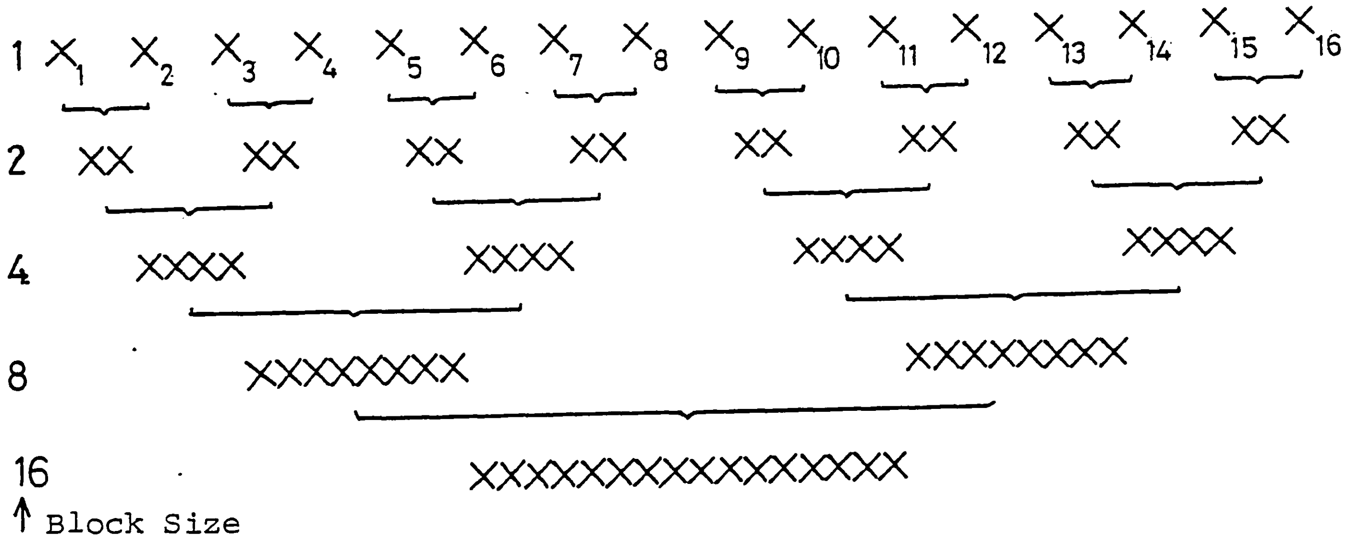
Appendix 2d T.S. of Spinning Cup and Drive Mechanism on Second Prototype Sprayer (mm)



Appendix 3 <u>Graphical Method to Obtain VMD and NMD</u> (droplet size categories calculated on a $\sqrt{2}$ progression)



Appendix 4 Blocking Process in Pattern Analysis
(Greig-Smith, 1959)



Variance is estimated by the mean square (MS):

for block size 1,

$$MS = \frac{\left[\tfrac{1}{2}(x_1 - x_2)^2 + \tfrac{1}{2}(x_3 - x_4)^2 + \ldots\ldots\ldots \tfrac{1}{2}(x_{15} - x_{16})^2\right]}{y}$$

where y is the number of pairs compared = 8

for block size 2,

$$MS = \frac{\left[\tfrac{1}{4}(x_1 + x_2 - x_3 - x_4)^2 + \ldots\ldots\ldots \tfrac{1}{4}(x_{13} + x_{14} - x_{15} - x_{16})^2\right]}{y}$$

where y is the number of groups compared = 4

Blocking Process in Two-Term Local Variance (Hill, 1973)

for block size 1,

$$MS = \frac{\left[\tfrac{1}{2}(x_1 - x_2)^2 + \tfrac{1}{2}(x_2 - x_3)^2 + \tfrac{1}{2}(x_3 - x_4)^2 + \ldots\ldots \tfrac{1}{2}(x_{15} - x_{16})^2\right]}{y}$$

where y is the number of pairs compared = 15

This eliminates the need for the number of samples to be a power of 2.

