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VARIABLE SPEED HYDRAULIC DRIVES FOR POTATO DAMAGE REDUCTION ON POTATO HARVESTERS

by

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A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

VARIABLE SPEED HYDRAULIC DRIVES FOR POTATO
DAMAGE REDUCTION ON POTATO HARVESTERS

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Research in the past few decades has revealed that potato damage during mechanical harvesting of potatoes is the main cause of economic loss to potato growers. This financial loss has been estimated to be of the order of millions of dollars every year in the United States and Canada. Studies conducted by Washington State University have shown that considerable reduction in damage to potatoes during harvest can be obtained by adjusting the conveyor speeds in relation to the forward speed and the yield. The concept of speed adjustment of the conveyors to forward speed of the harvester and yield conditions was incorporated into the design of variable speed hydraulic drives for the rear cross conveyor and the side elevator and the boom elevator on a Lockwood Mark 76 potato harvester.

A low pressure variable speed hydraulic drive system was designed for the Lockwood Mark 76 potato harvester, which was made available for this study by A.A. Kroeker and Sons Ltd., Winkler. The machine was field tested in the fall of 1975 and was used for approximately 400 hours. On 1975 09 04 a field day was held in co-operation with the Manitoba Department of Agriculture, the Manitoba Potato Growers' Association

and A.A. Kroeker and Sons Ltd., Winkler, at Winkler. The performance of the machine was observed by growers. The opinion was expressed that the hydraulic drive units should be designed for the Lockwood Mark VI which is more popular than the newer Mark 76.

Field tests were conducted to determine if there was any significant difference in the amount of damage inflicted on potatoes at slow conveyor speeds properly correlated to yield and forward speed compared to fast conveyor speeds. Tests were conducted on five fields and in each field eight samples were taken for the adjusted conveyor speeds and eight samples also were taken for fast conveyor speeds.

On the average total damage to potatoes was reduced to 12.5 percent when the conveyors ran slow and full compared to 18.1 percent when the conveyors ran fast. The slightly damaged potatoes were reduced from 41.9 to 36.7 percent when the conveyor speed was reduced. The average mass of the undamaged tuber was significantly higher when the conveyors ran slower compared to when the conveyors ran faster.

The measurement of the required operating torque for the side elevator and the rear cross conveyor gave a maximum torque of 134 N.m. Torque measurements on the boom elevator gave a maximum torque of 109 N.m when the outer boom was inclined.

An economic analysis showed that the project was economically feasible and could result in considerable savings to growers. Therefore, it was concluded that variable speed hydraulic drives for potato harvester conveyors were economically desirable and mechanically successful. These systems could be made available in kits for interested potato growers.

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INTRODUCTION

1.1 Scope of Study

1.1.1 Extent of potato damage

Potato damage, defined as any injury to potatoes caused by agents other than disease, insects or physiological factors, is estimated by various research workers to be about 30 to 33 percent during harvest alone (3, 5). From a study conducted in Idaho it was found that it is almost impossible to get ten undamaged potatoes from a storage bin (16). In one field in Alberta 100 percent damage was reported (38). About 70 percent of the total defects were found to be due to mechanical injury caused by the potato digger (13). The harvesting operation is considered to be the greatest source of injury to potatoes (3).

1.1.2 Effect of potato damage

With the increase in quality consiousness among housewives, damaged potatoes are not being accepted and therefore are contributing to waste (5). Damaged potatoes lose about 8.5 percent of their weight compared to a 5.5 percent loss by sound tubers. Furthermore, they act as a nucleus for further damage in storage (10). Skinning increases dry rot in storage. In addition, fresh market preparation needs more labor for sorting, trimming and quality control. Damage also leads to loss of raw product due to cutting and trimming (47). Last but not the least, potato damage leads to the processing of a low quality raw product to a low quality finished product. All these product losses ultimately contribute to financial loss.

1.1.3 Economic loss due to damage

The potato is one of the major horticultural crops of Canada in terms of quantity produced (3). In 1974, revenue due to potato crops in Canada was 22.6 million dollars (42). Farm value of the total potato production in the United States was 1197 million dollars in 1973 (46). Each year losses due to potato damage amount to millions of dollars (21).

Potato damage is considered to be the greatest cause of loss to potato growers (5). Financial losses due to mechanical injury are estimated to be 20 percent of gross potato crop income.

1.1.4 Chain speed and damage

It is reported that nearly 50 percent of the mechanical damage can be eliminated by proper harvester operation and soil conditioning (43). Experiments conducted by Smittle *et al.* (39) at Washington State University have shown that by properly co-ordinating chain speeds to forward speed, yield and soil conditions it is possible to reduce damage considerably. One potato processing company claimed that its growers enjoyed an average of 40 percent increase in bruise-free potatoes after the growers were educated in the use of the speed ratios developed by Washington State University (47).

1.2 The Objectives

In research carried on by Smittle *et al*. (39) sprockets of various sizes were used to get the desired speeds. This arrangement provided speed changes in steps only and required sprocket sizes to be changed depending on yield and soil conditions. The low-damage harvester developed by the University of Idaho and Washington State University was powered by hydraulic drive systems for infinitely variable chain speeds. The low-damage harvester was tested in the high yield conditions of Washington and Idaho (43).

Considering the interests of the Manitoba potato growers, the objectives of this study were:

1. To design, build and test low cost variable speed hydraulic drives for the rear cross conveyor, the side elevator and the boom elevator on a commercial potato harvester.

2. To determine the effectiveness of the reduction of chain speeds in reducing damage to potatoes in the low yield conditions of Manitoba.

It was hoped that the successful demonstration of the variable speed hydraulic drives would encourage manufacturers to produce the drive units and also would encourage growers to adopt the drive units. Perhaps the drive units could be supplied in kit form for use on older existing harvesters.

1.3 General Approach

A new Lockwood Mark 76 potato harvester was made available from A.A. Kroeker and Sons Ltd. for this study. A low pressure hydraulic system was designed and developed to drive the rear cross conveyor, the side elevator and the boom elevator. As the boom elevator needs to run at a slightly lower speed than the side elevator, depending on the amount of clods and stones in the field, two separate motors were used, one to drive the boom elevator and the other to drive the rear cross conveyor and the side elevator. The existing drive system also demanded such an arrangement.

The modified machine was taken to the field and put into operation on 1975 08 19. Damage studies were conducted at high and low chain speeds on five different fields. Eight samples of approximately 5 kg each were collected at the boom delivery point for both low and high chain speeds. Samples were tested for damage using catechol and classified as undamaged, slightly damaged, moderately damaged or seriously damaged. Five yield samples were taken near the test site in each field.

CHAPTER II

REVIEW OF LITERATURE

2.1 Importance of the Potato

Among the few crops which nature has provided that are capable of nourishing the great population of the world, the white potato is the most important (29). Both the nutritional and the medical value of the potato are quite significant compared to its cost. Today, potatoes form one of the main constituents of the food for many people of the world. For some it is the major food while for others it is only supplementary. Apparent per capita consumption of potatoes in Canada was 73.80 kg/year in 1973 (42).

2.1.1 Nutritional value of the potato

Beneath the skin of the white potato are liberal stores not only of energy but also of nitrogen and high quality protein that will support health and growth. Valuable minerals such as iron and magnesium and essential vitamins such as C and several of the B vitamins are present too (29).

2.1.2 Medical value of the potato

Potato consumption appears to partially prevent tooth decay. This may be because potatoes are not sticky. There may also be a cleansing effect of the fiber in the skin (29). The potato is naturally alkaline and helps maintain the alkalinity of the blood. This is claimed to aid in the prevention of such diseases as tuberculosis, heart disease, blood vessel disease, high blood pressure, gout and kidney disease (19). It is because of this nutritional and medical value of potatoes that a well balanced diet should contain some potatoes.

2.2 Potato Production

Rapid development in potato handling and processing machinery along with contract production for processing firms have resulted in an increase in the area planted to potatoes as well as the establishment of potato production as a special enterprise. Potatoes are the most important of the horticultural crops in terms of quantity produced and area planted in Manitoba and Canada.

2.2.1 Potato production in Canada

Table 2.1 shows the production of potatoes in Canada by province. Total production in 1974 was 2 427 440 000 kg.

2.2.2 Potato production in the United States

Table 2.2 shows the production of potatoes in the United States and the major growing areas. In 1973 the total potato production in the United States was 13 472 x 10^6 kg.

2.2.3 Potato production in Manitoba

The area planted to potatoes in Manitoba increased

Table 2.1 Potato Production in Canada in 1974(42)

Province	Average Yield (kg/m²)[1]	Total Area ($10^3 m^2$)	Total Production ($10^3 kg$)
Prince Ed. Island	2.51	186 155	467 389
Nova Soctia	1.63	17 806	28 940
New Brunswick	2.59	234 718	607 733
Oubec	1.78	214 483	382 158
Ontario	2.11	174 824	368 323
Manitoba	1.57	141 640	222 264
Saskatchewan	1.70	14 164	24 041
Alberta	1.95	93 078	181 440
B.Columbia	2.56	56 656	145 152
All Canada	2.14	1 113 524	2 427 440

Total value in 1974 =$226 558 000

Table 2.2 White Potato Production in United States in 1973(46)

State	Average Yield (kg/m²)[1]	Total Area ($10^3 m^2$)	Total Production ($10^6 kg$)
California	3.49	275 186	953
Florida	2.04	121 406	272
Idaho	2.69	1 307 134	3 538
Maine	2.35	554 419	1 315
Michigan	2.42	161 874	408
Minnesota	1.87	360 170	680
New York	2.52	218 530	544
North Dakota	1.63	534 185	862
Oregon	4.29	169 968	726
Pardue	2.24	121 406	272
Washington	4.82	331 842	1 588
Wisconsin	2.69	190 202	544
Others	2.01	926 730	1 860
All USA	2.56	5 273 053	13 472

Total value in 1973 =$1 197 000 000

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[1]To get the average yield in t/ha multiply kg/m² by a factor of ten

nearly 34.7 percent between 1964 and 1970 (3). Favorable agro-climatic conditions, along with the development of potato handling equipment, spread potato cultivation from the fine textured soils along the Red and Assiniboine Rivers to the coarse textured soils of Portage la Prairie, Carman and Winkler. Potato production in Manitoba during 1974 is listed in Table 2.1.

2.2.4 Potato varieties

Many varieties are grown in Manitoba but Red, Warba, Norland, Viking, Irish Cobbler, Norchip, Norgold, Red Pontiac, La Rouge, Netted Gem, Kennebec and Chiefton are grown for commercial purposes.

2.2.5 Markets for Manitoba potatoes

Decreases in potato production in eastern Canada and the United States due to poor seasons coupled with the increase in demand by the potato processing companies which have increased in number and capacity in Manitoba have strengthened the market for Manitoba potatoes. Fresh market potato production increased in Manitoba due to recent increased prices for potatoes (3).

2.3 Potato Cultivation in Manitoba

Rapid expansion of processing firms, advances in the technology of processing and handling equipment, improvement in potato varieties and disease control practices have made growing potatoes a specialized business requiring large capital investments and business and technical skills. The comments on potato cultivation in this section have been reviewed in reference three.

2.3.1 Soil and climate

Potatoes grow well in rich, deep, friable, well-drained, medium to sandy loam soils, free from stones and clods, slightly acidic and containing organic matter. The crop needs a good supply of moisture but cold, waterlogged soils are not suitable.

An average day time temperature of 15°C to 18°C with cool nights favours good tuber formation. Rainfall of 2.5 cm per week throughout the growing season gives best results. Five to 7.6 cm average monthly rainfall in Manitoba during the growing season is close to this figure. Because of the particularly suitable climatic conditions and the rapid development of potato handling equipment, potatoes are grown in all types of soil in Manitoba.

2.3.2 Cultural practices

2.3.2.1 Tillage practices The soil is tilled to a depth of 15 to 18 cm in the fall and in the spring. This, besides preparing a good seedbed and root bed, conserves moisture, helps to control weeds, loosens the soil and helps make nutrients available to the next crop.

2.3.2.2 Crop rotation Rotation of potato crop with some other crop is found to increase yields as well as control diseases such as scab, rhizoctonia, blackleg and wilts. Sod crops also add organic matter to the soil.

2.3.2.3 Planting and fertilization Cut potatoes are spaced 22 to 38 cm apart in rows. The rows are spaced 0.9 to 1 m apart depending on soil type and potato variety. The soil temperature should be 4.5^{0}C or higher.

Unless otherwise indicated by soil test, 67 to 90 kg/ha of nitrogen and 34 to 56 kg/ha of phosporous should be added to get good yields. Sandy soils usually require an additional application of 28 kg/ha of potassium.

2.3.2.4 Intercultivation In addition to the primary tillage operations frequent harrowing may be needed to control weeds, break clods and retain moisture. These operations should be done before hilling. After hilling chemicals may be used to control weeds and diseases.

2.3.2.5 Irrigation practices Where water is available, 4 mm per day may be added during the growing season. On loose soils sprinkler systems are preferable.

2.3.2.6 Harvesting The tops are killed by a rotobeater or chemical spray for early crops or by frost for late maturing crops. In Manitoba tubers are harvested by several methods. These include (i) digging, hand picking and bagging, (ii) digging, hand picking and the use of bulk boxes, (iii) indirect harvesting, (iv) direct harvesting and (v) direct-indirect harvesting. The most common method of harvesting is the direct method where a potato harvester lifts, cleans and delivers the potatoes to a truck. Indirect harvesting makes use of a windrower followed by a harvester.

2.3.2.7 Handling and storage Potatoes are carried to storage by truck. The potatoes may be graded, sorted and marketed or simply stored for a few days or several months before being taken to processing or delivered to market.

2.4 Potato Damage

Potato damage is any injury to potatoes caused by agents other than disease, insects or physiological factors. Hastings (13) reported that nearly 70 percent of the total defects are due to potato damage. Based on the size, shape and cause of injury, potato damage has been classified into three main categories by Thornton (3).

