UNIVERSITY OF ALBERTA

EVALUATION OF FERTILIZER NESTING BY PRESSURIZED LIQUID INJECTION

BY

(C)

WAYNE M. WASYLCIW

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Dedicated to:

Mike and Jean Wasylciw

For their support, patience and understanding.

Fred Michalchuk and Harry Wasylciw *(My D'idy)*

For teaching me that humility, generosity and the drive for knowledge are the highest of all virtues, since a man will ultimately be remembered for his actions rather than his words.

ABSTRACT

Concern with environmental issues has put into question the use of nitrogen fertilizers to increase food production. Recent research in nitrogen application has revolved around improving fertilizer application efficiency to reduce nutrient losses and environmental contamination. Fertilizer nesting, the placement of fertilizer in an evenly spaced grid below the soil surface, has shown promise in achieving this goal. Attempts to use this technique on a field scale have been partially successful by spoked wheel (point) injection. An alternative approach is to achieve nesting by pressurized liquid injection. To this end, a small, high pressure liquid nesting applicator was designed and constructed based on previous high pressure prototypes. High pressure fertilization field experiments were conducted on dark brown Chernozemic soils, with a loam texture, at the Agriculture Canada Research Station in Lethbridge, Alberta; under semi-arid climatic conditions. To test applicator effectiveness, fall and spring applications of liquid fertilizer were done with: pressurized liquid application, point injection and conventional fertilizer application techniques in four field experiments. Due to difficulties encountered in incorporating pulsing technology, pressurized liquid nesting was only compared to other techniques in one field experiment. However, fertilizer nesting and pressurized liquid banding were included, in some manner, in all experiments.

Fall application of fertilizer on one forage experiment and two winter wheat experiments showed no significant crop response to the various methods of fertilizer application used. Similar results were also obtained with spring fertilizer applications on barley. However, fertilizer nesting did show trends towards better crop response

in some of the parameters measured.

Soil core samples indicated that the total nitrogen applied by pressurized liquid injection could not be accounted for. Errors in recovery were attributed to two factors: the deposition of a large proportion of the fertilizer on the soil surface and the estimation of core sample mass through bulk density.

Soil penetration of fertilizer could not be measured on a consistent basis, but distribution results revealed 90% of the fertilizer recovered to be located in the top 6 cm of the soil profile. More work is required before pressurized liquid nesting can be considered a viable alternative to conventional fertilizer application techniques.

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LIST OF SYMBOLS

AM NIT	ammonium nitrate
AM Ph	ammonium phosphate
BCST	broadcast
c	speed of sound in liquid (m/s)
d_n	nozzle diameter (mm)
Db	soil bulk density (Mg/m^3)
DB	deep band
DMCSA	acronym for drill mounted continuous stream applicator
DR	dilution rate
H/P	high pressure
i.d.	inside diameter (mm)
K_1	fertilizer rate conversion factor (L/kg)
K_2	flow rate conversion factor for nozzle spacing
L_e	jet length (cm) velocity of the jet divided by the time of application
N	nitrogen
Ni	desired rate of nitrogen application (kg/ha)
NH_4	ammonium
NO_3	nitrate
o.d.	outside diameter (mm)
p	system pressure (MPa)
P	phosphorous
P_1	system pressure measured (MPa)
P_2	design pressure (MPa)
P_p	pulsing jet pressure (MPa)
P_r	penetration resistance (kg/cm^2)
P_s	continuous jet pressure (MPa)
P.I.	point injection
ppm	parts per million
P.T.O.	power take off

Q	liquid flow rate (L/min)
Q_1	nozzle flow rate measured (L/min)
Q_2	nozzle flow rate sought (L/min)
Q_{fert}	nozzle flow rate of fertilizer (L/min)
Q_m	nozzle flow rate of diluted mixture (L/min)
Q_n	nozzle flow rate (L/min)
Q_w	nozzle flow rate of water (L/min)
R_p	reduction in penetration
RPM	revolutions per minute
S	secondary penetration (cm)
SB	surface banding
Sp	nest spacing (cm)
T_c	cycle time (s or ms)
U	groundspeed (m/s)
UAN	urea ammonium nitrate
V	jet velocity (m/s)
Z	depth of penetration (cm or mm)
$\dot{Z}$	jet penetration rate (cm/s)
γ	liquid specific gravity
γ_L	specific gravity of liquid fertilizer
γ_m	specific gravity of diluted mixture
θ	angle of soil failure plane with respect to the vertical axis (degrees)
λ	jet type factor (continuous $\lambda=1$, fragmented $\lambda=2$)
ϵ	material strain (mm)
ρ	liquid density (g/cm^3)
ρ_j	jet liquid density (g/cm^3)
ρ_L	liquid density (g/cm^3)
ρ_t	density of target material (g/cm^3 or Mg/m^3)
σ_c	compressive fracture strength (MPa)

INTRODUCTION

The use of nitrogen fertilizers as the major nutrient source for crops has become one of the most important management inputs on Canadian prairie farms. Nitrogen fertilizer has enabled producers to maximize crop yields. Because agriculture is first and foremost a business, every effort must be made to maximize production with minimal input costs. Thus fertilizer nitrogen, being an input cost, must be utilized to its fullest potential for a farm operation to be successful.

One of the most important capital inputs for any grain producer is the soil resource itself. Attention must be paid to the health of the soil if any farming system is to be viable over the long term. As a consequence of soil degradation issues (wind and water erosion, organic matter losses) and ongoing concern with soil moisture conservation; reduced and zero tillage options have become more acceptable to help maintain or increase soil productivity. Unfortunately, conventional methods of nitrogen application are not always compatible with reduced and zero tillage practices.

Deep banding of nitrogen causes considerable soil disturbance, results in soil moisture loss, and requires substantial energy inputs; which is somewhat in conflict with the conservation philosophy. Application of high rates of nitrogen with the seed is limited due to toxic effects of fertilizer being placed in close proximity of the seed. Conventional broadcast methods of nitrogen application may result in significant losses to the atmosphere or denitrification. If soil moisture or precipitation is below normal, broadcasted nitrogen may not be leached into the plant root zone.

An alternative method of applying nitrogen which has been proposed is fertilizer nesting. Nesting is the deposition of fertilizer in discrete units several centimetres below the soil surface in an evenly spaced grid.

Broadcasting results in fertilizer spread uniformly across the soil surface. Banding results in fertilizer concentrated parallel to the direction of implement travel below the soil surface. Nesting concentrates the fertilizer below the soil surface both parallel and perpendicular to the direction of implement travel. The result is evenly spaced points (nests) of nitrogen fertilizer in high concentrations. Nesting of fertilizer has had limited success when used with common prilled fertilizer. Oversized Supergranules have shown more promise than standard prilled fertilizer in forming fertilizer nests. Unfortunately these solid forms of fertilizer require a mechanical tool, thus creating considerable soil disturbance, for proper fertilizer placement.

The advent of liquid fertilizer formulations now allows fertilizer nesting to be attempted with minimal soil disturbance. Formation of liquid fertilizer nests with a steel spoke-wheel assembly has shown promise in being an effective method of fertilizer nesting. Soil disturbance occurs only where the metal spoke enters the soil profile. The refinement of high pressure liquid jet technology has shown potential to further improve the liquid fertilizer nesting process. Initial experiments support the premise of placing liquid fertilizer in the soil profile by high pressure liquid jet. This would eliminate the requirement of a mechanical device to penetrate the soil profile. Surface soil disturbance would be limited to approximately the diameter of the jet entering the soil.

The goal of this project was two-fold: (1) develop an appropriate high pressure jet applicator to inject liquid fertilizer in nests, and (2), by means of a series of field experiments, test the hypothesis that pressurized liquid jet fertilizer nesting is superior to conventional fertilizer application techniques.

CHAPTER 1: REVIEW OF LITERATURE

1.1 Nitrogen Loss and Conventional Application Techniques

Nitrogen loss is inevitable when applying supplemental nitrogen to enhance crop growth. One only has to consult an elementary soil science textbook to realize nature has many processes associated with the nitrogen cycle to remove, or make unavailable, nitrogen to plants (Hausenbuiller, 1978).

Volatilization, immobilization, leaching and erosion require favourable conditions to remove nitrogen from plant use. The mechanism which dominates nitrogen loss varies from region to region. Climate, soil conditions and even tillage practices can make one mechanism favourable over another in depriving nitrogen from plants. Therefore statements made about decreasing nitrogen loss in one region may not apply to another region, or not even at all times. Thus a broad scope is required when approaching the problem of nitrogen loss from a placement standpoint.

1.1.1 Fall Application of Nitrogen

The effects of nitrogen loss are most pronounced when comparing crop response to fall and spring applications of nitrogen. In many cases, fall application of nitrogen is inferior to spring applications of nitrogen (Grant et al., 1985; Harapiak et al., 1986; Kucey, 1986). However, in some instances fall application of nitrogen resulted in increased crop yields (Harapiak et al., 1986; Kucey et al., 1986). In these instances, growing season soil moisture was below optimum values for crop growth.

In areas of high spring soil moisture, yields under fall applied nitrogen were inferior to those under spring applied nitrogen on Alberta soils (Nyborg and Leitch, 1979). Much of this shortcoming was attributed to the nitrification of ammonium fertilizer from fall application through spring planting (Malhi, 1978). Some of these losses can be offset by applying nitrogen in a less nitrifiable form. During spring thaw and soil saturation, fertilizers are only partially nitrified and thus less susceptible to denitrification (Nyborg and Leitch, 1979). The key is to delay the formation of nitrates until the plant can utilize the applied nitrogen. In fact, the use of nitrification inhibitors such as thiourea have shown a decrease in nitrate formation in early spring which resulted in a corresponding yield increase (Table 1).

Table 1. **Recovery of fall applied urea-N as nitrate-N and subsequent yield increase of barley (Adapted from: Nyborg and Leitch (1979), Table 4, p. 61)**

Method	Nitrate in Spring (%)	Yield Increase (100 kg/ha)
Mixed	74	11.2
Banded	38	12.2
Mixed with Thiourea	12	15.7
Banded with Thiourea	4	17.8

Thiourea is only one method of delaying the formation of nitrates. There are other methods which have shown success in delaying nitrate formation for both fall and spring nitrogen applications.

1.1.2 Nitrogen Banding

Deep banding is the procedure which concentrates fertilizer into evenly spaced parallel lines below the soil surface in the plant rooting zone. This method was successful in delaying the formation of nitrates for fall application of nitrogen on Indiana corn (Larsen and Kohnke, 1946). Nitrogen banding and thiourea application have slowed nitrate formation in pot and field experiments (Leitch, 1973).

The deep banding of nitrogen as urea, ammonium nitrate and anhydrous ammonia gave better yields than broadcasting of the same fertilizer forms of nitrogen on barley (Kucey, 1986). The absence of yield differences between the types of fertilizer used suggest position of fertilizer placement may be of greater importance than type of fertilizer applied. Heinonen and Huhtapalo (1978) found band placement of nitrogen midrow, 3 to 4 cm below seed, to have a greater yield increase than broadcast and incorporation to 6 cm and bands placed at eight other positions in the soil profile.

Banding has demonstrated a marked success in limiting nitrogen loss (Table 2; Nyborg and Leitch, 1979). Even though a characteristic shortcoming between fall and spring nitrogen applications was noted, banding had succeeded in limiting nitrogen loss versus other methods of application.

In conventional methods of fertilizer application, fertilizer is placed on or below the soil surface. Each granule is completely exposed to the elements or in contact with the soil. Denitrification and volatilization can affect each fertilizer particle simultaneously.

With banding, nitrogen fertilizer is concentrated below the soil surface. Air, moisture and soil exposure is limited to those fertilizer granules on the perimeter of the band. The outlying granules are sacrificed in order to maintain the integrity of

Table 2.	**Increase in N uptake of barley from urea (Adapted from: Nyborg and Leitch (1979), Table 9, p. 69)**	
Method	N-Uptake (% of spring banded treatment)	
	Fall	Spring
Top-dressed	38	68
Incorporated	51	91
Banded	68	100

those granules situated inside the band. Thus, a majority of the applied nitrogen is not lost and is available for plant growth.

1.1.3 Tillage, Nitrogen Placement and Environmental Concerns

Increasing interest in soil and moisture conservation has led many concerned producers to adopt zero-till and minimum till practices for cereal crop production. With these cropping strategies, nitrogen application is limited to placement with seed or broadcast.

High rates of nitrogen cannot be placed with seed as seedling injury can result due to localized saline conditions created by soluble nitrogen fertilizer (Follet et al., 1981; Robertson, 1982). The actual nitrogen rate at which seedling injury occurs is variable and dependent on soil texture, type of fertilizer applied and dispersion of seed and fertilizer in the soil profile; on most Western Canadian soils 34 kg N/ha is the upper limit (Harapiak et al., 1986).

In zero till and minimum till conservation strategies, the effect of crop residues on nitrogen placement must be considered.

Under zero till and minimum till systems microbial activity is increased in the top 7.5 cm of the soil versus conventional profile till situations. These increased microbial levels can result in immobilization of surface applied nitrogen (Doran, 1980).

Carefoot et al. (1990) found, under dry conditions, nitrogen immobilization losses higher under no-till compared to conventional till. Immobilization losses were attributed to the degree of contact between fertilizer nitrogen and crop residues. It was suggested that development of better fertilizer application techniques for no-till farming are required to reduce contact between crop residues and fertilizer nitrogen.

Crop residues enhance the volatilization of surface applied nitrogen (Hargrove et al., 1977). In broadcast applications or methods which incorporate surface residues, some nitrogen fertilizer is lost. To reduce these losses through volatilization, fertilizer nitrogen should be incorporated in the soil profile to minimize contact from crop residues (Baker et al., 1989).

From both agronomic and environmental perspectives, sound nitrogen placement practices can reduce runoff and deep leaching nitrogen losses; regardless of tillage strategy adopted.

Nitrates in surface runoff increased with surface broadcast of nitrogen fertilizer (Baker and Laflen, 1982; Timmons et al., 1973). Placement of nitrogen fertilizer below the soil surface was found to be effective in reducing runoff losses of nitrates (Baker and Laflen, 1983). Under conservation tillage practices, concentrated placement of nitrogen fertilizer below the soil surface did not increase nutrient runoff losses (Baker and Laflen, 1982).

Inhibiting nitrification can be effective in minimizing deep leaching losses of nitrates from the soil profile (Huber et al., 1980). Baker et al. (1975) could not attribute all the nitrates measured from subsurface drains to nitrogen fertilizer. However, 99 percent of the leachates collected consisted of nitrates. Since concentrated placement of nitrogen fertilizer has demonstrated a propensity to delay nitrate formation (Larsen and Kohnke, 1946; Leitch, 1973) perhaps deep leaching losses of nitrogen fertilizer can be minimized with better fertilizer placement techniques. With better fertilizer placement methods, both crop production and environmental concerns can be addressed in an effective manner.

Applying nitrogen to minimize soil surface disturbance and fertilizer-crop residue contact is incompatible with conventional application techniques. The result is a trade-off between soil moisture management and reduction of nitrogen losses.

1.2 Fertilizer Nesting

An extension of the banding application method is fertilizer nesting. The concentration of nitrogen in compact nests rather than thin bands further reduces the soil-fertilizer contact area. Thus biological activity is further hampered in nitrifying mineral nitrogen.

The concept of placing nitrogen in nests was introduced on Philippine rice paddies (Shiga et al., 1977). By placing urea in "mud-balls" below the soil surface, the floodwater concentration of dissolved fertilizer nitrogen was significantly reduced. The inability of the floodwater to remove large amounts of nitrogen resulted in greater nutrient benefit for the rice plant.

The ability of nesting to maintain the integrity of fertilizer nitrogen under saturated soil conditions received favourable attention in north central Alberta. Perhaps nesting could limit nitrogen losses in spring moisture saturated Alberta soils. If successful, nesting could further narrow the discrepancy between fall and spring nitrogen application. Nesting of nitrogen was found to be more effective than conventional fertilizer application techniques for fall application of nitrogen (Monreal, 1982).

From 1975 to 1977 three site years of experiments were conducted to compare fall incorporation, fall banding and fall nesting to spring incorporation. Of the three fall treatments, nesting crop yields were closest to spring crop yields (Nyborg and Malhi, 1979). The placement of fertilizer in discrete nests showed signs of nitrogen deficiencies in the early growing season, but, by mid season the nested fertilizer crops caught up.

Three additional site-year trials from 1977 to 1978 yielded similar results (Nyborg et al., 1979). This time nesting was tried on 30 × 30 cm and 60 × 60 cm grid spacings with 1.7 and 6.8 g pellets respectively, to make up the difference in grid spacing (the 1975 - 77 trials only used a 23 × 69 cm spacing with 6.8 g pellets). An added treatment in one experiment utilized spring nesting for further comparison.

The results of the second set of trials stood up to the first set of trials (Table 3). The yield difference between fall nesting and spring nitrogen application was further narrowed. A surprising result showed that spring nesting fared as well as spring banding on barley yields and nitrogen uptake (results not shown). In spring, the smaller granules on the smaller grid fared better. Again, as in the previous trials, there was poorer early season growth but these differences were not prevalent by mid-season.

Soil samples showed nests to have less nitrification by spring than fall incorporation or banding. The use of ammonium sulphate or urea in the nests did not increase nitrification.

There was also a suggestion that the reduction in surface area (exposed to soil) provided by the pellets lowered nitrogen immobilization losses by straw (Malhi et al., 1984; Nyborg and Leitch, 1979; Nyborg et al., 1979). This is beneficial for no-till applications.

In further experiments to test the effects of fertilizer application method and date of fall application on nitrogen losses, the nesting treatment again performed consistent to previous experiments (Malhi et al., 1984).

The results showed that delaying nitrogen application to late fall, when soil temperature and biological activity were lowered, led to a reduction in the yield difference between fall and spring crop yields and nitrogen uptake.

Of greater interest in these experiments was the introduction of aqua NH_3 as a substitute for solid pellets in 4 of the 74 experiments (Malhi et al., 1984). The liquid fertilizer performed with the consistency of pellets in reducing nitrogen losses (Nyborg and Leitch, 1979). The sample size was rather small but the success in using liquid fertilizer has great implications on machinery design. A pair of experiments utilized hand placement of liquid urea ammonium nitrate (UAN) in nests on

Table 3. **Summary of barley yield results of three experiments using different fertilizers, methods of application and time of application (Adapted from: Nyborg et al. (1979), Tables 1 and 2, p. 103 and Table 3, p. 105)**

Treatment	Site	Year	Yield (100 kg/ha)
None	1	1975/76	11.4
Fall Banded Urea	1	1975/76	26.6
Fall Banded Urea and Thiourea	1	1975/76	28.0
Fall Nested Urea and Thiourea	1	1975/76	35.3
Spring Incorp. Urea	1	1975/76	32.8
None	Avg. of 2	1976/77	10.5
Fall Incorp. Urea	Avg. of 2	1976/77	19.5
Fall Nested Urea	Avg. of 2	1976/77	30.0
Spring Incorp. Urea	Avg. of 2	1976/77	34.0
None	Avg. of 3	1977/78	13.7
Fall Incorp. Calcium Nitrate	Avg. of 3	1977/78	20.4
Fall Incorp. Urea	Avg. of 3	1977/78	24.6
Fall Nested Urea	Avg. of 3	1977/78	28.3
Fall Incorp. Ammonium Sulphate	Avg. of 3	1977/78	25.5
Fall Nested Ammonium Sulphate	Avg. of 3	1977/78	29.9
Spring Incorp. Urea	Avg. of 3	1977/78	31.1

microplots during the spring on winter wheat (Janzen et al., 1990). This method was compared to broadcast liquid UAN in one experiment. In the second experiment nesting was compared to broadcast and surface banding of liquid UAN. Yield and nitrogen uptake determinations showed nesting of liquid UAN to have superior fertilizer use efficiency to broadcast in five of eight comparisons. This advantage was diminished when sufficient precipitation leached the broadcast fertilizer into the rooting zone. It was suggested nesting with liquid UAN should be pursued on field scale experiments.

The general consensus of researchers is that nesting could be a viable commercial alternative to fall banding and broadcast application of fertilizer nitrogen. Experiments have also shown that fertilizer nesting with liquid UAN in spring can be effective if spring soil moisture or precipitation are low. Overall, a question still exists about applicability of nesting to no-till farming. In all of the experiments reviewed, the nests were tilled in the spring before sowing. Nests left in-situ may yield different results. This requires further study.

1.2.1 Optimum Fertilizer Nesting Parameters

In early fertilizer nesting research, a variety of nest spacings and depths were used in combination with pellet size to achieve the desired nitrogen application rate. The studies undertaken did not determine optimum parameters of nest spacing and depth required to achieve optimum yield and nitrogen uptake.

In the first experiments, nest spacing was in a 23 × 69 cm grid at a 5 cm depth to give a nitrogen rate of 56 kg/ha (Nyborg and Malhi, 1979). A further refinement to check if spacing affected yields nest spacings of 30 × 30 cm and 60 × 60 cm to a 5 cm depth were utilized (Nyborg et al., 1979). There was a greater yield increase with the smaller 30 × 30 cm grid. In the date-of-application study, pellets were placed on a 46 × 46 cm grid to a 5 cm depth while aqua NH_3 was placed at the same grid spacing but to a depth of 10 cm (Malhi et al., 1984). There were no differences in yield or nitrogen uptake between pellets and aqua NH_3. Even though trends were noted, no clear relationship could be established between nest spacing and nest depth on yield or nitrogen uptake.

A comprehensive study was undertaken to investigate optimum grid spacing and nest depth using liquid UAN in three grid spacing experiments with winter wheat (Janzen and Lindwall, 1989).

In the first experiment UAN was injected to depths of 2.5, 5.0, 10.0 and 15 cm while liquid ammonium nitrate and liquid urea were injected to a depth of 10 cm. All injections were made during spring on established winter wheat crops. Grain yields, straw yields and nitrogen uptake increased progressively to a depth of 10 cm. Beyond this depth yields and nitrogen uptake were reduced.

In the second experiment, longitudinal nest spacings of 20, 40 and 60 cm were combined with lateral nest spacings of 20, 40 and 60 cm in a factorial. Liquid UAN was injected during spring on winter wheat to a depth of 10 cm. Taking in account spatial uniformity to maintain crop evenness and minimize soil surface disturbance, a grid spacing of 40 × 40 cm would constitute a balance between the two factors.

The third experiment was performed to study the interaction between grid spacing and depth of nests. The results highlighted the absence of any interaction between the two parameters. In the final analysis, the optimum nest spacing and nest depth for liquid UAN was 40 × 40 cm at a 10 cm depth. This defines an appropriate benchmark for nesting applicator design to achieve.

1.2.2 Fertilizer Nesting and Fertilizer Application Technology

Fertilizer nesting is a relatively new concept compared to more conventional methods of fertilizer application. Regardless, design of fertilizer nesting machinery has been attempted in the past with varied success. Early nesting machine design proposals were limited by the form of fertilizer used in the nesting process.

One method of forming nests with standard prilled fertilizer utilized air seeder technology in conjunction with a pneumatically controlled gate actuator (Kusler, 1983). The device was developed for incorporation into the fertilizer delivery system of an air seeder. The actuator interrupted the flow of fertilizer from the delivery tube into the soil. Unfortunately difficulties arose in establishing a compact nest consistently. Placement of 90% of the nest material in 25% or less of the inter-nest spacing could not be achieved on a regular basis. This lack of consistency was attributed to the inherent random motion of the prilled fertilizer through the delivery system.

To circumvent the difficulties standard prilled fertilizer posed in the formation of nests, the utilization of Norsk Hydro Supergranules as the nesting medium was attempted. Each oversized pellet (1, 2 or 3 grams in mass) carries sufficient urea to form a nest without having to group individual pellets into one conglomeration. The scope of research into Supergranule nesting was limited to existing technology which could be utilized with little or no modifications (Wasylciw et al., 1988). Because of the large dimensions and brittleness of Supergranules, application with existing machinery was not practical. The precise metering of Supergranules required in fertilizer nesting would be a complicated design. Even if precision metering of Supergranules was achieved, difficulties would arise in developing a delivery system to minimize soil surface disturbance.

A practice which is becoming increasingly common is the use of liquid forms of fertilizer as a source of plant nutrients. One type of fertilizer being used is a slurry made up of animal waste by-products. This type of fertilizer is commonly sprayed onto the soil and incorporated or banded. The use of slurries in a high pressure application is highly impractical because of the intense refinement required to remove suspended solids inherent to slurries.

As mentioned earlier, manufactured forms of liquid fertilizer such as aqua NH_3 or liquid UAN are available. These forms of liquid fertilizer are preferred for nesting purposes for two reasons. One, the amount of solids in the liquid suspension is low and can be removed with a filter incorporated into any machine design. Two, this type of liquid fertilizer is available in many formulations which could be utilized for various soil test recommendations. In the past, liquid fertilizers in this form have been applied in the same manner as slurries. Presently, because of their superior characteristics, liquid suspensions have opened up a new era of machinery design for the application of fertilizers.

Nesting of liquid fertilizer has been achieved with a high degree of success by means of what is commonly termed point injection. The main feature of the point injector design is a spoked wheel which penetrates the soil to the depth corresponding to the length of spoke which protrudes beyond the circumference of the wheel. This device is an effective means of forming fertilizer nests but literature (Baker et al., 1989) and personal experience with the device have revealed some drawbacks with point injector design. The complicated wheel-hub arrangement consists of a set of teflon bearings and O-rings. With increased usage these elements wear which leads to fertilizer leakage from the hub and ultimately to wheel corrosion. The nature of the design leads to soil plugging in the spokes. Plugging leads to the absence of fertilizer nests; a condition which is hard to detect without constant vigilance. Finally, contact between the spoke and the soil leads to heavy wear on the spoke tips which are costly to replace.

Granted many of the problems associated with point injection could be solved with more intensive engineering but nesting by a high pressure pulsed liquid jet may provide a more reliable and elegant solution. Machinery is already available to band liquid fertilizer by means of high pressure (Clapp, 1984). The device has nozzles which are situated in close proximity to the soil surface. Fertilizer is banded into the soil profile by a continuous high pressure stream which cuts through the soil. This eliminates tool wear since no physical force is directly imparted by an implement for fertilizer deposition. The only soil surface disturbance detected is approximately 2 mm in width where the nozzle travels across the soil surface. The only aspect which requires attention to achieve nesting by this procedure is the interruption of the high pressure jet to create a pulsing effect.

1.3 The Pulsing Jet

The main focus of nesting liquid fertilizer via high pressure jet technology is the interaction between the fluid jetted through a nozzle and the soil which absorbs the fluid. An understanding of this process is required to make qualitative and quantitative decisions about the design of an applicator which is to deliver the liquid jet. There is an extensive amount of literature on the jetting of liquids under high pressure for various engineering purposes, namely: cutting, mining, cleaning and drilling (Crow et al., 1974; Gilpin et al., 1980; Odds, 1982; Vijay et al., 1982). A large amount of the literature develop rigorous mathematical models of jet penetration based on parameters derived through laboratory testing for specific materials. The result is a set of equations which pertain to those materials which behave according to model assumptions. Unfortunately, the bulk of research in high pressure jetting focuses mainly on the destructive characteristics of the jet.

For fertilizer nesting, the jet has a two-fold purpose. First, the energy of the jet is required to penetrate the soil. Second, the jet must function as a carrier to deliver the liquid into a compact nest. Therefore, fertilizer distribution through the soil profile must be addressed in conjunction with the penetration by the jet into the profile. This results in an area of uncertainty in terms of jet research. For most jetting applications, the energy spent fluid is considered a waste byproduct. For liquid fertilizer nesting, the final resting state of the liquid is most important. Nevertheless, a study on jet penetration theory is required to ensure the penetration aspects of high pressure liquid fertilizer nesting are properly addressed.

1.3.1 Penetration Theory

The majority of research into high pressure jetting of liquids has taken place to serve heavy industrial applications. The essence of industrial liquid jetting focuses on the destructive power a jet can induce. Once the jet has spent its energy, the liquid byproduct is considered waste which must be dealt with. The final resting state of the liquid fertilizer is of some importance in fertilizer nesting.

In general terms, jet penetration of solids is governed by the following inequality:

$$\sigma_c < 1/2\ \rho\ V^2 \qquad (1)$$

This relationship states penetration occurs when the compressive strength of the material being cut (σ_c) is less than the dynamic pressure of the jet ($1/2\ \rho\ V^2$) (Hashish and du Plessis, 1978).

In many jetting applications where nozzle movement is very slow such as drilling or cleaning, the analysis on the loading of the material affected is quasi-static. That is, time is not considered a factor in terms of force on the material being cut or cleaned. When the nozzle moves with considerable velocity parallel to the cutting face of the material, time dependence on loading becomes a factor (Hashish and du Plessis, 1977).

A model presented by Hashish and Reichman (1980) takes into account the effects of nozzle traverse rate on jet penetration by comparing the initial penetration rate ($\dot{z}$) to nozzle traverse rate (U). Initial penetration rate is calculated with the compressive strength (σ_c) and strain (ϵ) of the solid and the liquid density (ρ) and liquid velocity (V) of the jet in the following relationship:

$$\dot{z} = \left(1 - \frac{\sigma_c}{\rho V^2}\right)\left(\frac{\rho V}{\varepsilon}\right)V \qquad (2)$$

By comparing $\dot{z}$ to U three possibilities exist: (1) $U < \dot{z}$, and effects of static and dynamic pressure affect jet penetration, (2) $U \approx \dot{z}$ thus the effects of erosion must be considered in calculating jet penetration or, (3) $U > \dot{z}$ and jet penetration is governed by liquid drop impact. For each case, jet penetration is calculated by a separate equation based on careful measurement of strength and acoustical properties of the material being penetrated. This model assumes that the material being penetrated has a linear stress-strain relationship. Unfortunately most soils do not fall into this assumption (Holtz and Kovacs, 1981).

The dependence of jet penetration on pressure and traverse rate has been noted in several other publications (Burns et al., 1980; Gilpin et al., 1980; Walker and Stutte, 1986). In general terms, an increase in pressure increases jet penetration while an increase in traverse rate decreases penetration.

Pointkoski and Domier (1985) noted increased jet penetration with increased pressure was not linear for soil. They concluded a larger volume of flow (increased nozzle diameter) would be more effective than increasing pressure to achieve greater penetration. The researchers also observed that decreasing penetration was less dependant on traverse rates greater than 3 km/h.

Arya and Pickard (1958) formulated a general model of soil penetration where the jet is thought of as a solid particle moving through a stationary fluid. The researchers contemplated a jet of kinetic energy subject to drag loss associated with jet movement through air and then through soil. Although this model did not account for the effects of traverse rate on jet penetration, some interesting conclusions arose from this investigation. By measuring the penetration of diesel jets into graded glass beads and graded sand the following observations were made:

a) Standoff distance, the distance between the nozzle and soil surface should be as small as possible.

b) Using extreme pressures to increase penetration is inefficient. The use of thin solid streams is more effective.

c) Soil particle size and soil compactness can alter jet penetration.

d) Penetration may be enhanced by intermittent injection (pulsing) rather than a continuous stream jet.

The claim that increased standoff distance adversely affects penetration is widely held. Edwards et al. (1982) noted the inability of impulsive jets to stay coherent even over small distances in air. The physical size of the droplets in the centre of the jet were larger than the size of the droplets in the periphery of the jet. The drag force on the jet (from air) had a tendency to pull the stream apart into a diffuse mist. This resulted in a dramatic decrease in jet force with increased nozzle standoff distance (Figure 1).

Konig and Wulf (1984) reported the decrease in standoff distance resulted in an increase in dynamic jet force while static jet force remained constant. This, in effect implied air acts as a damper which absorbs a portion of the jet energy. In order to negate this effect, the high pressure nozzle should be located as close to the soil as possible.

Various research is in agreement with Pointkoski and Domier (1985) that increasing pressure is an inefficient method to increase jet penetration. Quadrupling pressure at best doubled soil penetration (Figure 2). Arya and Pickard (1958) explained this inefficiency by comparing the kinetic energy of the jet stream to the drag force exerted on the jet by the soil particles. Although quadrupling the jet pressure resulted in a four times increase in jet kinetic energy, this also resulted in

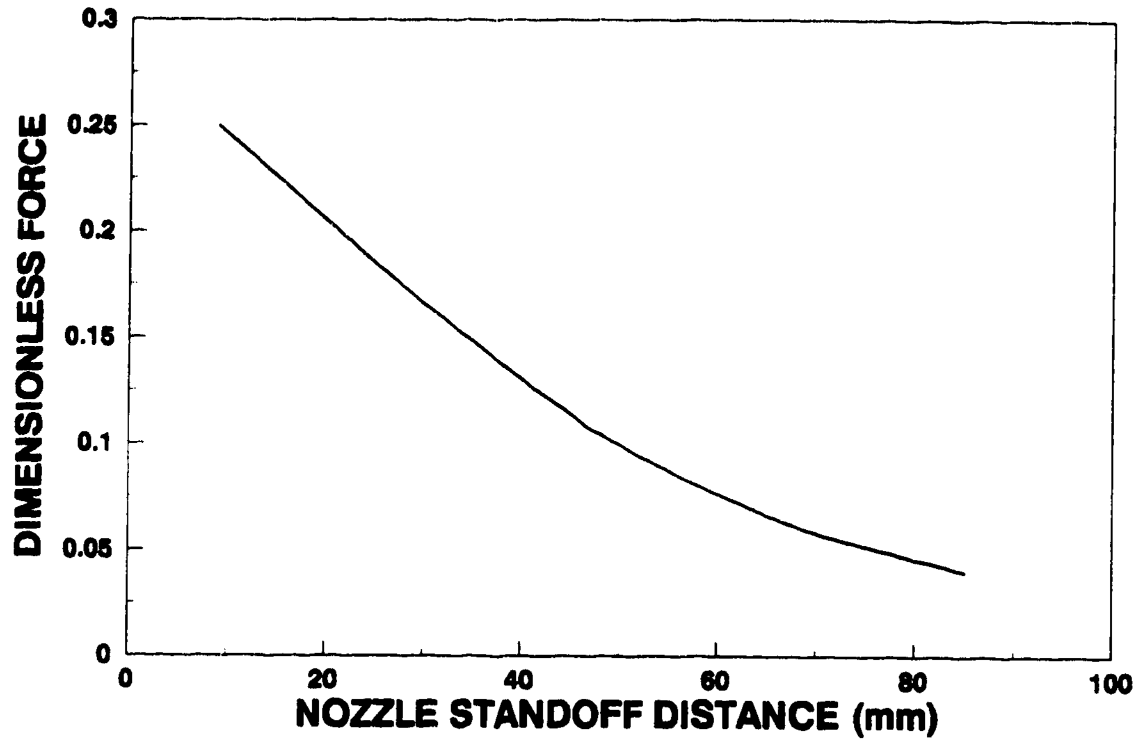

Figure 1. **Reduction in jet force with increasing nozzle distance from the target material (adapted from: Edwards et al. (1982) Fig. 6, pg. 136)**

a four times increase in drag force.