APPENDIX 5

SURVEY OF COMMERCIALLY AVAILABLE LOW OUTPUT PUMPS

TYPE OF PUMP	MODEL AND MANUFACTURER	FLOW RATE AT 100 rpm with nominal head (ml/min)	MATERIALS IN CONTACT WITH LIQUID
Centrifugal	Windscreen Pump Lucas U.K. Ltd.	very low	synthetic rubber
Centrifugal (magnetically coupled)	"Little Giant" Schuco Scientific Ltd.	low	polypropylene
Eccentric Shaft/ Flexible Liner	"Flexi-liner" Vanton Pumps Ltd.	630	various
Gear	GP3/8/100E Autometric Pumps Ltd.	1100	bronze
	"Midget" Crown Pump Manufacturers Ltd.	low	cast iron/steel or gun-metal/brass
Magnetic Liquid	Magnetic Liquid Pump J. Wolfe Ltd.	very low	magnetic fluid/plastic
Peristaltic Pump	AZA 8 Delasco Ltd.	800	(3 rollers)
	Hosepump SP 25 Bredel Ltd.	2000	(2 rollers)
	HR Flow Inducer Watson-Marlow Ltd.	575	(3 rollers)
	Minipuls HP2/HF Anachem Ltd.	840	(10 rollers)
	Pericycla Pump Schuco Scientific Ltd.	200	(3 rollers)
	WAB Tube Pump Glen Creston Ltd.	500	(2 rollers)
Piston Pump (rotating + reciprocating)	RP Lab Pump Fluid Metering Inc.	34	various

APPENDIX 6

EFFECT OF "WALKING SPEED" ON DROPLET PRODUCTION (UNMOUNTED 'MICROMAX')

Walking speed m/s	Micromax speed rpm	SINGLE PUMP						TWO PUMPS					
		6 mm tubing			8 mm tubing			6 mm tubing			8 mm tubing		
		Flow rate ml/min.	VMD	VMD/NMD	Flow rate ml/min.	VMD	VMD/NMD	Flow rate ml/min.	VMD	VMD/NMD	Flow rate ml/min.	VMD	VMD/NMD
0.29	500	100	932	1.4	125	865	1.5	200	824	1.3	250	868	1.3
0.58	1000	200	397	1.5	250	396	1.3	400	331	1.1	500	376	1.2
0.87	1500	300	254	1.3	375	276	1.5	600	300	1.4	750	323	1.5
1.16	2000	400	241	2.0	500	247	1.7	800	283	1.7	1000	300	1.7
1.45	2500	500	222	1.7	625	221	2.2	1000	260	2.1	1250	280	2.3
1.76	3000	600	169	3.3	750	201	2.2	1200	223	2.5	1500	252	5.3

power progression	$y = 277.2x^{0.89}$ $(r = 0.97)$	$y = 281.5x^{0.79}$ $(r = 0.97)$	$y = 309.1x^{-0.64}$ $(r = 0.94)$	$y = 5.8x^{-0.62}$ $(r = 0.93)$
log progression	$y = 323.8 - 396.9 \ln x$ $(r = -0.93)$	$y = 309.3 - 346.8 \ln x$ $(r = -0.91)$	$y = 332.3 - 295.6 \ln x$ $(r = -0.90)$	$y = 357.1 - 289.9 \ln x$ $(r = -0.89)$

APPENDIX 7

EFFECT OF "FRICTION DRIVE DIAMETER" ON MICROMAX SPEED AND DROPLET PRODUCTION

Friction drive diam (mm) Micromax rpm @ 1 m/s		9.5 2000		6.5 2500		5.4 3000	
Walking speed m/s	Flow rate[1] ml/min	VMD	VMD/NMD	VMD	VMD/NMD	VMD	VMD/NMD
0.29	125	865	1.5	700	1.2	613	1.2
0.58	250	396	1.3	279	1.4	236	1.5
0.87	375	276	1.5	240	1.4	214	1.8
1.16	500	247	1.7	222	1.7	183	3.4
1.45	625	221	2.2	190	3.9	181	4.6
1.76	750	201	2.2	184	4.6	165	7.9
0.29	250	868	1.3	697	1.1	563	1.3
0.58	500	376	1.2	316	1.3	273	1.4
0.87	750	323	1.5	280	1.7	226	2.1
1.16	1000	300	1.7	260	2.1	227	3.1
1.45	1250	280	2.3	239	4.5	204	12.2
1.76	1500	252	5.3	228	24.9	182	24.9

[1] Equivalent to using 8 mm tubing in peristaltic pump

Appendix 8 Droplet Production from a "Micromax" Mounted on a Wheelbarrow Sprayer,(1) or Driven by Electric Motor