2.4.1 Shatter damage

Shatter damage is that which results in tuber breakage which does not usually leave large areas of broken cells exposed on the tuber surface.

2.4.2 Mechanical damage

Mechanical damage is that which results from mechanical gouging or tearing of tubers and produces areas of ruptured cells exposed on the tuber surface.

2.4.3 Internal blackspot

Internal blackspot has no external symptoms but has a dark area under the tuber surface. This is normally due to pressure in the storage pile which results in the rupture of internal tissue leading to enzymatic reactions. This is not present during harvest (3). It is most common among tubers lacking in potassium or relatively dehydrated or warm tubers.

2.5 Damage Detection

As mechanical damage is normally not readily visible, chemical reagents are used to make the damaged tissues more visible. Damaged tissue exposes the enzyme tyrosinase which catalyses the oxidation of naturally occurring tyrosine. This reaction produces a reddish-brown decomposition product which finally produces the black colour of melanin. However, the rate of this reaction is slow and depends on the variety of the potato. Some monohydric phenols such as phenol, para-cresol and catechol are also oxidized by tyrosinase. Cresol can also be used (1). These reactions produce highly coloured quinons. Catechol turns black to purplish after 3 to 5 minutes when combined with the enzyme tyrosinase. However, catechol does not detect internal blackspot. Lye peeling, which consists of removing the skin, 48 hours after the infliction of the injury is used to detect this type of damage. But since this type of damage is not common during harvest, testing with catechol is quite adequate (3).

Catechol like other monohydric phenols is inexpensive but should be stored in airtight, light-proof containers. It is prepared by adding 12.5 g of the chemical catechol to 1 ℓ of water along with one fourth of a spoonful of liquid detergent. The solution can be stored for a year or longer (3).

2.6 Damage Evaluation

The method developed at the National Institute of Agricultural Engineering (NIAE) assesses potato damage based on the number of strokes needed to remove the damaged portion using a potato peeler which is set to remove 1.5 mm for each stroke. If only one stroke is needed the damaged tuber is termed as slightly damaged (SL). If two strokes are needed the tuber is moderately damaged (MD). If the tuber is cut or more than two strokes are needed to remove the damage, the tuber is classified as seriously damaged (SD) (3).

Another method used by researchers in New Brunswick expresses potato damage in terms of trim loss by measuring the weight of trim required to remove the damage. Trim weight is expressed as a percentage of the original sample weight (3).

2.7 Damage Index

The damage index (DI) for potato damage is a number which combines the relative importance of the various types of damage. The damage index is useful in evaluating potato harvesting and handling machines and assessing the economic importance of the total damage in a sample (3).

The NIAE method obtains the damage index by multiplying the damage percentages in the sample by various factors and adding the results. These factors are zero for undamaged (UD), one for slightly damaged (SL), three for moderately damaged (MD) and seven for severely damaged (SD). Thus the damage index by the NIAE empirical method is given as:

$$DI = 0(UD) + 1(SL) + 3(MD) + 7(SD)$$

The New Brunswick method obtains the damage index by a regression equation:

$$Y = C_0 + C_1X_1 + C_2X_2$$

where

Y = the damage index

C_0 = a constant

C_1 and C_2 = regression coefficients

X_1 and X_2 = types of injury defined as flesh and crack wounds.

There is apparently no correlation between the two methods of calculating the damage index.

2.8 Functional Elements of Potato Harvesters and Design Considerations

The requirement of being able to harvest large areas in a short season coupled with the scarcity of manual labour has contributed to the development of potato harvesting machines. The potato tuber is an underground modification of the stem and is attached loosely to the aerial shoot. This makes potato harvesting quite different from other root crops such as carrots and poses a problem in harvesting by mechanical means. The mechanical harvest of potatoes consists of two stages: (i) vine or top killing and (ii) tuber lifting and cleaning.

2.8.1 Top killing

Top killing prior to harvest reduces work, bruising and prevents losses due to oversized potatoes. When chemical spraying is used to kill the tops, the vines left behind can often cause blockage problems. Chemical vine killing also increases tuber moisture content. If a rotobeater is used to chop the tops, it may reduce the blockage problem but increase the cleaning problem. Pulling the vines out of the ridge is one of the possible means of getting rid of vine problems but it is rather a difficult operation. Generally the mechanical method is preferable to the chemical method. Hawkins (14) suggests that possibly much of the damage can be reduced by lifting the vines with the potatoes and then separating them by an airblast or an inclined plane. However, an airblast separation can be used only for small quantities (11). A mild frost early in the season can be beneficial in killing the vines but a severe frost is dangerous to the tubers.

2.8.2 Tuber lifting and cleaning

Lifting the tubers from the hill and cleaning them is done in several steps with a potato harvester.

2.8.2.1 Tuber digging Potatoes in the hill are lifted together with soil, stones and some tops and weeds by a blade, drum, dished disc or rotating rod (7, 14).

The blade share is relatively cheap, simple and most widely used. If the soil shear strength at the soil-blade interface is more than the soil to soil strength which is the case in loose, moist soil, there will be disruption of the hill ahead of the mouth of the harvester. This will cause loss of potatoes from the sides. Adding side guides decreases this problem but increases the soil metal friction and blockages. Blockages can be eliminated by a bar point but this breaks the ridge and potatoes will be lost at the sides. A "V" shaped share reduces this loss but needs to be run deep thus increasing the soil-metal friction. All these problems can be eliminated by using a disc in front of the share or by removing the tops and the weeds before harvest. Discs add to the cost and top removal adds one more operation.

Drum type shares tumble the potatoes through a large distance and can damage them. Soil driven discs do not lead to any of the above problems but do not scour well in adhesive soils. The disc type delivers the potatoes and soil at 45 degrees to the centre line of travel thus limiting the choice of subsequent steps to those which will continue the flow approximately in the same direction. Power driven double discs fitted with deflectors to deliver the potatoes and soil parallel to the harvester travel have been developed at the Scottish Institute of Agricultural Engineering and are reported to be working well (30). The rotary rod has been satisfactory where there have been problems with fibrous material but since there was increased draft the new concept of the vibrating blade has been developed.

Normally the conventional digger blade is placed in such a position that its rear edge comes midway on the primary chain as the chain goes around the cones. This helps in feeding the loose material onto the primary chain and helps reduce draft. However, it causes considerable damage to the potatoes because of the impact with the rapidly moving primary chain while the tubers are still held firmly in the soil. Usually the blade does not remove enough soil to provide clearance for the primary chain. This increases primary chain wear (21).

Another problem with the conventional blade is excessive spill out at the blade. The Idaho Crop and Livestock reporting service reported an average spill out loss of 0.35 kg/m^2. Vibrating blades were developed in Idaho to reduce machanical damage and draft, to assist in feeding material to the harvester, to enhance the soil separation, to allow fast digging speeds and to reduce overall maintenance. The development consisted of two separate blades, one in each row moving independently in opposite directions. The blades were supported in the middle so as to assist the feeding of materials to the chains and also to reduce damage at the blade and digger chain. However, this posed a problem of clogging with vines. So a new centrally pivoted full width blade was developed. This elminated the support between the rows and hence provided more clearance for trash.

The blade vibration caused rapid break-up of the soil and quicker soil separation. A blade angle of 25 degrees, a stroke length of 2.8 cm and a frequency of 2.5 Hz were reported to be the optimum operating conditions (21). The vibrating blade was found to reduce injury. In a 1972 test, 70.7 percent of the tubers were found to be uninjured with the vibrating blade compared to 59.8 percent uninjured when using a standard blade (21). Primary chain wear was reduced to 1/3 to 1/2 of that on standard diggers. The required draft was reported to be less. However, no net saving in energy was reported because of the additional energy needed to drive the vibrating blade. The vibrating blade was found to cut more tubers. Damage reduction was reported to be more significant in adverse digging conditions.

2.8.2.2 Soil separation It has been estimated that an average harvesting machine is faced with the problem of separating 26.4 t/ha of potatoes from 751.2 t/ha of soil, stones and tops. This means that at a forward speed of 3.22 km/h the machine must be able to handle, on the average, 2.36 t of soil, 0.23 t of stones, 0.27 t of clods, 0.01 t of tops and weeds and 0.1 t of potatoes each minute (14).

The second harvest step involves separation of soil from the tubers. This can be done by a rotating drum, a conveyor with agitation, seiving or riddling. The rotating drum tumbles the potatoes and causes damage. Conveying with agitation is accomplished either by a chain with eccentric agitation or a shaker conveyor. Chains with eccentrics for agitation are most commonly used but lead to damage if agitation is violent especially at the rear of the chains. Seiving or riddling causes no such damage except skinning which is not regarded as serious damage. However, if tubers are dropped onto the separating mechanism it leads to damage. Potatoes should not attain the speed of the riddle before the point of delivery. This can be achieved by sloping the riddle and installing retarding fences.

Replacing vibrating chains by rubber rolls results in practically no injury as the potatoes are handled very gently. The handling capacity per unit area is also increased. It has the advantage of more positive separation and works better under damp and muddy conditions (26). It was found to operate better under high yield than low yield. Anti-roll belts are found to be advantageous especially on the side elevator where roll back of tubers is common. Antiroll belts do not need any flights which helps in reducing drop heights thus reducing damage. The drop heights are reduced since no clearance is required for the flights.

2.8.2.3 Removal of vines and weeds A conveyor chain, also known as the deviner chain, has a space between consecutive links large enough to allow potatoes, stones and clods to separate from the vines and weeds. A roller of about 15 cm in diameter set towards the rear of the deviner grips only the vines and pinches off any potatoes still attached to the vines. Any remaining plant material with the potatoes can be removed by the deviner roller at the junction of the rear cross conveyor and side elevator.

2.8.2.4 Clod and stone separation Basic differences in physical properties such as resilience, hardness, electrical properties, specific gravity, shape, size and surface texture have been used to achieve separation. Viscoelastic studies on potatoes have indicated that they have a high relaxation constant and hence cannot be separated from stones and clods based on resilience and hardness without damaging the potatoes (17). By using brine or soil suspensions to separate potatoes from stones and clods based on gravity it is possible to get 100 percent separation. However, this affects storage quality.

Based on surface texture, potatoes can be separated from stones and clods by making potatoes, stones and clods move on a horizontal conveyor slanted sideways. It was observed that it is easier to pick potatoes from stones than stones from potatoes. So any such device must be set to leave a few potatoes in stones and clods rather than stones and clods in potatoes (14). Spectral reflectance with infra-red rays, γ-rays and x-rays promise 100 percent separation from clods and stones (30).

2.9 The Potato Combine and Its Parts

In potato combines, as marketed today, the following components are present:

(i) a digging device, normally a blade;

(ii) primary and secondary chains equipped with agitators to remove soil;

(iii) deviner chains and deviner rollers to remove plant material from potatoes;

(iv) a cross conveyor and side elevator to convey and elevate potatoes to desired height;

(v) a clod and stone separating device, normally a horizontal conveyor slanted sideways; and

(vi) a boom elevator to convey potatoes to a truck.

2.10 Causes of Potato Damage

2.10.1 Damage before lifting

The damage that occurs before lifting varies from 0 to 13.8 percent with an average of about 5 percent. Careless harvester steering, narrow row spacing, wide tractor tires and poor hills are found to be the cause. It was found that the average weight of the damaged tubers was slightly less than the undamaged ones. The smaller potatoes tended to grow shallower and hence were subject to injury (3).

2.10.2 Losses at the soil-machine interface

Losses at the soil-machine interface were found to vary from 0 to 21.1 percent with an average of about 9.2 percent (3). Injury to the potatoes was found to decrease as the depth of digging increased. The deeper operation decreases damage due to cuts but increases power consumption. The distribution of potatoes in the ridge depends on the cultural practices such as hilling, location of the seed in the ridge at the time of planting and rainfall intensity during the growing season. Location of the seed pieces either to the left or to the right may make the distribution asymmetrical. Damaged tubers have been found to be 22.5 percent heavier than undamaged tubers. This is because the bigger tubers tend to grow deeper and also tend to have difficulty getting onto the primary chain. The proper setting of the blade depth can eliminate most of the damage at the soil-machine interface.

2.10.3 After lifting damage

Several factors contribute to damage. Some of them are due to the machine while others are not machine related.

<u>2.10.3.1 Non-machine factors</u> Light soil and dry con-

ditions lead to bruising of the tubers since the soil and the tubers separate rapidly exposing the tubers to chain vibrations. Medium or heavy soils in damp conditions can reduce the bruising but will result in more soil going to storage and this could result in rotting due to heating (18). Fine textured soils produce clods in dry conditions and the clods can cause damage. Low soil moisture can lead to clogging in weedy conditions.

In an extensive survey conducted in 1968-69 fourteen different operators were compared. It was found that the resulting damage varied from 3 percent to 47 percent. This showed that the skill of the operator had considerable influence on the damage (31).

Shatter bruising increases as tuber moisture content increases whereas blackspot decreases with the increase in tuber moisture content (42). Total damage generally decreases as the ambient temperature increases. Shatter damage is at a minimum when air temperature is 18 to 24°C. Harvesting should be done when soil temperature is above 4.5°C to avoid excessive damage. Therefore early harvest is better though it reduces the yield slightly. For the same reason harvesting at about noon or in the afternoon decreases loss compared to harvesting in the morning or late at night (42).

Good cultural practices, to produce favourable soil structure coupled with the minimum number of field operations possible, avoid clod formation and thus reduce damage. Good planting practices such as even spacing and uniformly sized tubers help harvesting operations. Good weed control helps reduce blockage problems and also avoids some loss at harvest time.

Varieties show some difference in their resistance to shattering due to the difference in their skin texture. Though different varieties exhibit relatively small differences in their resistence to static forces, dynamic handling conditions produce large differences. Experiments conducted in Colorado show that Russet Burbank samples are more susceptible to bruising than Red McClure samples (9).

Results obtained by Zahara _et al_ (48) indicate that damage varies from field to field. This may be due to topography, soil conditions and soil types.