Pointkoski and Domier (1985) related jet diameter (d_n), jet pressure (p) and ground speed (U) to soil penetration (z) for a soil and developed the following relationship:

$$z = 11.2\ (d_n\sqrt{p}) + 26.3 \left(\frac{d_n}{U}\right) + 53.7\ x\ 10^{-3}\ d_n \left(\frac{p}{U}\right) - 14.1 \qquad (3)$$

As shown in term 1, soil penetration increases as the root of the applied pressure. Burns et al. (1980) noted that while pulsed jet penetration increased with increased pressure, the curve for concrete slabs remained relatively flat over a large pressure range. Thus design of a liquid nesting applicator should not revolve around

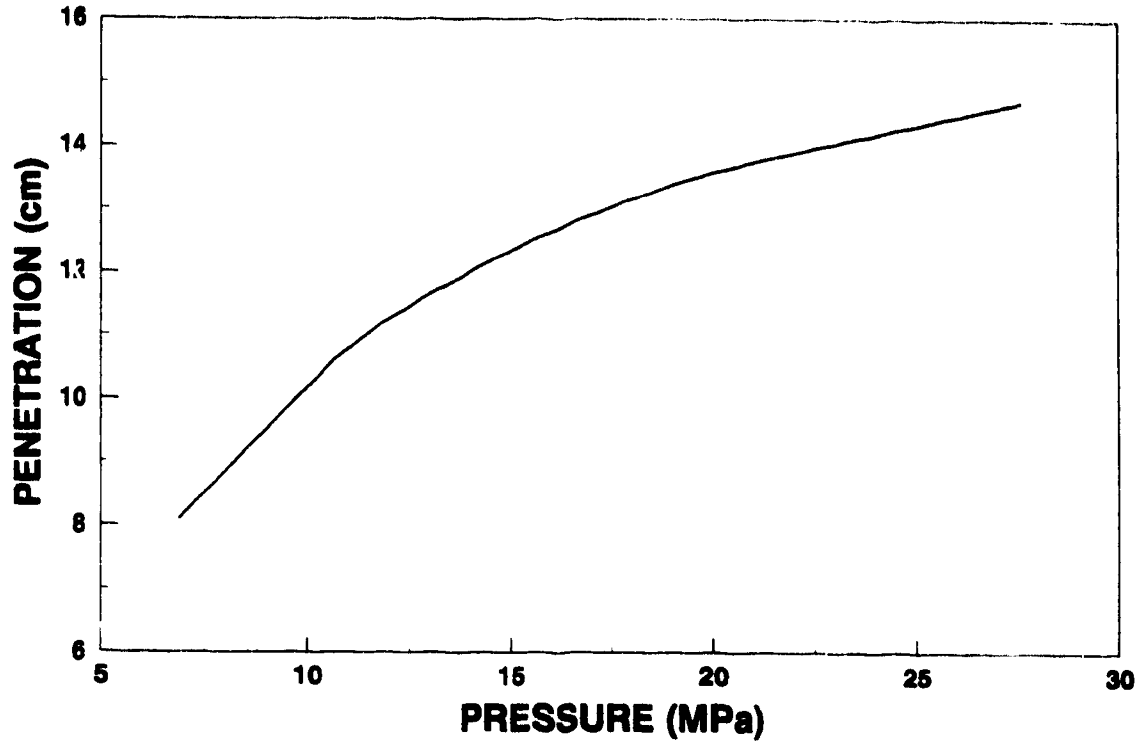

Figure 2. **Effect of increasing pressure on jet penetration into glass beads (adapted from: Arya and Pickard (1958) Fig. 7, pg. 18)**

the maximum attainable pressure on the high pressure pump chosen. Applicator design (fittings, hoses, nozzles and valves) should be determined by balancing hardware costs with sufficient pressure to achieve a suitable penetration depth.

Arya and Pickard (1958) found particle size as a factor in resulting jet penetration (Figure 3). Regardless of the pressure of the jet, soil penetration decreased with increased particle size. They attributed this phenomenon to impulse and momentum. With larger particles, more force is required to displace the soil from the jet path.

Walker and Stutte (1986) noted the effects of compaction and soil moisture on jet penetration in their experiments. Two separate penetration experiments on the same soil, only 14 days apart, resulted in differing jet penetrations. The increase in soil moisture and density on the latter date resulted in nearly 33% reduction in penetration. Also, the collision of the jet with large stems and small rocks resulted in stream path deflection and a "clumping" of liquid near the soil surface.

Pointkoski and Domier (1985) simulated residue cover in their experiments by placing straw layers on the soil surface. The jet cut through the straw with no effect on soil penetration. They did note however, at larger nozzle diameters, the effect of straw "hair pinning" into the kerf left by the penetrating jet.

Solie and Wittmuss (1983) presented a comprehensive model of soil penetration which incorporated the effects of soil properties on jet penetration. The model was developed around the presence of active and passive failure planes developed in soil by a penetrating jet. Active failure planes are classified as those which form in disturbed or tilled soil while passive failure planes result when the jet penetrates undisturbed soil. These failure planes are dependent on the angle of internal friction of the soil particles which is a function of soil moisture. The model is represented in the following equation:

$$Z = \frac{L_e}{\tan\theta} \sqrt{\frac{\lambda \ \rho_j}{\rho_t}} R_p + S \qquad (7)$$

L_e is defined as the jet length, a product of jet velocity and nozzle traverse rate. R_p is a function of internal friction which slows the jet (drag force) called the reduction in penetration. S is a parameter reported by Pack and Evans (1951) as secondary penetration, defined, in soil terms, as the inertia imparted by the jet on

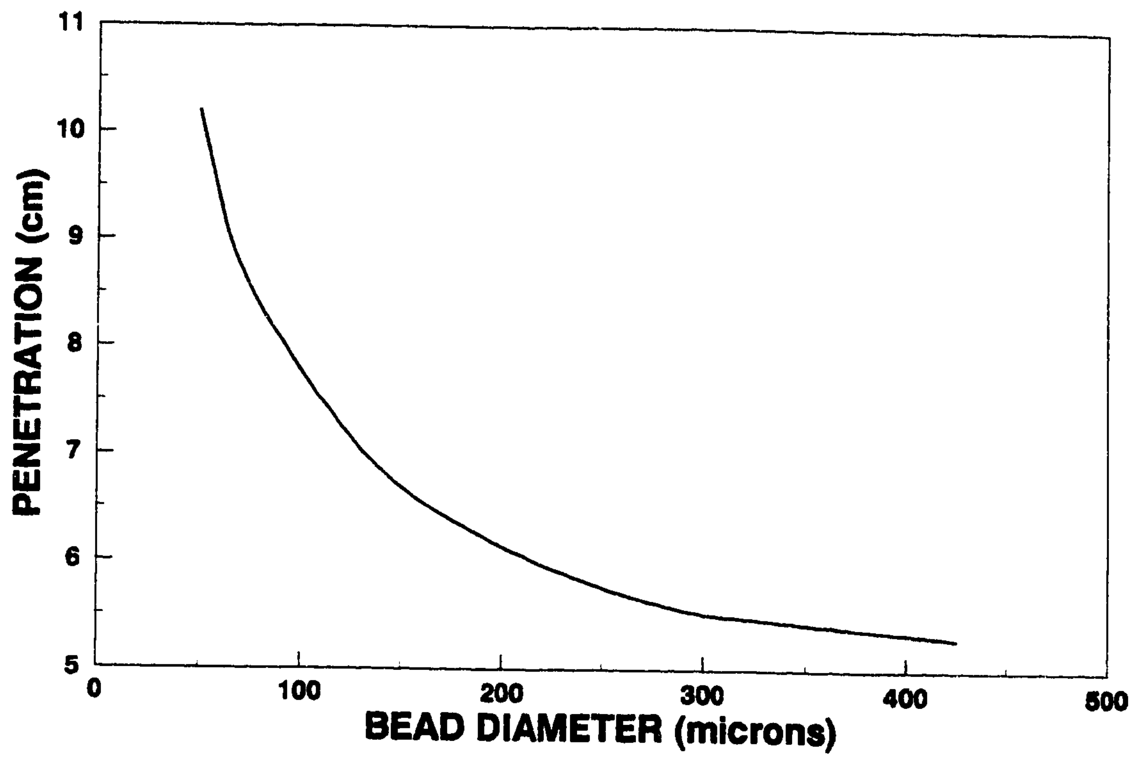

Figure 3. **Effect of particle size of jet penetration into glass beads (adapted from: Arya and Pickard (1958) Fig. 7, pg. 18)**

soil particles which causes penetration to continue after the jet has ceased. Solie and Wittmuss (1983) found the effects of this term to be negligible. The effects of liquid density are accounted for by the variable ρ_j. Soil wet density is represented by ρ_t and soil strength properties are accounted for by the internal friction factor θ. The term λ is a factor differentiating between continuous ($\lambda = 1$) and pulsed ($\lambda = 2$) jets.

Experimental results from Equation 4 yielded a family of curves for soil penetration based on soil moisture content with varying pressures for Judson silt loam. This sums up a problem with jet penetration in soils. There are general relationships which can give the effects of certain parameters on jet penetration into soils, but, due to soil variability, exact solutions are not possible unless soil characteristics are measured carefully. Even with this in mind, soil moisture can alter results substantially even over a short period of time. Therefore, concentration on exact parameters may be fruitless. A more constructive approach would be to concentrate on the measurement of penetration due to changes in applicator parameters rather than predicting the results given many unknowns.

The possibility of pulsing jets enhancing depth of penetration must also be considered. Arya and Pickard (1958) suggested using intermittent (pulsing) jets at low pressures to achieve the same depth of penetration as continuous jets at high pressures. Nebeker (1984) characterized this phenomenon of pulsing jets as the "waterhammer effect". The level of stress in steady and pulsed jets can be represented by the following simplified equations:

for steady state jets:

$$P_s = \frac{1}{2}\rho V^2 \tag{5}$$

for pulsed jets:

$$P_p = \rho\ c\ V \tag{6}$$

By dividing equation 5 by equation 6, the following result can be obtained:

$$\frac{P_s}{P_p} = \frac{V}{2\ c} \tag{7}$$

It is evident from equation 7 that for jet velocities (V) below the speed of sound in liquid (c), the stress level is much higher for a pulsed jet than a steady jet, resulting in the waterhammer effect.

Erdman-Jesnitzer et al. (1980) commented on the ability of pulsed jets to erode metals at 2/3 maximum pressure while at full pressure, continuous jets could not. Nebeker (1984) introduced a factor which changes the whole analysis of the problem, the difference between oscillating and interrupted jets.

An oscillating jet can be thought of as a series of high frequency pulses which modulate around an operating pressure. This is analogous to a voltage-time trace encountered with alternating current except, in this case, the zero voltage line (abscissa) is the pressure the pulses modulate around. To the naked eye the jet looks like a continuous stream, while in fact the jet is made up of jet bunches which create the waterhammer effect.

Interrupted jets are a series of discrete pulses which start at zero, reach maximum pressure and return to zero. This is the type of jet encountered in fertilizer nesting. What confounds the analysis is the amount of time the jet actually spends penetrating the material at any given point. In most rock cutting and drilling applications, the nozzle is thought to act in a quasi-steady state manner, i.e. the nozzle is stationary over time. Therefore the waterhammer stress is essentially induced at one point. In a simple analysis of nesting, a nozzle diameter of 1 mm travelling at a groundspeed of 3 km/h (833 mm/s) results in the jet acting on a single point for only 1.2×10^{-3} seconds (negating nozzle contraction effects). Thus, a typical pulse time of 30 ms, (the time from pulse initiation to a return to zero pressure) using the same nozzle diameter and traverse rate as above, results in the pulse being spread over 25 nozzle diameters. In essence the pressure difference is spread over a large area rather than being concentrated at one spot thus negating the waterhammer effect. This leads to the assumption that pulsing jets, as applied to fertilizer nesting, would not result in better soil penetration than continuous jets.

The distribution of the fertilizer pulse in soil, arguably the most important factor of fertilizer nesting, has received little attention. Granted, this aspect of nesting is more than likely dependent on soil properties; in a similar fashion to soil penetration models. Still little has been done beyond qualitative observations of jet pulses captured in experiments. As derived from literature, maximum soil penetration is of little value unless the fertilizer can be delivered into a compact nest.

Arya and Pickard (1958) theorized once the initial jet front has reached its maximum penetration, the bulk of the fluid behind the jet front conglomerates at the point of maximum penetration in a droplet shape. However, these results were observed with a stationary jet. This characteristic droplet shape may not be present when accounting for ground speed in the fertilizer nesting process. Walker and Stutte (1986) did not note any characteristic droplet shapes in fluorescent dyes injected into soil. For injections to a depth of 26 mm, the average overall width of the captured stream was approximately 5 mm. From this they concluded jet injection would limit application to chemicals which function well in narrow bands or can be displaced by soil moisture. Pointkoski and Domier (1985) noted the spread of the band seemed to vary with soil characteristics and operating conditions.

Beyond qualitative observations, little is known about the distribution of liquids jetted into soils. Perhaps this is one factor of fertilizer nesting which should be quantified in some manner.

CHAPTER 2: APPLICATOR DEVELOPMENT

One of the objectives of this project was to achieve nesting of liquid fertilizer by means of a pulsed high pressure jet. The Lethbridge Research Station possessed a drill mounted continuous stream applicator (DMCSA) which could be used as a starting point to develop a pulsing applicator design. The DMCSA contained all of the elements required, with some modifications and design additions, to achieve the nesting goal. Since the DMCSA was the basis for the pulsing design, a discussion of the DMCSA and its features gives insight to the evolution of the pulsing design.

2.1 The Drill Mounted Continuous Stream Applicator (DMCSA)

In the years prior to the onset of this project, much work was done with both low and high pressure liquid fertilizer applications. One of the results of earlier work was the development of a device which placed liquid fertilizer, by means of high pressure, in a continuous band below seed. This device consisted of two supply tanks, a hydraulic pump/motor combination with reservoir, a high pressure pump and high pressure nozzles with associated hardware all mounted on a Versatile-Noble 2000 hoe press drill. This device was aptly phrased the drill mounted continuous stream applicator or the DMCSA.

In terms of high pressure generation, the DMCSA had two components, the power source and the delivery source. The power source was required because of the mounting constraints placed on the design by the hoe drill. The tow bar could not accommodate mounting of the high pressure pump in close proximity of the tractor P.T.O. Therefore a hydraulic circuit was devised to power a hydraulic motor by means of a P.T.O. mounted remote hydraulic pump which in turn powered the high pressure pump. Plate 1 illustrates the awkward setup with the hydraulic reservoir and controls (centre-left, foreground), the hydraulic motor (centre, background) and the hydraulic pump (far-right, hanging on drill).

Although the power source was important, the main point of interest concerning the DMCSA was the Giant GP7024 pump (Plate 1: centre-right) and the accompanying apparatus which comprised the delivery source.

Figure 4 is a schematic which illustrates the elements which made up the delivery source on the DMCSA. A two-tank supply system was utilized in the delivery source design. One tank was used to hold the liquid fertilizer for application while a second tank held water to flush the system after use. The two tanks were connected to a 50 mm supply hose which had a 50 mm I.D. strainer. The 80 mesh stainless steel strainer (Fig. 4, #7) was required to filter out any large particles in suspension which could lodge in the nozzles and block liquid flow. A large diameter supply hose and strainer were required because of the high capacity of the Giant GP7024 triplex pump. The Giant pump (Fig. 4, #8) was capable of delivering 31.8 L/min at 45.5 MPa requiring 30 kW at 540 RPM. A smaller diameter strainer and supply line caused the pump to cavitate due to lack of liquid supply. The addition of the higher capacity strainer with associated supply line corrected this problem.

System pressure was adjusted by means of a Taylor Tools bypass unloader valve (Fig. 4, #13). To monitor system pressure, a glycerin filled pressure gauge (Fig. 4, #10) was connected to a gauge isolator and this apparatus was mounted to

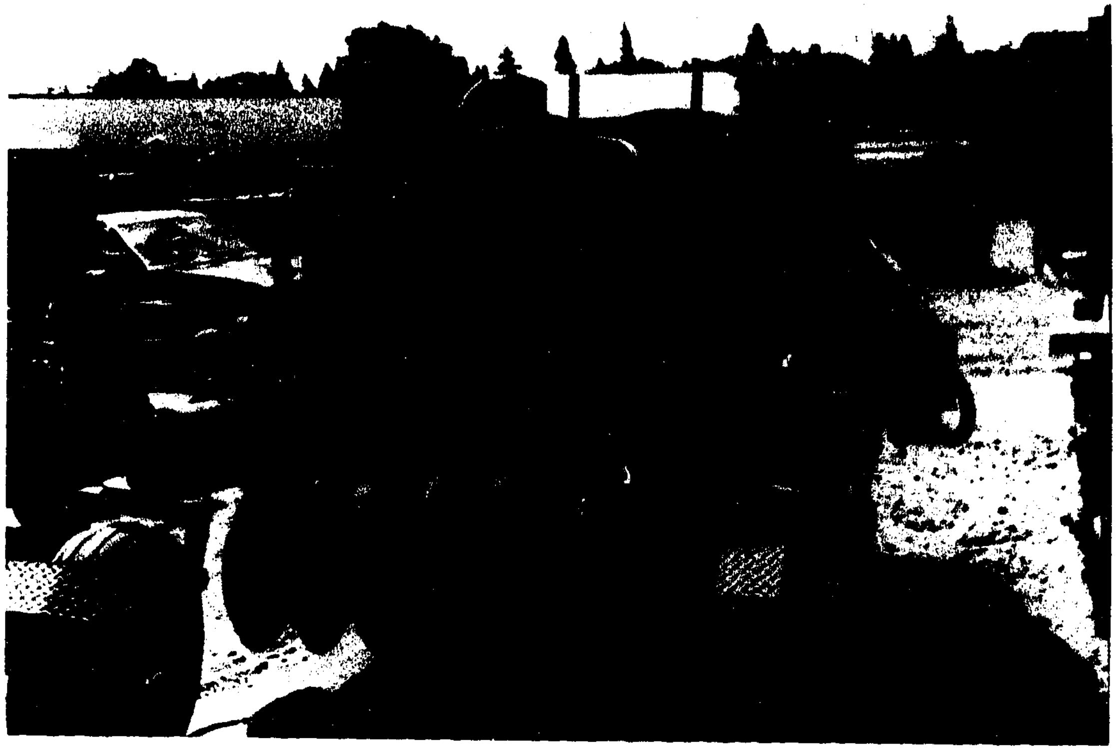

Plate 1. View of high pressure hardware on the DMCSA

one of the high pressure outlets on the pump. To protect the high pressure pump from damage on overload, an IMS pressure relief valve (Fig. 4, #9) set at a cracking pressure of 48.3 MPa was connected on the same fitting as the pressure gauge.

Because the supply tank was located at the front of the drill and the high pressure circuitry was situated at the rear of the drill, the bypassed fluid was returned to the supply line rather than the supply tank. This helped reduce some of the clutter associated with the myriad of hoses associated with this particular design.

Fertilizer which was not bypassed was delivered to the 10-run stainless steel manifold (Fig. 4, #14) under pressure. From the manifold, flow was divided to the 0.457 mm i. d. tungsten carbide nozzles (Fig. 4, #16) for soil application. The

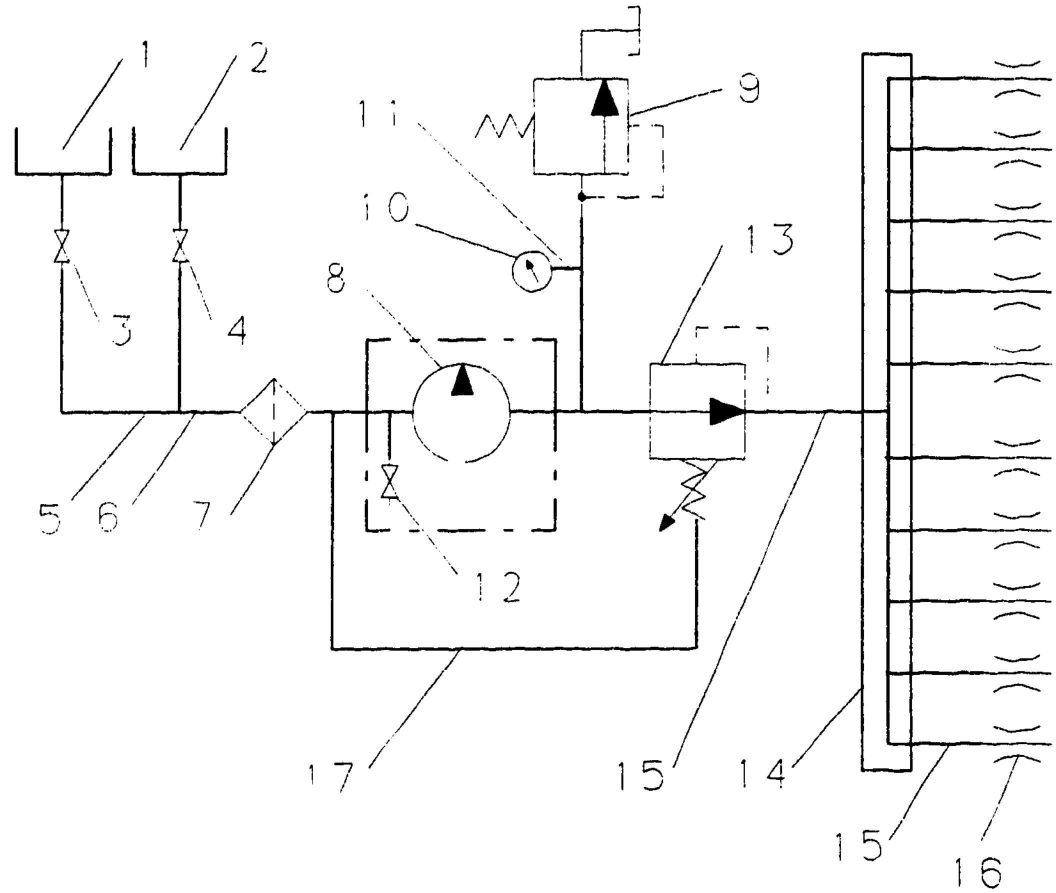

Figure 4. High pressure circuit schematic of the DMCSA

Component List:

1. reservoir (310 L)
2. flush tank (75 L)
3. 50 mm manual Boxer valve
4. 25 mm manual Burbank valve
5. 50 mm i.d. plastic supply hose
6. 50 mm i.d. plastic supply hose
7. 80 mesh stainless steel strainer
8. Giant high pressure pump
9. 48.3 MPa relief valve
10. 0 - 70 MPa glycerin pressure gauge
11. gauge isolator
12. manual drain valve
13. bypass unloader valve (35 Pa - 70 MPa adjustable)
14. stainless steel manifold
15. 6 mm i.d. Kevlar hose
16. 0.457 mm tungsten carbide nozzles
17. 25 mm i.d. plastic return line

carbide nozzles and associated nozzle holders were strung through the hollow tubing of the hoe point where standard prilled fertilizer would normally travel. The nozzle holder containing the carbide tip came out of the fertilizer tube directly behind the tip of the hoe point (Plate 2).

The first season of operation revealed some drawbacks of the DMCSA which put in question its' capability as a viable design to nest liquid fertilizer. First, nozzle proximity to the soil surface was sacrificed. Recalling statements from literature, maximum soil penetration occurs when the nozzle is located as close to the soil as physically possible. The nozzles were mounted in the solid leg of the drills' hoe point. Thus the nozzles could not passively follow the field terrain. As well, there was an offset distance of 1 cm from the bottom of the hoe points to the bottom of the nozzle holders. Ideally, the nozzle should follow the soil surface. This was not possible with the existing nozzle configuration. Therefore, a design modification was necessary to correct the shortcoming.

A second problem with the DMCSA was the inconsistent operation of the hydraulic drive which powered the high pressure pump. The power output of hydraulic pump-motor system exceeded the power requirements of the Giant pump. The result was excessive heating of the hydraulic fluid which decreased the input RPM to the high pressure pump. This ultimately led to inconsistent flow rates through the nozzles due to fluctuations of the liquid fertilizer system pressure. In terms of field experiments, this meant the applicator could run for only 10-minute intervals with 30 minute breaks between runs to allow the hydraulic fluid to cool down.

Plate 2. View of nozzle holder in the DMCSA hoe point

A third problem encountered was the sheer size of the machine. The power requirements of the hydraulic drive plus the weight of the Noble drill and all of the high pressure apparatus required a tractor with at least 50 kW engine power. The tractor which suited this purpose was a John Deere 2950 from the research station. The result was a very large machine which was very difficult to manoeuvre through plots. The tractor-applicator setup also created considerable site disturbance which limited fertilizer applications to pre-seeding.

A fourth drawback of the DMCSA was the constant plugging of nozzles. The unit would have at least one plugged nozzle after only a few minutes of operation. The exercise of unplugging the nozzles became commonplace and was awkward and time consuming due to the inaccessibility of the nozzles. The source of the plugging problem was found to be the combination of plain steel high pressure fittings and the highly corrosive liquid fertilizer. Since the strainer was located on the low pressure side of the pump, metal flakes from the corroded fittings were not filtered out of the liquid fertilizer. The corroded fittings also posed a safety hazard. Corrosion could make the fittings susceptible to pin leaks and burst failure due to the stress under high pressure. This would be a potentially dangerous situation where physical injury could occur. The remedy for this problem was quite clear. All of the fittings were replaced with stainless steel high pressure fittings, requiring complete disassembly and reassembly of the high pressure liquid circuit. Availability of some of the fittings required in stainless steel was limited, therefore design modifications were required.

With all of these factors taken into consideration a choice was made. Rather than make design modifications to an applicator which did not suit the projects needs; a new properly designed applicator to meet the requirements of the research station seemed more prudent. In order to investigate the effectiveness of nesting liquid fertilizer a small, plot size applicator was designed and built (Wasylciw and Lindwall, 1989).

2.2 Pulsing Applicator Design

The first season of fieldwork with the DMCSA was valuable from the point of setting goals towards the design of a new applicator. Many questions were raised which needed to be addressed in the new design of a new applicator. Three problems encountered on the DMCSA namely applicator size, power source and nozzle standoff distance were the main concerns which would have to be incorporated in the new design. Before these features could be incorporated, guidelines were needed in order to form a concept on which the applicator would be based. The guidelines were as follows:

1) Maximum system operating pressure of 34.5 MPa.

2) Three point hitch mount category I in accordance with ASAE Standard S217.10.

3) Pump powered by direct P.T.O. hookup type I in accordance with ASAE Standard S203.10.

4) Overall machine width not to exceed 2500 mm.

5) Variable spacing on nozzles up to a maximum 407 mm.

6) Two tank system each with minimum 50 L capacity.

7) Adequate drainage for thorough clean up.

8) Adjustable wheel height.

9) Minimize nozzle standoff distance from soil surface.

10) Achieve pulsing capability for fertilizer nesting.

Guidelines 1, 2 and 3 came about through interrelationship between available equipment, shortcomings with the DMCSA and cost. The centrepiece of the design was the Giant high pressure pump. At 540 RPM, the pump performance specifications indicated a pump output of 31.5 L/min at 34.5 MPa with a power requirement of 22.4 kW. This was suitable in terms of the tractors normally used for plot work. At these specifications there was no requirement for modification of the input speed to the pump. Therefore direct connection to the tractor P.T.O. was possible; thus negating the power source problems encountered with the DMCSA. A pressure of 34.5 MPa was suitable from the standpoint of the required high pressure fittings in terms of cost. Although the pump was capable of delivering sufficient flow at much higher pressures, literature suggested that higher pressure is an inefficient method for increasing soil penetration.

2.2.1 Frame Design

To meet the requirements for a plot size applicator, a frame had to be built. The constraints of a category I 3-point hitch mount meant the total mass of the applicator should be kept near 700 kg Fortunately a rigorous engineering analysis of the problem was not needed since a point injector designed by the resident engineer provided a model on which to base the high pressure application. A few modifications were made to accommodate mounts for the high pressure pump. Since the distance between the centreline of the P.T.O. shaft and the ground surface varies from tractor to tractor, adjustable wheels were included in the design. This was an important modification to minimize P.T.O. shaft pitch between the applicator and the tractor.

The standard plot width used at the Lethbridge Research Station was 2.5 m. Therefore the maximum width allowed for the applicator was 2.5 m. Although the applicator design called for the flexibility to space the nozzles to any width desired, the most common post-seeding fertilizer applications were made midrow. Since the majority seeders used at the Station have the seed boots at 200 mm spacings, the nozzle spacing most commonly used would be 400 mm. From these constraints the design called for a six-run applicator. To allow for the six runs and extra width for later additions, the overall width of the design was set at 2350 mm. Thus, longitudinal members of the frame consisted of 6 × 50 × 75 mm hollow structural steel 2350 mm long.

To allow for the mounting of the pump on the frame, the distance between the longitudinal member centres was set at 610 mm. The ends of the longitudinal members were welded together with 10 × 100 mm steel plate. To add strength for the undercarriage and facilitate mounting of the applicators' associated hardware, cross members of 6 × 100 mm square hollow structural steel were welded 500 mm from either end of the frame.

The pump was mounted to the frame with an undercarriage made of 6 × 50 × 75 mm hollow structural steel. To allow for suitable clearance of the P.T.O. shaft, the deck of the undercarriage was set 350 mm from the top plane of the frame.

A 400 × 100 × 100 mm box (with an open bottom) made of 6 mm plate steel was welded to one of the tank mounts to house the pressure gauge, bypass valve and relief valve assembly. This steel box was a necessary safety feature since hardware failure within close proximity of the operator could lead to serious physical injury.

In order for the nozzles to follow the soil surface contours, a runner system was used. The runner system consisted of three elements: endplate, connecting arm and runner. The system was allowed to pivot at both ends of the 800 mm long connecting arm. The connecting arm and runner were made of 25 mm stock and 25 mm hollow structural steel. The runner system was clamped to the rear member of the frame by U-bolts which fit into the endplates to allow for lateral spacing of the nozzles.

2.2.2 First Generation High Pressure Liquid Circuit

The DMCSA provided valuable information on the problems associated with the high pressure jetting of liquid fertilizer. During design and construction of the new applicator, difficulties were encountered with the incorporation of pulsing technology into the new design. Since the timetable for setting up experimental field trials was somewhat compressed, a decision was made to postpone the inclusion of the pulsing equipment into the design. The basic plan from the initial construction of the new applicator was to stay with the high pressure schematic developed in the DMCSA. This was done for two reasons. First, the general design itself was sound and the incorporation of high pressure technology into the design would not require any wholesale design changes. Second, the most costly components of the design namely the: pump, bypass valve, relief valve, pressure gauge and manifold were present. This would reduce the construction costs of a new applicator.

Figure 5 is the design schematic of the liquid delivery system incorporated into the new applicator. When compared to the schematic of the DMCSA illustrated in Figure 4 the only major design change was the positioning of the return line from the bypass unloader valve (Fig. 5, #12). The return line had to be repositioned because of the physical state of the liquid exiting the bypass unloader valve. The regulation of the pressure generated by the pump was accomplished with the bypass unloader valve by releasing excess liquid from the high pressure circuit. The released liquid was essentially throttled from a pressure of 34.5 MPa to atmospheric pressure resulting in the formation of vaporized liquid fertilizer in the return line. When this bypassed fluid was returned back into the suction line of the pump, the trapped vapour led to pump cavitation. To correct this problem the bypassed fluid was returned to the supply tank below fluid level. This served as an agitator for the supply tank as well as a possible recovery method for some of the vaporized liquid fertilizer.

Other differences noted between the schematics in Figures 4 and 5 dealt with improvements in the actual hardware used in the DMCSA.

For high pressure banding, the capacity of the nozzles at a prescribed pressure and the actual application rate of liquid fertilizer differed greatly. Since the application rate was much lower than nozzle capacity, the liquid fertilizer had to be diluted with water to be applied with the DMCSA. Because of this discrepancy, the two-tank system used in the DMCSA consisted of a high volume supply tank (Fig. 4, #1) and a low volume flush tank (Fig. 4, #2). The pulsing effect used to create fertilizer nests eliminated the need for fertilizer dilution. The supply and flush tanks were replaced with two tanks similar in size (Fig. 5, #1 and #2). By using four ball valves placed in strategic locations, both tanks could hold similar or different fertilizer mixtures or one tank could be used for flushing the system. As well, emptying and cleaning the system for winter storage was much less complicated than with the DMCSA.

The combination of the corrosive liquid fertilizer and the mild steel fittings

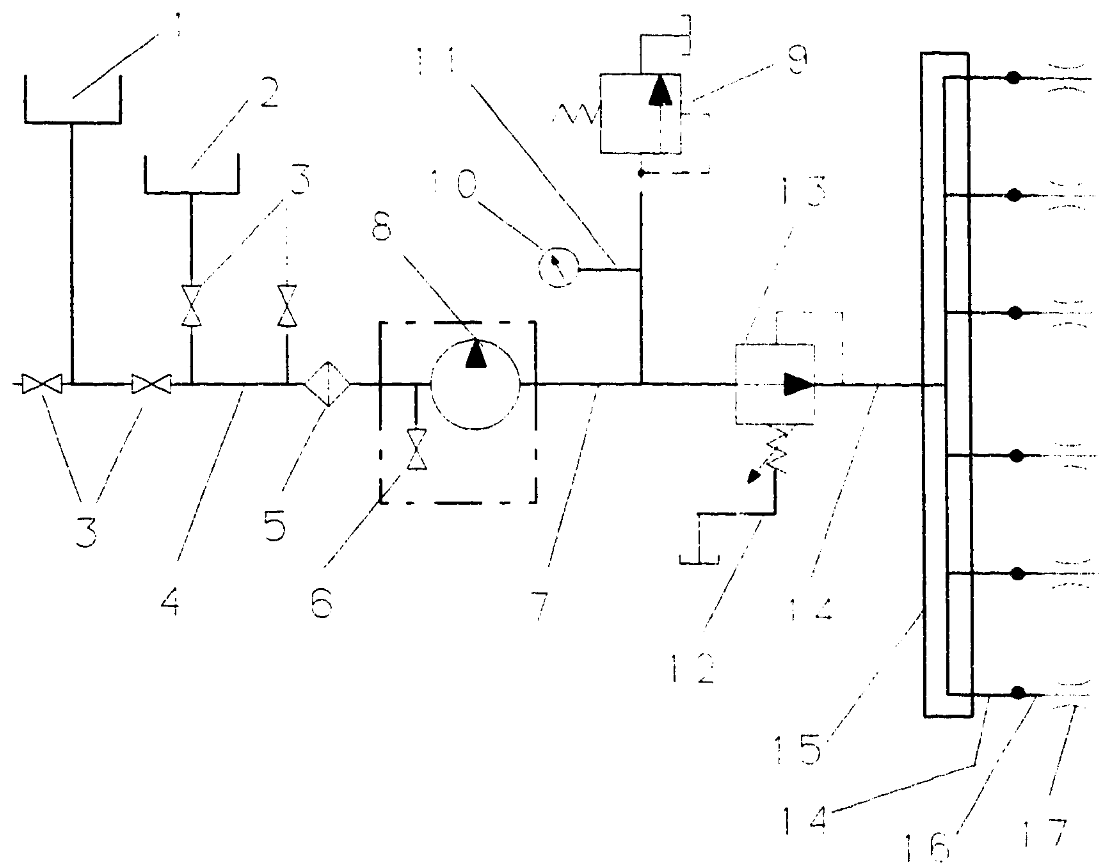

Figure 5. High pressure circuit schematic of the new applicator design

Component List:

1. supply tank (100 L)
2. supply tank (70 L)
3. 50 mm manual Boxer valves
4. 50 mm i.d. plastic supply line
5. 80 mesh stainless steel strainer
6. manual drain valve
7. 9.5 mm steel belted hose (69 MPa)
8. Giant high pressure pump
9. 48.3 MPa relief valve
10. 0-70 MPa glycerin pressure gauge
11. gauge isolator
12. 25 mm i.d. plastic return line
13. bypass unloader valve (35-70 MPa adjustable)
14. 6 mm i.d. Kevlar hose
15. stainless steel manifold
16. 6.35 mm stainless steel tube with 1.24 mm wall
17. 0.457 mm tungsten carbide nozzles

of the DMCSA made nozzle plugging a frequent occurrence. To rectify this problem all fittings on the suction side of the pump were replaced with plastic instead of mild steel. Plugging was more expensive to deal with on the high pressure side of the pump. The steel fittings in the new design had to be replaced with stainless steel fittings. The high pressure hose in the DMCSA had ends made of mild steel. These ends were prone to corrosion which not only led to plugged nozzles but could have resulted in a potentially hazardous situation of corrosion weakening the ends substantially. Since the ends needed replacement, the kevlar hose with mild steel ends were replaced with steel belted hose (with a lower coefficient of expansion) and stainless steel ends. The addition of small length of stainless steel tubing (Fig. 5, #16) to the nozzle holders facilitated easy connection of the nozzle to the manifold and was required for the incorporation of pulsing into the system.

2.2.3 Incorporation of the Pulsing Valve

In order to create the pulsing effect required for fertilizer nesting, a flow-interruption device was essential. In order to simplify the task of developing unproven technology to achieve this goal, a decision was made to incorporate a device designed for the sole purpose of nesting liquid fertilizer with a high pressure jet. To this end project funds were procured to purchase two solenoid valves and an electronic valve controller designed and developed by Rogers Engineering from Saskatoon, Saskatchewan for their version of a fertilizer nesting applicator.