Walking speed (m/s)	"Micromax" speed (rpm)	Flow rate (1 pump) (ml/min)	Wheelbarrow VMD (µm)	Wheelbarrow VMD/NMD	Motor driven VMD (µm)	Motor driven VMD/NMD	Flow rate (2 pumps) (ml/min)	Wheelbarrow VMD (µm)	Wheelbarrow VMD/NMD	Motor driven VMD (µm)	Motor driven VMD/NMD
0.58	1000	200	391	1.2	397	1.5	400	424	1.2	331	1.1
0.87	1500	320	259	1.6	260	1.1	640	301	2.0	306	1.1
1.16	2000	420	220	1.8	242	1.9	840	243	2.5	287	1.4
1.45	2500	520	222	2.9	222	1.7	1040	204	4.5	272	2.1
1.76	3000	620	207	6.4	174	3.4	1240	215	7.2	226	3.2

(1) using a Glen Creston Pump, with 6 mm tubing

Appendix 9 Laboratory and Greenhouse Experiments: significance of analysis of variance.

		cv (%)	Sprayer	Dose	Interaction	Block
atrazine						
radish	f	28	+++	+++	+++	NS
oats	f	29	++	+++	NS	NS
pendimethalin						
radish	f	32	NS	+++	NS	NS
oats	f	17	NS	NS	NS	++
paraquat						
radish	f	38	+++	+++	+++	NS
	d	31	+++	+++	NS	NS
	f:d	35	+++	+++	+++	NS
oats	f	27	+++	+++	+++	NS
	d	22	+++	+++	+++	++
	f:d	107	NS	NS	NS	NS
glyphosate						
radish	f	30	+++	+++	+++	NS
	d	32	+++	+++	+++	NS
	f:d	20	+++	+++	+++	NS
oats	f	48	+++	+++	+++	NS
	d	38	+++	+++	+++	NS
	f:d	32	NS	+++	NS	NS
2,4D ester						
radish	f	41	NS	+++	NS	NS
2,4D amine						
radish	f	45	+++	+++	+++	NS

+++	significant at 0.1%
++	significant at 1.0%
+	significant at 5.0%
NS	not significant

f = fresh weight
d = dry weight
f:d = fresh:dry weight ratio

Appendix 10 Droplet Spectrum Across the Wheelbarrow Swath

distance from centre of swath (m)		VMD (µm)	NMD (µm)	VMD/NMD
left	0.7	327	323	1.01
	0.6	327	262	1.25
	0.5	340	327	1.04
	0.4	314	258	1.22
	0.3	323	271	1.19
	0.2	318	232	1.37
	0.1	258	181	1.43
centre				
	0.1	310	189	1.64
	0.2	318	284	1.12
	0.3	318	258	1.23
	0.4	318	271	1.17
	0.5	323	301	1.07
	0.6	327	318	1.03
right	0.7	327	103	3.17
combined results		323	241	1.34
replicate	1	327	226	1.45
	2	314	228	1.38
	3	318	228	1.39
	4	314	241	1.30
	s	6.1	6.9	0.06

Appendix 11 Key

a) cyanazine

○ wheelbarrow sprayer: along swath (sample I)

● wheelbarrow sprayer: along swath (sample II)

■ wheelbarrow sprayer: across swath

□ knapsack sprayer: along swath

b) paraquat

○ wheelbarrow sprayer: angled (fresh weight)

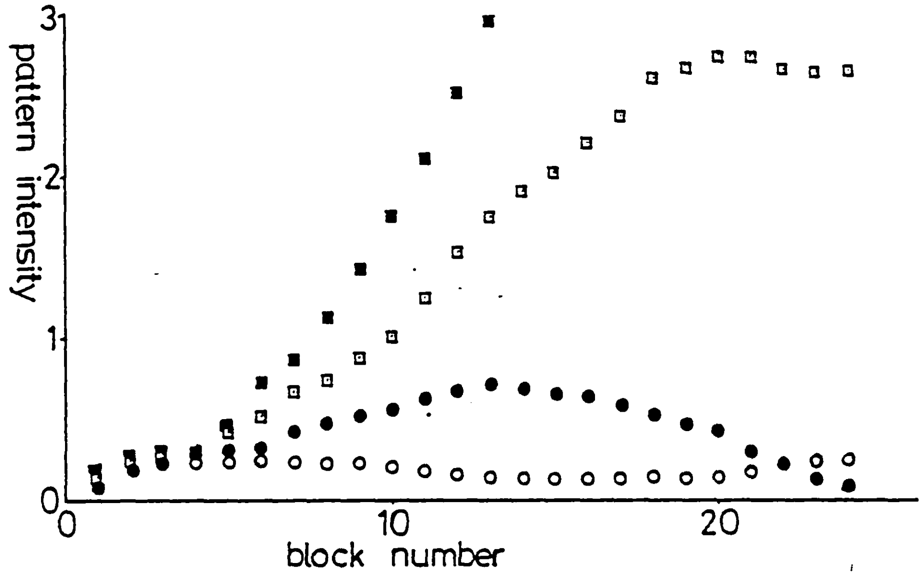
● wheelbarrow sprayer: horizontal (fresh weight)