Hand picking, though causing less damage during picking, leads to as much damage as caused by mechanical harvesting by the time the potatoes reach the storage place. This may be due to careless handling of the potatoes after picking (3). In a survey conducted in Idaho it was reported that single row machines caused less damage than hand picking. Single chain machines caused less damage than double chain machines. Picking into sacks was found to be better than picking into baskets. Trailer type digger-pickers caused more injury than single unit digger-pickers. The potato combine with proper adjustments caused the least damage (28).

2.10.3.2 Machine factors The main considerations in the development of machines should be the smooth flow of materials, avoidance of sharp drops and sudden changes in directions. Some important factors that affect damage are listed below.

A study conducted on seven different makes of harvesters in 1968-69 by O'leary (31) indicated that there is not much difference between different makes of machines as far as damage caused.

The forward speed determines the rate of work. A reasonable forward speed must be maintained for adequate field capacity. Results obtained by various researchers concerning the effect of forward speed on damage do not agree. Humphrey (16) concluded from his studies in Idaho that a forward speed of more than 2.41 km/h was bad from the point of view of damage. High field speeds mean high chain speeds and thus the tubers gain momentum which, when they come in contact with hard clods, rocks or parts of the digging machine, causes damage. This is especially true for potatoes with low moisture content. Research conducted by Green and others (3, 8) indicated that there was no significant difference between damage done at various speeds. In some light soils a high forward speed results in less damage than a low forward speed since enough soil is retained on the chain (14). The soil cushions the tubers from the chain. However, if the higher forward speed decreases the damage by retaining too much soil the overall result may lead to dry rot in storage because of the retained soil. When the forward speed and the chain speeds were properly co-ordinated an increase in forward speed was found to decrease damage by 66 percent (39).

It appears that the effect of forward speed on damage depends on soil type and condition and chain speeds.

Splits, lacerations and bruises are caused by the impact of tubers on solid surfaces. In a study conducted by Green (8) it was found that heavier potatoes cannot be dropped more than 15 cm onto bare chain. On rubber covered chain the drop can be increased to 45 cm. When potatoes were dropped onto potatoes there was no damage to the dropped tubers even at a drop of 60 cm. However, the potatoes which received the falling potatoes were damaged.

Experiments conducted on inclined planes suggested that there was not much difference between potatoes striking bare metal or resilient coating (8). Rubber coating appears to have less value if the drop is not vertical. It was also reported that a coating of less than 1.25 cm does not have much effect (14).

In tests conducted both in the field and on stationary diggers it was found that as the number of chains decreased, the damage decreased. A single long chain, the same length as two short chains, caused less damage because of the elimination of the drop (8). Hardenburg (11) reported 35 percent less injury with one continuous apron.

Potato samples taken off standard steel chains showed an average of 15 percent bruising. The potato damage was reduced to 2.1 percent when the chains were covered with rubber (16). The weight of the damaged tubers was found to be 20 to 30 percent higher than undamaged tubers (3). In

New Brunswick tests, damaged tubers were found to be 31 percent heavier (1). To reduce damage at drops, at least 1.25 cm thick rubber coating must be used at all drops. In heavy rain, rubber covered chain cannot be used as they become covered with mud (16).

Harvesting potatoes into water filled trucks reduced damage to 4.9 percent from 10.2 percent in conventional trucks, a reduction of about 50 percent (3). However, this method is not suitable for big acreages.

The main purposes of the chains are to remove soil from the potatoes and to convey the potatoes to the truck. High chain speeds remove soil faster and hence expose the potatoes to fast moving chains which damages the tubers. Potatoes change from zero velocity to the chain velocity in approximately 1 second in a distance of 90 cm (16).

Chain agitation can be provided to loosen the soil and remove it. In loose soil, agitation removes the soil too quickly and exposes the tubers to the chain. Violent agitation can throw the tubers into the air resulting in damage. Agitation was found to increase damage from 0.75 percent to 4.5 percent (17). It is recommended that the soil separating area be increased so that agitation can be eliminated.

Trim loss was found to increase exponentially with chain speed and skinning was found to increase linearly (3). Experiments have shown the main cause of damage to be glancing blows received by the tubers against chains, links and the digger blade. Hardenburg (11) reported that changes in chain speed from low to medium to high increased damage from 2.3 percent to 7.3 percent to 15 percent respectively. An increase in the primary chain speed resulted in a definite increase in injury even when the secondary chain speed was kept low.

For low soil moisture conditions, ground speed should be higher and the secondary chain speed lower. For higher soil moisture conditions the primary chain speed should be high and the forward speed low (1). To reduce damage all chain link ends must be turned in or shielded.

The primary and secondary chains handle mainly soil and hence their speed should be well co-ordinated with the forward speed and the soil type. This is because the bulk of the material lifted by the blade consists of soil. However, the rear cross conveyor, the side elevator and the boom elevator handle mainly potatoes. Thus their speed should be co-ordinated with forward speed and yield.

Theoretical harvester chain speeds have been calculated. Table 2.3 gives the theoretical chain speed and forward speed for a harvester with a 152 cm (60 in.) wide primary and secondary chain, a 147 cm (58 in.) wide rear cross conveyor and a 74 cm (29 in.) wide side and boom conveyor with 5 cm (2 in.) flights (43). In a study conducted at Washington State University it was found that the damage was reduced to 6.6 percent when the speeds of the secondary chain, the rear cross conveyor, the side elevator and the

Table 2.3 Theoretical Harvester Forward and Chain Speed Rates in mph[1] (43)

	Chain Speeds for Forward Speeds of							
	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
Heavy Soils								
Primary Chain	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.2
Secondary Chain	1.1	1.2	1.4	1.5	1.6	1.8	1.9	2.0
Light Soils								
Primary Chain	1.4	1.6	1.8	2.0	2.2	2.3	2.5	2.7
Secondary Chain	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.9
*100 cwt/acre**								
Rear Cross & Side Elevator	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5
Boom Elevator	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5
*200 cwt/acre								
Rear Cross & Side Elevator	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8
Boom Elevator	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5
*300 cwt/acre								
Rear Cross & Side Elevator	0.6	0.7	0.7	0.8	0.9	0.9	1.0	1.1
Boom Elevator	0.5	0.6	0.6	0.7	0.7	0.8	0.9	0.9
400 cwt/acre								
Rear Cross & Side Elevator	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
Boom Elevator	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.1
500 cwt/acre								
Rear Cross & Side Elevator	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
Boom Elevator	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4
600 cwt/acre								
Rear Cross & Side Elevator	1.0	1.2	1.3	1.4	1.6	1.7	1.8	1.9
Boom Elevator	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
700 cwt/acre								
Rear Cross & Side Elevator	1.2	1.3	1.5	1.6	1.8	1.9	2.0	2.2
Boom Elevator	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8

[1] 1 mph=1.61 km/h

* Speeds at these yields have not been adequately tested and must be considered as theoretical values

** 1 cwt/acre=0.011 kg/m^2=0.11 t/ha

boom elevator were reduced, compared to 18.5 percent tuber damage when the harvester was operated as it was delivered by the dealer. When the secondary chain speed was reduced to 80 percent of its initial speed, the damage was decreased to 10.4 percent (39).

2.11 Development in Potato Harvesting Machines

Attempts have been made in the past few decades to incorporate research findings into existing machines to reduce damage. The Departments of Agricultural Engineering at the University of Idaho and at Washington State University were the pioneers in this field.

As early as 1947 many potato combines were in use in Idaho. They were developed mostly by individual farmers. Improvements and engineering assistance were needed. With the co-operation of Idaho Potato Commission, the Idaho Agricultural Experiment Station launched a research project which provided engineering assistance to farmers to build better potato combines and also to build new machines. Humphrey (16) suggested to the farmers to follow the following guidelines to reduce damage:

(i) Reduce field speed of digger to 2.41 km/h or less.

(ii) Reduce the digger chain speed to 2.74 km/h or less.

(iii) Operate the digger chain with the raised portion of the link ends on the underside or shield the ends with belting.

(iv) Replace the kickers with idler wheels if soil conditions permit.

(v) Put rubber tubing on digger chain links.

(vi) Eliminate all drops of more than 15 cm whenever possible.

(vii) Put padding on the sacking platform.

(viii) Pad the bed of the truck in which the potatoes are hauled.

(ix) Reduce the speed of any transfer chain to 1.28 km/h or less.

(x) Put rubber tubing on all transfer, elevator and piler chains.

(xi) Pad the sides of the piler hopper.

(xii) Handle the sacked potatoes with care.

(xiii) Dig deep enough to avoid cutting tubers.

(xiv) Harrow prior to harvest to reduce the number of clods and to remove vines.

(xv) During the growing season keep machines out of the field as far as possible. i.e. minimize the field operations.

(xvi) Replace the vibrating chain belts by rubber rolls.

(xvii) Use good cultural practices during the growing period to establish good soil structure.

(xviii) Use good seed and planting methods to get evenly spaced tubers.

(xix) Establish proper soil moisture for harvesting (if irrigation possible).

(xx) Employ good weed control practices.

Modifications were done on some existing machines and some new machines were built using the design ideas suggested above. A single row potato sacking machine was built around a 66 cm digger. The frame was altered to allow for rubber separating rolls, a picking platform and a sacking device. The digger chains were covered with rubber. The rubber separating rollers were driven at different speeds. However, this idea was not used later as fixed roller speed did as good a job. The sacking hoppers were lined with sponge rubber sheet and the height was made adjustable (28).

A single row bulk handling machine with basically the same design features as above was constructed except that the potatoes were delivered directly to a bulk handling truck.

A two row bulk handling machine was built in two different models. The first model used a standard two row digger for the basic frame with rubber separating rolls mounted across the frame. The second model was designed without reference to any existing machine. Both were similar in design and were meant to be used in light soils were rocks were not a major problem. The harvester used two engines. The first one was used to drive the digging chains and the second to drive the elevators and rubber rolls. This provided good speed control of the chains.

A two row heavy duty bulk handling machine was designed to operate in severe conditions where rocks and clods were a problem. The construction was similar to the single row sacking unit. The original machine was powered by one engine but a second engine was added for better speed control (28).

As time passed potato harvesting machines were manufactured in large quantities by commercial companies. Many developments occurred but still the potato industry remained at a low level of mechanization. An estimate in 1974, placed the degree of mechanization at 30 percent of its then possible potential (47). Damage and loss due to damage remained high. This led to further attempts by the Departments of Agricultural Engineering at the University of Idaho and at Washington State University with financial support from the Thikol Chemical Company, the Idaho Potato Commission, the Washington Potato Commission and the Alberta Potato Commission to design a low damage harvester. Two low damage harvesters were developed. The machine for Idaho growing conditions had a small roll table while the machine for Washington conditions had no roll table as soil conditions there did not require a roll table. Many damage reduction concepts which led to the smooth flow of materials to reduce damage were incorporated (20, 23, 24, 25). Some of these concepts were:

(i) A vibrating blade.

(ii) A hydrostatic drive to supply power to the chains and the blade.

(iii) An increase in the length of the primary chain to reduce the angle of lift and thus prevent tuber roll.

(iv) A reduction in drop heights to reduce damage.

(v) A reduction in the slopes of the secondary chain and the side elevator by passing the chain over idler rollers just prior to the head shaft of each chain.

(vi) The elimination of the drop between the primary and secondary chains by carrying the deviner chain down and around the two nose cones with the digger chain.

(vii) A return side drive for the primary chain to further reduce drop onto the secondary chain.

(viii) A return side drive for the secondary chain to reduce the drop onto the cross conveyor.

(ix) A staggering of the discharge point of the secondary chain onto the rear cross conveyor to more uniformly load the rear cross conveyor.

(x) Removal of the flights on the side elevator to decrease the drops between the rear cross conveyor and the side elevator and also between the side elevator and the roll table. An antiroll belt was provided on the side elevator to avoid tuber roll.

(xi) A 5 cm diameter trash eliminator roll which rotated at about 250 rpm in the reverse direction, placed between the discharge of the side elevator and the roll table. It was found to reduce the number of trash pickers by one person.

(xii) An automatic boom height control device.

In addition special hilling discs were developed which were driven by a small tractor and were found to be effective in handling vine problems. It was found that the low damage harvester caused less damage than conventional harvesters. However, the reduction in damage was not as much as was expected.

CHAPTER III

DESIGN AND DEVELOPMENT

3.1 Conveyor Speeds

As was mentioned in the review of literature at a forward speed of 3.22 km/h a potato harvesting machine handles about 2.36 t of soil, 0.23 t of stones, 0.27 t of clods, 0.01 t of tops and weeds and 0.1 t of potatoes on the average every minute (14). Since the amount of soil handled in comparison to the amount of potatoes handled is very high and since the primary and secondary chains handle almost all the soil, the speed of the primary and secondary chains depends on soil type and forward speed. The rear cross conveyor receives a small amount of soil (about 15 percent of tuber weight) and almost all of the potatoes, stones and clods plus some vines (39). The side elevator receives potatoes, stones and clods. The boom elevator receives only potatoes.

As the present project deals with the adjustment of the speeds of the rear cross conveyor, the side elevator and the boom elevator, an attempt was made to develop a relationship between conveyor chain speed, yield, forward speed, soil, stones and clods.

3.2 Mathematical Formulation

For this analysis a harvester with rated lifting width of w cm working at a constant forward speed of S km/h in a field with y t/ha yield is assumed. Let η_c, η_s, η_{so} be the ratio by volume of clods, stones and soil lifted to the volume of potatoes lifted. Let ρ_p be the bulk density of the potatoes expressed in km/m^3.

It is further assumed that the potatoes, stones and clods are of uniform spherical shape with r cm diameter. Then the potatoes, stones and clods and loose soil if present, are assumed to move in a layer with depth equal to the diameter of the potatoes on a conveyor w cm wide.