The solenoid valve operated in a normally closed position by means of a stainless steel needle valve and orifice-seat configuration. The needle valve was lifted off the orifice by means of a magnetic field supplied by a steel wound coil in which the armature of the needle valve was situated. The valve was closed by a spring return when the magnetic field collapsed. Current for the coil was supplied by the controller which was connected to the battery of the tractor. The pulse duration and pulse frequency of the solenoid valve were dictated by the on-time (pulse duration) and cycle-time (pulse frequency) dialled in on the controller. The controller also had an option which allowed for operation of the valve in the open position for an unspecified length of time. This was not recommended for periods longer than one minute since coil burnout could result. Due to coil energizing limitations, the maximum allowable on-time was 25% of the cycle-time selected on the controller.

The solenoid valve was originally designed to house a single nozzle and thus one valve was required for each run on the applicator. The solenoid valves were expensive, therefore, the decision was made to investigate if one valve could be used to operate more than one nozzle. Methods were required to evaluate the quantity of fluid the valve could provide and quality of the jet which could be expected from a given valve nozzle configuration.

To determine flow, the valve was operated in an open position. Water under low pressure was fed through the valve for a measured time period and the volume of water collected was recorded. The collected data was translated to the design pressure of 34.5 MPa using the following elementary relationship:

$$Q_2 = \frac{\sqrt{P_2}}{\sqrt{P_1}} Q_1 \tag{8}$$

where:

Q_2 = flow at design pressure (L/min).

Q_1 = flow measured in the calibration (L/min).

P_2 = design system pressure of 34.5 MPa.

P_1 = pressure recorded during the calibration (MPa).

A correction factor was required to account for the fact that the specific gravity of liquid fertilizer differs from water. The correction was applied with the following relationship:

$$Q_{fert} = Q_w \frac{1}{\sqrt{\gamma_L}} \tag{9}$$

where:

Q_{fert} = corrected flow rate of liquid fertilizer (L/min).

Q_w = flow rate of water (Q_2) at 34.5 MPa determined with equation 8.

γ_L = specific gravity of the liquid fertilizer.

Using the average flow rate from the trials, the flow rate of liquid fertilizer through the valve at 34.5 MPa was estimated at 14.4 L/min.

The next step required, was to determine the nozzle flow rate at the design pressure. In this case the nozzle flow rate was determined by measuring the volume of water required to refill the tank to a set level. This gave the average volume used per nozzle per minute of operation. From equations 8 and 9, the corrected capacity of the nozzles was calculated as 2.20 L/min/nozzle at design pressure. This analysis showed the solenoid valve, with the capacity of 14.4 L/min, could supply flow for up to six nozzles.

To incorporate a valve-manifold configuration, a swivel would be required between the manifold and nozzle. The use of a rigid connection between the manifold and nozzle would not allow the runner assembly to pivot freely to follow the soil surface contours. A fully-flexible connection between the manifold and the nozzles may act as an accumulator by absorbing the energy of the jet when the valve initiates a pulse.

In order to investigate the effects of hose flexing on jet energy, a Setra Systems Model 204E pressure transducer was obtained on loan from the Alberta Farm Machinery Research Centre in Lethbridge. This pressure transducer emitted an increasing DC voltage with increased pressure applied to the diaphragm of the sensor. The calibration curve provided with the pressure transducer indicated a linear relationship between the pressure applied and sensor output voltage. When input pressure was increased by 6.9 MPa, the transducer emitted an output voltage of 1 volt (6.9 MPa) to a maximum of 5 volts (34.5 MPa). An instant visual record of pressure response over time was made by connecting the output leads from the transducer to an oscilloscope.

Plate 3 illustrates a typical pressure-time relationship observed on the oscilloscope for the pulsing valve and the pertinent elements associated in evaluating jet energy. When assessing the effects of hose flex on jet energy, the rise-time and maximum pressure attained were of main importance. If the rise-time was long and

Plate 3. Illustration of elements associated with pulse measurement

the pressure did not achieve maximum value, then a significant amount of the jet energy was lost in the flexing of the high pressure hose. The on-time and cycle-time indicated the accuracy of these values dialled in on the valve controller. Fall time indicated the ability of the spring return to seal the needle valve once the magnetic coil was de-energized.

The adverse effects that hose flexing might pose was quantified by comparing the pressure-time profile of various connections between the valve and nozzle holder. To represent the ideal situation a 1 m length of 6.25 mm o.d. stainless steel tubing, with 1.25 mm wall thickness, was connected between the valve and nozzle holder (Plate 4). The pressure-time profile was compared to the pressure-time profiles for

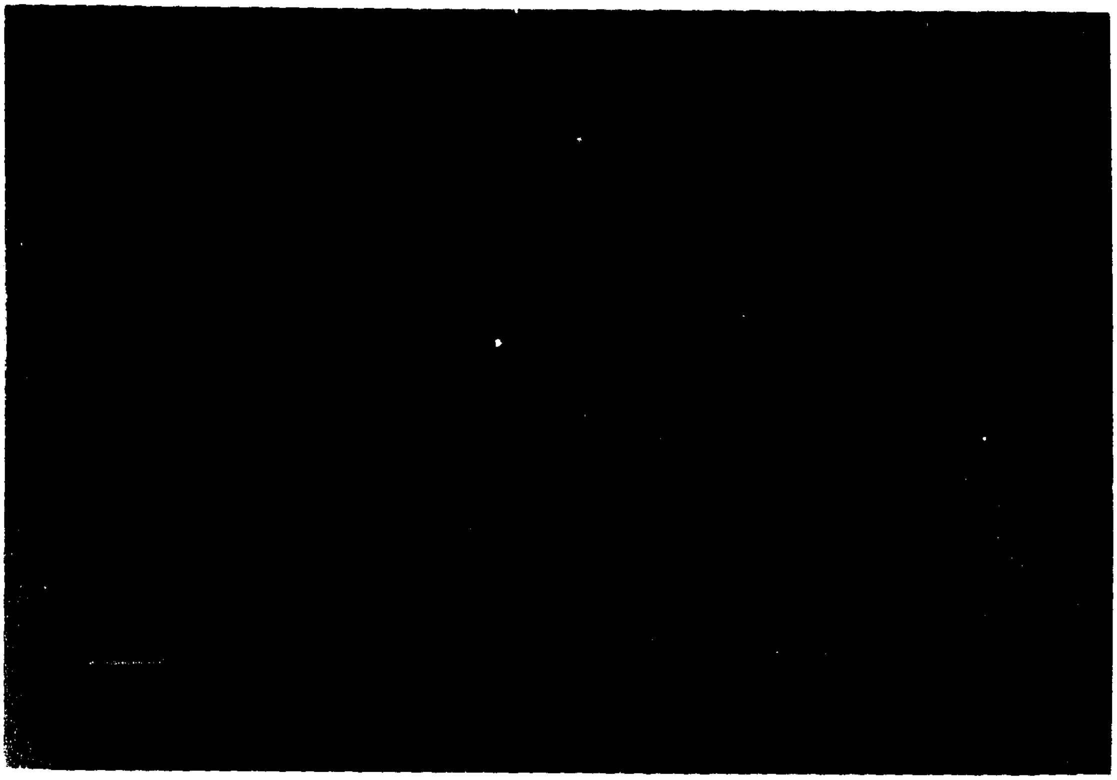

Plate 4. Pressure-time profile of steel tubing/nozzle combination: on-time 30 ms (y = 3.5 MPa/division x = 10 ms/division)

1 m of 6.25 mm i.d. flex hose and a combination of 30 cm - 6.25 mm i.d. steel belted hose and 0.70 m of stainless steel tubing. The pressure transducer was placed between the connected lines and the nozzle holder in each instance. Plate 4 is the pressure-time profile of the steel tube alone which represented the maximum transfer of energy. When compared to Plate 5 with flex hose only, there was a marked difference in the transfer of jet energy. The rise-time was one-third as long for the tube connection than the flex hose connection. The pressure rose to the set value of 20.7 MPa for the tube connection while the flex hose only reached a value of 17.2 MPa. This implied hose flexing absorbed much of the impulsive energy the opening of the valve could provide for jet penetration. Plate 6 illustrates the pressure-time

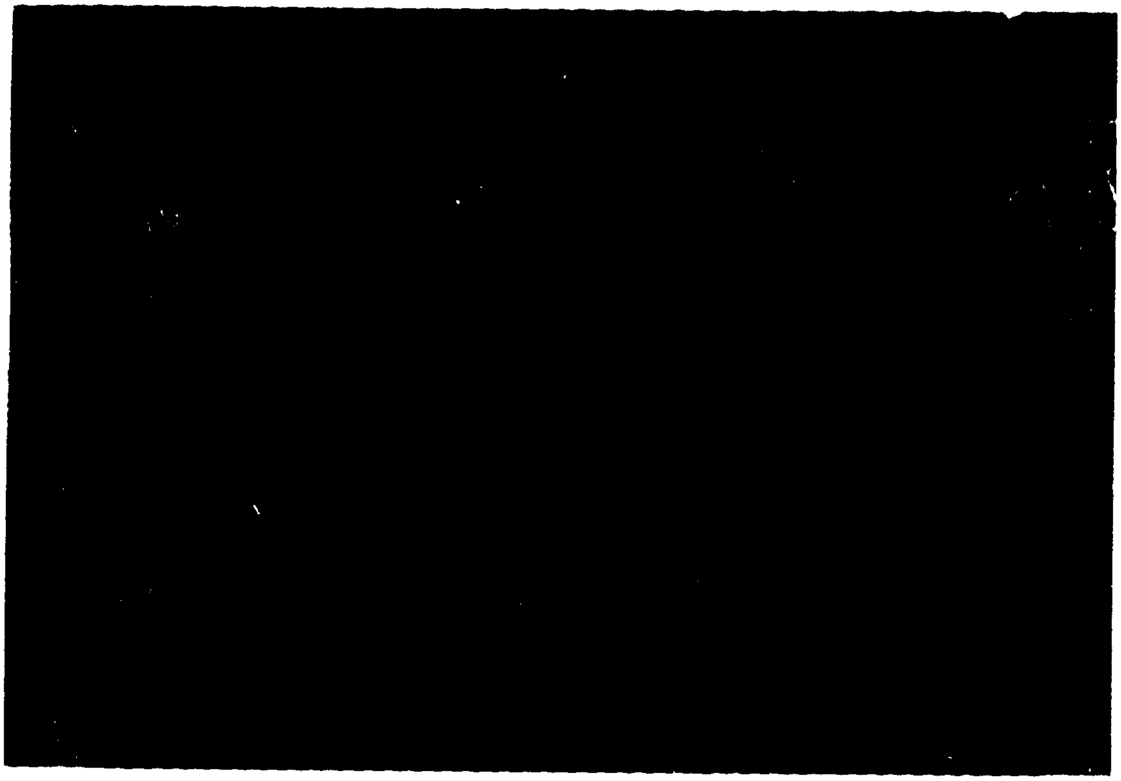

Plate 5. **Pressure-time profile of flexible hose/nozzle combination: on-time 30 ms (y = 3.5 MPa/division x = 10 ms/division)**

profile for the combination of the short length of flex hose with the steel tubing (1 metre total length). Duly noted was the slightly longer rise time than compared to Plate 4, but the characteristic pulse peak absent with the flex hose was present with the flex hose-tubing combination.

These findings implied short hose lengths combined with steel tubing could be used to connect the solenoid valves to the nozzles. By mounting a valve above the second and fifth runner plates, one valve could be used to operate three nozzles with lengths of flex hose no longer than 40 cm (Plate 7). Thus two valves were required instead of six.

By mounting the pressure transducer at strategic locations on the high

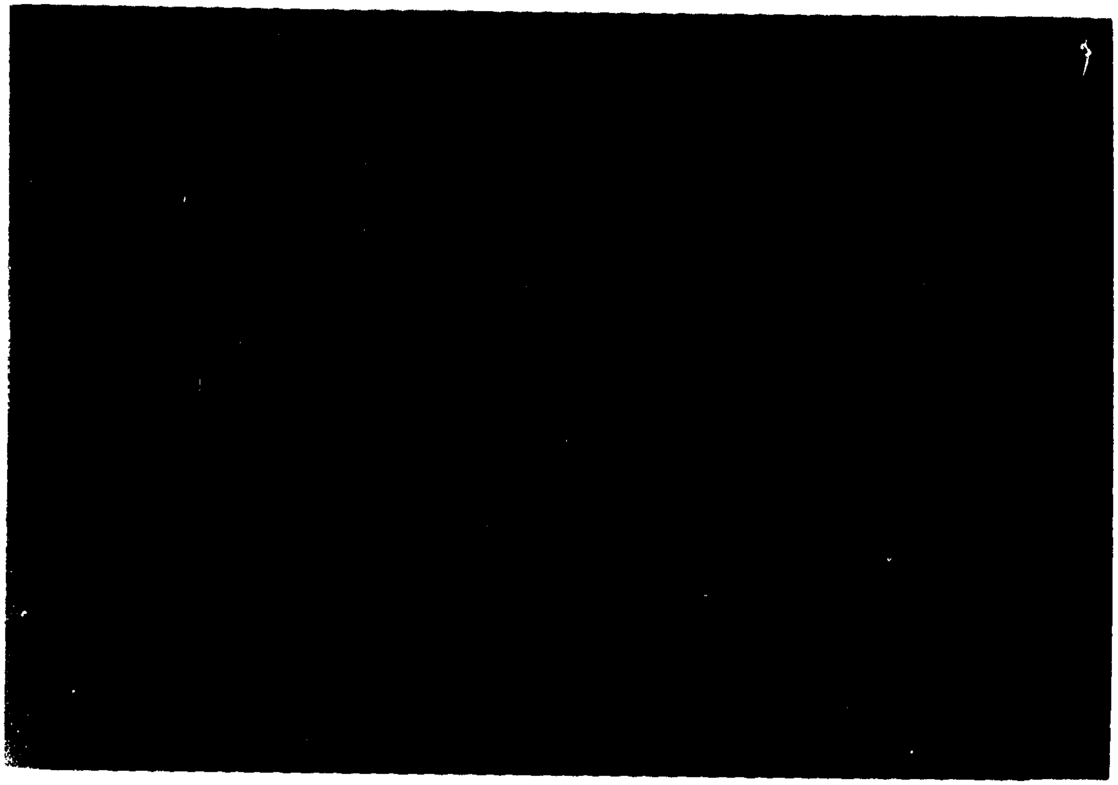

Plate 6. **Pressure-time profile of steel tubing/hose/nozzle combination: on-time 30 ms (y = 3.5 MPa/division x = 10 ms/division)**

pressure applicator, performance of the system design could be monitored. Plate 8 is the pressure-time profile of the pressure transducer situated right at the pressure gauge used to set the system pressure. In this instance the pressure was set at 20.7 MPa and the applicator was running on continuous stream. As noted in the caption, the recorded pressure was oscillating about 20.7 MPa (baseline was 1 division above the bottom of the plate). This verified the accuracy of the gauge used to set the system pressure of the applicator.

Plate 9 is the pressure-time profile of the transducer located just before the solenoid valve operating in pulsing mode. Again the system pressure was set at 20.7 MPa. When the valve opened there was a subsequent pressure drop of approximately

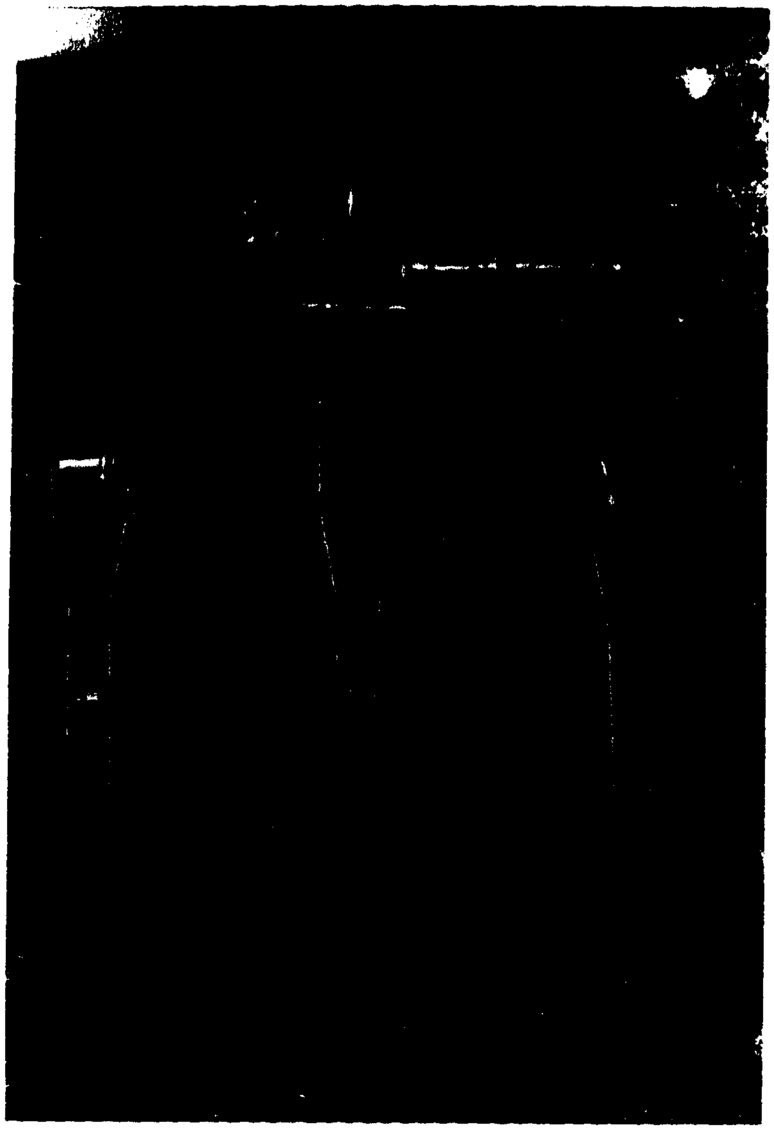

Plate 7. Illustration of final valve and nozzle configuration

1.8 MPa (interpolation of the mean value of the pressure spikes). When compared to Plates 4 through 6, which were located after the solenoid valve, the pressure drop was 3.5 MPa. In other trials, this noted pressure drop was not constant. When pressure was set at 34.5 MPa, the pressure measured at the nozzle was 27.6 MPa, was only 27.6 MPa, implying pressure loss across the solenoid valve increased linearly

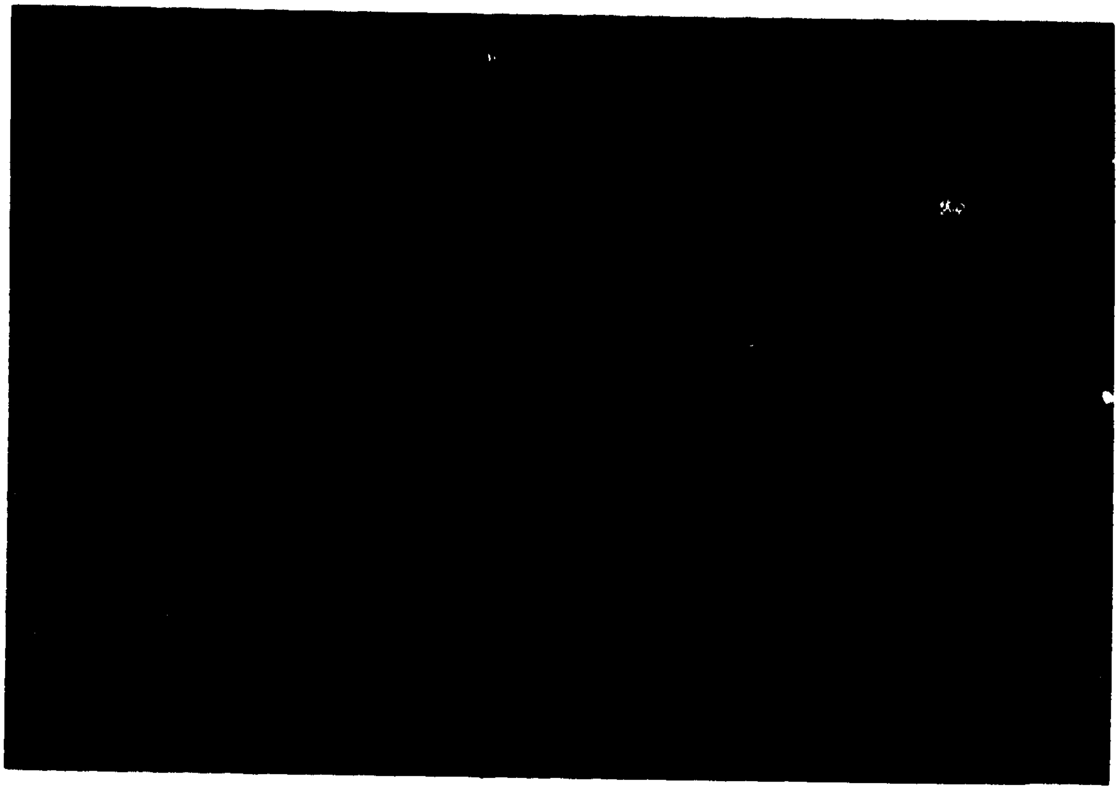

Plate 8. **Pressure recorded at the guage: continuous stream (y = 3.5 MPa/division x = 20 ms/division)**

with increasing pressure. In this instance, the transducer identified the discrepancy between the set system pressure and the actual nozzle pressure. In view of the discrepancy between the set pressure and the nozzle pressure, all referrals to pressure settings of the applicator throughout this study pertain to the gauge setting rather than the actual nozzle pressure.

Plate 10 is from one of the early pulsing trials. This is an example of the pros and cons with the incorporation of this valve system. The on-time in this trial was set at 30 ms and the cycle-time was set at 160 ms on the controller. The cycle-time measured here was exactly 160 ms. In fact, the cycle-time dialled in on the controller was consistently measured as set on the control box. However, the measured on-time

Plate 9. Pressure recorded before valve: pulsing on-time 40 ms, cycle-time 160 ms (y = 3.5 MPa/division x = 50 ms/division)

was approximately 70 ms while the controller read 30 ms. The problem was not the controller but the design of the solenoid valve. The prelo. ʝ of the spring which returned the needle valve armature back to the orifice seat was set by two screws on the cap of the valve body. This Plate is an example of how dramatically the on-time can change if the preload is not correctly set. Constant vigilance of this factor was required in the operation of the applicator.

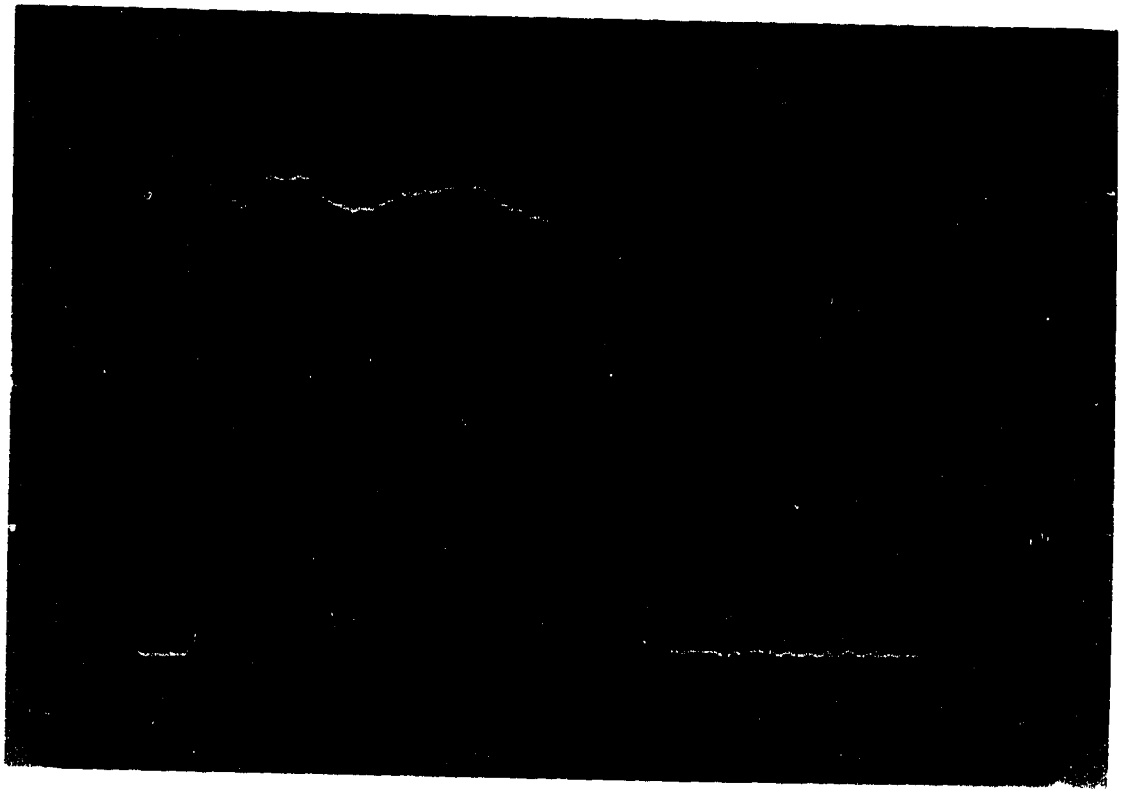

Plate 10. Pressure-time profile illustrating valve performance: on-time 30 ms, cycle-time 160 ms (y = 3.5 MPa/division x = 20 ms/division)

2.2.4 Final System Configuration

Once the solenoid valves were incorporated into the applicator design, a few modifications were required to overcome some problems with pulsing which were not anticipated. The first problem centred around the reaction of the bypass unloader valve to the introduction of pulsing to the high pressure circuit. The valve controller allowed the valves to pulse simultaneously or in sequence. Under simultaneous operation, no flow was exiting from the nozzles on an intermittent basis, thus, all the liquid had to be bypassed through the return line. When the solenoid valves opened, the unloader valve had to supply flow quickly. Because the response time of the solenoid valves was much faster than that of the bypass unloader valve, an unstable situation was created. This led to a system overload in which only the cracking pressure relief valve was able to save the high pressure pump. Connecting the solenoid valves in sequence kept the relief valve from cracking but the pulsing of solenoid valves was still too fast for the bypass unloader valve. The bypass unloader valve would slam quite hard indicating operation in this manner would lead to excessive valve wear. To alleviate this problem, a bleed line was connected between the main manifold and the tank return line. This bleed line was controlled by a high pressure needle valve (Fig. 6, #2). This needle valve allowed controlled constant flow through the bypass unloader valve; keeping the valve from operating in a nearly closed condition.

The final modifications encountered were the replacement of the Kevlar hoses between the bypass unloader valve/manifold and the manifold/solenoid valves. In a pulsing situation these hoses showed a propensity to flex indicating an energy loss to the system. These hoses were resized with the appropriate diameter stainless steel tubing (Fig. 6, #5) to eliminate the flexing effect. Once the system was set up, the pressure transducer indicated the pulsing design and incorporated supply line modifications did not significantly alter earlier observed conditions of applicator operation.

The final system configuration noting only those components or modifications made since the initial construction of the applicator is shown in Figure 6. Plate 11 is an overall view of the applicator with the given design modifications.

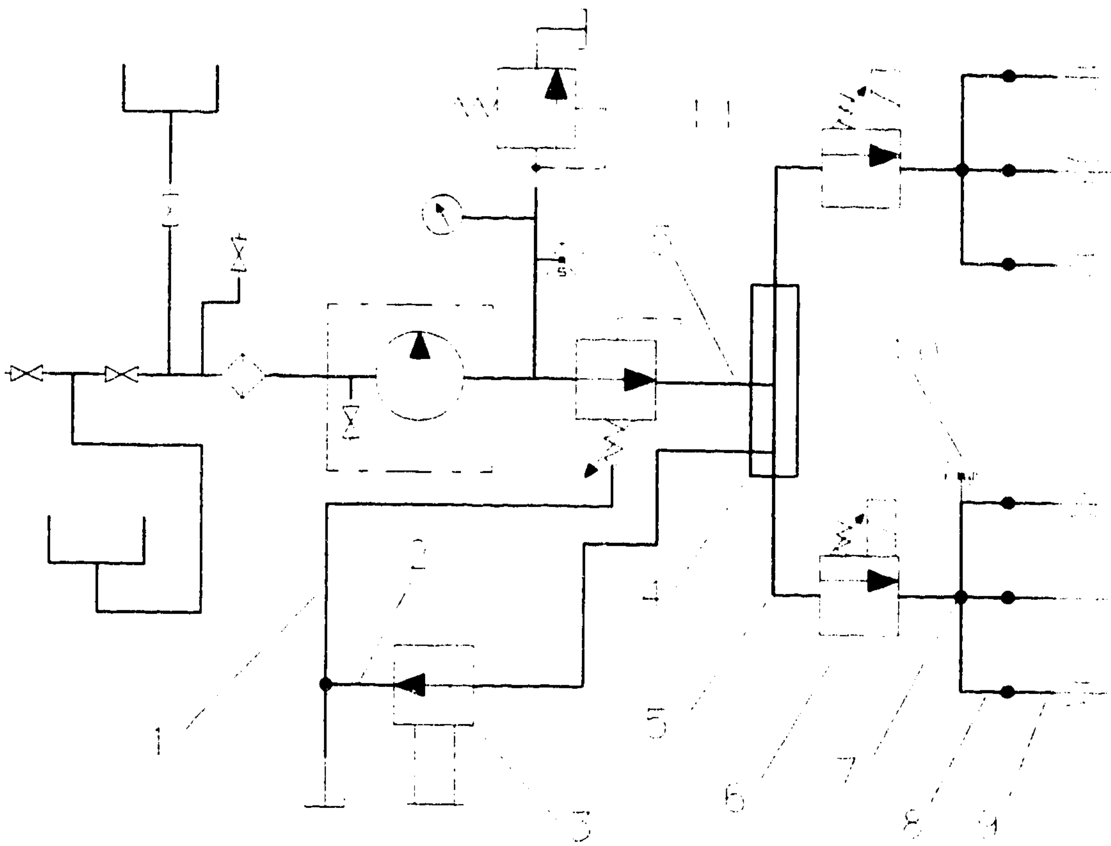

Figure 6. **High pressure pulsing circuit schematic**

Component List:

1. 25 mm i.d. return line
2. 6.25 mm stainless steel tubing
3. stainless steel manual needle valve
4. stainless steel manifold
5. 9.5 mm stainless steel tubing with 1.65 mm wall
6. stainless steel solenoid valve
7. stainless steel cross
8. 6 mm i.d. steel belted hose (69 MPa)
9. 6.35 mm stainless steel tubing with 1.24 mm wall
10. transducer location for plates 4, 5, 6 and 10
11. transducer location for Plate 8

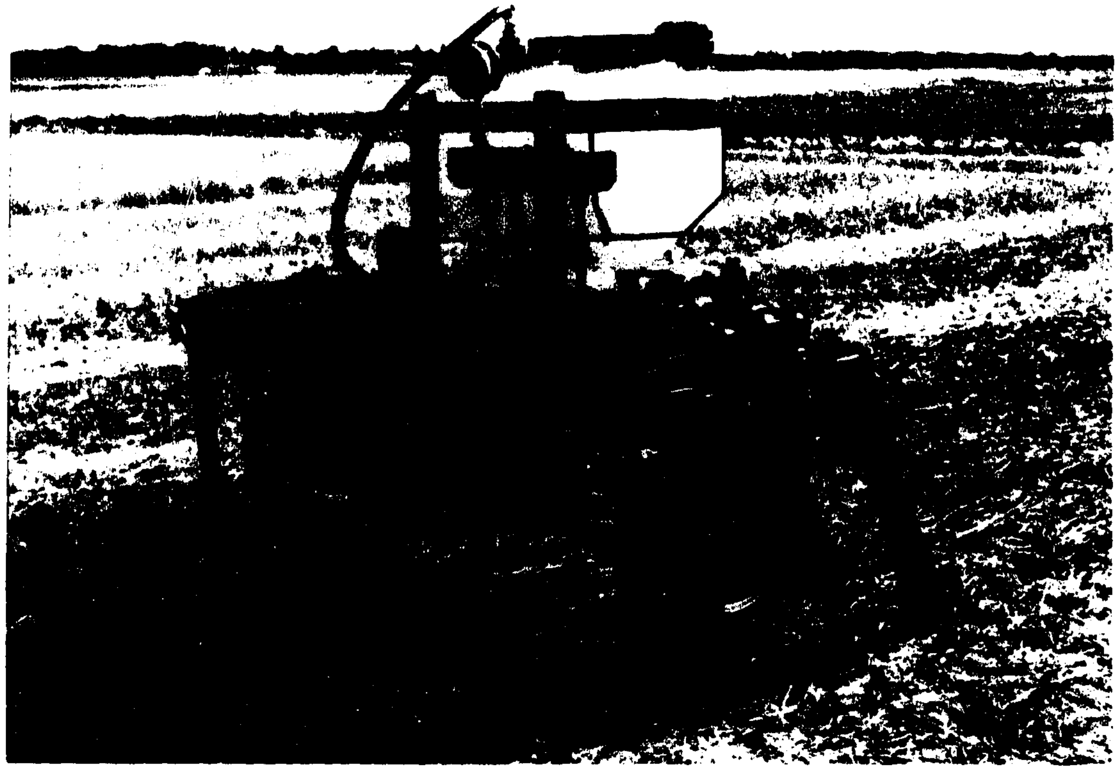

Plate 11. View of pressurized liquid nesting device

CHAPTER 3: EXPERIMENTAL METHODS

Because this project involved the implementation of a new design to investigate fertilizer nesting, much of the focus of the project revolved around developing a new implement. Most of the time was spent constructing a mechanically sound nesting applicator and mastering what was considered unproven technology. The scope and complexity associated with developing a pressurized liquid fertilizer nesting device overshadowed the actual goal of this project; to investigate the viability of fertilizer nesting using this proto-type applicator. The effectiveness of fertilizer nesting is contingent upon a properly designed applicator. However, to investigate the hypothesis that pressurized liquid fertilizer application is superior to conventional fertilizer application techniques, such as broadcast and deep banding, field experiments were required; comparing the methods of fertilizer application under varied cropping situations. Research has shown nesting of fertilizer nitrogen to be successful on a small plot scale by hand formation of nests (Monreal, 1981; Nyborg and Malhi, 1979). Research has also shown nest placement is important to maximize crop response to nitrogen (Janzen and Lindwall, 1989). Nest formation by a pressurized liquid jet is possible, but research is lacking when considering the fertilizer distribution which results from using this method. These factors must all be considered in the experimental design implemented to test the effectiveness of fertilizer nesting by pressurized liquid jet.

To investigate the effectiveness of pressurized liquid jet fertilizer application, four field experiments and one penetration experiment were conducted. The experiments compar' pressurized liquid fertilizer application to conventional methods of fertilizer application.

Three experiments compared fall application to spring application of fertilizer and one experiment dealt only with spring application of fertilizer. To investigate the flexibility of application methods, three crops were utilized; native grassland, spring barley and winter wheat Crops were harvested to determine yield, nutrient content and in the case of barley, protein content.

Soil core samples were taken from the crop experiments to investigate fertilizer distribution. Unfortunately severe damage to a solenoid valve and the valve controller resulted in very lengthy repair time. These setbacks resulted in pressurized liquid nesting being used in only one crop experiment. Because comprehensive data on fertilizer distribution by pulsed jet were lacking, a penetration experiment was devised.

To reduce the confounding effects of residual nitrogen in the soil, care was taken to select experimental sites which had not received significant amounts of fertilizer for at least 5 years prior to the initiation of these experiments.

3.1 Field Experiments

During the first season of field experiments in 1988, most of the summer was spent trouble-shooting and minimizing the plugging problems with the DMCSA. Concurrently, much time was spent obtaining data from the DMCSA to aid in the design of a new applicator as well as developing a suitable procedure to evaluate fertilizer distribution in the soil profile. Consequently, plans did not include the incorporation of fertilizer nesting in the initial field trials. The DMCSA was used to band liquid fertilizer in the preliminary field trials. By varying ground speed, pressure and dilution rate with the DMCSA in these experiments, preliminary data on soil penetration characteristics were obtained.

3.1.1 Experiment 1: 1988 Winter Wheat Experiment

The first experiment was designed to determine the response of winter wheat (var. Norstar) to method of nitrogen application and time of application. The experimental site was the west section of Treestrip (north of the Station) on a dark brown Chernozem with a loam texture. Immediately before seeding, 11 treatments received 40 kg N/ha by various application techniques.