□ wheelbarrow sprayer: angled (chlorophyll content)

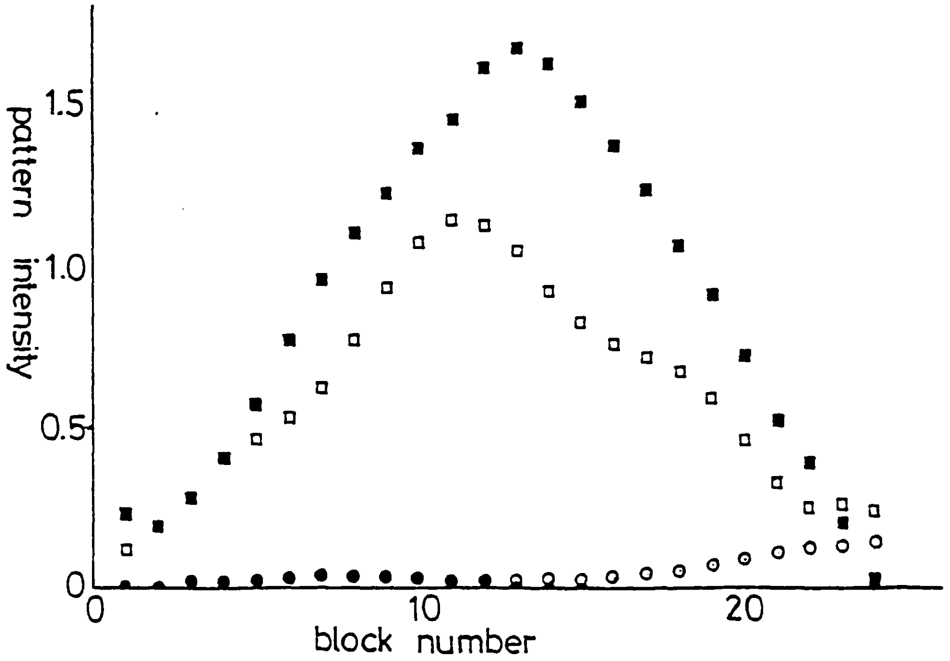
■ wheelbarrow sprayer: horizontal (chlorophyll content)

Appendix 11 Two Term Local Variance Analysis

a) cyanazine (525 gai/ha) applied pre-emergence in sweet corn



b) paraquat (100 gai/ha) applied to winter wheat grown in trays



Appendix 12 Basic Data for Retention Experiments

treatment		plant dry wt. (mg)	ground volume (µl/16 cm^2)$^+$			retained volume (µl/block)$^+$		
			n	$\bar{x}$	s	n	$\bar{x}$	s
glyphosate/paraquat expt.								
wheelbarrow :	radish	253	20	1.76	0.71	5	35.50	4.98
	oats	95	20	1.47	0.60	5	2.33	0.53
impact nozzle:	radish	282	20	60.83	5.90	5	104.40	18.66
	oats	77	20	46.63	3.21	4	4.95	1.99
fan nozzle:	radish	315	20	18.29	1.82	5	64.0	6.78
	oats	86				5	6.86	0.80
2,4D expt.								
wheelbarrow :	radish	1045	40	2.52	0.73	10	31.3	5.63
impact nozzle :	radish	1003	40	39.57	6.37	10	710.0	145.75

n = number of samples

$^+$ measured using fluorescent tracers

Appendix 13. Effect of an Oil Adjuvant on Soil Herbicide Activity

Sprayer	trietazine & linuron kgai/ha	mineral oil^{+} % v/v	visual assessment^{++} % kill	weed counts^{+++}				
				Cheno. album	Polygonum persicaria	Spergula arvensis	Stellaria media	total 4 spp.
wheelbarrow (15 l/ha)	2.5	0	84	11	29	6	2	48
"	3.5	0	95	6	12	2	0	20
"	2.5	20	88	6	25	1	1	33
"	3.5	20	97	4	19	0	2	25
impact nozzle (300 l/ha)	3.5	0	72	18	29	18	3	68
LSR	-	-	-	14	9	-	-	114
untreated no./m^2	-	-	-	59	34	336	12	441