The volume of potatoes handled can be expressed as

$$1000y/\rho_p \ m^3/ha \qquad \text{or} \qquad y/(10\rho_p) \ m^3/m^2.$$

If v m^3/m^2 is the total amount of material lifted and passed onto the conveyor then:

$$v(1 - \eta_c - \eta_s - \eta_{so}) = y/(10\rho_p)$$

so that

$$v = y/(10(1 - \eta_c - \eta_s - \eta_{so})\rho_p) \ m^3/m^2$$

In Δt seconds the harvester will move $S\Delta t/3600$ km. Then the area covered in Δt seconds will be $S\Delta tw/360$ m . The volume of material handled in the area covered is $V = vS\Delta tw/360 \ m^3$. Substituting for v from above gives

$$V = Swy\Delta t/(3600(1 - \eta_c - \eta_s - \eta_{so})\rho_p) \quad . \ . \ 3.1$$

To avoid any accumulation this material must be moved as it comes onto the conveyor. Assuming S_i km/h to be the speed of the conveyor, then the distance it moves in Δt seconds is $d = S_i \Delta t/3.6$ m.

If the amount of material received by the conveyor in Δt seconds is distributed evenly at a uniform depth of r cm over the conveyor width, w_i cm then the volume on the conveyor is

$$V_e = S_i \Delta t \, r w_i/(3.6(10^4))m^3 \quad . . . . 3.2$$

Assuming there is no build up material on the conveyor, the amount entering must be equal to amount taken away. Therefore equating Equations 3.1 and 3.2 and solving for S_i gives

$$S_i = 10Sy(w/w_i)/(r\rho_p(1 - \eta_c - \eta_s - \eta_{so})) \quad . . . . 3.3$$

Inspection of Equation 3.3 shows that the speed of the conveyor depends on the machine type, i.e. width of cut and width of chain, the amount of stones and clods on the chain, the amount of soil retained, the speed of the harvester, the yield of potatoes and the variety of potatoes. If the potatoes are not spherical, but oblong, then instead of using the diameter, r, use the least dimension. However, this assumes that the stones and clods are similar to potatoes in dimensions.

Equation 3.3 can be applied to the rear cross conveyor as well, if the dimensions of the rear cross conveyor are substituted. If the width of the rear cross conveyor is w_r cm and speed is S_r km/h then from Equation 3.3

$$S_r = 10Sy(w/w_r)/(r\rho_p(1 - \eta_c - \eta_s - \eta_{so})) \quad . \; . \; . \; . \; 3.4$$

Normally the side elevator is expected to run free of soil. Therefore $\eta_{so} = 0$ for the side elevator. Assuming the side elevator has a speed of S_s km/h and a width of w_s cm, S_s can be given by,

$$S_s = 10Sy(w/w_s)/(r\rho_p(1 - \eta_c - \eta_s)) \quad . \; . \; . \; . \; . \; . \; 3.5$$

Theoretically the boom elevator runs free of soil, clods and stones, i.e. $\eta_c = \eta_{so} = \eta_s = 0$. If the width is w_b cm, its speed S_b km/h can be given by,

$$S_b = 10Sy(w/w_b)/(r\rho_p) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 3.6$$

3.3 Actual Speed and Theoretical Speed of Chains

The actual speeds of the rear cross conveyor, side elevator and boom elevator on a new machine operated at standard power-take-off speed (1000 rpm) are listed in Table 3.1 together with theoretical speeds. The theoretical speeds are taken from Table 2.3 for two operating conditions. The first condition for a theoretical minimum chain speed has a low field speed of 2.58 km/h (1.6 mph) combined with a low yield of 11.2 t/ha (100 cwt/acre). For a theoretical maximum chain speed a higher field speed of 4.2 km/h (2.5 mph) and a higher yield of 33.6 t/ha (300 cwt/acre) have

Table 3.1 Actual and Theoretical Chain Speeds for Lockwood Mark 76 Potato Harvester

Chain	Speed Reduction Steps from 1000 rpm*	Chain Drive Sprocket[1] rpm Actual	Chain Drive Sprocket[1] rpm Theoretical Min	Chain Drive Sprocket[1] rpm Theoretical Max	Chain Speed[1] km/h (mph) Actual	Chain Speed[1] km/h (mph) Theoretical Min	Chain Speed[1] km/h (mph) Theoretical Max
Rear Cross	(3/4) (1/2) (20/34) (15/20) (abcc)	165	23	70	3.58 (2.22)	0.48 (0.3)	1.45 (0.9)
Side Elevator	(3/4) (1/2) (20/34) (18/25) (18/30) (abccc)	95	23	70	2.06 (1.28)	0.48 (0.3)	1.45 (0.9)
Boom Elevator	(3/4) (16/40) (18/26) (15/32) (accc)	97	23	59	2.10 (1.30)	0.48 (0.3)	1.21 (0.75)

[1]Pitch diameter of chain drive sprocket=10.9 cm
*Steps are (a) V-belt (b) gear box and/or (c) chain and sprocket

been assumed.

The theoretical speeds listed in Table 2.3 were for a particular machine working under ideal conditions. The Lockwood Mark 76 harvester has different specifications such as chain widths and width of cut, etc. and therefore the values may vary considerably for this machine. Furthermore, Equation 3.3 indicates that the soil conditions and the variety of potato also have an influence on the chain speed. Theoretically the rear cross conveyor and the side elevator should run at the same speed if the soil on each is negligible (Table 3.1). It was noted that the actual speeds on the Lockwood Mark 76 harvester were considerably different from the tabulated values of Table 2.3.

The reasons for these differences could be different chain widths but perhaps the actual values of Table 3.1 are in error for Manitoba conditions. For design purposes it was decided to use the speeds listed in Table 2.3 as a guide. The variable speed characteristic of hydraulic drives gave considerable flexibility. The rear cross conveyor's speed ratio with the side elevator was not changed initially.

3.4 Estimation of Torque Required for Chain Drives

The theoretical estimation of the torque required is rather difficult because of the uncertain nature of the forces acting on the conveyors. However, by making simplifying assumptions a theoretical estimate is presented below to obtain a design value. The derivation presented is for the general case of a conveyor inclined at an angle θ degrees to the horizontal.

In Fig. 3.1 a conveyor elevated to an angle θ degrees is shown loaded with potatoes on the upper side. Both the upper and the lower portion of the chain are supported by idlers. The following simplifying assumptions are made in order to derive an expression for the torque required to drive the conveyor:

1. The top of the chain is loaded uniformly with one layer of potatoes containing no stones or clods.

2. The top and bottom chains are fully supported on idlers so that catenary action can be neglected.

3. The force required to move the loaded chain on the idlers is large compared to the friction forces in the upper and lower sprocket antifriction bearings, i.e. neglect the friction of antifiction bearings for upper and lower sprockets.

4. A composite coefficient of friction is assumed for the idlers and any chain drag on the sides or supports of the conveyor chain.

5. The chain mass is w_c kg/m, the conveyor length (i.e. half the chain length) is ℓ metres and the chain width is h metres.

6. The mass of potatoes is w_p kg/m^2.

7. The pitch radius of the drive sprocket is r metres.

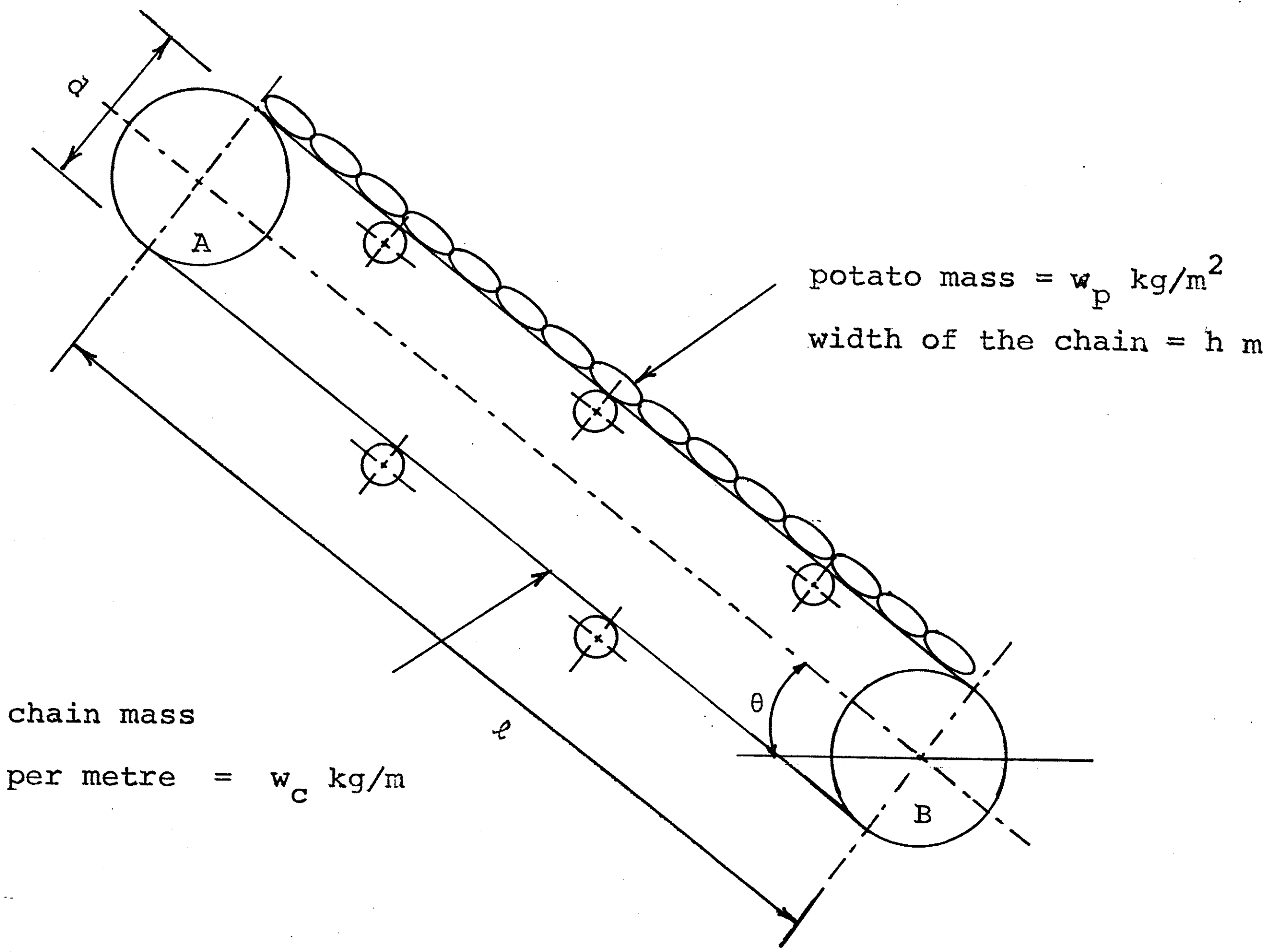


Fig. 3.1 Schematic Side View of an Elevating Conveyor.

Then with the above simplifying assumptions, the following forces can be determined.

1. Normal force on the upper chain

$$= (w_c + w_p h)\ g\ell \cos\theta$$

2. Direct force parallel to the upper chain

$$= (w_c + w_p h)\ g\ell \sin\theta$$

3. Normal force on the lower chain

$$= w_c\ g\ell \cos\theta$$

4. Direct force parallel to lower chain

$$= w_c\ g\ell \sin\theta$$

Summing for total force required at pitch diameter of drive sprocket A gives

$$F_T = \mu(w_c + w_p h)\ g\ell \cos\theta + (w_c + w_p h)\ g\ell \sin\theta + \mu w_c g\ell \cos\theta - w_c g\ell \sin\theta \quad \text{. . . . . 3.7}$$

The required torque, T, will be

$$T = F_T r \quad \text{. 3.8}$$

where

T = Torque, N.m

F_T = Resisting force, N

r = pitch radius, m

Substituting from Equation 3.7 and simplifying gives

$$T = \mu(w_c + w_p h)\, g\ell r \cos\theta + \mu w_c\, g\ell r \cos\theta$$

$$+ w_p h\, g\ell r \sin\theta \quad \ldots \quad 3.9$$

Equation 3.9 estimates the torque for a conveyor subject to the above simplifying assumptions. The torque estimated will be the required torque input to the drive sprocket at the delivery end of the conveyor. Suitable design factors would be used also.

The use of Equation 3.9 will be illustrated by estimating the torque needed for the rear cross conveyor. The dimensions and other physical parameters which follow are typical for the rear cross conveyor:

Width of rear cross conveyor,	$h = 0.85$ m
Length of rear cross conveyor,	$\ell = 2.33$ m
Elevation angle of rear cross conveyor,	$\theta = 0$ degrees
Acceleration due to gravity,	$g = 9.8$ m/s^2
Composite coefficient of friction,	$\mu = 0.2$
Pitch radius of drive sprocket,	$r = 0.0545$ m

Substitution into Equation 3.9 gives the estimated torque,

$$T_r = 20.7 \text{ N.m}$$

For the side elevator the dimensions were:

$\ell = 4.5$ m	$h = 0.85$ m
$\theta = 30$ degrees	$g = 9.8$ m/s^2
$w_c = 26.35$ kg/m	$r = 0.0545$ m

$w_p = 36.5\ kg/m^2$ $\mu = 0.2$

The estimated torque for the side elevator was

$T_{sc} = 72.1\ N.m$

The required torque for the boom elevator was similarly estimated. The boom elevator has approximately one third of its length inclined at an angle of 45 degrees while the remainder is horizontal. Equation 3.9 was used for each portion of the boom elevator and the results summed for the total torque. The pertinent dimensions were:

$\ell = 6.6$ m; $h = 0.85$ m

$\theta = 45$ degrees (1/3 of length); $r = 0.0545$ m

$\theta = 0$ degrees (2/3 of length); $\mu = 0.2$

$w_c = 26.35$ kg/m;

$w_p = 36.5\ kg/m^2$;

The estimated torque for the boom elevator was

$T_b = 79.1\ N.m$

3.5 Selection of Hydraulic Components

In order to avoid problems which are sometimes associated with high pressure systems it was decided to use a low pressure system. Inspection of the drive system present on the Lockwood Mark 76 showed that two separate motors (one to drive the rear cross conveyor and the side elevator and the other to drive the boom elevator) would be required. These two motors were to operate in parallel. The basic circuit was two separate open-center parallel circuits (Fig. 3.2).