Three treatments received surface injection of pressurized liquid urea ammonium nitrate (UAN). These three treatments were applied with the DMCSA at three different system pressures. The different pressures were used to investigate the effects of system pressure on soil penetration and determine if the anticipated increase in soil penetration would result in crop response. The three system pressures were repeated in three other treatments but banded to a depth of 10 cm to determine crop response to deep banding of pressurized liquid UAN. The other treatments were determined to include nesting by pressurized liquid jet but these treatments were not applied because of the technical difficulties previously mentioned.

To represent conventional methods of fall application of nitrogen, banding and broadcasting of nitrogen were used. Urea (46-0-0) and ammonium nitrate (34-0-0) were banded to a depth of 10 cm with a John Deere hoe drill. Broadcast treatments of urea and ammonium nitrate were applied with a Barber spreader. The last treatment was applied by injecting liquid UAN with the point injector to include fertilizer nesting in the experiment.

Allowances were made to include the spring applications of all treatments except deep banding. A check plot, which received no nitrogen, was also included to give 24 treatments in a block. Each treatment plot was 3 m wide and 20 m long. The experiment was replicated four times in a randomized block design.

The plots received a blanket application of Sweep herbicide (paraquat) at a rate of 2.47 L/ha mixed with 2,4-D at a rate of 1.23 L/ha, one week prior to seeding. On October 5th, 1988 the plots were seeded lengthwise with a John Deere hoe drill to a depth of 5 cm. Triple super phosphate (11-51-0) was placed with seed at a rate of 60 kg/ha.

To determine the depth of fertilizer penetration and fertilizer distribution from the six treatments utilizing the DMCSA, soil samples were collected from three of the replicates immediately after fertilization. Cores were taken with a 35 mm diameter Oakfield sampler. The samples were taken by penetrating the soil at the kerf left by the penetrating jet, (for surface application) or in the middle of the soil disturbance created by the hoe point (for deep band applications). The cores were divided into appropriate sample sizes. The samples were identified, placed in plastic bags, then stored in a cooler at 5 °C to reduce nitrogen mineralization and volatilization. The samples were later prepared for ammonium and nitrate analysis.

The soil analysis revealed the sampling technique did not accurately capture the kerf in the deep band UAN treatments. For this reason deep banding data were excluded from the fertilizer distribution analysis.

Spring inspection of the plots revealed the winter wheat was under severe competition from volunteer barley. The application of nitrogen would ultimately benefit the barley which would effectively choke out the winter wheat. Because of this, the spring nitrogen treatments were not applied. This decision left only 11 fall applications of nitrogen. Thus the experiment consisted of 12 treatments: 11 fertilizer applications and 1 control. The barley still managed to choke out the winter wheat. To salvage the fertilizer treatments of the previous fall, the green material was harvested on July 4th, 1989 to determine differences in dry-matter production.

Harvesting was done with a 0.54 m wide self propelled mower by taking a cut down the centre of each plot. The sample collected was weighed and a sub-sample was collected for moisture determination and nitrogen content (protein) analysis. The data collected were then subjected to the appropriate statistical analysis.

3.1.2 Experiment 2: 1988 Range Grass Experiment

Another experiment was established to determine the response of native grassland to method, and rate, of fall fertilizer application. The experiment was conducted south of Treestrip, again on a dark brown Chernozemic soil with a loam texture. The two methods of application utilized were: broadcast and high pressure surface banding. There was insufficient space for a complete randomized block design with point injection of liquid fertilizer. However, there was enough space though to apply all fertilizer treatments conducted in the main experiment. For comparison purposes only, the rates of nitrogen and phosphorous added in the experiment treatments were repeated in a separate experiment with point injection adjacent to the main experiment.

Two forms of fertilizer were applied in each treatment to measure the response of grass to varying rates of nitrogen and phosphorous. For the broadcast applications, urea (46-0-0) and triple super phosphate (11-51-0) were used. For the surface banding and point injection applications, liquid UAN and ammonium polyphosphate solution (10-34-0) were used.

Nitrogen was applied at rates of 40, 80 and 120 kg N/ha while the phosphate was applied at rates of 20, 40 and 60 kg P/ha. Nitrogen and phosphate were applied in separate passes and the rates were combined in a factorial design to yield nine treatments for each method of application. Due to space limitations, a complete factorial design could not be carried out. Moderate rates of nitrogen and phosphorous were applied by broadcast and surface banding with the DMCSA to compare pressurized liquid application to conventional grass fertilization techniques. Thus the check plots consisted of: no fertilizer, broadcast 40 kg P/ha, broadcast 80 kg N/ha, surface-banded 40 kg P/ha and surface-banded 80 kg N/ha. The plots were 3 × 20 m in size and arranged in a randomized block design replicated 4 times for both parts of the experiment.

Similar to the winter wheat experiment, data on fertilizer penetration and distribution from selected treatments applied with the DMCSA were collected. Samples were taken from both the nitrogen and phosphorous application treatments to investigate differences in soil penetration between the two fertilizer solutions. These samples were collected on October 18th immediately after the fertilizer was applied. Soil cores (20 mm in diameter) were taken from all 4 replicates. The samples were then stored in a cooler at 5 °C for later analysis.

The plots were harvested for dry-matter yields the following summer on June 26th, 1989. Samples were cut from the centre of each plot with a 0.54 m wide plot mower. The collected sample was dried (at 50 °C for 24 h) and weighed for yield and a sub-sample taken for moisture, nitrogen and phosphorous content. During the summer of 1990, inspection of the site revealed a residual fertilizer response. The plots were again staked out and harvested to assess the effects of the residual fertilizer on biomass yields.

3.1.3 Experiment 3: 1989 Barley Experiment

During the summer of 1989, the response of barley to spring applications of nitrogen was investigated. The experimental site was the central section of a field immediately adjacent to the field for Experiment 1. Three methods of nitrogen application: pressurized liquid surface banding, broadcast and fertilizer nesting were used to place nitrogen two weeks after seeding. This methodology was incorporated to ensure banding and nesting treatments were placed midrow. All treatments received an application of nitrogen in one form or another at 40 kg N/ha.

Surface banding was accomplished with the new applicator design. Three surface banding treatments with liquid UAN were applied to test the effects of varying system pressure on fertilizer penetration and distribution in the soil profile. In similar fashion, three other surface banding treatments with ammonium polyphosphate solution compared penetration effects with the different fertilizer formulations. Soil samples were taken one day after the treatments were applied and stored in the cooler at 5 °C for later fertilizer penetration and distribution determination.

The broadcast treatments consisted of urea and ammonium nitrate applications with a Barber fertilizer spreader. Two fertilizer nesting treatments were applied with the research station's point injector. One nesting treatment used liquid UAN while the second nesting treatment used ammonium polyphosphate solution. Nesting with the two solutions were done as a comparison of crop response to the surface banding applications. Allowances were made to include nesting with the newly constructed pressurized liquid applicator. Due to technical difficulties, these treatments were not completed and left as experimental controls.

One plot per replicate received hand placement of urea Supergranules at two depths. Two subplots 1.5 × 1.5 m square were staked out 6 m from either end of the plot. One subplot received 1 gram Supergranules placed at a 7.5 cm depth and the other at a depth of 15 cm. Placement was done by removing 35 mm diameter cores of soil with an Oakfield sampler, placing a granule at the desired depth and replacing the core over top of the granule. Granules were placed midrow at a spacing of 28.4 cm between nests to give a fertilizer rate of 40 kg N/ha. One control plot per replicate was included which received no fertilizer.

For weed control, plots received two blanket applications of herbicide. The first application was Rustler applied at 4.32 L/ha. The second application consisted of Sweep applied at a rate of 2.47 L/ha. Both were applied three weeks prior to seeding. Plots were seeded lengthwise with a John Deere hoe drill to a depth of 5.0 cm on June 12th. Barley (var. Galt) was seeded at a rate of 60 kg/ha. Plots were 3 × 20 m. The experiment consisted of 15 treatments in a randomized block replicated four times.

On September 13th, all plots except the Supergranule ones were harvested with a Hege plot combine. A 1.52 m cut was made down the centre of the plot and the grain saved for later yield and protein determinations.

One week after harvest, square metre samples were taken to compare Supergranule yields to the yields of other treatments. Supergranule plots were hand harvested by placing a square metre frame in the middle of the subplots. Square metre equivalents were taken from all other plots by randomly sampling the rows on either side of the cut made by the plot combine. The grain and straw from the square metre samples were separated by a thresher and the mass of both determined. Yield and protein contents were determined from the grain samples while nitrogen and phosphorous content were determined from the straw. To measure plant stalk height, 20 plants were randomly selected from each plot after harvest. For plant stalk height, a metre stick was used to measure the distance between the base of the plant stem and the base of the plant head.

3.1.4 Experiment 4: 1989-90 Winter Wheat Experiment

During the summer of 1989, inclusion of pulsing technology on the new applicator design was completed. One final crop experiment was conducted to investigate crop response of pressurized liquid nesting to other methods of fertilizer application. The experimental site, named P.O.W., was located northwest of the Station. The soil was a dark brown Chernozem with a loam texture. The experiment consisted of six fertilizer treatments and one control per block in randomized block design. The experiment was replicated four times. The plot sizes were 4 × 15 m.

All treatments were fall applications of fertilizer in various forms to give 40 kg N/ha. Conventional treatments consisted of the following: anhydrous ammonia before seed, broadcast ammonium nitrate (34-0-0) before seed, broadcast urea (46-0-0) before seed, deep band ammonium phosphate (23-24-0) with seed. The nesting treatments were done with the pressurized liquid applicator and the point injector before seeding. The nesting treatments had an additional amount of triple super phosphate (12-51-0) applied at 60 kg total product per hectare with the seed since nesting treatments were not applied midrow. The anhydrous application was made with the research station knife applicator with knives on 20 cm centres. Fertilizer was broadcast with a Barber spreader and deep banded with a Versatile 2200 hoe drill.

Winter wheat (var. Norstar) was seeded on September 25th, 1989 lengthwise on the plots at a rate of 67 kg/ha with a Versatile 2200 hoe drill to a depth of 5 cm. For weed control Sweep was applied at a rate of 2.47 L/ha twenty five days before seeding.

On June 25th, 1990 square metre samples were taken to compare crop performance at heading. Plots were harvested for crop yield determination on August 15th. Harvesting was done with a Hege plot combine by taking a 1.83 m cut down the centre of each plot.

3.2 Determination of Crop Parameters

Once the experimental plots had been harvested, certain procedures were employed to obtain data for statistical analysis. In cases such as grain yield, data were directly obtained by weighing samples and applying area conversions. In other cases such as nitrogen concentration, considerable sample preparation for laboratory analysis was required to obtain the desired result.

3.2.1 Yield Determinations

For Experiments 3 and 4, barley and winter wheat yield determinations were not complicated. The total mass of grain harvested was weighed and the sample mass was converted from kg per square metre of plot area to kg/ha, depending on the area of swath taken at harvest. The square metre grain and straw yields in Experiment 3 required 48 hours of oven drying at 30 °C before the grain and straw were separated. The samples were weighed, then a conversion applied to obtain kilograms per hectare from grams per square metre.

For Experiments 1 and 2, a slightly different method was required before the proper area conversions were applied. Because the samples weighed in the field were at differing moisture contents, the sample yields required conversion to yield on a dry basis. Sub-samples of approximately 1 kg in mass were taken from each plot, weighed, then placed in a 30 °C oven for one week. These samples were then further dried in a 50 °C oven for 24 hours. The samples were then weighed to determine moisture content on a dry basis. With this value, a dry basis correction was applied to the plot samples. The appropriate area conversions were then applied to obtain yield in kilogram per hectare dry basis.

3.2.2 Determination of Nitrogen and Phosphorous Content in Tissue Samples

In Experiments 1 and 2, an indication of fertilizer content was determined by measuring the nitrogen and phosphorous content in the plant tissue. To obtain these values, a sub-sample (approximately 100 grams) was taken from the dried samples used to obtain moisture content. These sub-samples were run through a rotary grinder to pass a 2 mm sieve. The ground material was taken to the laboratory for determination of nitrogen and phosphorous concentrations with a Technicon Autoanalyzer II. A small amount of the ground plant material was weighed then prepared in a Block Digestion Acid Digest (Technicon Industrial Systems, 1976). The concentration of nitrogen and phosphorous determined in solution was then converted to percent mass of sample used. This value was then multiplied by the crop yield to obtain nitrogen yield and phosphorous yield of the crops.

3.2.3 Determination of Protein Content

In Experiment 3, protein content was determined from barley samples which were cleaned to obtain bushel weight by the 1-dram volumetric method. The cleaned samples were ground with a rotary grinder to pass a 2 mm sieve. The resultant ground material was then prepared for laboratory analysis for protein determination by the Kjelhdahl method.

3.3 Machinery Calibrations

Throughout the crop experiments, several machines were used to apply fertilizer and seed. For research purposes, calibration was required to ensure each implement was applying the seed or fertilizer at the correct proportions stated in the experimental design. Because the machinery used to apply seed and fertilizer in the field experiments was continually used by the Research Station in other experiments, calibration was not required. Each implement had a set of calibration curves for the seed and fertilizer applied in the experiments conducted. These calibrations were periodically updated to ensure that the precision of the implements did not deviate because of machine wear. Thus, the application rates for each device were set with a high degree of confidence.

Even though a high degree of accuracy in application rates was achieved, an important note must be made. In some instances, a variety of factors did not result in fertilizer rates being precisely applied. The Barber spreader required an interchange of two drive wheels to set the desired application rate. Since this machine did not have an infinite amount of sprockets to achieve the precise application rate, settings were chosen to come as close as possible to the desired rate. In the majority of cases, deviation from the application rates stated was under 3%.

3.3.1 Calibration of Pressurized Liquid Applicators

Since the DMCSA and the redesigned liquid applicator were never used on station, these devices required calibration before use. In order to clearly understand the methodology behind the calibrations, a brief overview of pressurized liquid fertilizer is required.

On most common fertilizer delivery devices, fertilizer application rate is independent of ground speed. With pressurized liquid fertilizer application this is not the case. Liquid flows at a constant rate according to system pressure and nozzle size. Ground speed is set according to the flow rate through the nozzles. A second factor which complicates the procedure is nozzle capacity for continuous stream application. Because of the high flow rate at the nozzles, even at modest system pressures, liquid fertilizer cannot be applied at full strength. The fertilizer must be diluted with water to achieve the appropriate application rate. This changes the specific gravity of the solution which in turn affects flow rate according to equation 9.

Since application rate is affected by system pressure, ground speed and dilution rate, a dilemma was created. To investigate fertilizer penetration and distribution differences due to changes in pressure and ground speed, a series of pressures and ground speeds are required. Thus a calibration curve would be required for each dilution rate. Little advantage would be gained and much fertilizer would be wasted by calibrating for a series of dilution rates.

An alternate calibration method was employed which first required the determination of nozzle flow rates with water at an arbitrary system pressure. In the case with the DMCSA, a series of trials were conducted to determine the average flow rate per nozzle. The machine was run for a period of time and the volume of water used was measured. This volume was divided by the number of nozzles on the applicator and the average flow rate per nozzle was calculated in litres per minute.

An average volume per nozzle was determined since collecting flow from each nozzle would be inaccurate, due to spray from the jetted fluid. The volume of liquid was measured by determining the difference in liquid level in the tank between the beginning and the end of each trial. Because of the uniform rectangular shape of the tank, a relationship between the change in tank height level and the volume of liquid displaced was determined. This value was found to be 1.03 L per millimetre change in tank liquid level. To ensure the tank was situated in a level position, liquid level was measured at each corner of the tank. If all the measurements did not coincide, the mounting bolts of the tank were loosened and the tank "shimmed" to level before liquid level measurements were taken. This technique was useful in nitrogen and phosphorous applications since knowing the volume of liquid in the tank allowed for ease of change in dilution rates. Changing rates was done by calculating the amount of fertilizer at the current dilution rate, adding the required volume of fertilizer, then topping the tank off with water to reach the new dilution rate. The diluted mixture was agitated before trials were undertaken to ensure uniform dispersion of the solution.

On the new applicator, the supply tanks were conical in shape so differences in liquid level could not be used. In this case, volume replacement to the top of the tank was used to measure liquid displacement otherwise the same methodology was employed as on the water calibration. In the field experiments, nitrogen fertilizer at differing dilution rates were stored in the two supply tanks. Once one set of fertilizer applications were made at a given dilution rate, the corresponding tank was emptied and the third dilution rate was added to the emptied tank.

Once the nozzle flow rates were determined with water, a series of trial and error calculations were utilized to determine system pressure, gro[illegible] and dilution rate. The first step is to determine the application rate of [illegible] of the active nitrogen content of the liquid fertilizer:

$$Q = K_1 N_i \tag{10}$$

Where N_i is the desired rate of nitrogen application (kg/ha) and K_1 is a conversion constant (L/kg). K_1 can be calculated with the following formula noting % fertilizer is the percentage of active nitrogen or phosphorous in the solution and γ_L is the specific gravity of the fertilizer solution:

$$K_1 = \frac{1}{\gamma_L \frac{\%\ fertilizer}{100}} \tag{11}$$

With Q, the desired flow from the nozzle (Q_n) can be calculated by choosing the ground speed desired for the applicator:

$$Q_n = Q\ U\ K_2 \tag{12}$$

where:

Q_n = flow rate per nozzle (L/min).

Q = calculated from equation 10 (L/ha).

U = desired ground speed (km/h).

K_2 = conversion factor for the nozzle spacing of the applicator.

By picking a velocity to determine Q_n, the dilution rate can now be calculated. Recalling equation 9, the flow of the diluted mixture is calculated:

$$Q_m = Q_w \frac{1}{\sqrt{\gamma_m}} \tag{13}$$

where:

Q_m = average flow per nozzle of the diluted mixture (L/min).

Q_w = average flow per nozzle from the water calibration (L/min).

The specific gravity of the mixture (γ_m) can be calculated using the specific gravity of water (γ_w), and the specific gravity of liquid fertilizer (γ_L), using the following expression:

$$\gamma_m = \frac{Q_w - Q_n}{Q_w} (\gamma_w) + \frac{Q_n}{Q_w} (\gamma_L) \tag{14}$$

Now the dilution rate (D.R.) is calculated by the following expression:

$$D.R. = \frac{Q_m}{Q_n} - 1 \tag{15}$$

Once Q_m has been calculated for the given pressure and dilution rate, the diluted mixture is placed in the tank and the actual Q_m is measured. If the calculated and measured Q_m do not coincide, Q_m is substituted for Q_n in equation 12 and the velocity is recalculated to accommodate the actual flow rate. This calculation and calibration was made for every pressure change. With a change in pressure the same procedure is employed except Q_w for the new pressure is estimated by equation 8 (pg. 44-45).

Once the pressure, dilution rate and velocity were established, the actual tractor speeds were set by a simple distance/time calibration. The tractor with the applicator was run at an arbitrary RPM over a distance of 50 m. The time to travel this distance was recorded and compared to the calculated time to travel the distance based on the required velocity for fertilizer application. Adjustments were made to the tractor engine RPM until the measured and calculated time coincided. In the case of deep banding with the DMCSA, compensation for wheel-slip due to draft was made by running the 50 m course with the hoe points at a depth of 15 cm.

3.3.2 Calibration of Fertilizer Nesting Applicator

Because liquid nesting had lower volumes of liquid per unit time and no constant force being exerted from the nozzles, a system was devised to directly measure the flowrate from each nozzle. A galvanized metal tube was placed over the nozzle holder. On the end of the tube, a 4 L antifreeze bottle was connected to collect the effluent from the nozzle. Six such collection devices were constructed; one for each nozzle.

Upon initial water calibrations, it was noted the flow rate between some of the nozzles differed. Because one solenoid valve fed three nozzles a parallel piping system was involved. Changing one nozzle affected the flow rate from all three nozzles. Through trial and error, nozzles were switched until the flow rate from each nozzle matched as close as possible. Once the nozzles matched, calibrations with liquid fertilizer were made.

Experience with the applicator had shown that the runner design limited ground speed to 8 km/h. Beyond this speed the runners had a tendency to bounce over rough terrain which could result in erratic placement of nests. Thus, spacing of the nests was limited by the maximum achievable ground speed. Spacing between nests was a function of cycle-time and ground speed and was calculated as follows:

$$Sp = U\ T_c\ x\ 100 \qquad (16)$$

where:

Sp = spacing between nests (cm).

U = ground speed (m/s).

T_c = cycle-time (s).

The controller had a maximum cycle-time of 0.160 seconds. At a maximum ground speed of 8 km/h (2.22 m/s), the maximum spacing between nests worked out to 35.5 cm. Another factor to be considered was the on-time of the controller. This determined the amount of fluid in each nest. As the ground speed was increased, the on-time had to be decreased to keep the nest as compact as possible. With the water calibrations, it was discovered the solenoid valves could only operate at a minimum of 25 ms. Because maximum penetration was desired, the system pressure was set at 34.5 MPa. With these values, calibration with liquid fertilizer revealed the average flow rate per nozzle to be 568 mL/min. Dividing this value by the cycle-time of 160 ms or 6.25 pulses per second gave a volume of 1.51 mL per pulse. The required flow rate, velocity and volume per pulse were calculated using the previously established relationships, recalling the desired application rate was 40 kg N/ha in experiment 4.

Using equation 10, where K_1 = 2.79 L/kg for liquid UAN (28-0-0):

$$Q = 2.79\ (40)$$
$$= 112\ \text{L/ha}$$

To ensure that nitrogen would be available during a dry season the nests were spaced 20 cm apart. With a cycle-time of 160 ms or 6.25 pulses per second, the ground speed was calculated:

$$U = 6.25\ \text{pulses/s} \times 0.2\ \text{m/pulse} \times 3.6\ \text{km s/m h}$$
$$= 4.5\ \text{km/h}$$

The required flow per nozzle was calculated using equation 12, noting K_2 = 6.78×10^{-4} for nozzles on 0.406 m centres:

$$Q_n = 112\ (4.5)\ (6.78 \times 10^{-4})$$
$$= 0.340\ \text{L/min or } 340\ \text{mL/min}$$

The required volume per pulse was calculated as:

$$\text{volume per pulse} = 340\ \text{mL/min} \times 1\ \text{min/60 s} \times 1\ \text{s/6.25 pulses}$$
$$= 0.907\ \text{mL/pulse}$$

This value was much lower than the nozzle capacity of 1.51 mL/pulse determined in the calibration of liquid fertilizer alone; thus the flow was diluted.

Each pulse should carry the following amount of fertilizer:

amount of fertilizer per pulse = (0.907 mL/pulse)/(1.51 mL/pulse)

= 0.60 or 60% fertilizer

Thus the liquid solution should be 60% (28-0-0) and 40% water. Upon calibration at this dilution rate, the flow rate did not change appreciably; thus, the calculated parameters were used.

It must be stressed that the normal dilution of liquid fertilizer with water to achieve nesting was not necessary with this applicator. If the nest spacing was changed to 30 cm the dilution would not have been required. Dilution was necessary because of the desired nest spacing (20 cm) and the given calibration results. After field applications were completed, adjustments were attempted to decrease the volume of liquid per pulse. Tightening the preload on the solenoid valves was successful in accomplishing this task. The volume per pulse was reduced to 0.800 mL/pulse without any sacrifice in valve performance. This adjustment enabled 20 kg N/ha to be placed at a nest spacing of 35.5 cm at the maximum design speed of 8 km/h with no dilution.

Interrelationship between application rate, nest spacing, ground speed and system pressure must be stressed. At best, the setting of application rate required a complex set of calculations and machinery adjustments. For this reason the final calibrations carried out in 1990 centred around evaluating valve performance at a maximum cycle-time of 160 ms with varying on-times. With this information, proper nest spacing, ground speed and system pressure can be calculated for the required nitrogen application rate. Once these values have been chosen, a formal calibration can be made at the desired settings to confirm the calculations and adjustments made if necessary.

When calibrating the applicator for nitrogen placement on winter wheat (Experiment 4), two concerns arose which required investigation. First, a strong ammonia odour was detected implying volatilization of the liquid fertilizer being throttled through the nozzle. Second, the liquid in the supply tank heated up during operation. During the final calibrations, tank temperature was monitored with a mercury thermometer to evaluate temperature rise during applicator operation.

To evaluate the quality of the fertilizer coming out of the nozzles, a sub-sample of the liquid was collected randomly from a nozzle during each trial. These samples were taken throughout the calibration to evaluate fertilizer quality with tank liquid temperature rise. At the beginning and end of the trials, a sub-sample of liquid was taken from the tank to compare fertilizer quality. The liquid sub-samples were analyzed in the laboratory with the Technicon Autoanalyzer for nitrate in water (Technicon Industrial Systems, 1973b) and ammonia in water (Technicon Industrial Systems 1973a).

3.4 Fertilizer Penetration and Distribution Experiments

To investigate fertilizer penetration and distribution in the soil profile, a soil core sampling method was chosen. As opposed to dyes which give visual results of penetration, core sampling with subsequent laboratory analysis, can be used to determine fertilizer concentration at a given depth and provide an indication of soil penetration.

In the first three field experiments, a range of pressures and ground speeds were chosen to evaluate the effects of these parameters on fertilizer penetration and distribution. The values for pressure and ground speed used in each experiment are listed in Table 4.

In the winter wheat experiment, the design revolved around keeping the ground speed as constant as possible and varying pressure. In the grass experiment, a similar method was employed but the difference in ground speed between the two types of fertilizer applied permitted comparisons of penetration and distribution with changing velocity. In the barley experiment, pressure and ground speed were both varied for comparative purposes.

Since the cereal crops were direct-drilled into stubble and the grass was already established, penetration was being investigated under the conditions which cause most concern. Hard soil surfaces and trash (crop residue) cover allowed for investigation of soil penetration and fertilizer distribution under no-till conditions.

The method involved taking soil cores with a 35 mm diameter Oakfield soil sampler (20 mm sampler in the grass experiment) directly above the kerf left after fertilizer application. The removed cores were segmented with a straight edge and knife. The depth of penetration and extent distribution for the jetted fertilizer was not anticipated in the first year of testing (grass and winter wheat). Thus, cores were arbitrarily divided into 3 cm segments down to a depth of 15 cm. Sample analysis later showed further depth refinement was required. For better depth resolution, the

Table 4.	Pressure and groundspeed treatments in the fertilizer distribution experiments		
Experiment	Dilution Rate*	Groundspeed (km/h)	Pressure (MPa)
Winter Wheat			
T1: SB UAN	13:1	3.9	34.5
T2: SB UAN	10:1	3.5	13.8
T3: SB UAN	8:1	4.9	20.5
T4: DB UAN	13:1	3.9	34.5
T5: DB UAN	10:1	3.5	13.8
T6: DB UAN	8:1	4.9	20.5
Grass			
T1: SB AM Ph	19:1	7.3	25.6
T2: SB AM Ph	10:1	7.6	31.0
T2: SB UAN	6:1	4.5	34.5
T3: SB AM Ph	7:1	7.3	36.8
T3: SB UAN	4:1	4.5	39.6
Barley			
T1: SB UAN	6.1	4.0	22.1
T2: SB UAN	10:1	3.2	34.5
T3: SB UAN	12:1	3.0	42.8
T4: SB AM Ph	2:1	4.0	25.9
T5: SB AM Ph	6:1	2.0	37.8
T6: SB AM Ph	2:1	5.0	41.7
Penetration Experiment			
T1: Pulse UAN	-	2.5	34.5
T2: Pulse UAN	-	4.5	34.5
T3: Pulse UAN	-	6.5	34.5
T4: Pulse UAN	-	4.5	20.7
T5: Pulse UAN	-	2.5	20.7

* - dilution rate of water to fertilizer.

cores in the barley test were segmented into 2 cm cores to a depth of 8 cm.

To make one composite treatment sample, 10 cores were taken randomly per plot from different kerfs to ensure that the output from multiple nozzles were being included. The segments from each core were pooled, by depth, into one sample for each treatment. To account for background effects from nitrogen or phosphorous which are already present in the soil, a soil core was taken 10 cm on either side of each kerf sample. The "check" cores in each treatment were segmented and pooled, by depth, into one sample for laboratory analysis. Three replicates were sampled from the winter wheat and barley experiments and four replicates were sampled from the grass experiment. All soil samples were placed in bags and refrigerated at 5 °C soon after sampling to prevent mineralization and volatilization.

The soil samples were ground and sieved to pass 2 mm to remove the plant material. The remaining soil was ground to a fine powder with a mortar and pestle and a sub-sample taken. The exchangeable nitrate and ammonium from each sample was then extracted (Keeny and Nelson, 1982) and analyzed for concentration in parts per million. In the cases where available phosphorous was determined a sodium bicarbonate extraction was employed (Jackson, 1958) and the concentration in parts per million measured (Olsen et al., 1954).

To convert the parts per million (mg/kg soil) values to milligrams of nitrogen or phosphorous recovered, a standard bulk density of 1.30 Mg/m^3 was assumed and the volume of core for each depth calculated. With these values the fertilizer recovered for each depth was later converted to a percentage of the total amount of fertilizer recovered over all depths for comparison purposes. Upon analysis of the results, the assumption of a bulk density of 1.30 Mg/m^3 resulted in too broad of an estimate for soil mass. To get a better estimate of soil mass, the plots were restaked for the first three experiments and a bulk density sample was taken randomly from each plot in 3 cm depth increments to the depth of probe sampling. Although this procedure did not allow for an accurate calculation of the fertilizer recovered, a better estimate than the previously assumed value was obtained.

For fertilizer nesting, only one treatment was included in all the experiments conducted. Thus, a statistical determination of the effects of fertilizer penetration and distribution on nesting with varied pressure and ground speed could not be done. An experiment was devised to investigate nesting at three ground speeds (2.5 km/h, 4.5 km/h and 6.5 km/h) and two pressures (20.7 MPa and 34.5 MPa). The treatments were established on a barley stubble field (south of Treestrip) in a randomized block design and replicated three times. Plot sizes were 3 × 20 m. The valves were set at an on-time of 25 ms and a cycle-time of 160 ms. With increasing ground speed, the whole pulse could not be captured with one core sample. To capture the whole pulse a series of core samples were taken. From past experience of core sampling, the method of segmenting the cores became more refined. The top segment of each core was 3 cm in length. The finest depth resolution obtainable without consistently damaging the core was 1.5 cm. Thus segments were divided into 1.5 cm depth increments from the 3.0 cm to the 9.0 cm depth. With regards to the method of gathering cores and method of nitrogen analysis, the procedures remained the same as in other experiments.

At each site where core samples were taken, soil bulk density and penetration resistance readings were taken to examine fertilizer penetration and distribution effects in relation to basic soil parameters.

Bulk density cores were taken with a hand coring device developed on-station. The device in essence was a slide hammer with a barrel on the end which penetrates the soil. Inserted in the barrel was a brass sleeve 3 cm deep and 5 cm in diameter. Cores were taken in 3 cm intervals to a depth of 9 cm. Because the sleeve was a known volume, the samples were weighed intact then placed in a 50 °C oven for 72 hours. The samples were then reweighed to determine moisture content and dry bulk density with the known core volume.

The cone penetrometer used was a hand held type with a proving ring and dial gauge. A 1.3 cm diameter cone (75° angle) was used for readings. Two people were required to use this device effectively. One person was responsible for pushing the penetrometer in the soil at a constant rate and calling out the depths of penetration. The second person was responsible for recording the dial gauge readings when indicated. Starting at the soil surface, readings were taken in 3 cm increments to a depth of 9 cm. Because of the variability of this method, five separate readings were taken at each site and averaged for each depth increment.

During the penetration measurements, it was suggested some of the fertilizer may not be entering the soil but landing on the soil surface. A small experiment was devised to determine if this was possible. For one of the treatments at a system pressure of 34.5 MPa and ground speed of 2.5 km/h, cores were taken with a different sampling method. In this instance, the probe was pushed into the pulse kerf to a depth of 10 cm. Before the core was removed, a 48 mm radius was demarcated from the probe wall. The surface 1 cm of soil was scraped away and placed in a labelled sample bag. The core was removed and placed into another sample bag. This was done for four pulses and a fifth sample was collected near the cores as a check. The samples were then weighed and put through the laboratory analysis for nitrogen level determination. This would give an indication if splashing of the liquid fertilizer was occurring.

3.5 Statistical Analysis of Data

To determine the significance of treatment effects and differences in each experiment, statistical analysis was employed based on the experimental design of typically a randomized block model.

For the field experiments cereal crop yields were converted from a kilogram per plot measurement to a kilogram per hectare basis using appropriate conversion factors. For the forage and grass crops, a similar conversion was applied except yields in kilograms per hectare were expressed on a total biomass (dry weight) basis. The protein data collected from the barley experiment was converted from a percentage per sample basis to a kilogram per hectare basis. In a similar fashion, data collected on nitrogen and phosphorous concentrations in the forage samples were converted from a percentage basis to a kilogram per hectare dry basis by multiplying the dry biomass yield by percent concentration of nitrogen and phosphorous. The converted yield and plant fertilizer concentration data from each experiment were then subjected to a one-wav analysis of variance to determine treatment effects (GLM procedure; SAS Institute, Inc., 1985). In addition to this analysis, comparison among treatment means were made by orthogonal contrasts, Least Square means and the Duncan Multiple Range Test (SAS Users Guide; SAS Institute, Inc. 1985). For the grass forage experiment, the collected data were subjected to a three-way analysis of variance by SAS to investigate the effects and interaction between: method of fertilizer application, nitrogen rate of application and phosphorous rate of application. In the case of the grass experiment (Experiment 2), point injection results were analyzed separately from the other two methods of fertilizer application. This was necessary since block sizes were not equal and the point injection treatments were not randomized in each block with surface banding and broadcast treatments. In all statistical comparisons the level of significance of $P \leq 0.05$ was used. To achieve a higher level of confidence, in those experiments where differences were significant at the 5% level, statistical analysis was done again at the 1% level.

For the soil core nitrogen and phosphorous concentration studies, the data were converted from parts per million to a milligram basis by multiplying the parts per million recovered with the volume of core taken and an assumed bulk density of 1.30 Mg/m^3. To offset the effects of unequal recoveries of fertilizer from each sample, fertilizer concentration at each depth was converted to a percentage of the total amount of fertilizer recovered from all depths in each sample. From these converted values, the effects of ground speed and system pressure on the fertilizer distribution percentages at each depth in each experiment were analyzed in a one-way analysis of variance by SAS.

In an effort to relate soil parameters measured in the penetration experiment to the soil analysis results, the gathered data was subjected to simple correlation and forward selection regression analysis by SAS (PROC REG; SAS Institute Inc., 1985).

CHAPTER 4: RESULTS

4.1 Field Experiments

From 1982 through 1988, the Lethbridge region had undergone a period of drought. These conditions left the soil profile severely depleted of moisture; a factor which severely affected crop growth and particularly plant response to nitrogen application.

In 1988, annual precipitation was low at only 58% of the 90-year mean value (Table 5); a factor which must be considered in the analysis and interpretation of the data from Experiments 1 and 2. Clearly the low growing season precipitation and poor growing conditions in 1988 were not conducive to studying fertilizer application methods and comparative fertilizer response.

In 1989, annual precipitation was 10% higher than the 90-year mean. Except for the month of August, growing season precipitation was near or below normal values. The precipitation enhanced the forage crop growth in Experiments 1 and 2. However, it should be pointed out the precipitation, more than likely, did not fully restore the low soil moisture reserves from the preceding drought conditions.

In 1990, the total annual precipitation attained 81% of the 90-year mean value. This again compounded the effects of soil moisture on fertilizer response in Experiment 4.

Although detailed soil moisture data were not collected for these field experiments, the high Research Station Class "A" pan evaporation values, especially in 1988, epitomised the dry conditions encountered during the study. It was generally

Table 5.	Precipitation and Class "A" pan evaporation values by month and year for the Lethbridge Research Station during the field experiments.							
	Precipitation (mm)				Pan Evaporation (mm)			
	Year				Year			
Month	1988	1989	1990	Mean*	1988	1989	1990	Mean**
Jan.	8.3	26.5	12.8	18.7	-	-	-	-
Feb.	9.6	18.0	11.4	17.5	-	-	-	-
Mar.	17.4	43.3	17.8	24.0	-	-	-	-
Apr.	0.0	28.8	38.4	21.4	231.0	142.8	150.8	153.0
May	21.9	52.9	75.5	53.8	288.1	233.0	169.4	209.6
June	44.8	50.6	40.1	72.0	314.6	252.1	247.1	245.9
July	11.8	41.7	33.0	41.8	309.4	265.9	235.4	258.3
Aug.	62.6	78.4	35.8	42.1	238.8	200.4	237.6	219.4
Sept.	29.6	34.0	6.0	40.8	170.2	150.6	218.0	152.7
Oct.	11.4	19.4	12.8	22.0	119.6	113.0	135.6	112.2
Nov.	5.0	17.6	27.1	18.7	-	-	-	-
Dec.	12.3	31.0	18.2	18.6	-	-	-	-
Total	234.7	442.2	328.9	401.4	1670.9	1357.8	1393.9	1351.1
Mean	19.6	36.9	27.4	33.5	139.2	113.2	116.2	112.6

* - denotes 90-year station mean monthly values.