$^{+}$Sunspray 11E

$^{++}$16 days after treatment

$^{+++}$21 days after treatment

Appendix 14 Comparison of Sprayers Using Pre-emergence Herbicides in Maize: crop growth effects at growth stage of 3 leaves

treatment	dose (kgai/ha)	sprayer	crop germinat$^{\underline{n}}$ (no./10 m row)	% showing curly leaf symptom (a)
atrazine + alachlor	1.2+1.54	wheelbarrow	25.5	0
" "	" "	spinning disc	27.7	1.0
" "	" "	impact nozzle	25.1	0.7
2,4D amine	1.3	wheelbarrow	27.2	1.0
"	"	spinning disc	23.0	1.0
"	"	impact nozzle	24.7	1.0
(terbuthylazine+metolachlor) (b) + metolachlor	(1.125+0.375) + 0.36	wheelbarrow	26.2	0.2
" "	" "	spinning disc	25.8	1.5
" "	" "	impact nozzle	23.6	0.7
untreated			25.8	0.8

(a) pest damage?

(b) formulated mixture with extra metolachlor

APPENDIX 15 ANGLED SPRAYING WITH THE WHEELBARROW

(a) 2,4-D in Maize

Species present:

Acanthospermum hispidum
Amaranthus thunbergii
Chenopodium bontei
Datura sp.
Eleusine africana
Ipomoea sp.
Portulaca oleracea
Tribulus terrestris

Symptoms 20 days after spraying: very slight curling of a few leaves

(b) Paraquat in Sorghum

Species	Growth Stage	0.6 kg a.i/ha	0.3 kg a.i/ha
A. hispidum	flowering	@	@
A. thunbergii	"	@@@*	@
C. bontei	large plant	@@@*	@
C. myriocarpus	"	@	-
Datura sp.	"	@@@*	@@@*
Ipomoea sp.	"	@@@	@
P. oleracea	"	@	@
T. terrestris	"	@@	@@
C. ciliaris	flowering	@@	@
E. africana	large plant	@@	@@
U. mosambicensis	flowering	@@	@
Overall phytotoxicity (% burning)		50%	30%

@@@	Good control (80% burning)
@@	Significant burning (50 - 80%)
@	Slight effect (50% burning)
*	Lower leaves only, 0.4 m high

APPENDIX 16

WEED SPECIES OBSERVED ON CONTENT FARM AND FIVE LOCAL FARMS
(Dec. 30/31: 3 - 4 weeks after drilling)

	Content Farm Sebele	Kgosikwano	Mafite	Moane	Ntoro	Thomas	Tolale	Tlape
Commelina benghalensis		*		*	**			
Polygonum sp. (?)	*		*	*				
Chenopodium bontei	***	*					*	
Amaranthus thunbergii	***	**			**	***	*	**
Brayulina densa	*							
Gomphrena celosioides	*							
Portulaca oleracea	**					*		
Spergula arvensis (?)	*	*					***	
Cleome hirta	*	*			*		*	
Gynandropsis gynandra						*		
Geraniaceae spp. (?)	*							
Indigofera spp.					*			
Ceratotheca (triloba?)						*		
Tribulus terrestris	***		*	*	*			
Euphorbia hirta	*				*		*	
Hibiscus meeusii		*	***		*	***		***
Sida cordifolia						*		
Sida rhombifolia	*		**				*	**
Ipomoea spp.	**	***				***		*
Verbena officinalis			*		*		***	
Datura ferox	*							
Solanum spp.	*					*		
Cucumis myriocarpus	*	*	***	*				*
Acanthospermum hispidum	*	**					*	
Bidens pilosa	*							
Senecio apiifolius							*	
Xanthium strumarium		**						
Unidentified species		*		***	*			*
(Sedge spp.)	*				*	*	*	*
Cenchrus ciliaris	*							
Rhyncelytrium repens	*							
Urochloa mosambicensis	***	*			*		*	*
Eleusine africana	***						*	
Chloris virgata	*							
Aristida congesta	*							
Tragus (berteronianus?)	*				*	*	**	
Eragrostis (rigidior?)	*	*		(*)	*			**
Eragrostis (atherstonii?)			*					