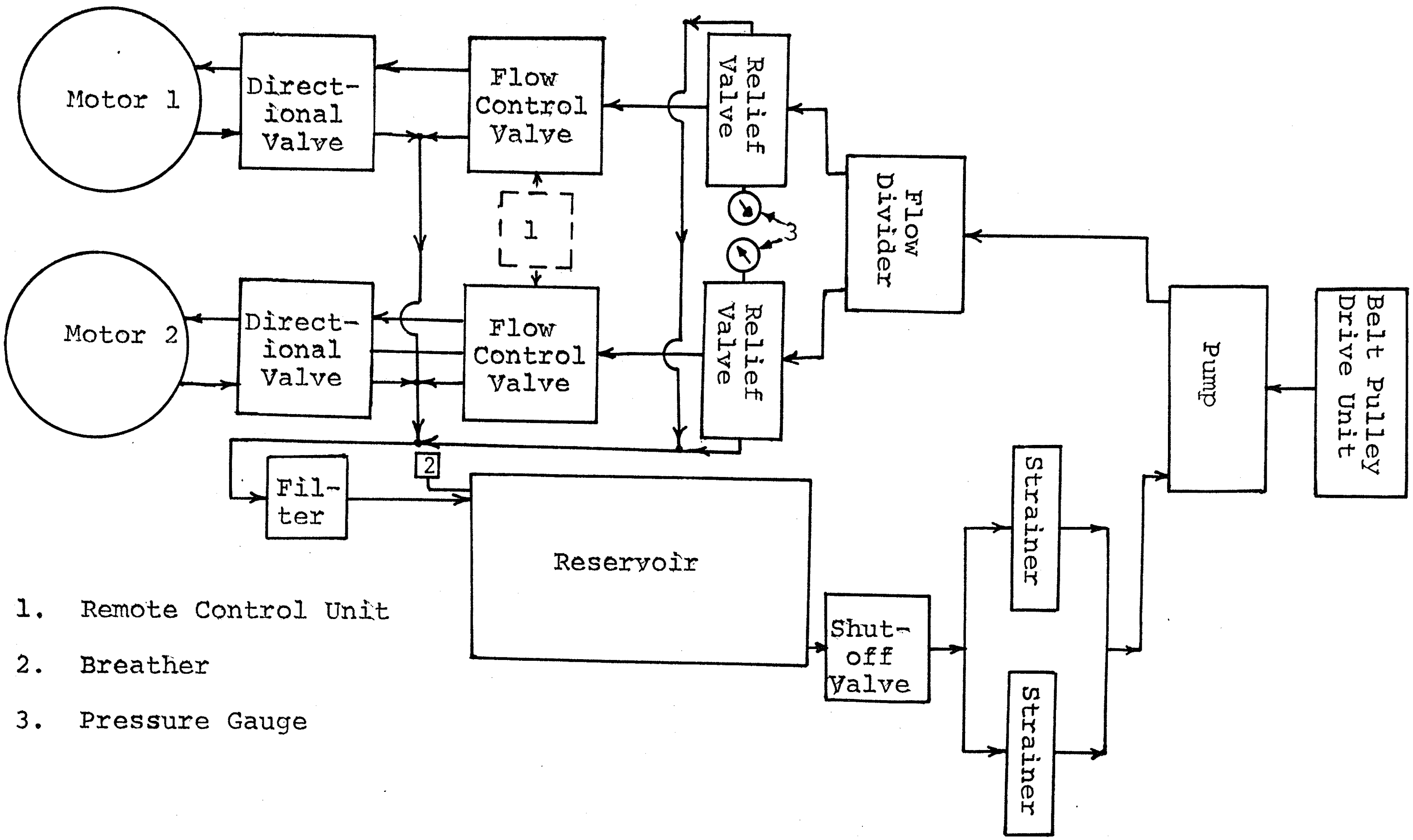
3.5.1 Selection of motors

A suitable drive point was selected to drive the side elevator and the rear cross conveyor (Fig. 3.3). From this drive point to the side elevator the drive undergoes two reductions (Table 3.1). The speed reductions were 18/25 and 18/30 for a combined reduction of 0.432. Therefore, the maximum speed required for the hydraulic motor was 70/0.432 rpm (162 rpm) (Table 3.1).

The above rotational speed represents the maximum required in order to replace the equivalent mechanical drive. In actual use the motor speed could be any speed between 0 rpm and 162 rpm. The hydraulic motor selection was based on obtaining a motor with the correct speed range and then checking for adequate torque.

A Charlynn hydraulic Orbit motor (M-206) rated at 6.895 MPa was available. The displacement of this hydraulic motor was 0.2442 ℓ/rev. The required flow for maximum speed was 39.6 ℓ/min. The maximum torque for this motor was 199.6 N.m.

The estimated required torques for the rear cross conveyor and the side elevator have been given above as 20.9 N.m and 72.1 N.m respectively. There were intervening speed reductions between the drive point and the drive sprocket for



1. Remote Control Unit
2. Breather
3. Pressure Gauge

Fig. 3.2 Schematic View of Initial Circuit Design.

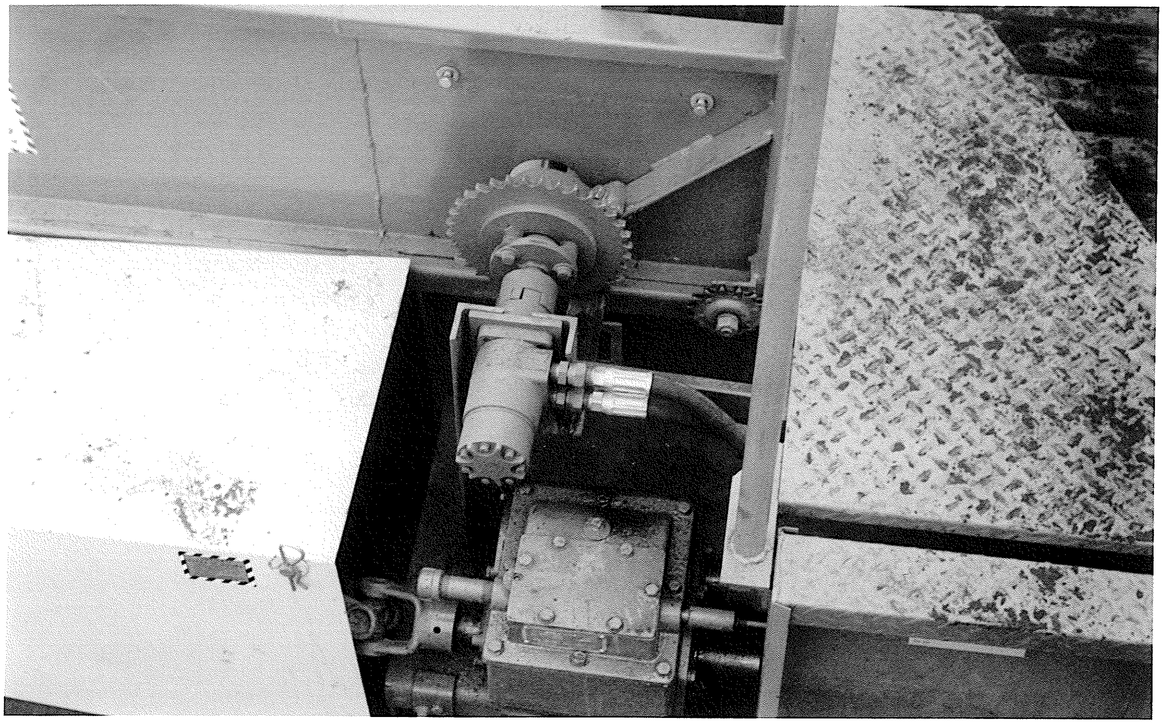


Fig. 3.3 View of Mount for Hydraulic Motor to Drive Rear Cross Conveyor and Side Elevator.

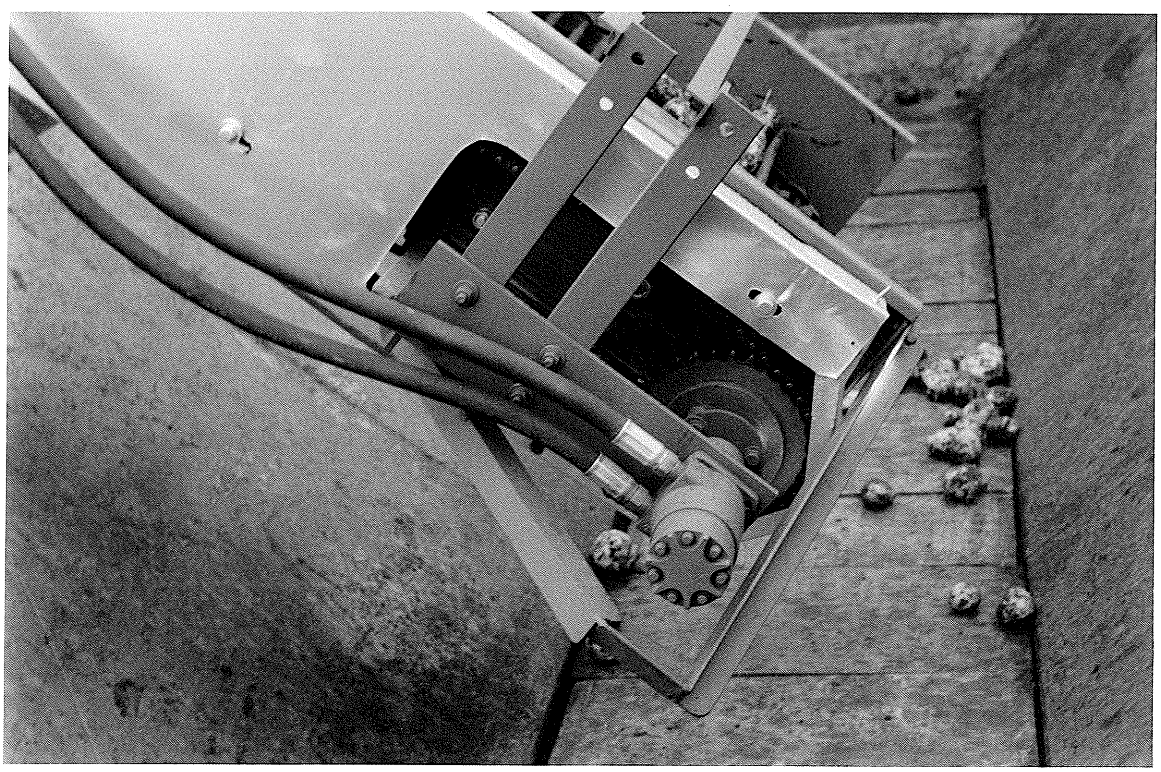


Fig. 3.4 View of Mount for Hydraulic Motor to Drive Boom Elevator.

each of the rear cross conveyor and side elevator. The drive reductions were 15/20 and (18/25)(18/30) respectively. Thus the required torque, T_t, at the drive point was

$$T_t = 20.7(15/20) + 72.1(18/25)(18/30)$$

$$= 46.7 \text{ N.m}$$

The above hydraulic motor was judged adequate and allowed for an overload factor of 4.3.

The boom elevator required a rotational speed anywhere between 0 rpm and 59 rpm. The torque requirement was 79.1 N.m. The drive point for the boom elevator is shown in Fig. 3.4 and is a direct drive. A similar hydraulic motor as was specified for the rear cross conveyor and side elevator drive was available. The speed range was adequate and the available torque at system design pressure allowed for an overload factor of 2.5. At maximum design speed the required hydraulic fluid flow was 14.4 ℓ/min.

3.5.2 Selection of hydraulic pump

A pump capable of supplying the total fluid flow needed and operating at system design pressure was required. The system design pressure was 6.895 MPa and the total required fluid flow was 54 ℓ/min. The hydraulic circuit design was based on the use of a flow divided for two circuits of equal fluid flow. Therefore, the required fluid flow was actually 79.2 ℓ/min (39.6 + 39.6 ℓ/min).

A surplus hydraulic pump was available at reasonable cost (Princess Auto and Machinery Ltd., Item 1201148 Catalog No. 133). The pump had the following specifications:

Maximum pressure = 8.23 MPa

Maximum flow (@1800 rpm) = 90.9 ℓ/min

This pump was selected as it had the required capacities.

3.5.3 Selection of accessories

The following accessories for the control and maintenance of the hydraulic circuit were used (See Fig. 3.2):

1. A surplus hydraulic oil reservoir of 75.7 ℓ capacity (Princess Auto and Machinery Ltd., Item 3215211 Catalog No. 133) (See Fig. 3.5).

2. Two hydraulic fluid strainers with 100 mesh wire element used in parallel on the suction line to the pump (Princess Auto and Machinery Ltd., Item 3215181 Catalog No. 133) (See Fig. 3.5).

3. A hydraulic fluid filter in the return line to the reservoir (Princess Auto and Machinery Ltd., Item 3215002 Catalog No. 133).

4. A proportional type flow divider to provide two equal flows in both circuits regardless of the individual circuit demands (Princess Auto and Machinery Ltd., Item 3203052 Catalog No. 133) (See Fig. 3.6).