** - denotes 25-year station mean monthly values.

observed that a few days after rainfall had occurred, hot-windy weather conditions always seemed to dry out the top 10 cm of the soil profile.

4.1.1 Experiment 1: 1988 Winter Wheat Experiment

Even though volunteer barley effectively choked out the winter wheat crop, the harvested forge crop revealed some differences due to method of fertilizer application (Table 6).

Method of application resulted in only one significant yield response to fertilizer application. The deep banded (DB) urea treatment resulted in significantly higher yields than the control treatment. All other methods of application had similar yields which were not significant in comparison to the control treatment. For orthogonal contrasts yields were combined by method of fertilizer application. The deep banded urea (DB UREA), ammonium nitrate (DB AM. NIT.) and urea ammonium nitrate (DB UAN) resulted in yield of 3341 kg/ha. The broadcast urea (BCST UREA) and ammonium nitrate (BCST AM. NIT.) had a combined yield of 3223 kg/ha. The surface banded urea ammonium nitrate (SB UAN) had a combined result of 3179 kg/ha while point injected urea ammonium nitrate (P.I. UAN) had a yield of 2976 kg/ha. Despite such large differences in combined yields, orthogonal contrasts showed no significant yield difference between method of fertilizer application.

The deep banded urea, deep banded ammonium nitrate, broadcast urea and point injected UAN treatments did show a significant nitrogen yield response over the control. The deep banded UAN at 34.5 MPa had a significantly higher nitrogen yield value than: deep banded ammonium nitrate, broadcast urea, point injected UAN and the control.

The deep banded UAN treatments at 13.8 Mpa and 20.5 Mpa had significantly higher nitrogen yields than the point injection UAN treatment and the control treatment. There was a trend towards higher nitrogen yields with pressurized liquid UAN treatments versus the other experimental treatments. However, orthogonal

Table 6. Total biomass and nitrogen yields for fall application of fertilizer by method on winter wheat for experiment 1.			
Treatment	Pressure (MPa)	Yield* (dry basis) (kg/ha)	N* Yield (dry basis) (kg/ha)
SB UAN	34.5	3071ab	66abc
SB UAN	13.8	3297ab	66abc
SB UAN	20.5	3170ab	67abc
DP UAN	34.5	3310ab	72a
DB UAN	13.8	3286ab	71ab
DB UAN	20.5	3348ab	69ab
DB UREA	-	3487a	60abcd
DB AM. NIT.	-	3275ab	59bcd
BCST UREA	-	3231ab	59bcd
BCST AM. NIT.	-	3215ab	69ab
P.I. UAN	-	2976ab	55cd
CONTROL	-	2703b	51d

* - means followed by the same letter in each column are not significantly different at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

contrasts did not reveal a significant difference in this trend.

From the data for 1988, there seemed to be no clear advantage in method of fertilizer application or type of fertilizer applied. Fertilizer nesting by point injection had the lowest but not significant forage yield and nitrogen yield values to all treatments except the control. Because the crop was harvested at an early stage of development, this result may have been indicative of time of harvest rather than method effectiveness. Past experimental results with fertilizer nesting have shown characteristic nitrogen deficiency in early growth stages (Nyborg and Leitch, 1979). Such results were not confirmed visually though because of the different stages of growth (between the winter wheat and volunteer barley) in the forage crop.

4.1.2 Experiment 2: 1988 Range Grass Experiment

Significant differences were noted between banding with pressurized liquid and broadcast with granular fertilizer (Table 7). Yield differences were not significant between both methods of application but pressurized liquid treatments had significantly higher nitrogen and phosphorous concentrations. This would imply greater availability of the nitrogen and phosphorous fertilizers by placement below the soil surface rather than on the soil surface.

When combining method of application and comparing the rates of nitrogen applied, the results indicated applying nitrogen at 80 kg N/ha to be optimum. At the 40 kg N/ha rate, all yield categories were significantly lower than their counterparts at the higher nitrogen levels. The 80 and 120 kg N/ha rates produced comparable results in all yield categories. The 80 kg N/ha treatments had slightly higher yields than the 120 kg N/ha treatments but this difference was not significant.

Increasing the rate of phosphorous application showed a tendency towards increasing yield but the results were not significant. However, at 20 kg P/ha, there was a significantly lower concentration of nitrogen than with the other rates of phosphorous application.

Interactions between method of fertilizer application and rate of nitrogen or phosphorous application were not significant. Similarly there was no significant interaction between the method of application and the combination of nitrogen and phosphorous rates. However, the interaction between rate of nitrogen and rate of

Table 7.	**Factorial comparisons of yield, nitrogen yield and phosphorous yield for grass biomass**		
Comparison	Yield (dry basis)	N Yield (dry basis)	P Yield (dry basis)
	(kg/ha)		
Surface Banding	1308	30*	2.9**
Broadcast	1315	26	2.7
Nitrogen Rate (kg/ha)			
40	1195*	22*	2.5*
80	1380	30	3.0
120	1360	32	2.9
Phosphorous Rate (kg/ha)			
20	1287	26**	2.7
40	1293	28	2.9
60	1356	30	2.9

* - denotes value in column group significant at the $P \leq 0.01$ level as determined by the Duncan Multiple Range Test.

** - denotes value in column group significant at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

phosphorous application, without accounting for method of application, implied that the lowest rates of nitrogen and phosphorous resulted in significantly lower grass yields than all other rates of application; at the five percent level (results not shown).

When broken down into their respective treatments some interesting trends are noted (Table 8). As mentioned previously, the interaction between method of application and the combination of nitrogen and phosphorous rates showed no significant results. However, orthogonal contrasts of the data in a one-way analysis

Table 8.	Breakdown of grass biomass yield data (dry basis) by method, rate and type of fertilizer application						
Fertilizer Type		**Surface Banded**			**Broadcast**		
Nitrogen	Phos.	Yield*	N Yield	P Yield	Yield*	N Yield	P Yield
------------------------------ (kg/ha) ------------------------------							
40	20	1127	22	2.4	1021	18	2.1
80	20	1400	30	3.0	1548	27	3.0
120	20	1318	35	2.9	1306	25	2.6
40	40	1254	24	2.6	1278	21	2.6
80	40	1249	32	2.9	1281	27	2.8
120	40	1313	34	2.9	1381	31	3.0
40	60	1188	25	2.7	1303	23	2.6
80	60	1546	35	3.4	1260	28	2.7
120	60	1378	37	3.1	1460	31	2.9
0	40	1162	19	2.4	911*	17	1.9
80	0	1535	34	3.1	1268	24	2.5
0	0	956*	16	1.9	-	-	-

* - yield values significantly different from all other yield values at the $P \leq 0.05$ level.

of variance revealed the control treatment (O N, O P), and the middle rate broadcast treatment (O N, 40 P), had significantly lower grass yields than all other treatments. The low grass yield with the fall broadcast of phosphorous alone implied the method application at the given P rate was ineffective for increasing grass yields. The low grass yield for the control treatment implied a fertilizer response was present even under the low precipitation levels encountered.

The results of the fertilizer nesting experiment with point injection adjacent to the main experiments were not statistically comparable with the main experiment, but there were noted trends between the two experiments (Table 9). In the case of yield alone, fertilizer nesting seemed to result in higher yields than either broadcast or pressurized liquid banding. Yield response had a tendency to increase with increasing levels of nitrogen and phosphorous but the values did not level off at the middle rates of application like the main experiment. Nitrogen concentrations in the plant material showed significant increases with each increase in the amount of nitrogen applied.

Over 1 year after the fertilizer was applied a fertilizer response was noted in both the main experiment and the point injection treatments (Table 10). Orthogonal contrasts with the control of treatment versus other treatments revealed a yield response to fertilizer application. This was feasible since precipitation values in the months between initial fertilization and harvest were low. Thus, plant use of nitrogen and fertilizer leaching losses more than likely did not remove appreciable amounts of fertilizer from the soil profile.

In a comparison between the methods of application, surface banding produced significantly higher yields than did the broadcast treatments. Although not statistically comparable, the point injection yields seemed to be on the same level as the surface banding yields.

Combining the data for interaction analysis showed that increasing nitrogen levels were ineffective in improving grass yields for both experiments. However, increasing phosphorous rates significantly increased yields in both experiments. In the main experiment, the lowest rate of phosphorous application resulted in sig-

Table 9. Point injection grass biomass yield data				
Nitrogen Rate	Phosphorous Rate	Yield (dry basis)	N Yield* (dry basis)	P Yield (dry basis)
(kg/ha)				
40	20	1370	23	2.4
80	20	1318	27	2.3
120	20	1367	32	2.5
40	40	1264	24	2.3
80	40	1330	25	2.1
120	40	1515	32	2.7
40	60	1253	22	2.1
80	60	1377	27	2.4
120	60	1503	31	2.3
Mean		1366	27	2.3
40	-	1296	23a	2.3
80	-	1342	27b	2.2
120	-	1461	32c	2.5
-	20	1351	27	2.4
-	40	1370	27	2.3
-	60	1378	27	2.3

* - values in column group followed by the same letter are not significantly different at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

nificantly lower yields than the other two rates of phosphorous application. In the point injection treatments, the highest rate of phosphorous application resulted in significantly higher yields than the lower rates of phosphorous application.

Looking at the data from an overall perspective, fall application of fertilizer on grass seemed to be more effective with pressurized liquid banding than with

Table 10. **Grass biomass yields of main experiment and point injection experiment for 1990 reharvest**

Comparison Method	Yield (dry basis)	Point Injection Yield (dry basis)
(kg/ha)		
Surface Banding	1277*	1285
Broadcast	1050	-
Nitrogen Rate		
40	1111	1309
80	1235	1249
120	1142	1297
Phosphorous Rate		
20	955*	1167
40	1205	1249
60	1329	1440**
Control	877***	-

* - value in column group significantly different at the $P \leq 0.01$ level.

** - value in column group significantly different at the $P \leq 0.05$ level.

*** - value significantly different than all values in column at the $P \leq 0.01$ level.

broadcast. Placing the fertilizer below the soil surface resulted in fertilizer being more readily available for plant utilization under critical situations than top dressing (Kucey, 1986). This was reflected in the nitrogen and phosphorous yield values of Table 7. In the point injection experiment: grass yield, nitrogen yield and phosphorous yield values were comparable to their surface banding counterparts in the main experiment. In a dry growing season, surface banding seemed to leave residual fertilizer in a state suitable for grass utilization the next season. Fertilizer nesting by point injection showed this tendency also. However, this may not be a general finding, but the result of ideal climatic conditions.

Irrespective of method of application, the rate of nitrogen and phosphorous application were definitely important. As the results demonstrated, grass yields were more responsive to increasing rate of nitrogen application than to increasing rates of phosphorous application.

4.1.3 Experiment 3: 1989 Barley Experiment

Overall, for the large plots no significant yield response to the method of fertilizer application occurred (Table 11). However, surface banding (SB) of ammonium polyphosphate (AM Ph) at the lowest system pressure (25.9 MPa) produced a significant yield advantage over two of the surface banded UAN treatments (22.1 MPa and 34.5 MPa), the urea broadcast treatment (BCST) and the control treatment. A possible explanation for this observation was the high rate of phosphorous (136 kg P/ha) when applying the ammonium polyphosphate at a rate of 40 kg N/ha. When combined, the surface banded UAN treatments produced an average yield of 2087 kg/ha while the surface banded ammonium polyphosphate treatments produced 2196 kg/ha. A comparison of surface banded UAN with surface banded ammonium polyphosphate yields by orthogonal contrasts revealed no significant yield advantage for either fertilizer despite the yield difference. Combining yields by method of application resulted in nesting yields being the highest at 2150 kg/ha, followed by surface banding at 2141 kg/ha and finally broadcast at 2078 kg/ha. Comparisons of these yield differences by orthogonal

Table 11. Grain and protein yields for large plot barley experiment			
Treatment	Pressure (MPa)	Yield*	Protein*
		(kg/ha)	
SB UAN	22.1	2013b	1392abcd
SB UAN	34.5	2047b	1446abc
SB UAN	42.8	2200ab	1379cd
SB AM Ph	25.9	2292a	1418abcd
SB AM Ph	37.8	2089ab	1451abc
SB AM Ph	41.7	2206ab	1444abc
BCST UREA	-	2036b	1461ab
BCST AM. NIT.	-	2120ab	1397abcd
P.I. UAN	-	2117ab	1466a
P.I. AM Ph	-	2183ab	1362a
Control	-	1994b	1387abcd

* - means followed by the same letter within each column are not significantly different at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

contrasts did not reveal a significant yield advantage for any treatment.

Similarly, protein contents did not respond in any particular pattern to method of fertilizer application or type of fertilizer applied. Point injected UAN and broadcast urea had significantly higher protein content in comparison to the point injected ammonium polyphosphate treatment and the surface banded UAN treatment at 42.8 MPa.

The barley microplot results revealed no significant differences between placement of fertilizer and yield (Table 12). Again, precipitation played a major factor as no difference was found between the treatments and the control. However, both Supergranule treatments did produce significantly higher yields than the surface

Table 12. Yield parameters from barley microplot (1 m^2) experiment				
Treatment	Pressure (MPa)	Yield*	Straw Yield*	Plant Height* (cm)
		(kg/ha)		
SB UAN	22.1	1510ab	1433ab	41.6c
SB UAN	34.5	1590ab	1393ab	42.7bc
SB UAN	42.8	1438b	1215b	43.6bc
SB AM Ph	25.9	1743ab	1355ab	43.6bc
SB AM Ph	37.8	1808ab	1445ab	45.4abc
SB AM Ph	41.7	1763ab	1298ab	43.5bc
BCST UREA	-	1338b	1223b	44.2abc
BCST AM NIT.	-	1553ab	1390ab	45.9ab
P.I. UAN	-	1570ab	1313ab	44.4abc
P.I. AM Ph	-	1873ab	1590ab	45.5ab
Sup. Gran. (7.5 cm)	-	1980a	1508ab	46.5ab
Sup. Gran. (15 cm)	-	2020a	1770a	47.4a
Control	-	1618ab	1445ab	41.6c

* - means followed by the same letter within each column are not significantly different at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

banded UAN treatment at 42.8 MPa and the broadcast urea treatment.

Combining treatment yield means by method of application resulted in fertilizer nesting yields to be the highest at 1846 kg/ha followed by surface banding at 1642 kg/ha and last, broadcast at 1446 kg/ha. Orthogonal contrasts showed differences in these yield values to be significant at the $P \leq 0.05$ level. These findings were quite different than the results of contrasts completed for the large plot experiments. The differences were attributed to the higher yield values obtained from the hand-placed Supergranule treatments.

Straw yield values were similar to grain yield values. The Supergranules placed to a 15 cm depth produced a significant straw yield advantage over the surface banded UAN treatment at 42.8 MPa and the broadcast urea treatment. No other significant effects were noted in the straw yield data.

There was no consistent pattern in plant heights, measured just before harvest, or correlation with grain yield and straw yield values. Plant heights were greatest with: both Supergranule treatments, followed by the point injected ammonium polyphosphate and broadcast ammonium nitrate treatments versus the surface banded UAN (22.1 MPa) treatment and the control. The Supergranules placed to a 15 cm depth also resulted in a taller stand of barley than all of the surface banded treatments except ammonium polyphosphate banded at a pressure of 37.8 MPa.

Overall, spring applications of fertilizer on barley using banding, broadcast, fertilizer nesting by point injection, or Supergranules did not result in any significant yield differences. For small plots (1 m^2) fertilizer nesting did result in superior yields than surface band or broadcast treatments. However, in the large plots, where Supergranule treatments were not included, the yield advantage was not evident. Fertilizer nesting with Supergranules showed some advantages in some of the crop parameters, compared to the surface banding treatments but this advantage was not consistent over all crop parameters measured.

4.1.4 Experiment 4: 1989-90 Winter Wheat Experiment

Fall application of nitrogen on direct-drilled winter wheat did not result in a significant yield response (Table 13). The yield from the control treatment was marginally lower than those from most treatments. Broadcast ammonium nitrate resulted in a 21% yield increase over the control. The pressurized UAN nesting treatment (H/P Nest UAN) resulted in a 7% yield increase over the control treatment. Despite such differences, orthogonal contrasts between these treatments and the control revealed no significant result. Fertilizer banding by anhydrous and deep banding (DB AM Ph) resulted in a yield mean of 1922 kg/ha. Fertilizer broadcast resulted in a yield mean of 2024 kg/ha. Fertilizer nesting resulted in a yield mean of 1995 kg/ha. Differences in these yield means were not significant. The trend towards increasing yields with surface placement of fertilizer did not seem to follow expected trends with fall placement of fertilizer nitrogen. One possible explanation was the low levels of soil moisture in the soil profile and the lack of growing season precipitation. This may have resulted in a shallow root zone for the winter wheat. Thus fertilizer placement near the soil surface may have been of greater benefit. Unfortunately no physical evidence was gathered to support this hypothesis.

Relatively poor forage yields implied the lack of precipitation was a factor in crop development. The sample yields (based on 1 m^2 samples) just after heading did indicate a significant crop response to fertilizer application. However, the differences in forage yields among fertilized treatments were not significant. The relative rank between forage yield and grain yield among the treatments was consistent except in the case of broadcast urea treatment. Because the crop response did not persist from forage to grain yields, it was most likely that low precipitation limited crop response

Table 13.	**Comparison of grain and biomass yields for method of fall fertilization on 1990 winter wheat experiment**	
Treatment	Yield	Square Metre Yield (dry basis)
	(kg/ha)	
Control	1858	3193*
Anhy.	1947	5355
Bcst Am. Nit.	2178	5562
Bcst Urea	1869	5540
DB AM Ph	1896	5015
H/P Nest UAN	2006	5600
P.I. Nest UAN	1983	5215

* - treatment mean significantly different from others in column group at $P \leq 0.05$ level.

and normal seed development in the winter wheat crop.

Under the given growing conditions, the method of fertilizer placement and the form of nitrogen fertilizer used did not significantly affect yields. However, fertilizer nesting by pressurized liquid injection or point injection did produce yields equal to those obtained with more conventional methods of fertilizer placement.

4.2 Fertilizer Penetration and Distribution

The second aspect considered in the experimental design was the penetration and distribution of fertilizer in the soil profile. From an agronomic perspective, it was necessary to note any similarities or differences in crop response to the distribution of the fertilizer in the soil. From an engineering perspective, little work has been done to verify the theories postulated on the jetting of liquid fertilizer into soil.

4.2.1 Analysis of Soil Sampling Methodology

One aspect of the soil sampling technique which requires discussion is the recovery fertilizer from the kerf formed by the jet. The mass of fertilizer applied in the experiments which should be captured by the soil probe was calculated and compared to the average of the actual mass recovered.

To determine the mass of fertilizer the probe should capture, a volume to mass conversion was required. The maximum volume of fertilizer which could be captured by the nozzle was calculated by relating the nozzle flow rate to the time of application. The flow rate was determined from the average flow per nozzle obtained from the fertilizer liquid calibrations. The flow time was determined by dividing the diameter of core taken (distance travelled) by the groundspeed of the applicator when the fertilizer was placed. From the volume of fluid which exited the nozzle, a simple conversion was applied to obtain the mass of fertilizer placed.

To determine the actual mass of fertilizer recovered, an approximation was required. Weighing each core in the field was not feasible since time (getting the samples into the cooler before mineralization and volatilization significantly altered results) and field conditions (the effects of wind and sloped land on a weigh scale) were factors to be dealt with. Thus accurate determination of the core sample mass was not possible. Because the soil analysis of fertilizer content was expressed in parts per million (mg fertilizer per kg soil), the mass of the soil sample was required to determine the actual mass of fertilizer recovered. To estimate the mass of soil at each depth, a bulk density sample of each plot was taken to the depth of soil sampling. This value was obtained from the average of bulk density values taken in the pulse penetration experiments. Applying this approximation to the calculated volume of the core permitted a reasonable estimate of the core soil mass and ultimately the mass of fertilizer recovered.

In most cases, the average amount of fertilizer recovered from each core was lower than the amount applied (Table 14). In some instances, the amount recovered exceeded the amount of fertilizer applied. Many factors caused this apparent discrepancy between the amount of fertilizer recovered and the amount applied.

The first source of error to be considered was the estimation of the mass of each core sample by using bulk density. Other than weighing each core individually in the field, an accurate method of determining core sample mass was unattainable. Weighing the total mass of sample from the field in a lab and dividing the mass by the number of cores may have provided a better estimate. However, there would still have been some errors with this estimate. Since the cores were taken in the top 15 cm of the soil profile, it was assumed that the spatial variability of estimating sample core mass by bulk density was fairly uniform. In each of the experiments conducted, the bulk density determination for each plot comparison indicated that the maximum deviation from the mean values was approximately 8%. This variability was considered acceptable and quite consistent throughout the soil profile. Upon perusal of the ammonium and nitrate concentration data, an overwhelmingly high proportion of the fertilizer was concentrated in the top 6 cm of the soil samples collected. Therefore, errors in fertilizer recovery from the lower depths would be

Table 14.	**Comparison of the applied and recovered amounts of liquid fertilizer**			
Experiment	Liquid UAN (28-0-0)			
	Amount Applied		Amount Recovered	
	NH_4	NO_3	NH_4	NO_3
	(mg)			
Winter Wheat	6.9	6.9	7.5	3.3
Grass				
80 kg/ha N	8.3	8.3	4.8	1.4
120 kg/ha N	12.2	12.2	8.7	1.9
Barley	13.8	13.8	16.0	7.8
Penetration Experiment				
34.5 MPa	65.0	65.0	68.5	30.2
20.7 MPa	48.9	48.9	39.1	16.4
Experiment	Liquid Ammonium Polyphosphate (10-34-0)			
	Amount Applied		Amount Recovered	
	NH_4	NO_3	NH_4	NO_3
	(mg)			
Grass				
20 kg/ha P	-	3.6	-	0.8
40 kg/ha P	4.8	7.2	7.6	1.2
60 kg/ha P	7.2	10.8	16.3	3.8
Barley*	55.2	-	33.2	-

* - samples analyzed for ammonium content only.

quite small considering the relative concentration of fertilizer between shallow and deep core samples.

The second factor to be considered was the sensitivity of the soil analysis and the soil sampling techniques. The Technicon Autoanalyzer was very sensitive and could detect minute changes in ammonium and nitrate levels. Sampling the kerfs left by the DMCSA or the pulsing applicator required cores being taken from each nozzle. If one nozzle flow rate was higher than the others, the actual amount of fertilizer applied in one kerf may have been higher than the others, and the actual amount of fertilizer in the pooled sample may be over estimated by an outlying value. Related to this issue was the variable movement of the applicator over the field terrain. This movement, or speed variation, was associated more with the DMCSA. The DMCSA was pinned to the drawbar of the tractor at one point and the machine itself was quite large. Because of these facts, the DMCSA had a tendency to roll with variations in field terrain. Because the hoe points were not penetrating the soil, there was no draft to keep the speed of the DMCSA uniform. This could have resulted in non-uniform placement of the fertilizer.

The above analysis may help explain the over-estimation of the amount of fertilizer recovered but the explanation for significant under-estimation of fertilizer recovered is still of some concern. Calibration results and crop yield results indicated the correct amount of fertilizer was being placed. Excavation of kerfs to a depth of 20 cm during the barley placement trials showed maximum penetration of fertilizer into the soil profile to be approximately 7 cm. This was found with the pulsing applicator as well. For reasons unknown, the DMCSA was found to have penetration below 10 cm. The minimum depth of sampling in the barley experiment was 8 cm. With the DMCSA, sampling was done to a depth of 15 cm. Thus sampling depth was ruled out as a source of error. Examination of the hole left by the sampling probe, when samples were obtained, was done to ensure the probe sample was taken at the proper angle with respect to the kerf. This ruled out the possibility of cutting the kerf and capturing only a portion of the fertilizer applied. By comparing the average bulk densities to the highest and lowest values measured at each depth, estimation of bulk density, at best, could account for only 15% of the discrepancy between the amount of fertilizer applied and amount recovered. There are two possible sources of error still to be considered.

First, there was the possibility that a high proportion of the fertilizer was not entering the kerf. Upon impact with the soil, a portion of the liquid may have been dispersed and remained on the soil surface. This would result in a discrepancy in the amount of fertilizer recovered from the kerf.

Second, a phenomenon reported by Nyborg and Leitch (1979) was considered. They observed a proportion of ammonium nitrogen in liquid fertilizer to be non-extractable with potassium chloride from soil until an unspecified period of time had passed. Thus, an amount of fertilizer may be present but not detected.

Investigations to determine the available ammonium from the soil were not completed because the soil was quite dry, and under the windy conditions, a considerable amount of weathering occurred and a visual determination of the kerf was not possible two days after fertilizer injection. Therefore, attempts to locate the kerf after a period of time with any degree of accuracy was not possible.

To investigate the possibility and extent of fertilizer deposition on the soil surface, the methodology used in obtaining core samples from the other experiments was repeated with some refinement. First, the pulsing applicator was run on similar terrain found in the crop experiments. System pressure was set at 34.5 MPa and ground speed of the applicator at 2.5 km/h. With the on-time set at 25 ms this allowed the capture of a pulse completely with a 3.5 cm diameter core. The cycle-time was set on the controller at 160 ms which converts into 11.1 cm spacing between pulses. The probe was inserted to a depth of 10 cm. Before the probe was removed, a radius of 5 cm was marked around the probe and the top 1 cm of surface soil removed and placed in a sample bag. The core sample was then removed and placed in a separate sample bag. The same methodology was employed with the background sample taken 20 cm away from the sampled pulse. Before the samples were stored in the cooler, the soil from each sample was removed from the bag and weighed to eliminate conversion by an estimated bulk density. Soil sample analysis was then done using the same methods employed in the crop experiments. The results of the analysis were then multiplied the mass of the sample obtained to determine the amount of ammonium and nitrate recovered.

The results from the experiment indicated some interesting trends (Table 15). First, by relating the surface recovery of NH_4 to the total NH_4 applied, 27% of the fertilizer applied was recovered from the soil surface. This finding implied a significant amount of fertilizer applied by jetting was dispersed on the soil surface. Second, even by carefully weighing the samples, nearly 8% of the fertilizer could not be accounted for. Perhaps this 8% is further dispersed outside the 5 cm surface

Table 15. Comparison of the applied and recovered amounts of ammonium and nitrate levels from surface and subsurface soil samples

Recovery Zone	NH_4	NO_3
	(mg)	
Subsurface Recovery	44.6	34.4
Surface Recovery	17.6	12.9
Total Recovery	62.2	47.2
Total Applied	67.6	67.6

sample taken around the probe. Third, the levels of nitrate recovered were lower than the levels of ammonium recovered. This is similar to the results summarized in Table 14. The reasons for this discrepancy are unknown.

4.2.2 Fertilizer Penetration and Distribution

In order to compare fertilizer recovery between treatments at different depths, some data conversion was necessary. Because the amount of fertilizer recovered between treatments was inconsistent, comparison between treatments may have led to significant results because of recovery errors rather than treatment effects. To eliminate this recovery error, the amount of fertilizer recovered at each depth was expressed as a percentage of the total amount of ammonium and nitrate recovered at each depth. For each experiment the results were then statistically analyzed for comparisons of fertilizer distribution at each depth. Comparisons were done for: ammonium only, nitrate only, combination of ammonium and nitrate and phosphorous in the case of the grass experiment.

Combining the ammonium and nitrate results of fertilizer distribution for the DMCSA showed no significant differences (Table 16). Analysis for treatment effects in separating the distributions by ammonium and nitrate yielded similar results (data not shown). From the data collected, penetration was difficult to determine. First, resolution due to core sampling was only 3 cm. Fertilizer placed to a depth of 12.2 cm could yield a result similar to fertilizer placed to a depth of 15 cm. Second, recovery values less than 2% were very small amounts of fertilizer (under 10 ppm). In many cases, recovery values differed slightly for ammonium, nitrate or phosphorous values in comparison to the background samples taken. Due to soil variability, these values may have been somewhat suspect and detection of positive values may have been in error.

Winter wheat results showed no significant differences in fertilizer distribution with changes in groundspeed or system pressure. Keeping groundspeed relatively constant and increasing pressure two and a half times over the lowest pressure did not affect fertilizer distribution. There seemed to be a trend for greater distribution with lower pressure but this was not significant.

Fertilizer distribution on the grass treatments yielded similar results to those found in the winter wheat treatments. Changing pressure while leaving velocity constant resulted in no significant differences in fertilizer distribution; regardless which type of fertilizer was used. With pressure kept relatively constant, there seemed to be a trend for increased fertilizer distribution lower in the soil profile with decreased groundspeed. However, cross comparisons for this effect did not yield any significant results.

As mentioned earlier, penetration determination by this analysis was suspect.

Table 16. Results of fertilizer distribution comparisons for the DMCSA						
Winter Wheat Experiment		Percent of Recovered Sample By Depth				
Gauge Pressure (MPa)	Velocity (km/h)	0-3 cm	3-6 cm	6-9 cm	9-12 cm	12-15 cm
		(%)				
34.5	3.9	79.4	13.5	2.4	2.2	2.5
13.8	3.5	70.5	12.0	4.7	7.7	5.1
20.5	4.9	76.0	21.7	1.2	0.4	0.7
Grass Experiment						
Gauge Pressure (MPa)	Velocity (km/h)	Percent of Recovered Sample By Depth				
		0-3 cm	3-6 cm	6-9 cm	9-12 cm	12-15 cm
28-0-0 N Distribution		(%)				
34.5	4.5	49.5	25.4	9.1	7.2	8.8
39.6	4.5	68.2	24.7	1.5	2.1	3.5
10-34-0 P Distribution						
25.6	7.3	68.5	23.0	5.8	0.0	2.7
31.0	7.6	68.4	25.0	2.1	1.9	2.6
36.8	7.3	78.0	9.7	1.8	10.1	0.4
10-34-0 N Distribution						
31.0	7.6	90.8	7.4	0.6	0.5	0.7
36.8	7.3	76.9	8.4	6.3	7.9	0.5

Excavation of kerfs made by the DMCSA were done mainly as a qualitative analysis rather than a quantitative analysis. Because the soil was quite dry, dissipation of the liquid was quite rapid. In many trials, detecting the depth of the kerf was quite difficult and in some instances undetectable even though the kerf line was easily located on the soil surface. Due to these inconsistencies, kerf excavations were done mainly as a qualitative analysis. Excavations did reveal kerfs penetrating 11 cm into the soil profile, but not on a consistent basis to warrant comparisons between treatments.

Excavation of kerfs from surface banding with the plot size applicator were quite different than those kerfs from the DMCSA applications. To a depth of 3 cm, the kerf was more defined than those encountered with the DMCSA. However, no evidence of jet penetration beyond a depth of 7 cm was documented. This was somewhat confounding since the nozzle holder was situated flush with the bottom surface of the runner; to increase jet penetration. The well defined kerf near the soil surface implied penetration was increased, but a decrease in penetration was often encountered. It was later concluded that this discrepancy was due to nozzle mounting. In the case of the DMCSA, nozzles were mounted in a rigid position. In the new design, the nozzles were mounted to the runner which pivoted to follow the soil surface. It was possible a recoil effect from the jet force imparted on the soil, plus the movement of the nozzle over the soil surface, impaired maximum jet penetration.

The results from penetration experiments on barley produced similar results to those encountered with the DMCSA (Table 17). The liquid UAN treatments showed no significant effects in fertilizer distribution with increasing pressure. However, for the ammonium polyphosphate treatments, significantly more fertilizer was recovered at the 6 to 8 cm depth at a pressure of 37.8 MPa, and a groundspeed of 2.0 km/h. Further comparisons across the type of fertilizer used found this difference to be statistically significant. This was consistent with earlier findings by

Table 17. Fertilizer recovery from barley penetration experiment						
Gauge Pressure (MPa)	Velocity (km/h)	Fertilizer Recovered By Depth			
		0-2 cm	2-4 cm	4-6 cm	6-8 cm
28-0-0 Fertilizer		(%)			
22.1	4.0	60.2	25.3	12.5	2.0
34.5	3.2	47.9	35.8	13.5	2.8
42.8	3.0	54.6	35.0	9.1	1.3
10-34-0 Fertilizer					
25.9	4.0	64.0	27.5	6.7	1.8
37.8	2.0	49.5	28.7	15.7	6.1*
41.7	5.0	60.8	32.0	6.4	0.8

* - mean significantly different from others in whole column at the $P \leq 0.05$ level.

Pointkoski and Domier (1985). They reported significantly better penetration with groundspeeds less than 3.0 km/h. At groundspeeds greater than 3.0 km/h, the velocity of the implement was not a significant factor in jet penetration. Therefore, the significant increase in fertilizer penetration encountered was most likely due to the very low groundspeed used in this treatment.

To analyze fertilizer distribution in the pulsing experiment, a comparison of treatment effects on fertilizer distribution required a slightly modified analytical technique. For groundspeeds of 4.5 km/h and 6.5 km/h, two and three cores, respectively, were required to capture the whole pulse. The amounts of fertilizer recovered at each position was still expressed as a percentage of the total recovery of fertilizer over all cores taken in the treatment. However, for comparison of distribution between treatments the values for all positions within a depth interval were combined for treatments where multiple cores were taken (Table 18).

Table 18. Distribution of recovered fertilizer from fertilizer penetration experiment						
Gauge Pressure (MPa)	Velocity (km/h)	Fertilizer Recovered By Depth				
		0-3 cm	3-4.5 cm*	4.5-6 cm	6-7.5 cm	7.5-9 cm
		(%)				
34.5	2.5	78.3	9.5a	5.1	5.2	1.9
34.5	4.5	91.0	7.5ab	0.7	0.6	1.2
34.5	6.5	92.3	1.8b	1.8	1.6	2.5
20.7	4.5	82.5	5.0ab	4.1	3.8	4.6
20.7	2.5	91.8	4.5ab	1.6	1.0	1.1

* - means followed by the same letter in column are not significantly different at the $P \leq 0.05$ level as determined by the Duncan Multiple Range Test.

For the depth interval of 3 to 4.5 cm, fertilizer distribution was significantly different between the groundspeeds of 2.5 km/h and 6.5 km/h at a system pressure of 34.5 MPa. This was consistent with findings obtained for fertilizer penetration in the barley experiment (Table 17). For the 4.5 to 6 cm and 6 to 7.5 cm intervals, the same trend was evident for the treatment with the lowest groundspeed and the highest pressure. However, this trend was not statistically significant in comparison with the other treatments.

Comparison of fertilizer distribution data (Tables 17 and 18) suggest pulsing and continuous stream jets have comparable fertilizer distribution patterns. Excavation of soil samples from the kerfs created by the pulsing treatments revealed soil penetration to be similar to those encountered with continuous stream jets in the barley trials. This supports the findings of Nebeker (1984). The configuration of the pulsing effect on this applicator can be considered an interrupted jet rather than an oscillating jet. Even though the pulse pressure varied with time, the actual pressure at each point as the nozzle moved was constant. Therefore the pulsing induced by the applicator could be considered to be of a variable pressure continuous stream jet rather than an oscillating jet.

The results in Table 18 were further analyzed with forward selection regression/simple correlation analysis (PROC REG: SAS Institute, 1985) to determine if there was any functional relationships between: the fertilizer distribution at each depth (variable: fert.) and measured parameters. By looking at past literature (Pointkoski and Domier, 1985) and perusal of the data, the applicator parameters chosen for the analysis were: gauge pressure (p) in MPa, groundspeed (U) in km/h, the ratio of pressure to groundspeed and the square root of the gauge pressure. The soil parameters included in the analysis were: moisture content (MC) in percent mass, dry bulk density (Db) in Mg/m^3 and penetration resistance (Pr) in kg/cm^2.