*** very common ** common * present

APPENDIX 17

SUSCEPTIBILITY TO HERBICIDES OF WEED SPECIES OCCURRING IN BOTSWANA TRIALS

(index figure = no. of trials)

	PRE-EMERGENCE											POST-EMERGENCE					
	Alachlor	Atrazine			Atrazine + alachlor	2,4-D amine		Metolachlor	(terbuthylazine + metolachlor)		(terbuthylazine + metolachlor) + metolachlor	2,4-D			paraquat		
Dose kg ai/ha:	1.54	0.8	1.2	1.6	1.2+1.54	0.86	1.1	1.08	1.0	1.5	1.5 + 0.36	0.1	0.55	1.1	0.15	0.3	0.6
Acanthospermum hispidum	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R	^{2}R*	-	^{1}R	^{1}MR
Amaranthus thunbergii	^{1}R	-	-	-	-	-	-	^{1}MS	-	-	-	^{1}R	^{1}R	^{2}R/^{1}S*	-	^{1}R*	^{1}MR
Brayulinea densa	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chenopodium boutei	^{1}MR	^{1}S	^{2}S	^{1}S	^{1}S	^{1}R	^{1}R/^{1}S	^{1}MR-MS	^{1}S	^{1}S	^{2}S*	^{2}R*	^{1}R*/^{1}S	^{3}S*	-	^{1}R	^{1}MS/S^{1}
Cleome hirta	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R	^{1}MR	-	-	-
Cucumis myriocarpus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	^{1}MR
Datura sp.	-	-	-	-	-	-	R^{1}	-	-	-	-	-	-	^{1}R	-	^{1}S	^{1}S
Gomphrena celosioides	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R	^{1}R*	-	R	^{1}MR/M^{1}S
Ipomoea sp.	^{1}R	-	^{1}MR	-	-	-	-	^{1}R	-	-	-	-	-	^{1}R	-	-	-
Portulaca oleracea	^{1}R	^{1}S	^{1}S	^{1}S	-	^{1}S	^{1}S	^{1}R*	^{1}R	^{1}MS	^{1}S	^{1}R	^{1}S	^{1}R/N^{1}R	-	-	S*
Tribulus terrestris	^{1}R	R	^{3}MR	^{1}R	-	^{1}R	^{3}S	^{1}R	^{1}R*	^{1}R*	^{2}MR	^{1}R	^{1}MR	^{1}S/^{1}S	-	^{1}R*	^{1}MS/S
Cenchrus ciliaris	-	-	^{1}R*	-	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}MR
Chloris virgata	-	-	-	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R*	^{1}R*-MR
Eleusine africana	^{1}S	^{1}R	^{2}R*	^{1}MS	^{1}S	R	R/^{1}S	^{1}S	^{1}R	^{1}MR	^{2}MS	^{1}R	^{1}R	^{2}R	^{1}R	^{1}R/R^{1}*	^{2}MR
Eragrostis sp.	-	-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R	^{1}R	^{1}R	^{1}R	^{1}MR
Urochloa mosambicensis		-	-	-	-	-	-	-	-	-	-	^{1}R	^{1}R	^{1}R	^{1}R	^{1}R/R^{1}*	^{2}MR

S*	> 95%	control
S	90-95%	"
MS	80-90%	"
MR	60-80%	"
R*	40-60%	"
R	> 40%	"

APPENDIX 18 SUSCEPTIBILITY OF WEEDS IN TABLE APPENDIX 17 ACCORDING TO COMMERCIAL HERBICIDE RECOMMENDATIONS

(Combination of label recommendations, and Anon [1974])

	alachlor	atrazine	atrazine + alachlor	2,4-D amine pre-em	Metolachlor	"Gardomil"	"Gardomil"+ metolachlor	2,4-D post-em	paraquat
Doses: 10% clay	)1.54	1.2	1.54 + 1.2	1.30	)1.08	1.5-1.75	+0.36	) 0.9	)0.25-1.10
kg a.i/ha 20% clay	)		1.54 + 1.6	1.58	)	1.75-2.0	+0.58	)	)
Acanthospermum hispidum	X	/	/	X	X	/*	/	X	/
Amaranthus thunbergii	(/)	/	/	(/)	(/)	/	/	/*	/
Chenopodium bontei	(/)	/	/	?	(/)	/	/	?	/
Cleome hirta	X	/*	/*	?	(/)*	/*	/	?	/
Datura spp.	X	(/)	(/)	X	(/)	/	/	(/)	/
Ipomoea spp.	X	(/)	(/)	?	?	?	?	?	/
Portulaca oleracea	X	/	/	?	(/)	/	/	?	/
Tribulus terrestris	X	/	/	(/)	X	X	X	(/)	/
Chloris virgata	/	?	/	?	/	/	/	?	/
Eleusine africana	/*	(/)*	/*	(/)*	/*	(/)*	/	X	/
Urochloa mosambicensis	/*	(/)	/	?	/	(/)*	/	?	/