5. Flow control valves to provide variable fluid

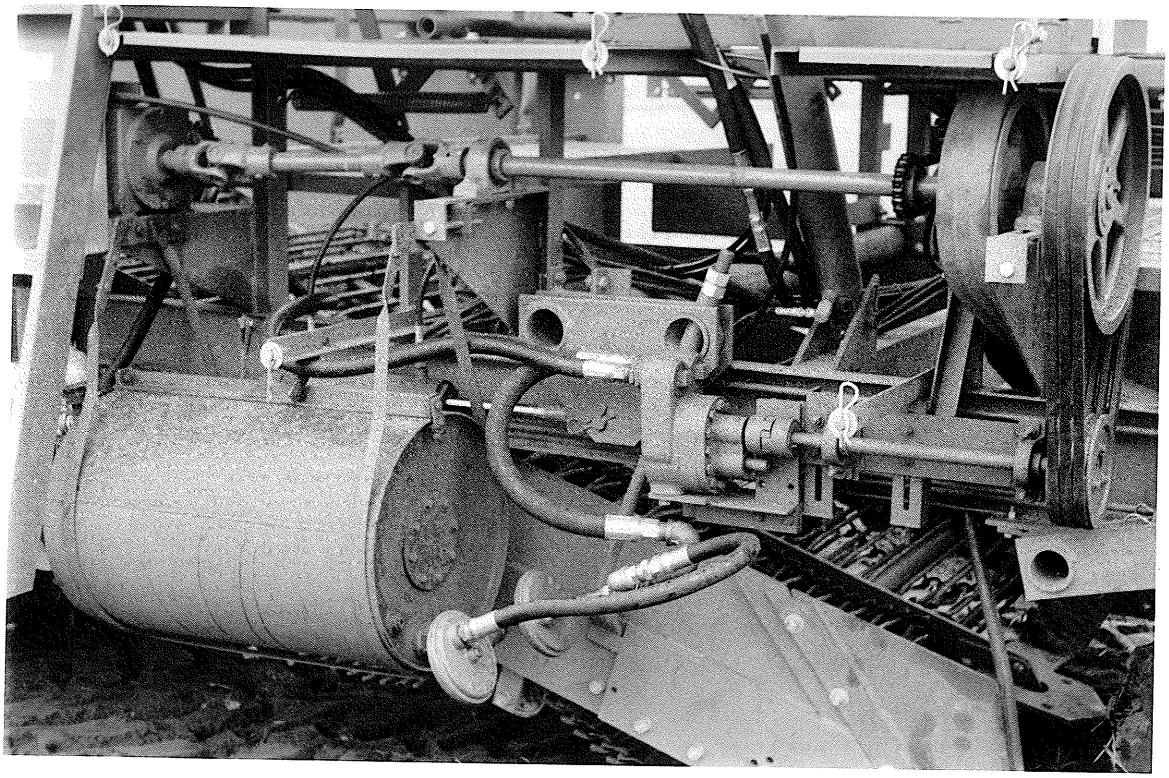


Fig. 3.5 General View of Pump, Pump Drive and Reservoir Area.

Fig. 3.6 View of Control Panel Illustrating the Flow Control Valves and Accessories.

flow for speed control of the motors (Princess Auto and Machinery Ltd., Item 3203087 Catalog No. 133) (See Fig. 3.6)

6. Pressure relief valves (one in each circuit) to protect the circuit from overpressures (Princess Auto and Machinery Ltd., Item 3203037 Catalog No. 133) (See Fig. 3.6).

7. Two directional control valves to give forward or reverse direction for the motors (Gresen Model SPD 4)(See Fig. 3.6).

8. A dust cover and vent for the fluid reservoir (Princess Auto and Machinery Ltd., Item 3203072 Catalog No. 133).

9. A shutoff valve to permit servicing of the strainers (Princess Auto and Machinery Ltd., Item 3203072 Catalog No. 133).

10. Various hydraulic plumbing components selected to minimize pressure drops (37). In general steel pipe (nominal size = 3/4 in.) was used except where flexibility was required. Hydraulic hoses (nominal size = 1/2 in.) were used in some cases to simplify the plumbing (See Figs. 3.2, 3.3, 3.4, 3.5 and 3.6).

3.6 Design of Pump Drive

Inspection of the original mechanical drive system on the harvester showed that the input power-take-off shaft drove a secondary shaft through a multiple V-belt and pulley drive. There was a speed reduction from 1000 rpm (standard pto rotational speed) to 750 rpm for the secondary shaft. It was convenient to use the secondary shaft for the power source to drive the hydraulic pump (See Fig. 3.5).

The design speed for the hydraulic pump was 1800 rpm. Therefore a speed increase was required. The speed increase ratio from the secondary shaft was 1800/750 = 2.4. A V-belt drive was selected. The transmitted power, based on maximum pump capacities, was estimated from the equation:

$$P = pq/60 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.10$$

where

P = power, kW

p = pressure, MPa

q = volume flow, ℓ/min

Therefore,

$$P_{max} = 8.23 \times 90.9/60$$

$$= 12.5 \text{ kW}$$

From a V-belt manufacturer's catalog (D74 Dodge Canada) a suitable V-belt and pulley combination was selected to transmit the above power. A 39.1 cm (15.4 in.) pitch diameter three groove pulley driving a 16.3 cm (6.4 in.) pitch diameter three groove pulley with three B66 belts was selected.

3.7 Design of Motor and Pump Mounts

The pump, motors, reservoir and the control panel were mounted on the harvester. Figs. 3.3 to 3.5 show these units mounted on the harvester. All the mountings were designed in such a way that they could be detached easily from the machine. Therefore, no parts were welded to the machine. The dimensions of the parts of the mounts were not strictly selected on strength consideration but more from the point of conformity with other members already on the machine and the availability of the material. Steel angle shapes and plates were used. The parts were considerably over designed from a mechanical strength consideration. Some of the components such as the stub shaft for the pumps and the short shafts coupled to the motor shafts were selected based on matching the size to the components to which they were coupled. For these reasons a detailed design of the components based on mechanical strength was not done.

Most of the material used for the construction of the mountings was mild steel angles and plates. Unless otherwise mentioned the angles were 50.8 mm x 50.8 mm (2 in. x 2 in.) and the plates were 9 mm (3/8 in.) thick. The bolts were generally 9 mm (3/8 in.) in diameter.

The pump was driven by a stub shaft through a flexible coupling to take up any possible misalignment (Fig. 3.5). The stub shaft was mounted on two ball bearings. The diameter of the shaft was 25.4 mm (1 in.). The pump end of the shaft was machined to 20.6 mm (13/16 in.) diameter to match the pump shaft size. The bearings were mounted on a 101.6 mm (4 in.) wide plate 304.8 mm (12 in.) apart.

A 76.2 mm (3 in.) wide plate was welded to the pump end of the above plate. Two angles were bolted on to this 76.2 mm wide plate, one on each side, with their backs next to each other and other side facing up (see Fig. 3.5 under pump). On the top of the angles a 101.6 mm (4 in.) wide plate with two 12.7 mm (1/2 in.) diameter holes was welded. This plate was the base for the pump mount and the pump was bolted using the tapped holes in the pump and 12.7 mm (1/2 in.) diameter bolts. At the other end of the shaft a 162.6 mm (6.4 in.) pitch diameter pulley was attached using a square key and bushing. This was driven by three B66 V-belts connected to a 391.2 mm (15.4 in.) pitch diameter pulley keyed to the main drive shaft.

The entire pump mount unit was bolted to two slotted angles mounted 152.4 mm (6 in.) apart in such a way that the mount could move vertically in order to provide adequate belt tension. The belts were tightened by adjusting two bolts which tightened against the main frame and pump mount.

The slotted angles were welded to two other angles which in turn were welded to a 76.2 mm wide plate. This plate was bolted to the machine frame by six bolts. In order to provide additional support in the vertical direction an angle was welded to one of the slotted angles and the other end bolted to the machine frame.

The motor driving the rear cross conveyor and the side elevator was coupled to a short 25.4 mm (1 in.) shaft through a flexible coupling. The short shaft was welded on center to a 101.6 mm (4 in.) diameter circular plate. The plate was bolted to the existing sprocket using spacers welded to the plate (See Fig. 3.3). The holes for bolts were spaced equally on a 76.2 mm diameter circle. This arrangement allowed for easy replacement of the chain drive, if necessary.

A 101.6 mm x 101.6 mm (4 in. x 4 in.) steel plate with 4 holes drilled in it was used to mount the motor. Two angles, one on each side, were bolted to the mounting holes provided on the motor with the plate clamped in between. The rear angle was bolted directly to the machine frame through a base plate to which it was welded. The other angle was welded to another angle which ran perpendicular to both the angles in the forward direction. The perpendicular angle was bolted to the frame. In order to keep the flexible coupling from separating in use, an additional angle was welded to the mount providing axial rigidity.

The boom motor was coupled to the sprocket in a similar fashion (See Fig. 3.4). A 101.6 mm x 406.4 mm (4 in. x 16 in.) steel plate was bolted to the mounting holes of the motor and the other end of the plate was bolted to two vertical angles spaced 101.6 mm (4 in.) apart. Each of these angles was welded to another angle directed to the boom elevator. The other ends of these two angles were welded to a 38.1 mm (1.5 in.) wide plate which was bolted to the boom elevator.

An additional angle was welded across the angles welded to the 38.1 mm wide plate and to the 101.6 mm wide plate to protect the motor from moving axially when in operation. To the top end of the vertical angles, two long 25.4 mm x 25.4 mm (1 in. x 1 in.) angles were bolted so that they extended across and over the boom. Each of these long angles was welded to another angle on the forward side of the boom elevator where a connection was made to the frame. An angle frame was welded around the motor to protect it from damage from the truck box.

3.8 Mounting of Accessory Equipment

The reservoir was slung in two loops formed from 3 mm (1/8 in.) thick by 25.4 mm (1 in.) wide flat steel strip (See Fig. 3.5). The ends of the loops were twisted to bring them into the plane of 38.1 mm (1.5 in.) wide flats. The loops were welded to the flats which were bolted to the frame. Lateral stability during operation was provided by a short brace from the frame to an angle attached to the top of the reservoir.

The control panel was mounted as shown in Fig. 3.6. The accessories were bolted to the panel. Because of the many hydraulic components involved, the plumbing was complicated and swivel ended hydraulic hoses were used to make the connections easier.

CHAPTER IV

FIELD TESTING PROCEDURES

The procedures adopted for the field tests of the modified harvester were as follows:

1. Preliminary field testing of the harvester,
2. Selection of the test sites,
3. Recording of the experimental conditions,
4. Sampling procedure,
5. Determination of yield,
6. Determination of speed,
7. Damage testing and classification, and
8. Determination of actual torque requirements.

4.1 Preliminary Field Testing

The first task was to check out the machine in the field. As the design had been based on theoretical estimates of the loads involved it was necessary to find out whether the machine functioned properly in field conditions. The machine was taken to the Lockwood dealer's workshop in Winkler, Manitoba and operated at no load on 75 08 18. The no load test was successful and the machine was taken to the field on 75 08 19 where it worked well. Therefore, it was decided to demonstrate the harvester to interested potato growers at a field day.

The preliminary field test revealed that the operator did not operate the tractor at rated engine speed. The power-take-off speed was only 667 rpm instead of the assumed rated speed of 1000 rpm. Although the harvester had worked satisfactorily in the preliminary field test and at the demonstration field day, it was felt that the maximum speed of the side elevator might not be high enough in high yield conditions. Therefore the original motor driving these two conveyors was replaced with a motor capable of higher maximum speed (Charlynn M-204). The motor had a displacement of 0.1688 ℓ/rev and a maximum torque rating of 165.4 N.m at 8.23 MPa. The design factor for torque was reduced to 3.5 but this was felt to be adequate. The maximum speed for the same flow of hydraulic fluid was increased by 48 percent.

The preliminary tests also indicated that the difference in speed between the rear cross conveyor and the side elevator was too high. The difference was reduced by 39 percent by replacing an eighteen tooth sprocket with a twenty-five tooth sprocket in the chain drive to the side elevator. However, it was found later that in weedy conditions this change was not desirable. The problem of blockages on the rear cross conveyor in weedy conditions was partially overcome by increasing the speed of the rear cross conveyor by 29 percent and by adjusting the spring tension on the deviner roller.

The preliminary field testing and the demonstrations at the field day gave an opportunity to adjust the modified harvester to the optimum operating procedure. Comments from the growers and the operators aided in these adjustments. For example, it was found that the tractor operator made the decisions as to setting the conveyor speeds. Since the control panel was out of his reach a remote control device was added to the system (See Appendix A for details).

4.2 Selection of the Test Sites

The test sites were selected in the fields which were being harvested by the grower. The size of the test site was based on the size and configuration of the field. For a small field the site covered a major portion of the field, whereas for a large field it covered only a few rows. This method of selecting the sites had the advantage of confining the tests to more uniform field and machine operating conditions. The uncontrollable factors were the variations in the soil and in the climatic conditions, the potato variety, the date and the time of day of the sampling.

4.3 Experimental Conditions Noted

Information which was related to the experiments such as harvester make and model, date and time, grower, soil type and condition, soil temperature at a depth of 15.2 cm, ambient temperature and potato variety was recorded. Temperature was measured using a simple mercury-in-glass thermometer.

4.4 Sampling Procedure

Based on the work of Ahmad (3) it was decided that eight samples replicated on five fields would be adequate in order that the accuracy of the results of the experiments be at the 5 percent significance level. For yield estimation five samples per field were taken. Yield samples were collected at random on the test site. Samples for damage testing at slow (adjusted) speed and at high speed were taken on adjacent rows as nearly opposite as possible. Yield samples were dug by hand. Samples for damage testing were collected at the delivery point of the boom elevator using a simple catching device.

4.5 Determination of Yield

The yield was determined by taking the average mass of five samples and multiplying by a conversion factor to obtain t/ha. The row spacing was 96.52 cm (38 in.) and a 4.19 m (13.76 ft) length of row was dug to collect the sample. The conversion factor was 2.47 to obtain yield in t/ha (sample mass in pounds multiplied by ten gave yield in cwt/acre).

4.6 Determination of Speeds

Two markers were fixed along the row 30.48 m apart. Two more markers were fixed across several rows 30.48 m apart and opposite the first two. This arrangement avoided error due to parallax. The time in seconds for the harvester to pass the two markers was measured using a stop watch.