The correlation analysis revealed no consistent pattern between the parameter measured and fertilizer distribution over depth (Table 19). At some depths, the parameter had a high correlation with fertilizer distribution. At other depths a high negative or no correlation occurred between the measured parameter and fertilizer distribution. No definite relationship could be established between the measured parameters and fertilizer distribution.

The results of the correlation analysis were reflected in the regression models for each depth. A requirement for entry of a variable into the model was a level of significance of 0.25 or less. As illustrated, even at this low level of significance, the

Table 19. Regression analysis of fertilizer distribution characteristics for various application and soil parameters

	Correlation Coefficients						
Depth Range (cm)	p	U	p/U	√p	MC	Db	Pr
0-3	0.00	0.48	-0.54	0.00	-0.57	0.72	0.68
3-4.5	0.23	-0.71	0.84	0.23	0.04	-0.71	-0.29
4.5-6	-0.09	-0.36	0.44	-0.09	0.59	-0.51	-0.81
6-7.5	0.02	-0.32	0.48	-0.02	0.27	-0.89	-0.65
7.5-9	-0.35	0.39	-0.51	-0.34	0.40	-0.10	-0.29

	Regression Results	
Depth Range (cm)	Model	R^2
0-3	fert. = 6.17 √p + 78 Db - 43.5	0.83
3-4.5	fert. = 0.65 p/U + 0.3	0.70
4.5-6	fert. = - 5.1 MC - 0.71 Pr + 71.2	0.89
6-7.5	fert. = - 3.91 Db + 53.5	0.79
7.5-9	no variables met requirements	-

variables which entered into the model were not consistent over each depth range. Functional relationships may have existed between fertilizer distribution and the measured parameters. However, establishing such relationships under variable field conditions was a somewhat high goal to achieve.

The fertilizer distribution data for the treatments described in Table 18, where multiple cores were required to capture the pulse, was re-organized in Table 20. This two dimensional representation implied fertilizer was distributed in uniform fashion below a soil depth of 3 cm. What was indirectly evident from these results

Table 20. **Distribution of fertilizer pulse by depth and horizontal position for groundspeeds greater than 2.5 km/h**

Treatment	Depth (cm)	Direction of Travel →		
		Core Position (cm)		
		0 to 3.4	3.4 to 6.8	6.8 to 10.2
		(%)		
U = 4.5 km/h p = 34.5 MPa On-time 25 ms	0.0 to 3.0	72.0	19.0	-
	3.0 to 4.5	4.4	2.1	-
	4.5 to 6.0	0.5	0.2	-
	6.0 to 7.5	0.2	0.4	-
	7.5 to 9.0	0.5	0.7	-
U = 6.5 km/h p = 34.5 MPa On-time 25 ms	0.0 to 3.0	45.1	31.7	15.4
	3.0 to 4.5	0.7	0.3	0.8
	4.5 to 6.0	0.2	0.6	1.0
	6.0 to 7.5	0.3	0.9	0.4
	7.5 to 9.0	1.5	0.4	0.7
U = 4.5 km/h p = 20.7 MPa On-time 25 ms	0.0 to 3.0	48.5	34.1	-
	3.0 to 4.5	3.2	1.7	-
	4.5 to 6.0	2.9	1.2	-
	6.0 to 7.5	2.8	1.0	-
	7.5 to 9.0	3.2	1.5	-

was the discrepancy between the on-time dialled in on the valve controller and the actual on-time produced by the valve. With a theoretical on-time of 25 ms and groundspeed of 4.5 km/h and 6.5 km/h, the length of the kerf left by the pulse should have been 3.1 cm and 4.5 cm, respectively. The actual length of kerfs encountered were approximately 5.5 cm and 8 cm. This translated into an actual on-time of approximately 40 to 45 ms. These values did not actually affect fertilizer rates since this discrepancy was accounted for with the fertilizer calibrations. These results implied that valve performance was a definite factor in producing compact nests; especially at high groundspeeds. Penetration results implied that the nozzle setup, combined with valve performance, was incapable of producing a "teardrop" shaped nest postulated by Arya and Pickard (1958). Interpolation of the data from Table 20 implied the shape of the pulses encountered in the soil profile were more likely similar to the representation on the right side of Figure 7 than the ideal representation on the left hand side of Figure 7.

Perhaps the most consistent result observed in Tables 16 through 18 was that approximately 90% of the total fertilizer recovered was in the top 6 cm of the soil

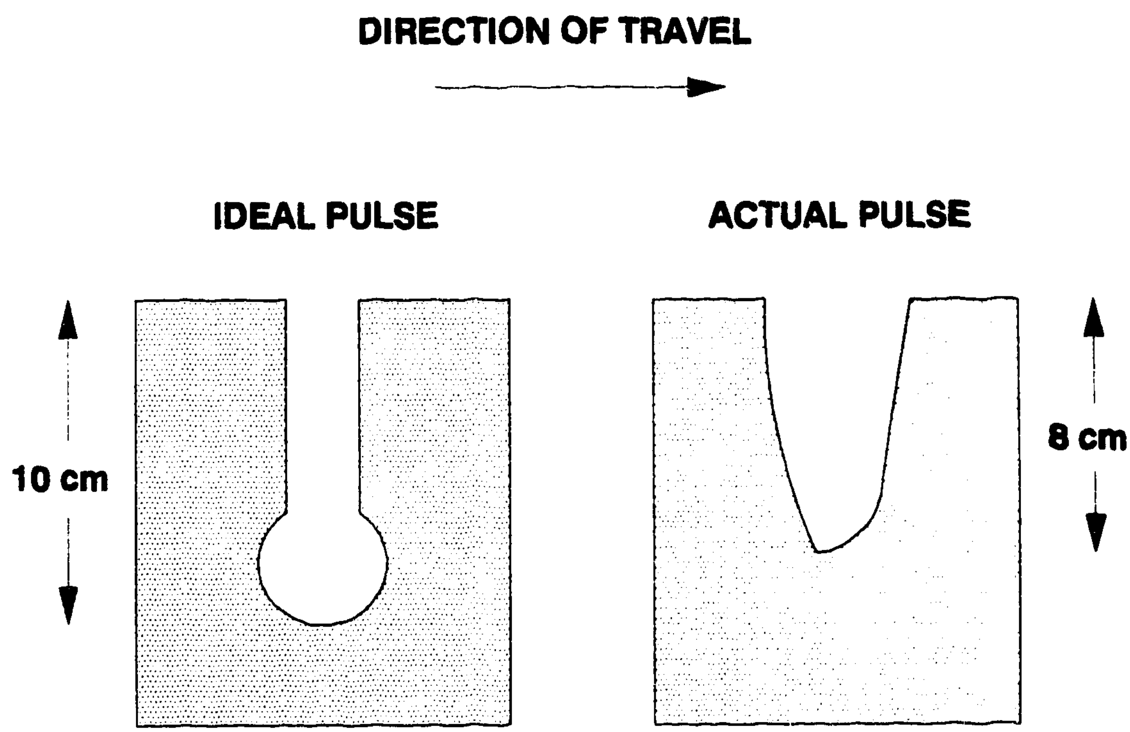

Figure 7. Interpolation of the pulse shape in the soil profile

profile. Regardless of system pressure, ground speed or fertilizer type used, fertilizer distribution was fairly constant. For both pulsing and continuous stream applications, this observation held true. This finding would not be particularly desirable if the majority of fertilizer was placed above the seed rather than below seed (since seeding depth for cereals is typically 5 to 6 cm).

4.3 Applicator Performance Results

The pressurized liquid nesting applicator provided a useful insight for many aspects of fertilizer nesting which required clarification before this technology could be widely promoted.

One of the problems encountered with the existing design was the balancing of flow between nozzles and the difficulty in maintaining consistent valve operation. Some of the results of the numerous calibrations conducted are summarized in Table 21. Valve 1 was used to feed nozzles 1, 2 and 3 while nozzles 4, 5 and 6 were fed by valve 2. During the first calibration conducted in 1989 nozzle switching was done to balance the flow between nozzles as close as possible. Even with due care and attention, variations in flow among nozzles was as high as 14%. Nozzle matching was a difficult task since replacement of one nozzle affected the flow of all three nozzles in the nozzle bank.

Besides matching nozzle flow, adjustment of valve flow was also required to ensure application uniformity. Because of the high flow rate encountered during the first calibration, the fertilizer application treatments required in Experiment 4 required dilution. Adjustments to the preload on the valve in the 1990 calibrations

Table 21.	Comparison of pulsing calibrations throughout applicator development for each nozzle at a gauge pressure of 34.5 MPa								
Date	On-time (ms)	Cycle-Time (ms)	Flow at Each Nozzle (mL/min)						Mean (mL/min)
			1	2	3	4	5	6	
Oct 18/89	25	160	622	551	613	636	555	593	595
Nov 1/90	25	160	291	273	280	290	269	284	281
Nov 1/90	25	140	325	310	315	310	275	295	305

cut the flow rate in half, thus eliminating the need for fertilizer dilution even at low rates of nitrogen application. However, this adjustment did not permit the valves to operate consistently for the fastest on-time of 20 ms. Consistent operation of the valves at the lowest possible on-time was found to be 25 ms.

Increasing the cycle-time to 140 ms resulted in an increase in flow through the nozzle. However, the valve response did not change accordingly. Valve 1 had an average nozzle flow rate of 317 mL/min while Valve 2 had an average nozzle flow rate of 293 mL/min. For the 160 ms cycle-time, the average flow rate per nozzle was uniform. This illustrated that changing cycle-time to accommodate nest spacing required vigilance to ensure proper calibration.

The calibration curves for cycle-times of 140 and 160 ms with varying on-times revealed some interesting relationships about valve performance (Figure 8). Because of the constraint that on-time could only be set at 25% of the cycle-time, the highest allowable on-time was 35 ms. Unfortunately the valve would not operate consistently at on-times less than 25 ms. Thus decreasing cycle-time limited the selection of on-time which could be used. Of even greater interest was the relationship between cycle-time and actual pulse volume. Decreasing the cycle-time actually increased the flow rate. The actual volume per pulse decreased because more pulses were produced for each time interval.

These findings revealed another limitation encountered with valve/controller performance. Janzen and Lindwall (1989) found that the optimum nest spacing for maximum fertilizer use and efficiency was 40 cm. Using equation 16, noting a cycle-time of 160 ms, the resultant groundspeed would be:

Eq. 16 $U = Sp/T_c$

$U = 40 \text{ cm} / 0.160 \text{ s} = 250 \text{ cm/s or } 9 \text{ km/h}$

This groundspeed is much too fast to apply liquid fertilizer efficiently with this applicator in a research plot situation and more than likely too fast for field applications. Since 160 ms was the slowest cycle-time, nest spacing was limited to the maximum allowable groundspeed and the slowest cycle-time. For the sake of argument let the maximum groundspeed be 8 km/h. Employing equation 16, the maximum nest spacing becomes 35.6 cm. The maximum volume per pulse from Figure 8 is 1.201 mL/pulse which produces a nozzle flow rate (Q_n) of 0.450 L/min.

Employing Equations 10 and 12 the maximum rate of nitrogen application is determined to be:

Eq. 12 $Q = Q_n / U (6.78 \times 10^{-4}) = 0.450 / 8 (6.78 \times 10^{-4}) = 83 \text{ L/ha}$

Eq. 10 $N_i = Q / K_1 = 83 / 2.79 = 29.7 \text{ kg/ha}$

For modest rates of nitrogen application this value is acceptable. Unfortunately higher rates of nitrogen application would require nest spacings to be reduced. This exercise illustrates the fact the maximum cycle-time on the controller

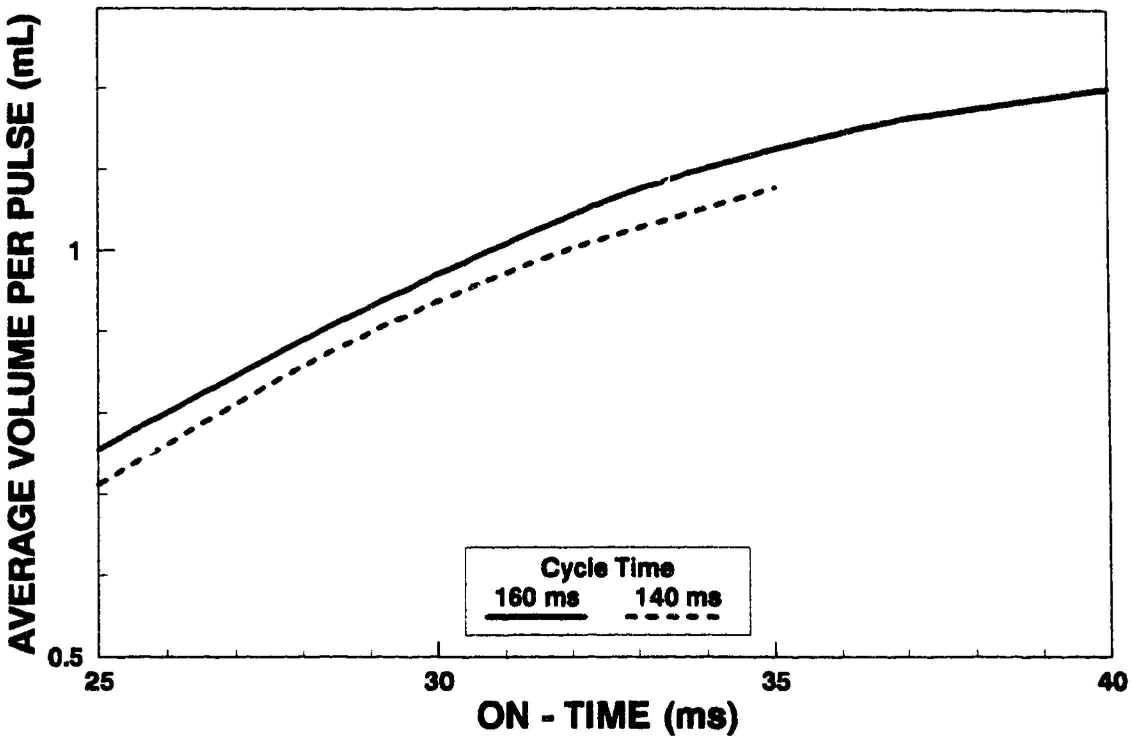

Figure 8. Relationship between pulse volume and on-time for a system pressure of 34.5 MPa

is actually too fast to accommodate a variety of nest spacings and nitrogen application rates. Granted, the preload on the valves could be decreased to allow for the 1989 calibration values, but this required a significant fertilizer dilution to apply 40 kg N/ha in Experiment 4.

Another aspect of machine performance which required some consideration was potential heating of the liquid. From Table 21, the total flow for the six nozzles at an on-time of 25 ms, cycle-time of 160 ms and pressure of 34.5 MPa was 1.69 L/min. The specifications for the Giant pump at 34.5 MPa indicated a pump flow rate of 31.8 L/min. This resulted in 95% of the flow generated by the pump to be bypassed back to the reservoir. Since the capacity of the supply reservoir was 100

L there was a complete volume change in the tank approximately every 3 minutes of operation. This value would decrease with continued pump operation. Bypassing this large amount of fluid, at high pressure, combined with a complete volume change resulted in significant heating of the liquid. During three calibration trials tank liquid temperature was monitored to assess the effects of liquid heating.

The liquid temperature rose steadily with time (Figure 9). There was no indication of fluid temperature levelling off at a maximum value in any of the trials. What further complicated this issue was the fact that the applicator was not continuously running during the temperature measurements. The actual running time of the applicator was approximately two-thirds of the time represented in the figure. Under continuous operation, liquid temperature would increase much faster. Considering the volume of liquid would decrease as operation continues, an unstable situation could result. Most likely the liquid would continue to heat up and eventually start to boil; a highly undesirable situation.

This problem could be solved by properly sizing the pump to the flow requirements of the nozzles. Unfortunately high pressure pumps are quite expensive and budget constraints may not be practical for optimum pump sizing.

During fertilizer application and system calibration an ammonia "odour" was sometimes detected. Concerns arose that the high pressure actually caused some vaporizing of the fertilizer constituents, thus decreasing the quality of liquid exiting the nozzle. Another concern was the possibility of fertilizer volatilizing with the heating of the liquid. To investigate these possibilities, samples of liquid exiting the

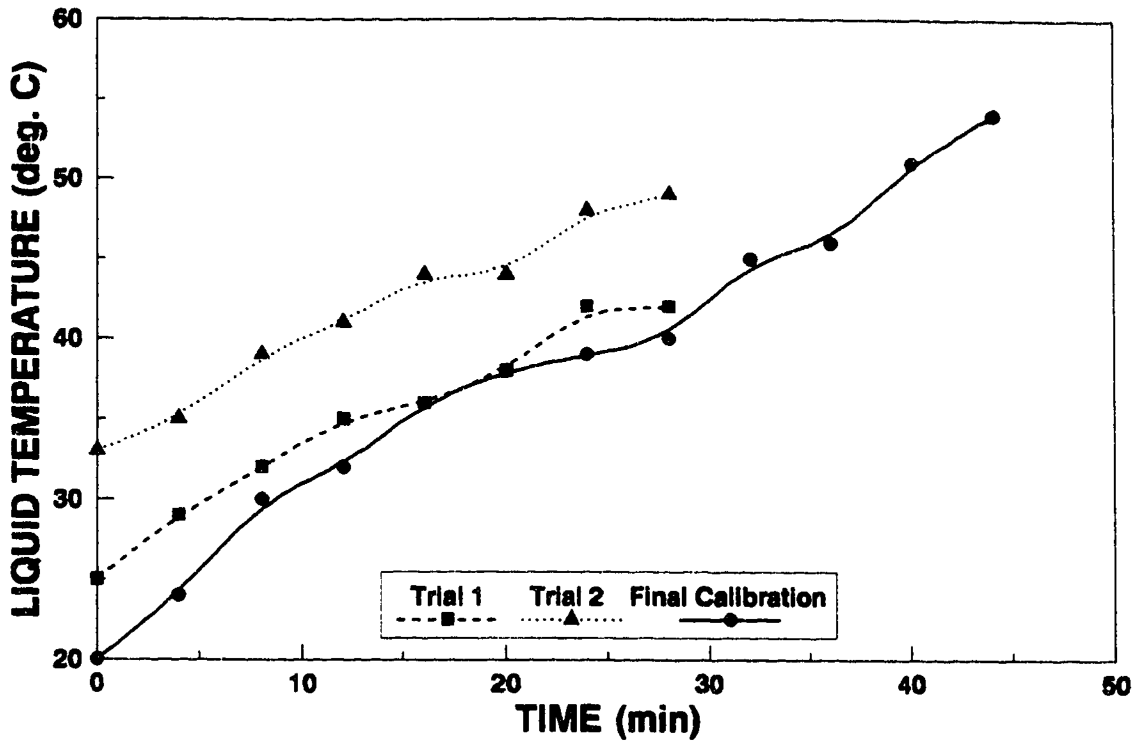

Figure 9. Rise in tank liquid temperature with applicator operation

nozzle and tank samples collected at the end of the calibration trials were compared with samples taken from the liquid reservoir before the calibration (Table 22).

A 2% drop in the mass of fertilizer constituents exiting the nozzle compared to the check was noted. This implied a small portion of vaporization occurred as the liquid exited the nozzle. There was also a 0.5% drop in quality of the total fertilizer constituents in the sample obtained from the tank at the end of the trial as compared to the check. This was most likely due to the vaporization of liquid as it exited the bypass unloader valve, but such a small difference may possibly be attributed to sampling error.

Table 22. **Comparison of fertilizer quality between check samples and fertilizer samples collected during calibrations**

Sample	Ammonium	Nitrate	Urea	Total
	(% w/w)			
Check	7.3	6.8	12.2	26.2
Nozzle	6.7	6.1	11.5	24.3
Tank	7.1	6.7	12.0	25.8
Theoretical	7.0	7.0	14.0	28.0

Plotting the results of the fertilizer samples obtained from the nozzles against tank liquid temperature revealed no particular trends (Figure 10). The ammonium, nitrate, urea and total nitrogen values remained essentially constant throughout the calibration exercise. Slight fluctuations in quality among the constituents were noted. The reason for this was unclear, but it could have been attributed to sampling error.

The results from this analysis implied that the ammonia odour detected was due to the vaporization of the liquid exiting the nozzles. This value seemed to be relatively constant throughout the trials. The quality of the liquid did not seem to change with an increase in tank liquid temperature. However, if the applicator was allowed to run for a longer period of time, there was evidence the temperature of liquid could increase dramatically. Perhaps the quality of the fertilizer constituents would deteriorate rather significantly as the liquid temperature continued to rise beyond the range observed in this study.

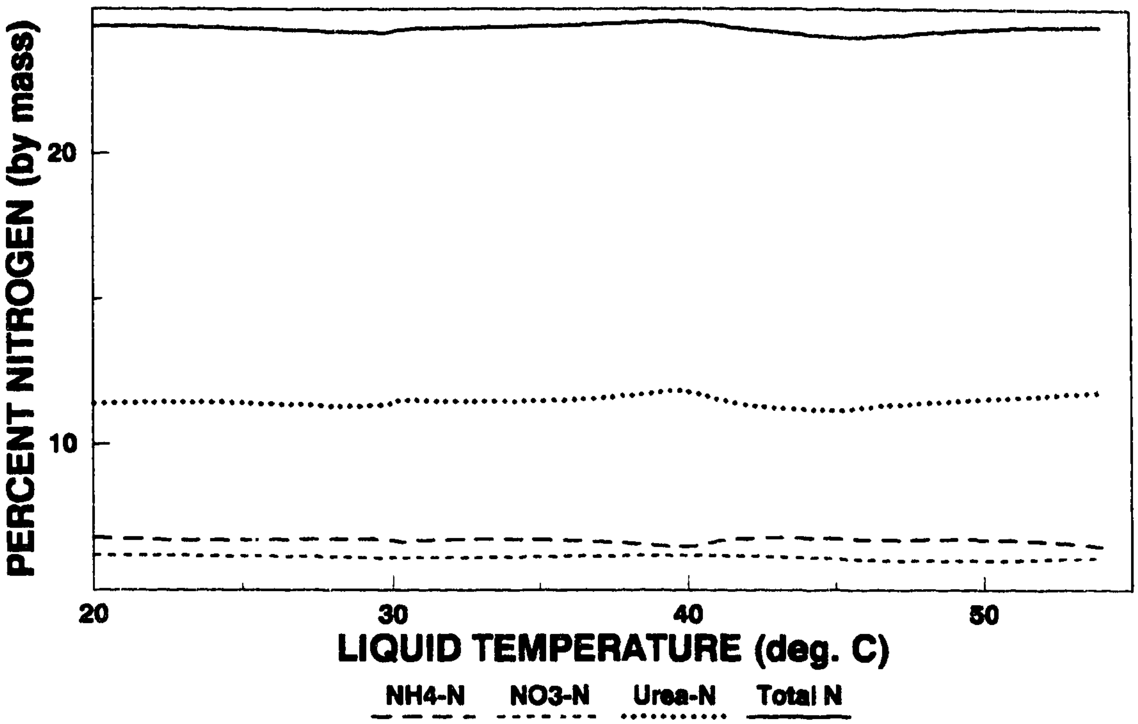

Figure 10. Relationship between fertilizer quality and tank temperature

CHAPTER 5: CONCLUSIONS

In general, the field experiments indicated there was little or no response to fertilizer application treatments. While other factors may have contributed to these findings, the drought conditions experienced during the experiments was the main factor contributing to the lack of fertilizer response. These adverse conditions limit the number of conclusions that can be drawn related to the feasibility of high pressure fertilizer injection technology compared to conventional fertilizer application methods.

In Experiment 2, the effects of increased fertilizer uptake for surface banding versus broadcast was noted in the significant differences in nitrogen and phosphorous yields (uptake) between the two methods of application. However, this did not translate into significant yield differences. This implies surface banding did result in more effective nutrient uptake, but drought conditions suppressed any potential yield benefit. This was further supported by the fact that the biomass yields at reharvest, nearly 20 months after initial fertilization, showed a significant fertilizer response over the control. The yield results from the point injection trials, although not statistically comparable, indicated that this method of fertilizer application produced similar or higher yields than those obtained by surface banding. This implies fertilizer nesting can be as effective as conventional fertilizer application techniques, even under limiting moisture conditions.

Fertilizer nesting with hand-placed Supergranules, provided further evidence that this technique can be an effective management practice for cereal crop production. However, it should be noted that the point injection treatments in the same comparison, generally, did not result in any yield advantages compared to the other treatments. As well, the Supergranules were hand-placed on small plots rather than applied on a field scale. Field scale placement of fertilizer nests, in Experiment 4, by pressurized liquid nesting and point injection treatments showed some evidence of being an effective placement technique; in view of the higher mid-season biomass yields. However, the lack of a significant yield response at harvest (another effect of low growing season precipitation) over the other methods of fertilizer application, or the control, did not provide sufficient evidence to conclude that nesting was superior to the other methods of fertilizer application.

Overall, the field experiments did not provide sufficient evidence to state unequivocally that nesting was superior to conventional fertilizer placement techniques. However, the results from the nesting experiments did indicate that this method may be an acceptable fertilizer placement technique; particularly for forage production. Fertilizer nesting was usually equivalent to conventional application techniques; even under limiting moisture conditions. Perhaps, under more favourable precipitation and soil moisture regimes nesting may produce superior results.

Sufficient data were not collected to comment, in detail, on the effectiveness of pressurized nesting versus the other application techniques in a crop situation. However, sufficient information on fertilizer distribution, and applicator performance, were gathered to evaluate the effectiveness of this technology to deliver liquid fertilizer in compact nests on a field scale.

Results from the core analysis showed that increasing pressure did not significantly increase fertilizer penetration into the lower regions (6 to 10 cm) of the soil profile. This was reflected in the lack of significant differences in fertilizer distribution, at each depth, in the soil core analysis. There was a trend towards increased fertilizer distribution at lower soil depths at applicator groundspeeds less than 3.0 km/h. The viability of pressurized fertilizer nesting on a field scale must be questioned; if low groundspeeds (< 5 km/h) are required to place liquid fertilizer, in significant proportions, to a depth of 10 cm.

Incorporating the pulsing design did not increase fertilizer penetration into the soil profile. Approximately 90 percent of the fertilizer recovered was in the top 6 cm of the soil profile. The existing system design did not incorporate pulsing in an appropriate manner to fully utilize the advantages of the pulsing effect. The pulse did not effectively impact on a small enough area of soil as the applicator moved. Therefore a differential pressure effect was not experienced at a single point.

The evaluation of applicator performance demonstrated that the general design of the high pressure circuit was sound; once the appropriate calibrations and adjustments were made. Problems encountered usually involved the controller and valve operation. A considerable amount of fine tuning of the valve was required to achieve the desired response. Calibrations showed that the cycle-time of the controller was too fast to achieve a broad range of nitrogen application rates, while the on-time was too slow to form compact nests given the current pulsing system.

A small decrease in fertilizer quality from fluid collected at the nozzles was measured. This reduction in fertilizer quality was inevitable with pressurized liquid application. Throttling liquid from a pressure of 34.5 MPa to atmospheric pressure undoubtedly vaporized some of the liquid. Fortunately this effect was constant and the reduction in fertilizer quality was relatively small.

One factor which was critical in the design of the high pressure applicator was the pump size. A simple calculation, allowing for 25 percent of the flow to be diverted back to the reservoir, showed that the pump was capable of supplying flow to 84 nozzles. Given the spacing of 40 cm between nozzles, this indicated that a 34-m wide applicator could be used with the existing pump. Because of the high capacity of the pump, tank heating led to an unstable situation where the liquid could eventually boil.

The benefits of low draft and minimal soil disturbance are appealing for fertilizer application on grass and no-till crops. With some design refinements, to increase fertilizer penetration at increased groundspeed, pressurized liquid nesting could be competitive with more conventional methods of fertilizer application. With the present technology, this method of application was at least comparable to broadcast fertilizer application. Refining the pulsing process is the key to making pressurized liquid nesting a viable option to more traditional fertilizer application techniques. If the majority of fertilizer in pressurized liquid nesting could be placed to a depth of 8 to 10 cm in more compact nests, pressurized liquid nesting should be as effective as point injection and could be applicable to cereal crop production.

CHAPTER 6: RECOMMENDATIONS

The design and construction of the applicator provided insight into many design problems which could be encountered by implementing pressurized liquid fertilizer nesting technology. As well, difficulties tended to appear where none were anticipated. In many cases solutions to problems were often not evident until the analysis was completed.

With pressurized fertilizer nesting technology many problems need to be overcome before a field scale applicator can be considered a viable design.

One of the biggest problems encountered was the calibration and the complex trial and error calculations required to apply fertilizer at the desired rate. These calculations were required because application rate was dependent on groundspeed. If this dependency did not exist, pressurized liquid nesting would be much less complicated and a more viable product. The dependency of application rate on groundspeed could be eliminated by the introduction of speed compensation into the valve controller. By implementing a microprocessor into the valve controller, a Hall-effect sensor could monitor groundspeed from a series of magnets placed on one of the applicator support wheel-hubs. With a real-time approximation of groundspeed, the microprocessor could initiate pulsing cycle-time for the desired rate of fertilizer application. Implementation of this proposed design would not be difficult but cost may be a limiting factor.

If speed compensation is not desired, the controller should be at least extended in cycle-time to accommodate a broader range of application rates. The process of backing off the valve preload and recalibrating the applicator is too complex an undertaking for production designated machines.

The applicator seemed to achieve poorer soil penetration than the DMCSA. This problem was likely due to the recoil of the runner as the pulse was initiated. The runner could not be rigidly connected because a pivoting motion was required for the nozzle to follow the soil surface contours. By attaching a spring loaded arm between the runner connecting arm and the runner, sufficient force could be created to make the runner solid yet allow the runner to follow the surface contours.

One problem which was solved but which cannot be stressed enough was the necessity of stainless steel fittings on the high pressure side of the pump. The corrosive nature of the liquid fertilizer coupled with the small diameter of the nozzles created serious plugging problems. Any foreign matter located on the high pressure side of the pump became lodged in the nozzles and was extremely difficult to remove. Stainless steel fittings eliminated this problem.

Results revealed that pressure seemed to be an ineffective means of increasing fertilizer distribution and penetration. When the applicator was operated at a system pressure of 20.7 MPa, rather than 34.5 MPa, fertilizer penetration and distribution were equally effective. A low capacity pump (around 8 L/min) with a pressure of 20.7 MPa may be an adequate size for an applicator of this scale. Besides eliminating the heating problem, the cost of fittings, hoses and other associated hardware for a 20.7 MPa machine are much less.

Last, but most important, pulsing should be implemented to achieve the advantage of increased penetration that pulsing should theoretically produce. One approach would be to use large nozzles to increase flow rate and decrease the on-time of the valve. The main problem for this design is that valve response must be very fast and precise to allow maximum flow in the shortest amount of time. A more elegant approach would be to rotate the nozzle in the opposite direction of applicator motion, at the same speed as the applicator, when the pulse is initiated. This would ensure the pulse is essentially placed at one spot. A considerable amount of engineering would be required to develop a rotational mechanism, with a spring return, which would rotate at the proper speed precisely when the pulse is initiated. However, as it stands there are not many other options to implement pulsing correctly.

When all is considered, pressurized liquid nesting is very versatile and could have an important niche in the fertilizer application marketplace. This technique is particularly well suited to fertilizer application on grasses and in no-till situations. If the pulsing problem can be dealt with successfully, pressurized liquid nesting could be competitive with conventional methods of fertilizer application. In the present situation, some problems have to be overcome and the solution may be more costly than economics warrant, because in the end economics will decide whether or not pressurized liquid fertilizer nesting is a viable option.

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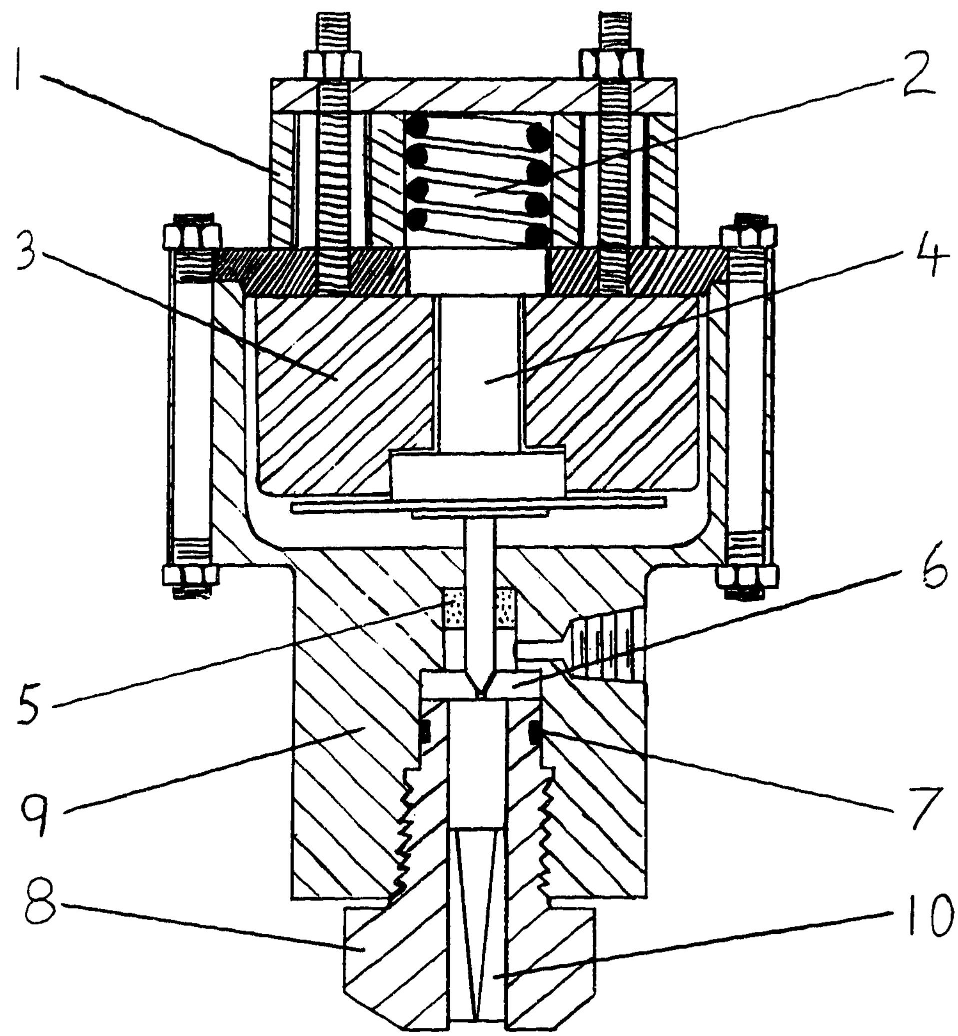
APPENDIX A



Schematic of Solenoid Valve

Valve Parts:

1. Valve Cap Body (preload adjustment)
2. Spring Return
3. Magnetic Coil
4. Needle Valve Assembly
5. Seal
6. 2 mm Stainless Steel Orifice (valve seat)
7. O-Ring Seal
8. Hex Nut (nozzle holder, not used)
9. Valve Body
10. Nozzle (not used)

APPENDIX B

TREATMENT LISTS FOR EXPERIMENTAL DATA

Experiment 1. Winter Wheat

1	Fall applied 28-0-0 surface band DR 13:1	
2	Fall applied 28-0-0 surface band DR 10:1	
3	Fall applied 28-0-0 surface band DR 8:1	
4	Fall applied 28-0-0 deep band DR 13:1	
5	Fall applied 28-0-0 deep band DR 10:1	
6	Fall applied 28-0-0 deep band DR 8:1	
7	Fall applied 46-0-0 deep band prilled urea	
8	Fall applied 34-0-0 deep band ammonium nitrate	
9	Fall applied broadcast urea	
10	Fall applied broadcast ammonium nitrate	
11	Fall applied 28-0-0 point injection	
12	Fall applied 28-0-0 pulse DR 13:1	NOT DONE
13	Fall applied 28-0-0 pulse DR 10:1	NOT DONE
14	Fall applied 28-0-0 pulse DR 8:1	NOT DONE
15	Spring applied 28-0-0 surface band DR 13:1	NOT DONE
16	Spring applied 28-0-0 surface band DR 10:1	NOT DONE
17	Spring applied 28-0-0 surface band DR 8:1	NOT DONE
18	Spring applied broadcast urea	NOT DONE
19	Spring applied broadcast ammonium nitrate	NOT DONE
20	Spring applied 28-0-0 point injection	NOT DONE
21	Spring applied 28-0-0 pulse DR 13:1	NOT DONE
22	Spring applied 28-0-0 pulse DR 10:1	NOT DONE
23	Spring applied 28-0-0 pulse DR 8:1	NOT DONE
24	Check	

Experiment 2. Grass

1	Surface band AM Ph/UAN 20 P/40 N
2	Surface band AM Ph/UAN 20 P/80 N
3	Surface band AM Ph/UAN 20 P/120 N
4	Surface band AM Ph/UAN 40 P/40 N
5	Surface band AM Ph/UAN 40 P/80 N
6	Surface band AM Ph/UAN 40 P/120 N
7	Surface band AM Ph/UAN 60 P/40 N
8	Surface band AM Ph/UAN 60 P/80 N
9	Surface band AM Ph/UAN 60 P/120 N
10	Broadcast 20 P/40 N
11	Broadcast 20 P/80 N
12	Broadcast 20 P/120 N
13	Broadcast 40 P/40 N
14	Broadcast 40 P/80 N
15	Broadcast 40 P/120 N
16	Broadcast 60 P/40 N
17	Broadcast 60 P/80 N
18	Broadcast 60 P/120 N
19	Point Injection AM Ph/UAN 20 P/40 N
20	Point Injection AM Ph/UAN 20 P/80 N

Experiment 2. Treatment List Continued

21	Point Injection AM Ph/UAN 20 P/120 N	
22	Point Injection AM Ph/UAN 40 P/40 N	
23	Point Injection AM Ph/UAN 40 P/80 N	
24	Point Injection AM Ph/UAN 40 P/120 N	
25	Point Injection AM Ph/UAN 60 P/40 N	
26	Point Injection AM Ph/UAN 60 P/80 N	
27	Point Injection AM Ph/UAN 60 P/120	
28	Check 0P 0N	
29	Broadcast 40P 0N	
30	Surface Banded 40P 0N	
31	Broadcast 0P 80N	
32	Surface Banded 0P 80N	

Experiment 3. Barley

1	Surface Band UAN DR 6:1	
2	Surface Band UAN DR 10:1	
3	Surface Band UAN DR 12:1	
4	Surface Band AM Ph DR 2:1	
5	Surface Band AM Ph DR 6:1	
6	Surface Band AM Ph DR 2:1	
7	Broadcast Urea	
8	Broadcast Ammonium Nitrate	
9	Point Injection UAN	
10	Point Injection AM Ph	
11	Pulse UAN	NOT DONE
12	Pulse AM Ph	NOT DONE
13	Supergranule 7.5 cm deep	
14	Supergranule 15 cm deep	
15	Check	

Experiment 4. Winter Wheat 1990

1	Check	
2	Fall Anhydrous Ammonia before seed 40 kg N/ha	
3	Fall Broadcast 34-0-0 before seed 40 kg N/ha	
4	Fall Broadcast 46-0-0 before seed 40 kg N/ha	
5	Fall Deep Band 23-24-0 with seed 180 kg total/ha	
6	Fall Pulse 40 kg N/ha seed with 60 kg 11-55-0	
7	Fall Point Injection 40 kg N/ha seed with 60 kg 11-55-0	
8	Spring Pulse 40 kg N/ha seed with 60 kg 11-55-0	NOT DONE
9	Spring Point Injection 40 kg N/ha seed with 60 kg 11-55-0	NOT DONE
10	Spring Broadcast 34-0-0 seed with 60 kg 11-55-0	NOT DONE
11	Spring Broadcast 46-0-0 seed with 60 kg 11-55-0	NOT DONE

Winter Wheat Crop Data (1988): NCON in percent mass dry basis. YIELD is expressed on a wet basis.