* recommendation for related species

X poor control
(/) variable control
/ good control

Appendix 19 Herbicides for Mixed Cropping

The following herbicides have given weed control which was considered adequate by the authors, while being tolerated by the crops in the mixtures.

Herbicides	Crop Mixtures	Source
alachlor	$\left.\begin{array}{l}\text{maize}\\ \text{sorghum}\end{array}\right\} + \left\{\begin{array}{l}\text{cowpea}\\ \text{hyacinth bean}\\ \text{soya bean}\end{array}\right.$	Moody, 1978a
ametryne	$\text{sorghum} + \left\{\begin{array}{l}\text{chickpea}\\ \text{groundnut}\\ \text{pigeon pea}\end{array}\right.$	Shetty & Krantz, 1978
	maize + rice + cassava	Ebner, 1982
atrazine	sugar cane + yam	Kasasian, 1978
atrazine + metolachlor	maize + yam + cassava	Akobundu, 1978b
butachlor	maize + cowpea ± mung bean	Moody, 1978a
linuron	$\text{millet} + \text{sorghum} + \left\{\begin{array}{l}\text{cowpea}\\ \text{groundnut}\end{array}\right.$	Ogborn, 1978a
methabenzthiazuron	sorghum + pigeon pea	Shetty & Krantz, 1978
prometryne	sorghum + pigeon pea	Shetty & Krantz, 1978
propachlor	sorghum + some legumes	Parker, 1979
terbuthylazine	sorghum + pigeon pea	Shetty & Krantz, 1978
trifluralin	maize + groundnut	Moody, 1978a

Appendix 20 Manufacturers of Equipment Used

Equipment	Model	Supplier
chromatography paper		Whatman Ltd.
constant power supply	B30/10	Farnell Instr. Wetherby.
droplet analyser:	Optomax System 3	Micro Measurements Ltd, Saffron Walden, Essex.
	Laser Droplet and Particle size analyser, type ST1800	Malvern Instr. Ltd., Malvern
	Fleming Particle Size Analyser, type 526	Fleming Instr., Stevenage.
flow meter-electronic	Litre-meter	Litre Meter Ltd., Aylesbury.
microsyringe		Agla Ltd.
motor stationary drive unit	CV Hainsworth Speedranger	JH Fenner Ltd., Hull.
peristaltic pumps: and tubing	Mk IV Flow Inducer	Watson-Marlow Ltd., Falmouth.
	WAB Pump	Glen Creston Ltd., London.
sampling paper	Kromecote	David Micro Ltd., London
spectrofluorimeter	spectrofluometre JY3	Jobin Yvon, France.
spectrophotometer	DB. GT.	Beckman Ltd.
tachometer-electronic		Graham White Instr., St. Albans.
tubing connectors etc:	brass	C.T. Ltd., Guildford.
	plastic	Griflex Products Ltd., Wrexham.

Appendix 21 Sprayer and Nozzle Manufacturers

E. Allman & Co. Ltd, Birdham Rd, Chichester, Sussex.	Polypack
Berthoud S.A., 69220 Belleville s/Saone, France	Cosmos H2
Birchmeier/Ciba-Geigy A.G. CH 4002 Basel, Switzerland.	Birky
Cooper, Pegler & Co. Ltd, Burgess Hill, Sussex.	CP15, CP3 VLV nozzles
Eho Kone O.Y. 29250 Nakkila, Finland	ground-actuated sprayer
Geest Overseas Mechanisation Ltd, West Marsh Rd, Spalding, Lincs.	Groom System
Horstine Farmery Ltd, North Newbald, Yorks.	Microdrop
I.C.I. Plant Protection Div., Fernhurst, Haselmere, Surrey.	Polyjet nozzles Electrodyn
Jaydon Engineering Co. Ltd, Beacon House, 28 Worple Rd, London SW19.	Polyrow
Micron Sprayers Ltd, Three Mills, Bromyard, Hereford.	Handy, Herbi Micromax
Ets. Puteaux, 78150 Le Chesnay, France.	Herbi-net Junior
Richmond Gibson Ltd, Downton, Salisbury, Wilts.	Vortex
Spraying Systems Co., North Ave, Wheaton, Ill. 60187, U.S.A.	8001 fan nozzle
Spraygen Works, Hills Industries Ltd, Caerphilly, Glamorgan.	Spraygen 375
Tecnoma S.A., 51206 Epernay, France	T5

Appendix 21 cont.