The average speed was calculated from

$$s = 3.6\ d/t \quad \ldots\ldots\ldots\ldots \quad 4.1$$

where

s = average speed, km/h

d = distance between markers, m

t = average time for machine to pass markers, s

The lengths of the primary chain, the secondary chain, the rear cross conveyor, the side elevator and the boom elevator were measured. A distinct mark was made on a link of each conveyor chain. The time needed for the marked link to complete a convenient number of integral revolutions was recorded for each conveyor. The speeds of the primary chain and the secondary chain were related to the forward speed. If the operating gear was not changed, which was the case in this experiment, it was not necessary to measure the speed of the primary and secondary chains more than once. Similarly, since the speed of the rear cross conveyor was related to the speed of the side elevator only the measurement of the side elevator speed was necessary. Forward speeds and chain speeds for each operating conditions were determined at least three times in each field.

4.7 Damage Testing

The samples were brought to the laboratory and tested for damage. A catechol solution was used to make the damaged areas detectable quickly. The potatoes were immersed in the solution for 2 min and then dried for 10 min. The damage, if any, showed up as dark red to purplish stains. An ordinary potato peeler was used to trim the stained area. A slice approximately 1.5 mm (1/16 in.) thick was removed by one stroke of the peeler. The damage was classified depending on the number of strokes required to remove the stain:

1. No strokes (no stain) = undamaged
2. One stroke = slightly damaged
3. Two strokes = moderately damaged
4. More than two strokes = severely damaged

4.8 Torque Determination

In order to provide information for future studies the actual amount of torque needed to drive the conveyors in field conditions was measured. An ordinary torque wrench was used with a clamp. The clamp was made by bending a 1.25 cm (1/2 in.) square rod so that it hooked onto two adjacent spacers on the sprocket (Fig. 3.3). During the measurement of the torque, the side elevator and the rear cross conveyor were partially filled with soil. It was hoped that this would give a true value for the torque needed in field conditions. For the boom elevator the torque was measured in a raised as well as a lowered position. The maximum torque was measured in the raised position. Three readings were taken for each conveyor to obtain an average value.

CHAPTER V

ECONOMICS OF USE

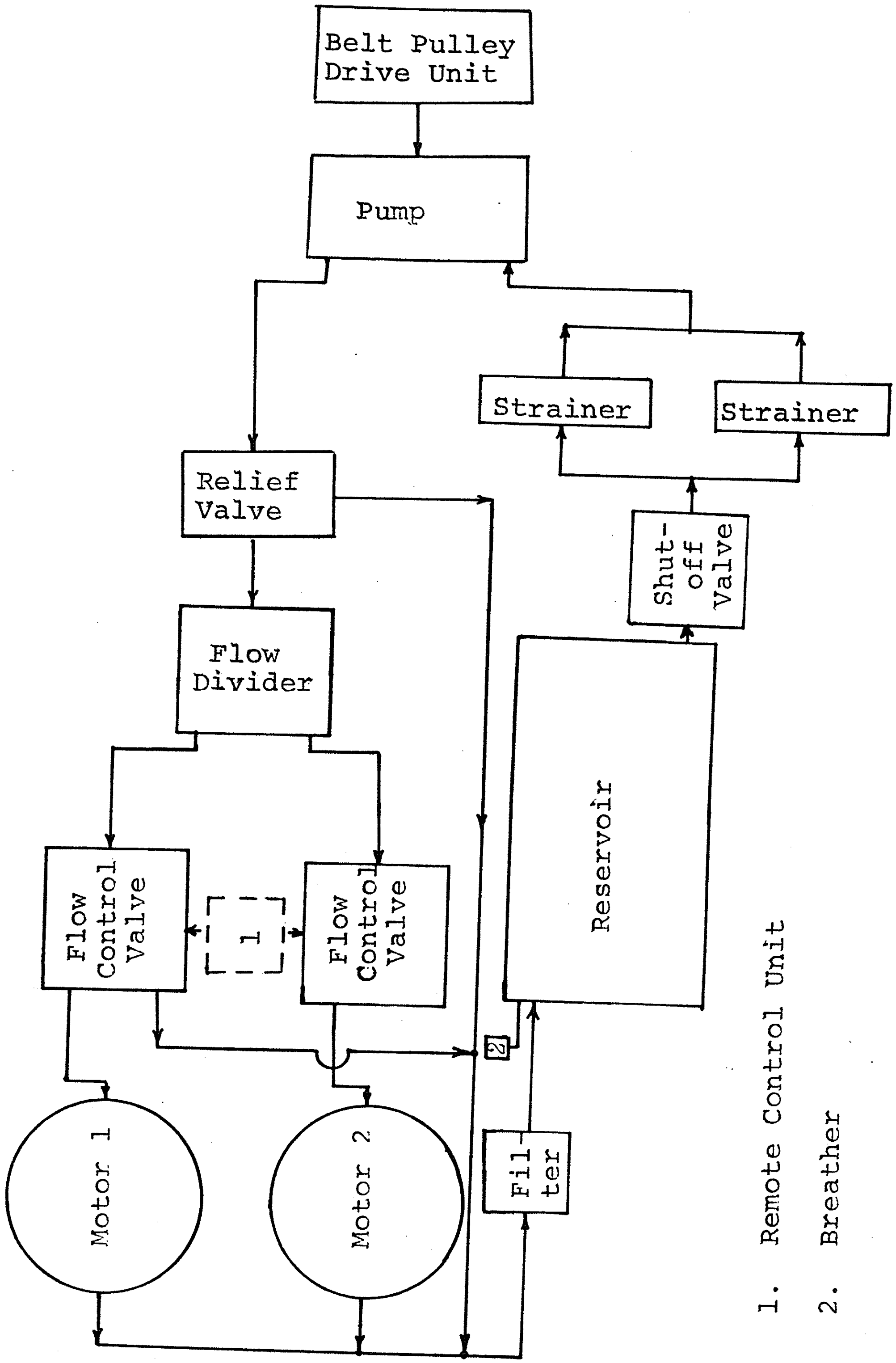
5.1 Economic Implications of Variable Speed Hydraulic Drive

In judging any new developments, the value of the developments is usually decided in terms of dollars saved by incorporating such developments. It is not worthwhile to make any expenditure if the return from the expenditure does not justify it. Therefore, to convince potato growers about the advantages of variable speed hydraulic drives it was necessary to calculate the dollars saved by such improvements. In this Chapter an estimation of the total savings due to the variable speed hydraulic drives is presented.

5.2 Cost Analysis

The increase in the per hour operating cost of the machine is determined by calculating the added fixed and operating costs due to the addition of the hydraulic drive units.

The fixed costs consist of depreciation, interest on initial investment, taxes, insurance and housing as applied to the added components. The cost of the components which were incorporated for experimental purposes only is not considered. The excluded components were the two directional valves, the pressure gauges and one relief value. The circuit diagram for the simplified system is shown in Fig. 5.1.



1. Remote Control Unit
2. Breather

Fig. 5.1 Schematic View of Hydraulic Circuit (Final).

Table 5.1 lists components as well as their costs. Table 5.2 lists the materials used for the mounts and their costs.

The labor cost for construction was estimated at $350.00 consisting of one technician and one assistant for one week.

The total initial cost was obtained by summing the component, material and construction labor costs to give approximately $1346.00.

The following assumptions were made to calculate the annual cost of the modifications:

1. Service life is 8 years (2000 hours of operation),
2. Yearly operation is 250 hours,
3. No salvage value,
4. Interest on initial investment is 10 percent,
5. Straight line depreciation.

The calculation of the annual cost was as follows:

$$\text{Depreciation per year} = \frac{1436 - 0}{8}$$

$$= \$155.75$$

$$\text{Interest on initial investment} = \left(\frac{1346 + 0}{2}\right)\left(\frac{10}{100}\right)$$

$$= \$67.30$$

$$\text{Taxes and insurance (1 percent of initial cost per year)} = 1346 \times \frac{1}{100}$$

$$= \$13.46$$

Table 5.1 First Cost of Components Used (1975 Prices)

Item No.	Item Description	Cost per Unit ($)	Quantity No.	Cost ($)
1	Hydraulic gear pump	49.00	1	49.00
2	Charlynn orbit motor (M-206)	129.95	1	129.95
3	Charlynn orbit motor (M-204)	114.00	1	114.00
4	Oil reservoir	29.98	1	29.98
5	Flow control valve	49.50	2	99.00
6	Proportional type flow divider	34.95	1	34.95
7	Gresen relief valve	19.50	1	29.50
8	Gresen line type filter	11.50	1	11.50
9	Oil strainers	14.50	2	29.00
10	Breather (Dust proof vent)	0.99	1	0.99
11	Shutoff valve	3.95	1	3.95
12	Pump drive components (two pulleys, 3 V-belts, bearings and couplings)			202.14
13	Hydraulic hoses			
	1. Rear cross conveyor and side elevator motor lines	8.30	2	16.60
	2. Pump to flow devider line	18.20	1	18.20
	3. Boom elevator line (two pieces)	15.86	2	31.72
		14.78	2	29.56
	4. Return line	14.30	1	14.30
14	Hydraulic hose fittings	2.15	8	18.00
15	Short hoses and couplings		6	25.00
16	Reducers, bushings elbows, tees ,etc.			25.00
17	12-volt electric screw jack	12.50	1	12.50
18	3-way switch	3.50	1	3.50
	Total			928.34

Table 5.2 Cost of Frame and Mounting Materials (1975 Prices)

Item No.	Material	Specification	Cost per Unit ($)	Quantity	Total Cost ($)
1	Flat	1. 9 mm x101.6 mm x1.25 m	53.00/100 kg	9.48 kg	5.02
		2. 9 mm x76.2 mm x1 m	53.00/100 kg	5.69 kg	3.02
		3. 3 mm x25.4 mm x4 m	53.00/100 kg	2.53 kg	1.34
2	Angles	1. 50.8 mm x50.8 mm x5.5 m	67.00/100 kg	13.91 kg	9.32
		2. 25.4 mm x25.4 mm x3 m	80.00/100 kg	3.79 kg	3.03
3	Rods	1. 25.4 mm x65 cm	39.00/100 kg	2.58 kg	3.59
		2. 11 mm x160 mm	67.00/100 kg	0.49 kg	0.33
		3. 8 mm x2 m	80.00/100 kg	0.76 kg	0.61
4	Bolts with nuts and washers	1. 9 mm x25.4 mm	3.00/dozen	2 dozen	6.00
		2. 9 mm x38.1 mm	3.48/dozen	3 dozen	10.44
		3. 9 mm x152.4 mm	6.36/dozen	2	1.06
		4. 12.7 mm x38.1 mm	7.08/dozen	2	1.18
5	Sheet	1 mm x1.22 m x3 m	15.00 each	1	15.00
	Sub total				59.94
6	Contingency (10 percent of above)				5.99
	Total				65.93

Repair and maintenance cost (10 percent of initial cost per year) $= 1346 \times \frac{10}{100}$

$= \$134.60$

Summing the above charges gives \$371.01 for the total annual cost of the modifications. Based on 250 hours of use each year the cost per hour was approximately 1.50 \$/h.

In the above calculations there was no charge made for housing, fuel or operating labour since these items were assumed to be the same for the conventional mechanical drive. The hydraulic drives if used exclusively would eliminate some costly chains and sprockets but no account was taken of this.

5.3 Savings due to Damage Reduction to the Potatoes

In the following analysis the following assumptions are made:

1. Percent damage reduction = P percent
2. Machine operating speed = 3.22 km/h (2 mph)
3. Field efficiency = 70 percent
4. Rated width of the machine = 193 cm (76 in.)
5. Yield = y t/ha
6. Value of potatoes = x \$/t

Using the above data, the potential savings in dollars per hour can be estimated as:

Savings, \$/h = 0.435 yxp

The net savings per year can be expressed as:

$$\text{Net savings, \$/year} = (0.435\ yxp - 1.5)250 \quad . \ . \ . \ 5.1$$

An estimate of how much savings can be expected under typical conditions is presented with the results and discussion in the next Chapter.

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Potato Damage Results

As potatoes are produced and marketed on a unit mass basis, the damage study results were calculated on a unit mass basis. The raw data obtained is listed in Appendix B. Appendix C contains the calculations for reducing the data to a percent basis and lists the results for each sample. The field conditions are listed in Table 6.1 and the overall results are listed in Table 6.2. For the purpose of discussion in this Chapter the moderately and the severely damaged potatoes will be added together and collectively represent the total damage.