CODE	YIELD kg/plot	MC (%)	NCON (%)	CODE	YIELD kg/plot	MC (%)	NCON (%)
11	10.40	66.4	2.15	13	9.00	[illegible]	2.13
21	9.80	69.6	2.20	23	13.50	67.2	1.93
31	10.40	65.1	2.00	33	11.30	67.1	2.20
41	9.50	62.9	2.20	43	13.00	68.1	2.23
51	8.95	65.8	2.43	53	13.50	65.8	2.15
61	10.50	65.8	2.20	63	14.10	74.1	2.10
71	11.05	60.7	1.93	73	11.60	72.4	1.84
81	9.60	63.7	1.90	83	12.75	69.6	1.48
91	9.75	62.5	1.78	93	11.40	64.1	1.85
101	8.65	61.9	2.05	103	11.95	69.5	2.33
111	9.10	65.2	1.95	113	11.20	66.1	1.59
121	9.25	65.0	2.08	123	10.80	66.9	1.68
131	8.50	64.9	1.79	133	9.45	68.1	1.81
141	7.35	64.3	1.98	143	9.10	69.8	1.85
151	9.35	64.0	2.03	153	9.10	69.2	1.94
161	7.80	65.6	2.13	163	9.20	66.6	1.50
171	8.85	25.3	2.03	173	10.60	71.8	1.84
181	8.20	65.4	2.03	183	9.40	29.0	1.79
191	8.00	64.1	2.18	193	9.80	64.9	1.85
201	7.60	64.2	2.13	203	8.20	65.3	1.68
211	8.00	66.5	1.90	213	11.95	68.6	1.69
221	7.70	63.6	1.85	223	11.55	70.0	2.00
231	8.80	59.2	1.95	233	9.40	69.6	2.13
241	7.75	65.6	2.05	243	10.50	68.7	1.75
12	10.75	65.0	2.13	14	8.80	65.0	2.25
22	9.75	64.3	2.05	24	9.40	63.3	1.90
32	11.10	67.0	2.18	34	7.90	64.9	2.03
42	8.70	63.6	2.18	44	10.55	66.3	2.06
52	10.25	63.9	2.03	54	8.20	64.5	2.05
62	9.55	63.9	2.00	64	11.25	65.6	1.85
72	9.00	64.5	1.95	74	13.25	66.6	1.31
82	9.30	64.3	2.09	84	11.20	68.2	1.73
92	8.65	60.6	1.93	94	8.70	66.7	1.78
102	12.30	68.3	1.95	104	8.85	64.5	2.23
112	9.20	62.9	1.93	114	7.80	67.1	1.95
122	7.85	62.0	1.84	124	7.45	63.9	1.65
132	8.10	63.1	1.70	134	7.35	63.2	1.53
142	7.35	62.7	1.80	144	7.55	66.9	1.93
152	9.20	65.3	1.58	154	7.45	68.6	1.70
162	8.70	66.1	1.63	164	7.30	64.1	1.43
172	8.60	60.4	1.58	174	8.50	66.6	1.80
182	8.40	61.0	1.91	184	5.85	62.1	1.78
192	11.00	67.8	1.94	194	8.00	65.7	1.90
202	9.10	66.7	1.96	204	6.75	64.8	1.95
212	8.30	63.9	2.09	214	5.45	63.8	1.75
222	6.95	60.4	1.73	224	8.30	68.0	2.25
232	7.95	62.8	1.98	234	8.55	67.6	2.23
242	8.20	64.1	1.80	244	8.10	64.7	1.95

GRASS CROP DATA (1988): CODE refers the plot identifier. For example CODE 21 identifies treatment 2, replicate 1. YIELD values are expressed on a wet basis. PCON and NCON are phosphorous and nitrogen contents extracted from the plant tissue and are expressed on a percent mass basis. NOTE treatments 19 through 27 are the point injection treatments from adjacent plots. These values are not statistically compatible with the rest of the treatments.

CODE	YIELD kg/plot	MC (%)	PCON (%)	NCON (%)	CODE	YIELD kg/plot	MC (%)	PCON (%)	NCON (%)
11	2.55	45.9	2.23	1.95	13	1.90	46.7	2.15	1.90
21	3.23	45.6	1.88	1.95	23	2.55	45.6	2.15	2.16
31	2.60	46.2	2.15	2.54	33	2.30	48.0	2.08	2.68
41	3.25	46.6	1.70	1.48	43	2.10	46.5	2.18	1.98
51	2.80	46.1	2.43	2.53	53	2.15	45.9	2.20	2.41
61	2.93	47.3	2.30	2.78	63	2.15	44.4	2.05	2.53
71	2.30	47.5	2.20	2.15	73	2.25	46.1	2.23	2.05
81	3.75	47.3	2.15	2.06	83	2.30	44.6	2.10	2.33
91	2.90	45.5	2.48	2.69	93	2.65	45.7	2.03	2.54
10	2.30	45.2	2.10	1.76	103	2.35	46.3	2.05	1.88
111	3.60	46.0	1.65	1.46	113	2.95	45.1	1.98	1.93
121	2.90	44.4	1.98	1.96	123	2.55	45.7	2.00	2.06
131	2.95	44.6	1.88	1.48	133	2.25	45.4	2.13	1.85
141	2.80	41.2	2.23	2.01	143	2.45	45.1	2.13	2.04
151	3.05	39.6	2.30	2.28	153	2.40	46.6	2.05	2.19
161	2.40	43.1	2.13	1.83	163	2.15	46.3	2.03	1.99
171	2.40	45.6	2.08	2.10	173	2.45	45.0	2.13	2.33
181	3.65	46.4	1.78	1.70	183	2.35	45.2	2.05	2.30
191	2.50	45.1	2.03	2.13	193	2.25	47.5	1.90	1.89
201	2.45	45.1	1.70	2.10	203	2.20	46.3	1.90	2.10
211	2.75	45.6	1.95	2.49	213	2.30	46.5	1.85	2.20
221	2.35	46.1	1.85	2.02	223	3.05	47.2	1.48	1.63
231	2.65	48.0	1.65	2.03	233	4.70	37.8	1.43	1.78
241	2.85	46.2	2.00	2.48	243	2.90	47.2	1.90	2.19
251	2.20	48.3	1.75	2.09	253	2.25	42.4	1.73	1.76
261	2.75	45.0	1.95	2.13	263	2.30	46.2	1.85	2.30
271	2.90	45.6	1.88	2.28	273	2.85	45.5	1.35	2.20
281	1.50	46.3	2.00	1.70	283	2.35	45.5	2.08	1.68
291	1.40	46.4	2.05	1.95	293	2.10	45.5	2.10	1.79
301	2.70	41.9	1.98	1.58	303	2.15	46.6	2.13	1.65
311	2.40	45.9	1.80	1.75	313	2.50	44.4	1.95	1.70
321	3.35	46.4	1.83	1.85	323	2.85	45.8	2.00	2.13
12	2.25	46.2	2.15	2.05	14	2.45	47.1	2.13	1.90
22	2.80	45.9	2.33	2.33	24	2.60	44.9	2.18	2.23
32	3.00	45.3	2.28	2.75	34	2.80	46.5	2.18	2.61
42	2.45	45.9	2.33	2.23	44	2.30	44.9	2.20	2.08
52	2.60	46.3	2.33	2.55	54	2.50	45.5	2.30	2.68
62	2.90	45.1	2.25	2.58	64	2.50	44.8	2.18	2.58
72	2.60	45.9	2.25	2.23	74	2.45	45.4	2.30	2.05
82	2.95	46.6	2.18	2.45	84	3.50	45.8	2.28	2.35
92	2.75	46.9	2.15	2.70	94	2.75	45.0	2.18	2.68
102	2.00	67.5	2.10	1.86	104	2.30	44.9	2.00	1.65

GRASS DATA CONTINUED:

CODE	YIELD kg/plot	MC (%)	PCON (%)	NCON (%)	CODE	YIELD kg/plot	MC (%)	PCON (%)	NCON (%)
112	2.90	44.6	2.05	1.91	114	2.80	44.3	2.05	1.75
122	2.80	44.8	2.03	2.13	124	2.10	45.8	2.08	1.51
132	2.25	45.8	2.05	1.84	134	2.65	44.3	2.00	1.70
142	2.40	45.3	2.20	2.13	144	2.25	43.7	2.20	2.19
152	2.95	44.1	2.13	2.23	154	2.25	45.1	2.13	2.20
162	2.80	45.0	2.08	1.91	164	3.00	46.4	1.68	1.46
172	2.50	44.0	2.20	2.13	174	2.50	43.0	2.08	2.18
182	3.20	41.5	[illegible]	2.60	184	2.20	44.0	1.95	1.75
192	7.10	45.6	[illegible]	1.15	194	3.10	45.9	1.88	1.81
202	3.15	46.8	1.55	1.86	204	2.85	46.3	1.90	2.15
212	2.85	46.3	1.63	2.25	214	3.15	46.5	1.98	2.35
222	2.20	47.1	1.90	2.08	224	2.65	45.0	2.00	2.08
232	3.55	46.5	1.35	1.78	234	2.25	46.6	1.88	2.15
242	4.25	47.8	1.45	1.71	244	2.45	46.8	1.90	2.43
252	3.60	50.8	1.38	1.29	254	2.35	47.0	2.00	1.98
262	3.70	48.2	1.38	1.48	264	2.45	46.0	1.85	2.23
272	9.40	43.7	1.25	1.73	274	1.95	46.5	1.78	2.41
282	2.05	45.7	1.83	1.60	284	1.75	45.1	2.08	1.65
292	1.85	45.7	2.03	1.85	294	1.95	45.4	2.10	1.69
302	2.10	45.7	2.00	1.60	304	2.20	45.7	2.13	1.69
312	2.55	45.9	2.03	2.15	314	2.60	44.4	2.00	1.84
322	3.25	46.6	2.15	2.44	324	2.90	44.9	2.23	2.43

GRASS REHARVEST (1990):

Because of a visual crop response to the fertilizer treatments noted in 1990, the plots were restaked and harvested again in 1990. There was no fertilizer placed on the plots between the 1988 harvest and the data presented here. The crop parameters listed are expressed in the same terms as the initial experiment.

CODE	YIELD kg/plot	MC (%)	CODE	YIELD kg/plot	MC (%)
11	3.87	16.0	13	3.97	31.0
21	3.91	20.5	23	4.11	33.0
31	3.73	24.0	33	3.89	31.5
41	4.13	21.0	43	3.93	28.0
51	3.91	19.0	53	3.92	34.0
61	3.49	23.0	63	4.01	39.5
71	3.53	18.5	73	3.99	32.5
81	3.71	19.5	83	4.10	35.0
91	3.43	25.0	93	3.85	39.5
101	3.72	11.0	103	4.46	29.0
111	4.00	19.0	113	4.00	27.0
121	3.97	14.0	123	3.91	29.5
131	3.32	13.5	133	3.93	24.5
141	3.61	16.5	143	3.88	32.0
151	3.86	17.0	153	3.69	38.5
161	4.01	13.0	163	3.94	27.5

GRASS DATA 1990 continued:

CODE	YIELD kg/plot	MC (%)	CODE	YIELD kg/plot	MC (%)
171	3.77	16.0	173	4.12	32.5
181	3.95	17.0	183	3.94	31.0
191	3.82	17.0	193	4.29	18.0
201	3.87	18.5	203	4.40	29.0
211	3.85	25.5	213	4.14	32.5
221	3.61	19.0	223	4.08	27.0
231	3.72	21.0	233	4.01	20.0
241	4.01	25.5	243	4.42	35.0
251	3.83	34.0	253	4.24	21.5
261	3.86	19.0	263	4.08	24.0
271	4.00	24.5	273	5.19	22.0
281	4.08	16.0	283	4.86	27.5
292	3.47	15.0	293	4.19	26.0
301	3.98	12.5	303	4.91	26.5
311	3.82	19.5	313	4.35	27.5
321	3.70	19.5	323	4.66	34.0
12	3.97	14.5	14	3.91	16.0
22	3.55	22.0	24	4.18	30.5
32	3.72	23.5	34	4.12	41.5
42	4.12	19.0	44	3.81	26.0
52	3.90	16.5	54	3.85	43.5
62	3.51	20.5	64	2.61	37.0
72	3.89	16.5	74	3.81	20.5
82	3.66	17.0	84	3.91	33.0
92	3.92	26.0	94	3.80	32.0
102	4.00	12.0	104	3.92	29.0
112	3.94	18.5	114	4.00	26.0
122	3.61	19.0	124	4.05	23.0
132	3.87	13.0	134	4.08	25.0
142	3.96	16.0	144	4.18	30.0
152	3.71	22.5	154	3.88	31.0
162	4.10	12.0	164	4.14	12.5
172	3.91	16.0	174	3.92	33.0
182	3.86	19.0	184	4.47	27.5
192	3.98	26.0	194	4.30	33.0
202	4.09	37.0	204	4.07	30.0
212	3.97	28.0	214	3.87	41.5
222	4.08	19.5	224	4.02	32.0
232	3.74	23.0	234	3.95	36.0
242	4.98	25.0	244	4.16	39.0
252	4.52	22.0	254	4.27	32.0
262	3.88	26.0	264	3.86	32.5
272	3.96	36.0	274	4.07	42.5
282	4.68	10.5	284	4.09	26.0
292	4.04	14.0	294	5.06	28.0
302	4.34	17.0	304	4.12	21.5
312	4.28	15.0	314	4.18	24.0
322	4.42	22.0	324	4.07	28.0

BARLEY CROP DATA:

Below is the harvest data for the barley crop experiment. **HEIGHT** refers to the plant stalk height measured in each plot, this value was the average of 20 measurements. **YIELD** refers to the amount of grain harvested from each plot. **BWT** refers to the bushel weight of a sub-sample measured by the 1 dram method. **M^2 TOT** and **BAR** refer the total sample (grain and straw) and the mass of harvested grain respectively taken from the square metre samples. **PROT** refers to the protein analysis of sub-samples taken from the plot and square metre harvests.

CODE	HEIGHT (cm)	YIELD kg/plot	BWT lb/bu	m^2 TOT kg/m^2	m^2 BAR kg/m^2	m^2 BWT lb/bu	PROT kg/ha	m^2 PROT kg/ha
11	40.5	5.422	47.5	0.261	0.148	47.5	1380	1351
21	38.7	4.700	46.0	0.248	0.128	45.5	1443	1495
31	36.7	5.360	47.5	0.216	0.126	47.0	1409	1351
41	40.1	5.884	48.0	0.325	0.198	46.5	1455	1466
51	43.3	4.787	49.0	0.299	0.160	46.5	1466	1409
61	40.9	5.735	49.5	0.222	0.146	47.0	1438	1294
71	40.2	5.140	48.0	0.163	0.089	46.5	1466	1466
81	40.9	5.051	48.0	0.205	0.116	46.0	1374	1466
91	40.0	5.002	47.0	0.211	0.104	46.0	1495	1541
101	39.2	5.639	50.0	0.235	0.128	47.0	1351	1294
111	45.2	5.304	48.0	0.278	0.147	46.0	1340	1236
121	37.8	4.754	49.5	0.188	0.098	47.0	1323	1553
131	47.6			0.308	0.173	45.5		1426
141	46.0			0.308	0.168	46.0		1438
151	36.5	5.158	48.0	0.178	0.098	46.5	1340	1397
12	37.9	5.750	49.0	0.196	0.105	45.5	1380	1409
22	44.2	5.872	49.5	0.261	0.129	47.0	1397	1656
32	44.8	5.935	47.0	0.224	0.136	47.0	1455	1587
42	44.3	7.036	48.5	0.265	0.142	47.0	1426	1403
52	41.7	6.419	48.0	0.228	0.126	47.0	1466	1627
62	41.5	6.858	48.5	0.357	0.203	48.0	1438	1443
72	43.8	5.444	49.5	0.201	0.107	46.5	1426	1409
82	44.3	5.554	49.0	0.237	0.128	45.5	1409	1518
92	41.4	6.001	50.0	0.225	0.123	46.0	1415	1386
102	45.0	6.412	48.5	0.325	0.183	46.5	1346	1386
112	45.0	5.180	49.0	0.325	0.174	46.0	1294	1386
122	38.7	4.981	46.5	0.306	0.169	45.0	1282	1369
132	45.4			0.300	0.181	47.0		1369
142	43.6			0.340	0.178	47.5		1380
152	43.0	6.220	49.0	0.263	0.145	47.0	1397	1409
13	46.0	6.777	50.5	0.310	0.173	48.0	1455	1558
23	44.2	7.174	48.5	0.345	0.198	47.5	1484	1524
33	46.8	7.988	48.5	0.320	0.177	46.5	1311	1380
43	44.8	7.831	48.5	0.338	0.189	48.0	1380	1541
53	49.7	7.101	48.0	0.370	0.204	46.5	1461	1639
63	48.2	7.116	48.0	0.348	0.201	46.0	1409	1627
73	47.1	6.817	49.0	0.261	0.145	46.0	1455	1472
83	50.7	7.979	49.5	0.382	0.201	46.5	1397	1541
93	50.3	7.785	48.0	0.372	0.217	47.5	1397	1409

BARLEY DATA continued:

CODE	HEIGHT (cm)	YIELD kg/plot	BWT lb/bu	m^2 TOT kg/m^2	m^2 BAR kg/m^2	m^2 BWT lb/bu	PROT kg/ha	m^2 PROT kg/ha
103	51.8	7.234	47.5	0.507	0.274	46.5	1288	1512
113	47.4	7.140	49.0	0.279	0.164	47.5	1254	1225
123	51.7	7.803	49.0	0.421	0.220	46.0	1351	1495
133	46.0			0.421	0.248	48.0		1340
143	52.6			0.514	0.264	47.0		1587
153	43.2	6.380	48.5	0.298	0.165	46.0	1426	1351
14	42.1	6.592	49.5	0.410	0.178	46.5	1351	1581
24	43.6	7.204	47.0	0.339	0.181	47.0	1461	1288
34	45.9	7.539	49.5	0.301	0.136	44.5	1340	1587
44	45.2	7.197	47.5	0.311	0.168	45.5	1409	1524
54	46.7	7.158	49.0	0.404	0.233	46.0	1409	1455
64	43.4	7.189	49.5	0.297	0.155	46.5	1489	1754
74	45.8	7.415	49.5	0.399	0.194	45.5	1495	1570
84	47.8	7.264	49.0	0.353	0.176	46.0	1409	1587
94	45.7	7.021	47.5	0.345	0.184	46.5	1558	1558
104	46.0	7.332	50.0	0.294	0.140	47.5	1466	1610
114	47.6	7.052	49.0	0.386	0.218	46.5	1340	1472
124	44.2	6.940	48.0	0.360	0.168	46.0	1409	1685
134	47.0			0.366	0.190	46.5		1409
144	47.4			0.354	0.198	46.0		1702
154	43.6	6.550	46.0	0.486	0.239	43.0	1386	1714

WINTER WHEAT CROP (1990) DATA:

MC refers to the moisture content of the square metre samples taken during mid-season. CODE refers to the treatment and replicate of the sample. YIELD is mass of grain harvested from the plot MINUS the area from which the square metre samples were taken during mid-season. M^2 WT is the wet mass of the square metre samples.

CODE	MC (%)	m^2 WT kg/m^2	YIELD kg/plot	CODE	MC (%)	m^2 WT kg/m^2	YIELD kg/plot
11	52.9	0.267	4.507	13	46.7	0.482	5.795
21	49.7	0.498	4.964	23	37.8	0.605	5.918
31	41.7	0.651	4.941	33	43.0	0.562	6.282
41	48.1	0.579	4.671	43	47.7	0.425	5.363
51	47.5	0.603	4.474	53	44.4	0.375	4.363
61	48.3	0.510	4.792	63	41.0	0.657	5.888
71	46.1	0.536	3.104	73	45.1	0.514	6.336
81			4.516	83			4.171
91			4.997	93			6.316
101			5.419	103			5.974
111			4.527	113			5.455
12	59.7	[illegible]	5.253	14	51.0	0.282	4.107
22	54.3	[illegible]	5.267	24	36.1	0.541	4.451
32	53.7	[illegible]	6.760	34	47.9	0.499	5.061
42	46.8	0.673	5.439	44	40.5	0.539	4.296
52	49.7	0.491	6.495	54	50.1	0.537	4.730

WINTER WHEAT 1990 DATA CONTINUED:

CODE	MC (%)	m^2 WT kg/m^2	YIELD kg/plot	CODE	MC (%)	m^2 WT kg/m^2	YIELD kg/plot
62	45.0	0.601	5.765	64	46.7	0.472	4.777
72	55.0	0.475	6.242	74	41.8	0.561	5.298
82			5.951	84			5.144
92			6.400	94			5.057
102			5.807	104			5.002
112			6.258	114			4.876

APPENDIX C

WINTER WHEAT SOIL CORE DATA:

DATA KEY:

CODE - A three number code which identifies the sample taken. The first number identifies the treatment. The second number denotes the replicate. The third number denotes the sample as a kerf sample (1) or a background sample (0).

NO# - Denotes the nitrate concentration from the core sample at the designated depth. The depth is in descending order in 3 cm intervals.

AM# - Denotes the ammonium concentration recovered from the same sample.

The actual concentration values are expressed in parts per million divided by 10. For example, the actual value for CODE 111, N01 is 176.2 ppm nitrate recovered.

CODE	NO1	NO2	NO3	NO4	NO5	AM1	AM2	AM3	AM4	AM5
111	1762	596	318	355	303	2810	1030	508	493	542
110	727	1290	523	332	497	716	891	632	462	606
211	1013	552	601	430	235	2233	1030	689	580	354
210	682	648	430	406	272	541	712	534	568	491
311	1412	1073	482	328	304	2737	1948	834	586	567
310	609	773	358	422	340	564	652	104	1582	562
121	845	134	71	52	38	2562	73	58	75	52
120	102	91	43	44	21	415	13	6	15	4
221	641	676	46	406	400	2312	788	13	517	558
220	24	70	61	59	57	13	7	7	5	2
321	931	293	72	56	62	3070	149	11	7	16
320	78	138	52	50	45	2015	482	13	10	20
131	356	260	78	50	52	877	196	29	22	39
130	73	62	37	20	13	556	25	16	26	17
231	452	126	64	57	47	1624	44	17	137	28
230	83	97	34	24	34	153	72	10	15	40
331	586	267	48	60	76	1963	372	15	12	9
330	90	82	72	58	58	919	61	21	00	2

GRASS SOIL CORE ANALYSIS DATA:

DATA KEY:

CODE - The code is a three number identification of the sample. The first number in the code refers to the treatment number of the sample. The second number refers to the replicate. The third number refers to the sample type. The sample taken from the ammonium polyphosphate kerf is designated 2, the urea ammonium nitrate kerf is designated 1 and the background sample is designated 0.

PH# - Each core sample was segmented into 3 cm sections from 0 to 15 cm. The # refers to the depth the sample was from. The numbers increase with descending depth. The PH designates the sample core analysis for phosphorous concentration.
NO# - This designates the core analysis for nitrate concentration.
AM# - This designates the core analysis for ammonium concentration.

Concentration values are expressed in parts per million divided by 10. For example, the number in CODE 111, PH1 is actually 70.2 ppm of phosphorous recovered from the sample.

PHOSPHOROUS ANALYSIS:

CODE	PH1	PH2	PH3	PH4	PH5
112	702	176	125	112	156
110	251	106	104	122	88
212	2240	171	107	128	180
210	483	230	205	214	245
312	1260	243	196	127	142
310	430	247	170	201	187
122	704	129	97	100	82
120	213	178	113	118	175
222	765	164	101	81	86
220	307	246	99	79	82
322	2810	105	48	1616	56
320	217	76	69	74	70
132	1036	92	99	100	87
130	307	140	99	107	104
232	160	582	97	121	127
230	356	209	135	141	168
332	2104	1276	273	228	208
330	471	275	176	149	148
142	328	260	167	160	157
140	336	182	148	193	176
242	792	241	223	185	174
240	454	241	187	153	131
342	1468	182	138	150	134
340	270	145	127	145	140
112	702	176	125	112	156
110	25	106	104	122	88

NITROGEN ANALYSIS:

CODE	NO1	NO2	NO3	NO4	NO5	AM1	AM2	AM3	AM4	AM5
212	3001	596	50	46	90					
211	1560	63	35	27	20	131	5275	42	39	52
210	21	3	2	3	4	56	41	32	23	34
312	3825	82	104	69	63					
311	681	4	17	11	14	4900	84	43	68	65
310	18	3	2	4	4	52	49	41	26	28
222	9819	161	36	37	52					
221	2360	151	128	112	99	3083	492	41	45	46
220	47	7	0	0	2	67	43	16	18	25
322	4584	631	2125	65	28					
321	17	81	14	10	13	38	187	19	29	37
320	162	46	22	14	17	31	11	6	12	2
232	3489	123	19	12	28					

CODE	NO1	NO2	NO3	NO4	NO5	AM1	AM2	AM3	AM4	AM5
231	21	2	2	2	1	48	13	5	8	7
230	35	0	0	0	0	52	21	3	7	5
332	9188	1751	19	17	118					
331	2780	339	25	25	34	9985	1168	84	223	119
330	24	2	12	3	4	83	37	51	58	37
242	1183	444	49	93	93					
241	21	7	8	18	121	1137	98	34	53	113
240	31	2	2	6	4	3343	160	73	38	42
342	8173	2895	62	76	95					
341	1851	316	28	18	13	5087	800	61	34	22
340	4	0	2	18	7	43	25	32	17	17

BARLEY SOIL DATA:

DATA KEY:

CODE - A three number code which identifies the treatment. The first number denotes the treatment of the sample core. The second denotes the replicate and the third identifies the sample as a kerf sample (1) or a background sample (0).

AM# - The cores were taken in 2 cm depth increments from 0 - 8 cm in descending order. The numbers represent the concentration of ammonium recovered from each core sample.

NO# - This number represents the concentration nitrate recovered from each core sample. For treatments 4, 5 and 6 this value represents nitrate in the soil only. These treatments were done with ammonium polyphosphate which theoretically contained no nitrate as an active ingredient. However, trace amounts may have been present.

The concentration values are expressed in parts per million divided by 10 of the sample analyzed. For example, CODE 111, AM1 is actually 487.6 ppm recovered in the 0 - 2 cm depth.

BARLEY SOIL DATA:

CODE	AM1	AM2	AM3	AM4	NO1	NO2	NO3	NO4
111	4876	14	1024	11	1508	227	1058	150
110	32	09	05	11	125	80	47	34
211	3262	3238	808	51	1286	1592	932	295
210	12	05	12	02	133	71	35	60
311	4291	2107	40	07	1485	1191	405	149
310	244	03	06	08	133	102	63	73
411	8068	3409	542	38	307	375	394	243
410	113	12	06	09	154	111	72	47
511	7346	4317	1871	869	331	438	434	417
510	37	13	11	13	127	79	72	55
611	11902	6929	715	18	17	393	462	155
610	150	07	02	04	128	72	43	36
121	940	2818	90	11	1862	1364	622	191

CODE	AM1	AM2	AM3	AM4	NO1	NO2	NO3	NO4
120	71	08	03	00	134	131	89	62
221	5656	2662	515	16	1808	1238	840	231
220	45	16	15	06	130	172	106	89
321	5077	3517	829	60	1737	1371	897	434
320	148	08	08	06	178	207	95	64
421	7126	2207	314	17	308	567	398	156
410	43	16	12	12	148	84	76	49
521	7808	3730	1181	333	354	640	574	345
520	199	25	24	25	175	182	120	72
621	9624	4027	499	17	304	462	403	191
620	108	07	07	04	103	92	69	49
131	4564	730	22	08	1562	902	444	265
130	265	06	01	06	240	103	57	52
231	5185	3739	13[illegible]	169	1605	1401	903	557
230	148	08	[illegible]	06	178	207	95	64
331	3013	1393	255	08	1107	1203	770	142
330	41	05	50	08	159	155	200	143
431	10812	4889	983	133	305	379	445	373
430	131	14	09	12	110	110	70	43
531	6290	3281	2453	463	267	562	589	519
530	154	15	11	12	127	105	68	84
631	9841	4963	901	80	268	544	609	213
630	80	97	02	05	142	290	155	177

PLOT BULK DENSITY DATA FOR ESTIMATING CORE SAMPLE MASS:

DATA KEY:

CODE - The two number code refers to the plot from which the sample was taken. Bulk density values were recorded in 3 cm increments to a depth of 15 cm. The samples are in descending depth with the increase in number.
M# - Refers to the moisture content in percent dry basis of the bulk density sample.
DB# - Refers to the bulk density recorded at the given depth in Mg/m^3.

In the case of the barley experiment, bulk density data was recorded to a depth of 9 cm.

WINTER WH[illegible]AT (1988) SOIL DATA:

CODE	M1	M2	M3	M4	M5	DB1	DB2	DB3	DB4	DB5
11	6.5	7.5	11.0	12.7	15.2	1.08	1.14	1.24	1.29	1.32
12	8.2	9.1	10.3	11.8	14.7	0.92	1.17	1.3	1.31	1.30
13	5.0	7.9	10.4	12.2	13.8	1.20	1.22	1.26	1.25	1.28
21	7.4	10.5	11.6	13.7	16.1	1.17	1.28	1.24	1.27	1.37
22	7.4	9.8	11.1	12.4	14.9	1.13	1.16	1.25	1.32	1.33
23	7.3	10.1	12.4	13.6	15.0	1.17	1.23	1.27	1.28	1.30
31	6.8	9.2	11.8	12.8	15.5	1.21	1.19	1.31	1.33	1.31
32	7.1	8.3	10.9	13.0	15.3	1.23	1.25	1.27	1.31	1.34
33	6.6	8.4	9.4	11.5	13.7	1.14	1.22	1.24	1.31	1.28

GRASS SOIL DATA :

CODE	M1	M2	M3	M4	M5	DB1	DB2	DB3	DB4	DB5
11	6.8	7.4	11.7	13.5	15.5	1.23	1.23	1.28	1.30	1.34
12	7.4	8.0	10.5	14.7	16.2	1.20	1.27	1.29	1.33	1.33
13	6.3	6.9	10.3	15.0	15.3	1.14	1.21	1.25	1.29	1.32
21	4.8	7.7	9.8	13.0	15.7	1.25	1.29	1.33	1.37	1.35
22	6.4	7.5	8.3	12.1	13.8	1.17	1.22	1.39	1.43	1.44
23	5.8	9.6	10.9	13.9	14.7	1.03	1.18	1.25	1.39	1.41
31	6.5	9.4	10.3	12.6	15.3	1.22	1.20	1.22	1.33	1.32
32	8.0	9.1	10.5	13.0	17.3	1.26	1.27	1.34	1.29	1.37
33	6.4	8.3	12.4	14.8	15.4	1.16	1.24	1.22	1.27	1.30
41	6.1	8.2	9.8	13.1	14.8	1.18	1.23	1.27	1.29	1.27
42	6.3	7.8	9.9	12.2	14.9	1.09	1.26	1.30	1.31	1.34
43	5.7	10.2	12.0	14.7	16.5	1.23	1.28	1.31	1.30	1.30

BARLEY SOIL DATA:

CODE	M1	M2	M3	DB1	DB2	DB3
11	2.6	6.3	9.8	1.15	1.27	1.29
12	4.2	8.7	10.0	1.18	1.23	1.34
13	5.4	7.2	11.7	1.02	1.14	1.26
21	5.9	7.7	11.2	1.22	1.27	1.31
22	6.1	8.3	10.6	1.27	1.26	1.30
23	5.0	8.6	10.3	1.13	1.22	1.28
31	4.8	7.4	11.0	1.18	1.26	1.27
32	3.1	6.7	10.8	1.23	1.25	1.32
33	6.9	9.5	11.7	0.97	1.13	1.26
41	5.6	7.9	10.3	1.16	1.24	1.30
42	4.7	7.0	10.0	1.20	1.27	1.42
43	3.9	6.2	9.9	1.20	1.23	1.27
51	6.7	8.7	12.4	1.14	1.19	1.24
52	4.8	7.9	12.0	1.19	1.24	1.27
53	7.1	9.5	10.4	1.29	1.28	1.35
61	5.3	7.2	11.5	1.17	1.21	1.26
62	4.0	7.2	12.1	1.22	1.26	1.31
63	4.2	7.8	11.3	1.15	1.23	1.29

PENETRATION EXPERIMENT DATA:

DATA KEY:

CODE - A three number code which identifies the sample. The first number represents the treatment number. The second number denotes the replicate. The third represents the position of the core if more than one core was taken to capture the pulse. A complete sample is denoted by the number 1. In a two core sample, 2 denotes the core taken at the start of the pulse. The 4 denotes the core taken at the end of the pulse. In a three core sample these numbers still hold, but the number 3 denotes the center core taken. The number 0 denotes the background core sample.