Triomf Farmers Organisation (Pty) Ltd, 72-90 Stanhope Place, Durban, S.Africa.	Norman-King Carpi
Turbair Ltd, Brittanica House, Waltham Cross, Herts.	Weeder
Universal Gerwin Div., Leigh Products Inc., Saranac, Michegan 48881, U.S.A.	2995 wheelpump
Walkover Ltd, 21 London Rd, Gt Shelford, Cambridge.	Walkover

Appendix 22 The Sprayers Used in Botswana

a) wheelbarrow sprayer

Appendix 22 cont.

b) hand-held spinning disc sprayer

c) knapsack sprayer

Appendix 23 Chemical Manufacturers

i) Herbicides: South Africa

Bayer S. Africa (Pty) Ltd, PO Box 1366, Johannesburg 2000.

Atrazine 80 WP	atrazine

Ciba-Geigy (Pty) Ltd, PO Box 92, Isando 1600

Dual 720 EC	metolachlor
Gardomil 500 FW	terbuthylazine + metolachlor

I.C.I. (S. Africa) Ltd, PO Box 11270, Johannesburg 2000.

Gramoxone	paraquat

Monsanto S. Africa (Pty) Ltd, PO Box 78025, Sandton 2146.

Lasso 384 EC	alachlor

Shell Chemicals S. Africa (Pty) Ltd, PO Box 494, Johannesburg.

Shellamine 7.2	2,4D diethylamine salt

ii) Herbicides: U.K.

Cyanamid of GB Ltd, Agricultural Div., Gosport, Hants.

Avenge	difenzoquat
Stomp	pendimethalin

FBC Ltd, Hauxton, Cambridge.

Bronox	trietazine + linuron
Vectal sc	atrazine

I.C.I. Plant Protection Div., Fernhurst, Haselmere, Surrey.

Gramoxone	paraquat

Midox Ltd, Ashford, Kent.

Delozin S	chlorthal-dimethyl + methazole

Monsanto Ltd, Agriculture Div., Burleys Way, Leicester.

Roundup	glyphosate

Murphy Chemical Ltd, Hitchin, Herts.

Forlay MCPB	MCPB sodium salt

Shell Chemicals Ltd, Agricultural Div., 39-41 St Marys St., Ely, Cambs.

Fortrol	cyanazine

Appendix 23 cont.

iii) Other Materials

BDH Chemicals Ltd, Broom Rd, Poole, Dorset.

fluorescein sodium	fluorescent dye

BP Trading Ltd, Agricultural Dept., Sunbury, London.

Ulvapron	anti-evaporant oil

ESSO

Essol D200/240	heavy oil

I.C.I. Plant Protection Div., Fernhurst, Haselmere, Surrey.

Agral 90	non-ionic surfactant

Shell Chemicals Ltd

Dutrex 217 UK	heavy oil

Skilbeck Ltd, 55-57 Glengall Rd, London SE15.

lissamine scarlet	dye

Appendix 24 Names of Crops Used in the Text

banana	*Musa sapientum*
cassava	*Manihot esculenta* Crantz
chickpea	*Cicer arietinum*
cotton	*Gossypium* spp.
cowpea	*Vigna unguiculata* (L) Walp.
groundnut	*Arachis hypogoea* L
hyacinth bean	*Lablab purpureus* (L) Sweet
maize	*Zea mays* L
mung bean	*Vigna radiata* (L) Wilczek
pearl millet	*Pennisetum glaucum*
pigeon pea	*Cajanus cajan* (L) Millsp.
rice	*Oryza sativa*
rubber	*Hevea brasiliensis* (Muell.) Arg.
sorghum	*Sorghum bicolor* (L) Moench
soya bean	*Glycine max* (L) Merr.
sugar cane	*Sacchrum officinarum* L