AM# - The core in each sample taken is segmented into five depths. The first depth is 0 - 3 cm the rest of the segments are in 1.5 cm increments in descending order. The values in this column are the ammonium concentrations recovered.

NO# - These are the values of the nitrate concentrations recovered from the core segments.

The values in each column are expressed in parts per million divided by 10. For example, the actual value for CODE 111, AM1 is 2122.5 parts per million recovered from the sample.

CODE	AM1	AM2	AM3	AM4	AM5	NO1	NO2	NO3	NO4	NO5
111	21225	3577	382	01	00	6833	1435	734	225	67
110	11	02	00	00	00	79	61	32	37	38
212	20289	2185	69	03	188	6107	891	193	170	273
214	1729	322	00	00	463	2818	381	176	137	472
210	07	00	00	00	06	24	11	09	02	17
312	4506	280	45	02	1557	1432	301	363	221	416
313	8719	35	03	07	08	2917	128	106	96	211
314	5903	07	07	06	07	2180	107	86	115	176
310	09	13	11	13	12	108	50	46	58	63
412	273	174	73	48	42	279	401	426	457	542
414	1404	112	43	19	23	448	218	259	214	281
410	59	24	13	18	38	102	54	80	70	77
511	11673	544	44	41	25	3951	656	297	166	250
510	26	19	21	16	21	74	39	39	32	32
121	29777	6731	931	29	02	11016	2444	604	375	154
120	02	00	00	09	06	39	28	24	33	28
222	18513	1465	330	02	02	5689	755	460	267	406
224	8950	2645	15	145	44	3082	959	151	376	335
220	35	30	00	02	07	32	18	15	38	18
322	8642	207	117	13	06	3291	165	334	165	180
323	4396	27	18	682	23	1487	256	215	547	284
324	2339	656	79	31	215	882	333	291	396	501
320	26	13	15	59	05	30	31	32	48	33
422	16137	305	38	22	13	5655	395	327	382	410
424	3273	214	48	41	22	1863	232	126	393	411
420	11	17	11	07	12	43	26	36	27	33
521	9969	443	353	26	97	3423	625	515	480	448
520	03	24	31	31	28	54	33	28	27	28
131	16905	4055	68	03	00	4490	1487	330	256	131
130	39	00	00	00	00	85	46	52	65	26
232	26543	3873	33	29	05	9539	1663	103	119	227
234	4649	467	02	11	68	1773	358	256	251	283
230	17	00	05	01	00	74	27	22	24	24
332	12969	104	18	11	52	4719	239	117	183	456
333	5601	28	10	08	32	2151	142	87	152	293
334	688	48	800	28	23	264	157	501	176	224
330	28	27	11	16	16	27	13	21	23	40

CODE	AM1	AM2	AM3	AM4	AM5	NO1	NO2	NO3	NO4	NO5
432	7833	160	160	24	100	1863	312	617	536	607
434	4185	67	19	21	26	1671	232	81	96	277
430	31	16	16	16	16	82	40	33	33	44
531	9705	1329	31	15	11	3423	663	393	266	277
530	22	11	11	08	09	107	44	39	33	33

PENETRATION EXPERIMENT SOIL DATA:

DATA KEY:

CODE - A two number designation of the sample. The first number refers to the treatment from which the sample was taken. The second refers to the sample replicate. The bulk density data was taken in 3 cm increments to a depth of 9 cm.

M# - The moisture content in percent mass of dry sample taken from the bulk density core.

DB# - The bulk density in Mg/m^3 of the sample taken. The depth of the sample taken increases with increasing DB#.

PD# - Refers to the penetrometer reading taken starting at the soil surface (PD1) and increasing in 3 cm depth increments to a depth of 9 cm. There are five sets of four readings per plot. The readings are expressed in kg/cm^2

BULK DENSITY DATA:

CODE	M1	M2	M3	DB1	DB2	DB3
11	6.2	9.6	11.6	0.96	1.11	1.28
21	5.7	9.4	12.0	1.35	1.34	1.46
31	5.3	10.6	13.1	1.44	1.29	1.24
41	5.7	11.0	13.3	1.29	1.53	1.24
51	6.7	11.2	13.3	1.23	1.38	1.31
12	5.8	10.8	12.6	1.16	1.15	1.04
22	4.8	8.6	11.2	1.23	1.52	1.33
32	5.4	9.9	12.8	1.19	1.49	1.31
42	5.2	9.3	12.5	1.28	1.32	1.46
52	5.1	9.7	12.2	1.36	1.34	1.29
13	5.8	10.6	13.3	1.15	1.39	1.37
23	5.3	9.9	12.5	1.25	1.28	1.25
33	4.9	9.2	11.5	1.15	1.36	1.41
43	5.6	10.5	12.9	1.34	1.39	1.22
53	5.7	10.6	13.4	1.41	1.[illegible]5	1.36

PENETROMETER DATA:

CODE	PD1	PD2	PD3	PD4	PD1	PD2	PD3	PD4
11	2.2	5.4	11.4	25.6	2.2	5.4	21.8	35.4
	3.8	5.4	14.7	23.9	1.1	6.0	26.1	31.6
	2.2	5.4	19.0	24.5				
21	1.1	14.7	27.7	32.6	2.2	16.3	29.9	23.9
	1.6	38.1	46.2	40.8	0.5	16.3	29.9	27.2
	0.5	10.9	32.6	29.9				
31	12.5	16.3	25.6	25.0	7.6	21.8	35.4	29.9
	2.2	16.3	29.9	32.6	14.1	10.9	21.8	24.5
	0.5	13.6	24.5	23.9				
41	2.7	16.3	21.2	13.1	0.5	10.9	14.7	32.6
	1.1	16.3	13.6	27.2	1.6	13.6	27.2	32.6
	1.9	6.5	14.7	14.7				
51	0.5	3.8	9.2	29.4	1.1	3.8	10.9	23.4
	5.4	18.0	18.0	27.2	2.2	3.8	7.6	13.6
	6.0	29.9	19.6	14.7				
12	3.3	10.9	24.5	31.0	2.7	11.4	19.6	31.0
	1.1	9.2	16.9	24.5	2.2	11.4	18.0	19.0
	2.7	10.9	19.6	31.0				
22	1.1	24.5	35.4	32.6	2.2	24.5	33.7	25.6
	1.6	8.2	21.8	24.5	0.5	9.2	16.3	19.6
	1.1	16.3	22.3	22.8				
32	1.1	8.2	16.3	21.8	5.4	8.2	16.3	14.7
	1.1	6.5	7.1	15.2	1.1	9.2	16.9	43.5
	2.2	29.9	20.1	27.2				
42	0.5	6.5	16.3	25.6	2.2	16.3	33.7	29.4
	7.6	13.6	40.8	29.9	1.6	10.9	21.8	29.9
	0.5	5.4	16.3	29.9				
52	1.1	5.4	21.8	31.0	0.5	5.4	14.7	24.5
	1.1	8.7	16.3	35.4	0.5	6.5	24.5	29.9
	0.5	8.2	29.9	31.0				
13	1.6	11.4	22.8	20.1	2.2	20.1	17.4	18.0
	1.6	9.2	11.4	21.2	1.1	5.4	10.9	24.5
	2.2	9.2	8.7	16.9				
23	1.1	21.8	54.4	57.1	16.3	8.2	19.0	29.9
	0.5	13.6	19.0	26.7	0.5	8.2	22.8	25.6
	0.5	9.2	21.8	24.5				
33	1.1	3.8	16.9	23.4	1.1	5.4	9.2	22.3
	2.2	19.0	20.1	26.1	2.2	12.5	29.9	38.1
	2.2	10.9	25.0	26.7				
43	2.2	8.2	16.3	23.4	1.1	8.2	15.8	19.6
	0.5	14.7	20.1	29.9	5.4	5.4	16.3	35.4
	2.2	8.2	16.9	19.0				
53	16.3	24.5	40.8	35.4	5.4	14.7	16.3	16.9
	1.6	7.1	19.0	27.2	8.2	13.1	22.8	25.6
	2.7	7.6	19.6	23.9				

SOIL PULSE SAMPLES TAKEN TO MEASURE FERTILIZER DISPERSION:

DATA KEY:

AM - the concentration of ammonium recovered from the soil core in parts per million.

NO_3 - the concentration of nitrate recovered from the soil core sample.

The amount of fertilizer recovered in milligrams can be calculated by the following formula:

$$\text{mg recovered} = (\text{MASS}) / 1000 \times \text{AM or } NO_3$$

RECOVERY OF FERTILIZER FROM PULSE SAMPLES:

SAMPLE	MASS (g)	AM (ppm)	NO_3 (ppm)
Check	115.91	2.0	15.1
1	137.05	435.8	347.5
2	140.36	213.0	172.5
3	145.94	427.0	343.3
4	116.97	232.0	189.5

RECOVERY OF FERTILIZER FROM SURFACE SAMPLES:

SAMPLE	MASS (g)	AM (ppm)	NO_3 (ppm)
Check	94.48	1.7	13.6
1	87.54	147.5	96.0
2	80.16	246.5	207.5
3	85.80	243.0	204.0
4	62.27	282.0	227.5

APPENDIX D

The following is the listing of the SAS programs used to do the statistical analysis of data. The data was first analyzed in Lethbridge on the VAX mainframe. Refinements in the analysis were further done at the University of Alberta on the VM computer system. The file listings are from the work done at the University.

SAS FILE FOR THE WINTER WHEAT (1988) CROP ANALYSIS:

```
FILENAME yield 'EXPT1';
DATA ALL;
INFILE YIELD;
INPUT TRT 2.0 REP 1.0 TWT 6.2 MC 5.1 NCON 5.2;
  YIELD=TWT*(1-MC/100)*919.86;
  NYIELD=YIELD*NCON/100;
OUTPUT ALL;
  PROC SORT DATA=ALL;
  BY TRT REP;
    PROC GLM DATA=ALL;
    CLASS REP TRT;
    MODEL YIELD NYIELD = REP TRT;
  MEANS TRT;
CONTRAST 'CHK VS ALL' TRT 1 1 1 1 1 1 1 1 1 1 1 -11;
CONTRAST 'DB VS SURFACE' TRT 6 6 6 -5 -5 -5 -5 -5 6 6 -5 0;
CONTRAST 'LIQ VS PRLD' TRT 4 4 4 4 4 4 -7 -7 -7 -7 4 0;
CONTRAST 'HP VS BDCST' TRT 1 1 1 1 1 1 0 0 -3 -3 0 0;
LSMEANS TRT;
LSMEANS TRT/PDIFF;
MEANS TRT/ALPHA = 0.05 DUNCAN;
TITLE 'WINTER WHEAT ONE-WAY';
PROC PRINT;
RUN;
```

GRASS EXPERIMENT ANALYSIS FOR 1989 DATA:

```
FILENAME CROP 'EXPT2 DAT A1';
DATA ALL DUMP;
INFILE CROP;
INPUT TRT 2.0 REP 1.0 METHOD 1.0 PRATE 1.0 NRATE 1.0
     TWT 6.2 MC 5.1 PCONC 5.3 NCONC 5.2; (FOR 1990 DATA NO N/P CONC)
  PFERT=PRATE*20;
  NFERT=NRATE*40;
  FACTOR=919.86;
IF REP=2 AND TRT=19 THEN FACTOR=410.10;  (ONLY HALF THE PLOT WAS
IF REP=2 AND TRT=27 THEN FACTOR=410.10;   HARVESTED IN THESE TREATMENTS)
IF REP=3 AND TRT=23 THEN FACTOR=410.10;
  YIELD=TWT*FACTOR*(1-MC/100);
  NYIELD=YIELD*NCONC/100;
  PYIELD=YIELD*PCONC/100;
OUTPUT ALL;
IF TRT < 19 OR TRT > 27 THEN OUTPUT DUMP;
```

1988 GRASS ANALYSIS PROGRAM CONTINUED:

```
   PROC SORT DATA=ALL;
   BY TRT METHOD PFERT NFERT REP;
PROC GLM DATA=DUMP;
CLASS REP METHOD PFERT NFERT;
MODEL YIELD NYIELD NCONC PYIELD PCONC = REP METHOD NFERT PFERT
METHOD*NFERT
METHOD*PFERT NFERT*PFERT METHOD*NFERT*PFERT;
MEANS METHOD NFERT PFERT METHOD*NFERT METHOD*PFERT NFERT*PFERT
METHOD*NFERT*PFERT;
TITLE 'HIGH PRESS. GRASS FACTORIAL';
PROC GLM DATA=DUMP;
CLASS REP TRT;
MODEL YIELD NYIELD NCONC PYIELD PCONC = REP TRT;
LSMEANS TRT;
LSMEANS TRT/PDIFF;
MEANS TRT/ALPHA=0.05 DUNCAN;
TITLE 'H.P. - BCST ONE WAY';
PROC PRINT;
RUN;
```

SAS PROGRAM FOR POINT INJECTION TREATMENTS OF THE 1989 GRASS DATA:

```
FILENAME CROP 'EXPT2 DAT A1';
DATA ALL SEP;
INFILE CROP;
INPUT TRT 2.0 REP 1.0 METHOD 1.0 PRATE 1.0 NRATE 1.0
     TWT 6.2 MC 5.1 PCONC 5.3 NCONC 5.2;
  PFERT=PRATE*20;
  NFERT=NRATE*40;
  FACTOR=919.86;
IF REP=2 AND TRT=19 THEN FACTOR=410.10;
IF REP=2 AND TRT=27 THEN FACTOR=410.10;
IF REP=3 AND TRT=23 THEN FACTOR=410.10;
  YIELD=TWT*FACTOR*(1-MC/100);
  NYIELD=YIELD*NCONC/100;
  PYIELD=YIELD*PCONC/100;
OUTPUT ALL;
IF TRT > 18 AND < 28 THEN OUTPUT SEP;
  PROC GLM DATA=SEP;
  CLASS REP NFERT PFERT;
  MODEL YIELD NYIELD PYIELD = REP NFERT PFERT NFERT*PFERT;
  MEANS NFERT/ALPHA=0.05 DUNCAN;
  MEANS PFERT/ALPHA=0.05 DUNCAN;
  MEANS NFERT*PFERT=0.05 DUNCAN;
TITLE ' P.I. FACT.';
PROC PRINT;
RUN;
```

SAS ANALYSIS OF 1990 GRASS DATA FOR BOTH EXPERIMENTS:

```
FILENAME CROP 'EXPT290 DAT A1';
DATA ALL DUMP SEP;
INFILE CROP;
INPUT TRT 2.0 REP 1.0 METH 1.0 NRATE 1.0 PRATE 1.0 MC 4.1 TWT 4.2;
  FACTOR=787.40;
  YIELD=TWT*FACTOR*(1-MC/100);
OUTPUT ALL;
IF TRT > 18 AND TRT < 28 THEN OUTPUT SEP;
IF TRT < 19 OR TRT > 27 THEN OUTPUT DUMP;
  PROC SORT DATA=DUMP;
  BY TRT REP METH;
 PROC GLM DATA=DUMP;
   CLASS REP TRT METH NRATE PRATE;
   MODEL MC YIELD=REP METH NRATE PRATE METH*NRATE METH*PRATE
   NRATE*PRATE METH*NRATE*PRATE;
    MEANS METH NRATE PRATE METH*NRATE METH*PRATE NRATE*PRATE
    METH*NRATE*PRATE;
 TITLE '1990 GRASS YIELDS FACTORIAL';
   PROC GLM DATA=DUMP;
     CLASS REP TRT;
     MODEL MC YIELD=REP TRT;
     LSMEANS TRT;
     LSMEANS TRT/PDIFF;
     MEANS TRT/ALPHA=0.05 DUNCAN;
   TITLE 'H.P. - BCST  ONE-WAY';
     PROC GLM DATA=SEP;
       CLASS REP TRT;
       MODEL MC YIELD=REP TRT;
       LSMEANS TRT;
       LSMEANS TRT/PDIFF;
       MEANS TRT/ALPHA=0.05 DUNCAN;
     TITLE 'P.I. ONE WAY';
       PROC GLM DATA=SEP;
       CLASS REP NRATE PRATE;
       MODEL YIELD= REP NRATE PRATE NRATE*PRATE;
       MEANS NRATE PRATE NRATE*PRATE;
       TITLE 'P.I. FACTORIAL';
   PROC GLM DATA=ALL;
     CLASS REP TRT;
     MODEL MC YIELD=REP TRT;
     MEANS TRT;
     LSMEANS TRT;
     LSMEANS TRT/PDIFF;
     MEANS TRT/ALPHA=.05 DUNCAN;
   TITLE 'GRASS 90 ONE-WAY';
CONTRAST 'HP VS PI' TRT -1 -1 -1 -1 -1 -1 -1 -1 -1 0 0 0 0 0 0 0 0 0
1 1 1 1 1 1 1 1 1 0 0 0 0;
CONTRAST 'HP VS BDCST' TRT -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1
0 0 0 0 0 0 0 0 0 0 0 0 0;
CONTRAST 'CHECK VS ALL' 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
```

GRASS PROGRAM CONTINUED:

```
1 1 1 -31 1 1 1;
PROC PRINT;
RUN;
```

SAS PROGRAM FOR BARLEY CROP ANALYSIS:

```
FILENAME YIELD 'EXPT3';
DATA ALL NEW;
INFILE YIELD;
INPUT TRT 2.0 REP 1.0 HT 4.1 TWT 5.3 BWT 4.1 MSQWS 4.3 MSQ 4.3 MSQBWT 4.1
PLOT 3.0 PROT 5.0 MSQPROT 5.0;
  YIELD= TWT*328.1;
  MSQYIELD= MSQ*10000;
  STYIELD=(MSQWS-MSQ)*10000;
OUTPUT ALL;
 IF TRT < 13 THEN OUTPUT NEW;
 IF TRT > 14 THEN OUTPUT NEW;
   PROC SORT DATA=ALL;
   BY TRT REP;
     PROC SORT DATA=NEW;
     BY TRT REP;
PROC GLM DATA=ALL;
CLASS REP TRT;
MODEL YIELD MSQYIELD STYIELD MSQBWT BWT HT PROT =REP TRT;
TITLE 'BARLEY GLM';
CONTRAST 'HP VS BCST' TRT -1 -1 -1 -1 -1 -1 3 3 0 0 0 0 0 0 0;
CONTRAST '28-HP VS PI' TRT -1 -1 -1 0 0 0 0 0 3 0 0 0 0 0 0;
CONTRAST '10-HP VS PI' TRT 0 0 0 -1 -1 -1 0 0 0 3 0 0 0 0 0;
CONTRAST 'LIQ VS PRI' TRT -1 -1 -1 -1 -1 -1 4 4 -1 -1 0 0 0 0 0;
CONTRAST 'CHECK VS ALL' TRT 1 1 1 1 1 1 1 1 1 1 0 0 0 0 -10;
LSMEANS TRT;
LSMEANS TRT/PDIFF;
MEANS TRT/ALPHA=.05 DUNCAN;
PROC GLM DATA=NEW;
CLASS REP TRT;
MODEL YIELD MSQYIELD STYIELD MSQBWT BWT HT PROT =REP TRT;
TITLE 'BARLEY GLM ON SHORT';
CONTRAST 'HP VS BCST' TRT -1 -1 -1 -1 -1 -1 3 3 0 0 0 0 0;
CONTRAST '28-HP VS PI' TRT -1 -1 -1 0 0 0 0 0 3 0 0 0 0;
CONTRAST '10-HP VS PI' TRT 0 0 0 -1 -1 -1 0 0 0 3 0 0 0;
CONTRAST 'LIQ VS PRI' TRT -1 -1 -1 -1 -1 -1 4 4 -1 -1 0 0 0;
CONTRAST 'CHECK VS ALL' TRT 1 1 1 1 1 1 1 1 1 1 0 0 -10;
LSMEANS TRT;
LSMEANS TRT/PDIFF;
MEANS TRT/ALPHA=.05 DUNCAN;
PROC PRINT;
RUN;
```

SAS PROGRAM FOR WINTER WHEAT DATA:

```
FILENAME YIELD 'EXPT4';
DATA ALL SHORT;
INFILE YIELD;
INPUT TRT 2.0 REP 1.0 MC 4.1 MSWT 4.3 WT 5.3;
 FACTOR=378.07;
IF TRT>=8 THEN FACTOR=364.07;
 MSQY=MSWT*10000;
 YIELD=WT*FACTOR;
OUTPUT ALL;
IF TRT < 8 THEN OUTPUT SHORT;
 PROC SORT DATA=ALL;
 BY TRT REP;
TITLE 'CONVERTED DATA';
 PROC GLM DATA=ALL;
 CLASS TRT REP;
 MODEL YIELD MSQY MC= REP TRT;
CONTRAST 'CONTROL VS. ALL' TRT -10 1 1 1 1 1 1 1 1 1 1;
CONTRAST 'DB VS BDCST' TRT 0 0 1 1 -2 0 0 0 0 0 0;
CONTRAST 'LIQ VS PRLD' TRT 0 0 1 1 1 -3.5 -3.5 0 0 0 0;
CONTRAST 'FALL VS SPRG' TRT 0 1 1 1 1 1 1 -1.5 -1.5 -1.5 -1.5;
CONTRAST 'PI VS BDCST' TRT 0 0 1 1 0 0 -2 0 0 0 0;
CONTRAST 'HP VS BDCST' TRT 0 0 1 1 0 -2 0 0 0 0 0;
 LSMEANS TRT;
 LSMEANS TRT/PDIFF;
 MEANS TRT/ALPHA=.05 DUNCAN;
TITLE 'WINTER WHEAT 90';
 PROC GLM DATA=SHORT;
  CLASS REP TRT;
  MODEL YIELD MSQY MC= REP TRT;
  LSMEANS TRT;
  LSMEANS TRT/PDIFF;
  MEANS TRT/ALPHA=0.05 DUNCAN;
 TITLE 'WITHOUT CHECKS'
PROC PRINT;
RUN;
```

GENERAL PURPOSE SAS PROGRAM FOR ANALYSING SOIL CORE DATA:

```
FILENAME NSOIL 'SOILB DAT A1';
DATA NEW;
INFILE NSOIL;
INPUT TRT $ REP $ D1 $ D2 $ D3 $ D4@@; (FOR DEEPER DEPTHS ADD D5)
PROC SORT DATA=NEW;
BY TRT REP;
 PROC GLM DATA=NEW;
 CLASS REP TRT;
 MODEL D1 D2 D3 D4 = TRT;
```

PROGRAM CONT'D:

```
  LSMEANS TRT;
  LSMEANS TRT/PDIFF;
  MEANS TRT/ALPHA=0.05 DUNCAN;
PROC PRINT;
TITLE 'BARLEY FERTILIZER DISTRIBUTION';
RUN;
```

NOTE THE DATA FOR THIS PROGRAM WAS WORKED ON IN A SPREADSHEET AND PUT INTO A FILE FOR SAS ANALYSIS. THE ACTUAL WORK DONE ON THE SPREADSHEET TAKES EXTRANEOUS AMOUNTS OF SAS CODE TO COMPLETE. THE MANIPULATIONS CENTERED AROUND SUBTRACTING THE BACKGROUND SAMPLES FROM THE KERF SAMPLES, SUMMING THEM, THEN FINDING THE PERCENTAGE RECOVERED AT EACH SOIL DEPTH.

SAS PROGRAM FOR ANALYSIS OF GRASS CORE DATA:

```
FILENAME NSOIL 'SOILG DAT A';
DATA FIRST NEW;
INFILE NSOIL;
INPUT TRT $ REP $ D1 $ D2 $ D3 $ D4 $ D5@@;
IF TRT > 2 OR TRT < 6 OUTPUT FIRST;
IF TRT < 3 OR TRT > 5 OUTPUT NEW;
PROC SORT DATA=NEW;
BY TRT REP;
PROC SORT DATA=FIRST;
BY TRT REP;
  PROC GLM DATA=FIRST;
  CLASS REP TRT;
  MODEL D1 D2 D3 D4 D5 = TRT;
  MEANS D1 D2 D3 D4 D5/ALPHA=0.05 DUNCAN;
PROC PRINT;
TITLE 'GRASS P FERTILIZER DISTRIBUTION';
  PROC GLM DATA=NEW;
  CLASS REP TRT;
  MODEL D1 D2 D3 D4 D5 = TRT;
  MEANS D1 D2 D3 D4 D5/ALPHA=0.05 DUNCAN;
PROC PRINT;
TITLE 'GRASS N FERTILIZER DISTRIBUTION';
RUN;
```

SAS PROGRAM FOR REGRESSION ANALYSIS OF PENETRATION EXPERIMENT DATA:

```
FILENAME NSOIL 'SPREG DAT A.';
DATA NEW;
INFILE NSOIL;
INPUT P1 4.1 U 4.1 D1 5.1 (D2-D5) (4.1) M1 4.1 (M2-M3) (5.1)
 (DB1-DB3) (5.2) P1 4.1 (P2-P4) (5.1);
   R=P/U;
   S=P**0.5;
OUTPUT NEW;
PROC REG SIMPLE CORR DATA=NEW;
MODEL D1 = P U R S M1 DB1 P1/SLENTRY=.25 SLSTAY=.25 SELECTION=FORWARD;
 PROC PRINT;
 TITLE 'FOR DEPTH 1';
PROC REG SIMPLE CORR DATA=NEW;
MODEL D2 = P U R S M2 DB2 P2/SLENTRY =.25 SLSTAY =.25 SELECTION=FORWARD;
 PROC PRINT;
 TITLE 'FOR DEPTH 2';
PROC REG SIMPLE CORR DATA=NEW;
MODEL D3 = P U R S M2 DB2 P2/SLENTRY = .25 SLSTAY =.25 SELECTION=FORWARD;
 PROC PRINT;
 TITLE 'FOR DEPTH 3';
PROC REG SIMPLE CORR DATA=NEW;
MODEL D4 = P U R S M3 DB3 P3/SLENTRY =.25 SLSTAY =.25 SELECTION=FORWARD;
 PROC PRINT;
 TITLE 'FOR DEPTH 4';
PROC REG SIMPLE CORR DATA=NEW;
MODEL D5 = P U R S M3 DB3 P3/SLENTRY =.25 SLSTAY =.25 SELECTION=FORWARD;
 PROC PRINT;
 TITLE 'FOR DEPTH 5';
RUN;
```

APPENDIX E

CALIBRATION DATA FOR THE DMCSA TRIALS ON WINTER WHEAT AND GRASS:

KEY:
H_1 - Tank liquid height at the start of the trial in millimetres.
H_2 - Tank liquid height at the end of the trial in millimetres.
ΔH - Change in liquid level.
F - Flow in L/min ($\Delta H \times 1.03$).
DR - The dilution rate of the liquid in the trial.
p - Pressure set at the gauge in MPa.

PHOSPHOROUS LIQUID TRIALS (10 - 34 - 0):

p = 25.6 **DR** = 19:1

H_1	H_2	ΔH	F
247	227	20	20.6
227	205	22	22.7
205	185	20	20.6
185	165	20	20.6
165	145	20	20.6
		AVG.	21.0
		10 NOZZLES	2.10

p = 31.0 **DR** = 10:1

H_1	H_2	ΔH	F
192	169	23	23.7
169	146	23	23.7
146	123	23	23.7
123	100	23	23.7
100	76	24	24.7
		AVG.	23.9
		10 NOZZLES	2.39

p = 36.8 **DR** = 10:1

H_1	H_2	ΔH	F
241	219	22	22.7
219	194	24	25.8
194	170	24	25.8
170	146	24	25.8
146	244	24	25.8
		AVG.	25.2
		10 NOZZLES	2.52

NITROGEN CALIBRATIONS FOR GRASS AND WINTER WHEAT (28 - 0 - 0):

p = 34.5 **DR** = 13:1

H_1	H_2	ΔH	F
227	204	23	23.7
204	181	23	23.7
181	159	22	23.0
159	136	23	23.7
136	113	23	23.7
		AVG.	23.6
		10 NOZZLES	2.36

p = 34.5 **DR** = 6:1

H_1	H_2	ΔH	F
240	217	23	23.7
217	193	24	24.7
193	169	24	24.7
169	146	23	23.7
146	122	24	24.7
		AVG.	24.3
		10 NOZZLES	2.43

NITROGEN CALIBRATIONS CONTINUED:

p = 39.6 **DR** = 4:1

H_1	H_2	ΔH	F
183	158	25	25.8
158	134	24	24.7
134	109	25	25.8
109	84	25	25.8
84	78	26	26.8
		AVG.	25.8
		10 NOZZLES	2.58

p = 20.5 **DR** = 8:1

H_1	H_2	ΔH	F
215	198	17	17.5
198	178	20	20.6
178	163	15	15.5
163	148	15	15.5
148	131	17	17.5
131	115	16	16.5
115	99	16	16.5
		AVG.	17.1
		10 NOZZLES	1.71

p = 13.8 **DR** = 10:1

H_1	H_2	ΔH	F
223	220	13	13.4
220	206	14	14.4
206	193	13	13.4
193	181	12	12.4
181	168	13	13.4
168	154	14	14.4
		AVG.	13.6
		10 NOZZLES	1.36

CALIBRATIONS FOR THE BARLEY TRIALS WITH THE NEW DESIGN:

With the plot size applicator measurement of flow rate was done by volume replacement of liquid in the tank. Trials were 1 minute in length and not many were done since conservation of the fertilizer was required. The water trial was 2 minutes in length.

KEY: TOTAL - volume replaced during the trial in litres.
F - flow per nozzle per minute (TOTAL / 6).
FOR WATER:

p = 41.4

TOTAL	F
29.5	2.46
31.0	2.59
34.3	2.86
34.4	2.87
34.3	2.86
33.8	2.82
AVG.	2.74

BARLEY TRIAL CALIBRATIONS CONTINUED:

FOR LIQUID UAN (28 - 0 - 0) FERTILIZER:

p = 22.1 DR=6:1		p = 34.5 DR=10:1		p = 42.8 DR=12:1	
TOTAL	F	TOTAL	F	TOTAL	F
12.8	2.13	15.6	2.79	17.1	2.85
12.6	2.10	15.9	2.65	16.9	2.82
12.9	2.15	16.0	2.67	16.8	2.80
12.7	2.12	16.3	2.72	16.9	2.82
AVG.	2.12	AVG.	2.66	AVG.	2.82

FOR LIQUID AMMONIUM POLYPHOSPHATE (10 - 34 - 0):

p = 25.9 DR=2:1		p = 37.8 DR=6:1		p = 41.7 DR=2:1	
TOTAL	F	TOTAL	F	TOTAL	F
14.2	2.37	16.1	2.68	16.8	2.80
13.9	2.32	16.4	2.73	16.6	2.77
13.8	2.30	16.4	2.73	16.9	2.83
14.0	2.34	16.3	2.73	16.8	2.80
AVG.	2.33	AVG.	2.72	AVG.	2.80

CALIBRATIONS FOR PULSING VALVE AND PULSE TRIALS:

LOW PRESSURE CALIBRATION OF VALVE:

No nozzle on valve, no pulsing, trials 1 minute in length. For machine design purposes.

VOLUME	p	RATE
(L)	(kPa)	(L/min)
1.11	241.3	1.11
1.32	241.3	1.32
1.46	220.6	1.46
1.42	206.9	1.46
1.40	206.9	1.40
1.40	206.9	1.40
1.40	206.9	1.40
AVG.	218.9	1.36

PULSING CALIBRATION OCTOBER 18, 1989:

Pressure 34.5 MPa Cycle-Time 160 ms On Time 25 ms

Trial broken down into two parts. Seven trials were done then a 1 hour break was taken before the next set of trials were done. TEMP refers to the tank liquid temperature in degrees C taken during each run. Valve 1 ran nozzles 1 to 3. Valve 2 ran nozzles 4 to 6. The trials were 1 minute in length. The liquid was diluted: 60 % UAN and 40 % water. Temperature at start was 24 deg. C.

TRIAL	VOLUME PER NOZZLE (mL)						TEMP
	1	2	3	4	5	6	
1	650	570	630	655	595	620	29
2	630	550	615	650	575	620	32
3	620	520	605	655	585	625	35
4	620	550	605	645	585	605	36
5	620	550	610	625	560	580	38
6	610	560	615	625	555	590	42
7	615	545	600	635	555	590	42
8	630	580	640	660	575	610	35
9	625	550	615	635	570	590	39
10	625	540	620	645	570	590	41
11	625	555	605	625	560	580	44
12	610	550	615	635	560	590	44
13	615	545	605	615	550	570	48
14	615	545	600	610	550	565	49
AVG/NOZ.	622	551	613	636	555	593	
AVG/VALVE		595			595		

CALIBRATION OF APPLICATOR WITH PRELOAD ADJUSTMENT AND NOZZLE BALANCING:

Medium: water Pressure: 34.5 MPa Cycle-Time: 160 ms On-time: 25 ms

Trials were 1 minute in length except the 50/50 dilution trial which was 2 minutes in length.

TRIAL	VOLUME PER NOZZLE (mL)					
	1	2	3	4	5	6
1	365	430	340	300	290	335
2	310	360	280	320	320	390
3	310	368	283	325	325	390
AVG	328	386	301	317	313	372
AVG/NOZZLE		338			334	

Change nozzles on positions 2 and 6:

TRIAL	VOLUME PER NOZZLE (mL)					
	1	2	3	4	5	6
1	330	305	325	325	330	325
2	325	310	320	335	335	325
3	328	308	323	325	333	325
AVG	328	308	323	328	333	325
AVG/NOZZLE		320			329	

Trial with 50/50 dilution of UAN and water. Trial time was 2 minutes:

TRIAL	VOLUME PER NOZZLE (mL)					
	1	2	3	4	5	6
1	570	530	530	570	610	590
2	570	530	540	570	630	590
3	570	530	535	565	620	590
AVG	570	530	535	568	620	590
AVG/NOZZLE		545			592	

PULSING CALIBRATION ON NOVEMBER 1, 1990:

Pressure: 34.5 MPa Trial Time: 1 minute Medium: Liquid UAN

The first 12 trials had temperature monitoring and random samples taken from the nozzles to check for fertilizer quality. Cycle-Time and On-time were varied to give an idea how flow changes with these parameters. The liquid was allowed to cool for 2 hours for trials 13 through 15.

TRIAL	C. TIME (ms)	ON TIME (ms)	VOLUME PER NOZZLE (mL)					
			1	2	3	4	5	6
1	160	25	300	270	280	285	[illegible]35	260
2	160	25	270	270	280	265	[illegible]5	255
3	160	25	300	295	295	28[illegible]	255	270
4	160	25	295	275	270	[illegible]65	240	255
5	160	25	290	255	275	[illegible]	240	245
6	160	30	355	340	350	4[illegible]	355	415
7	160	30	350	330	340	39[illegible]	360	400
8	160	35	420	375	400	475	435	480
9	160	35	415	375	390	[illegible]70	440	475

PULSING CALIBRATION CONTINUED:

TRIAL	C. TIME (ms)	ON TIME (ms)	VOLUME PER NOZZLE (mL) 1	2	3	4	5	6
10	160	40	440	400	415	495	470	500
11	160	40	440	395	410	490	450	500
12	140	35	450	400	435	500	470	515
13	140	35	445	405	430	495	470	510
14	140	30	390	375	385	440	430	445
15	140	30	390	370	385	435	435	445
16	140	25	325	310	315	310	275	295
17	140	25	325	315	320	310	280	295

ANALYSIS OF LIQUID FERTILIZER DURING THE CALIBRATION:

Values are expressed percent fertilizer per mass of liquid. Tank temperature at the start of the trial was 17 degrees C. AM is the amount of ammonium in the analysis and NO_3 is the amount of nitrate in the analysis.

TRIAL	AM	NO_3	UREA	TOTAL	TEMP
check	7.3	6.8	12.1	26.2	17
1	6.8	6.2	11.4	24.4	20
2	6.7	6.2	11.5	24.4	24
3	6.8	6.1	11.2	24.1	30
4	6.6	6.1	11.6	24.3	30
5	6.8	6.1	11.4	24.3	32
6	6.7	6.2	11.6	24.5	36
7	6.4	6.2	12.0	24.6	38
8	6.8	6.2	11.4	24.4	40
9	6.8	6.1	11.1	24.0	45
10	6.7	6.0	11.3	24.0	46
11	6.8	6.0	11.6	24.4	51
12	6.5	6.1	11.8	24.4	54
end tank sample	7.1	6.7	12.0	25.8	54