On the basis of the experiments conducted towards the end of September and during the first two days of October, 1975, it was found that on the average 12.5 percent of the potatoes were damaged when the harvester was digging potatoes with the conveyor speeds adjusted (slow) to the yield conditions as compared to 18.1 percent when the conveyors were moving at high speed. This is a reduction in damage of 30.8 percent. Furthermore, it was found that on the average skinning increased from 36.7 percent to 41.9 percent when the conveyors were operated at high speed. This represents a reduction in slight damage of 12.5 percent. However, inspection of Table 6.2 reveals that the amount of damage var-

Table 6.1 Field Conditions
Grower:A.A.Kroeker and Sons Ltd.,Winkler
Harvester Make and Model:Lockwood Mark 76

Field No.	1	2	3	4	5
Date and Time	75 09 23 11 30	75 09 24 12 00	75 09 26 12 45	75 09 30 13 00	75 10 02 12 30
Soil Type and Condition	-Light -Moist -Grassy	-Light -Moist -Very Grassy	-Light -Moist -Good	-Light -Moist -Extremely Grassy	-Light -Moist -Good
Ambient Temp(°C)	16.4	18.3	23.3	-2.2	21.1
Temp at 15 cm Depth(°C)	13.3	14.4	16.7	0.0	5.6
Variety	Kennebec	Kennebec	Boison	Chiefton	Netted Gem
Whether Wind-rowed	Yes	Yes	No	No	No
Yield (t/ha)	28.09	24.82	23.85	19.21	15.06
Forward Speed (km/h)	3.13	3.07	3.14	3.16	3.07
Speed of Primary (km/h)	3.28	3.22	3.30	3.31	3.22
Speed of Secondary (km/h)	2.43	2.39	2.44	2.45	2.39

Table 6.2 Effects of Variable Speed Hydraulic Drives on Damage

Grower: A.A.Kroeker and Sons Ltd., Winkler　　Harvester Make and Model: Lockwood Mark 76

Field	Speed[1] (km/h)			Percent Damage[2]/Average Mass (g)				Percent[3] Damage
No.	Rear	Side	Boom	UD	SL	MD	SD	MD+SD
1	1.60	0.85	0.77	40.39/160	50.61/210	1.64/220	7.36/330	9.00
	2.71	1.43	1.82	30.99/140	51.68/220	8.16/240	9.17/240	17.33
2	2.13	1.13	0.89	49.04/180	34.03/180	2.39/210	14.54/330	16.93
	2.82	1.50	1.74	39.57/170	37.53/200	7.25/180	15.64/240	22.89
3	1.16	0.62	0.74	43.18/160	44.53/210	2.50/400	9.79/210	12.29
	2.45	1.30	1.65	41.65/140	42.95/200	3.34/200	12.06/200	15.40
4	2.49	1.32	0.52	47.02/150	41.95/210	1.94/320	9.09/320	11.04
	2.62	1.39	1.74	30.25/140	49.13/190	2.04/200	18.58/230	20.62
5	1.83	0.97	0.55	73.85/140	12.72/210	0.38/140	13.05/220	13.43
	2.50	1.32	1.76	57.33/130	28.23/200	1.28/200	13.15/220	14.43
Over-all Average			Slow	50.70	36.77	1.77	10.77	12.54
			Fast	39.96	41.91	4.41	13.72	18.13

[1]Rear=Rear Cross Conveyor ; Side=Side Elevator ; Boom=Boom Elevator
[2]UD=Undamaged ; SL=Slightly Damaged ; MD=Moderately Damaged ; SD=Severely Damaged
[3]MD+SD=Total Damage

ies considerably from field to field. The data of Table 6.2 were analysed by statistical methods to determine any significant trends.

The analysis of variance table based on a completely randomized block design with more than one reading per block is listed in Appendix D. In the analysis of variance the blocks were the fields and the treatments were the slow or fast conveyor speeds.

The percent undamaged potatoes was significantly higher for the slow speed treatment (1 percent level). The percent of damaged potatoes was significantly higher at the fast chain speeds (5 percent level). The percent of slightly damaged potatoes was not significantly different for the two speeds. Although the differences in the percent undamaged potatoes were significantly different between fields the differences between fields for total damage were not significant.

Perhaps the percent of slightly damaged potatoes was not significantly different for the two speeds because of the late harvest date when the tuber skins are normally tougher than for earlier lifted tubers. The reason why potatoes are more prone to damage when the conveyor runs faster may be that their momentum is greater and hence when they hit any objects such as stones and clods the impact forces are higher. Another reason may be that when the chain is only partially filled with tubers at high speed the potatoes bounce and roll as they are conveyed and this repeated bouncing and rolling repeatedly stresses the potato tissue.

Another source of impact to the potatoes is when potatoes are transferred from one conveyor to another. Finally there is the impact of the potato dropping from the boom elevator to the truck box or to the top of the potato pile.

6.2 Variation Among the Fields

The analysis of variance shows that there was a significant difference between fields in the percent of undamaged and slightly damaged potatoes. This may be due to the different field conditions such as soil type and condition, weed growth and soil temperature on the day of harvest as well as different potato varieties. The ambient temperature on the day of harvest also has a considerable effect.

Fields one and two were adjacent and had similar conditions except for weed growth. Field two was very weedy. The heavy weed growth required that the rear cross conveyor ran faster than in field one even though field two had a lower yield than field one. Field two had less skinning. This may be due to the presence of weeds which might have cushioned the potatoes.

Field three does not show much difference in the amount of damage at high and low speed though the damage done at low speed is slightly less. Ideal conditions existed on that day which might indicate that variable speed drives have more advantage in poor digging conditions. Also field three was planted to a new variety which may have had higher damage resistance.

Field four was harvested in very bad conditions. The temperature was very low and the field was very weedy. There was a large difference in the amount of damage at slow and fast chain speeds. The effect of speed reduction could be more significant for low yield conditions particularly when field conditions are bad.

Field five had generally good conditions for harvest. The potato variety was Netted Gem. The speed of the conveyors at slow speed could not be adjusted properly. The oblong shape of these potatoes prevented them from spreading evenly across the conveyor width. The tubers tended to pile up and perhaps the lack of rolling contributed to the low percent of slight damage in this case. This variety is known for its tough skin and had the lowest values of slightly damaged tubers for all tests.

6.3 Yield and Speed

Equation 3.3, developed in Chapter 3, illustrates that the speed of a conveyor depends on the forward speed of the harvester, the yield, the presence or the absence of stones or clods and the average size and shape of the potatoes. The forward speeds of the harvester was almost constant during the experiments. The varietal differences influenced the conveyor speeds considerably. No conclusive inference can be drawn from the results on the dependence of the conveyor speed on yield except the two lowest yields did have the lowest conveyor speeds.

A conveyor is said to be running full when one layer of potatoes is moving over it. In the field a subjective judgement is made as to the fullness of the conveyor. Often the potatoes were in more than one layer especially near the receiving side of the conveyor while the oposite side was not fully covered with potatoes.

6.4 Machine Performance

During the harvesting season of 1975 the machine worked for about 400 hours. There was no major problem during the entire period. A minor problem of blockages at the deviner roller at the point of transfer from the rear cross conveyor to the side elevator occurred several times. This problem was noted as being present on almost all makes and models.

On harvesters with mechanical drive units normally a slip clutch slips thus protecting the drive system. With the hydraulic system the same function is accomplished by the relief valve which opens allowing the motor to stall. The problem could be avoided by using a higher speed on the side elevator. Therefore, the side elevator had to be run faster than desirable. Another method of preventing this type of blockage would be to provide higher torque with a high pressure system.

The best way to solve the problem would be to prevent any blockages. On this particular machine the roller on the deviner was too tight. After loosening the roller the clogging problem was considerably reduced. Other suggestions for overcoming blockages are given in Chapter eight.

During the entire season there was no problem of overheating of the hydraulic oil or of any of the components. The large capacity reservoir was specified to avoid any overheating problems.

6.5 Damage and Average Tuber Mass

Inspection of Table 6.2 indicates that as the average tuber mass increases, the chance of receiving damage also increases.

When the conveyor ran faster the average masses of the damaged and undamaged tubers were less than at slow speed. This could be due to the fact that at higher conveyor speeds even the smaller potatoes acquired high momentum. However, the analysis of variance did not confirm this except in the case of the undamaged potatoes. Both fields and speed treatments showed significant differences for undamaged potatoes (1 percent level). No other comparisons were significant. The difference between fields is probably due to differences in field conditions or varietal differences.

6.6 Economic Feasibility

In Chapter five it was shown that the annual savings due to damage reduction could be expressed as (Equation 5.1)

$$S = (0.435\ yxp - 1.5)250$$

or

$$S = 109\ yxp - 375$$

where

S = savings due to damage reduction, \$/year, and

y, p and x are as defined in Chapter five.

In this section the 1974 average yield in Manitoba and the average wholesale farm price for potatoes during a six month period in 1975 were used to illustrate the potential savings.

The potato marketing board was consulted as to the method used to evaluate potato damage. Potato damage is evaluated as follows:

1. Ninety percent of the potatoes can be 10 percent skinned and the remaining 10 percent can be 100 percent bruised and yet the lot will make the grade. In Manitoba no penalty is normally assessed for skinning as skinning done during harvest disappears within a few days. Skinning due to piling which leads to discolouration and bad appearance is sometimes penalized. The only losses from skinning are due to dry rot and loss of mass in storage. Because these losses are difficult to quantify in dollar value, they will be neglected in this discussion.

2. Five percent of the potatoes may have damage that can be removed by removing 5 percent of the total mass of

the potatoes and the lot will still make Canada No. 1 grade.

3. Five percent of the potatoes may have damage that can be removed by removing a maximum of 10 percent of the total mass of the potatoes and the lot will make Canada No. 2 grade.

The above classification is not absolutely rigid but only a guide line. Common sense and experience of inspectors are often invaluable in deciding the classification. For these reasons it is difficult to get an accurate cost of damage. The values calculated below are to illustrate the approximate potential savings if potato damage could be reduced. The data used were:

1. Average yield in Manitoba (1974), $y = 15.7$ t/ha
2. Average wholesale farm price (1975), $x = 110$ \$/t

In the present damage study the total overall damage exceeded 5 percent. Thus, any reduction due to slow conveyor speeds is potentially a saving. The difference in total damage is 18.1 - 12.5 = 5.6 percent. Substituting the above values in Equation 5.1 gives

$$s = 109 \times 15.7 \times 5.6 \times 110/100 - 375$$

$$\simeq 10\ 150 \text{ \$/year}$$

This amount is significant and illustrates that efforts to reduce damage are very worthwhile. A reduction in damage of only 1 percent has a potential saving of approximately

1500 $/year based on the assumed values above.

6.7 Other Economic Benefits

In addition to the savings due to damage reduction there may be other benefits such as reduction in the wear and tear on conveyor chains. Because of the slow movement of the conveyors the whole machine operated much smoother and quieter. Some sprockets and chains could be eliminated entirely which would partially offset the cost of the hydraulic drives.

6.8 Possible Disadvantages

Any defects in a mechanical drive system such as a broken chain can be detected easily and corrected in the field. However, the failure of a hydraulic drive system may be due to a fault in a pump or motor which cannot be repaired in the field. In the harvest season any delay may be critical. Such failures are not common in modern hydraulic devices and generally daily maintenance requirements are not excessive.

6.9 Measurement of Actual Torque Requirements

The actual torque requirements of the boom elevator, the side elevator and the rear cross conveyor are not constant for one complete revolution of the driving sprockets. As the sprocket teeth make contact between links the torque requirement increases, reaches a maximum and then decreases as the teeth disengage. The maximum torques measured for the boom elevator, the side elevator and the rear cross conveyor are tabulated in Table 6.3.

The actual torque requirements as determined by direct measurement were higher than the values estimated for design purposes. The net effect was to reduce the actual overload factors to 1.48 for the rear cross conveyor and the side elevator and 1.83 for the boom elevator.

Table 6.3 Measured Torque Requirements for Potato Harvester Conveyors (Lockwood Mark 76 Model)

Name of the Conveyor	Maximum Torque Measured (N.m)	Remarks
Rear cross conveyor and Side elevator	135.0	
Boom elevator	83.8	Outer boom elevator relatively flat
Boom elevator	109.0	Outer boom elevator inclined

CHAPTER VII

CONCLUSIONS

From the results of this study as presented in Chapter 6, the following conclusions were drawn:

1. On the average 50.7 percent of the potatoes were undamaged when the speeds of the conveyors were properly adjusted to yield, forward speed and field conditions compared to 40.0 percent undamaged potatoes when the conveyors were running fast.

2. Field conditions had a significant effect on the amount of undamaged potatoes.

3. The average mass of an undamaged tuber when the conveyor speeds were adjusted properly was higher than the average mass of an undamaged tuber when the conveyor speeds were high.

4. On the average 36.8 percent of the potatoes were slightly damaged when the speeds of the conveyors were properly adjusted compared to 41.9 percent when the conveyors were running fast.

5. The average mass of a skinned tuber when the conveyors were running slow or fast did not differ significantly.

6. On the average 12.5 percent of the potatoes were damaged when the conveyors were running slow and full compared to 18.1 percent when the conveyors were running fast.

7. Field conditions did not have any significant ef-

fect on total damage.

8. The average mass of the damaged tubers when the conveyors were running fast did not differ significantly from the average mass of the damaged tubers when the conveyors were running slow.

9. Under the low yield conditions of Manitoba, slowing down the conveyors reduced damage to the potatoes.

10. The Lockwood Mark 76 potato harvester equipped with variable speed hydraulic drives worked satisfactorily throughout the 1975 potato harvesting season for about 400 hours.

11. Slightly higher torque capacities would ensure positive drive of the conveyors in adverse operating conditions.

12. The economic analysis shows that considerable savings are possible if the amount of damage can be reduced by installing hydraulic drives.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

Based on observations during this study, the following precautions or recommendations are offered:

1. For the design speed of the conveyors it must be realized that the tractor was not operated at rated engine speed. The actual engine speed used must be determined.

2. Higher overload factors must be used for the rear cross conveyor and side elevator motor. Alternately the mechanical drive could be restored for the rear cross conveyor.

3. The cost of the V-belt and pulley drive to the pump was quite high. There may be an economic advantage in replacing the drive with a chain and sprocket drive. The chains removed from the side elevator drive or boom elevator drive could be used.

Suggested future studies could be as follows:

1. Design changes involving the relocation of the deviner roller currently located at the junction of the rear cross conveyor and the side elevator.

2. Some tractors may have adequate hydraulic capacity to deliver the required flow of hydraulic fluid to the hydraulic motors. This would eliminate the need for a pump, the pump drive unit and other accessories. Such tractors

should be identified to the growers.

3. The Lockwood Mark VI is more popular than the Lockwood Mark 76 and therefore variable speed hydraulic drives for the Lockwood Mark VI potato harvesters should be designed.

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APPENDIX A

DESIGN OF REMOTE CONTROL

FOR CHANGING HYDRAULIC MOTOR SPEED

Design of Remote Control for Changing Hydraulic Motor Speed

Approximately 10 degrees rotation of the lever of the flow control varied the motor speed from zero to maximum. An electrical control unit powered by the tractor battery was a convenient way of accomplishing the remote control of the hydraulic motor speed. A linear actuator was selected to move the flow control lever. The 12-volt electric screw jack (Princess Auto and Machinery Ltd., Item No. 1106114) had a 8.89 cm (3.5 in.) stroke. A linkage system as illustrated in Fig. A.1 was designed and fabricated.

From the theory of mechanism it can be shown that for the mechanism shown

$$2L^2(1 - \cos\theta) + 2aL\sin\theta - (\ell^2 + 2a\ell) = 0 \quad . . . \text{A.1}$$

where

L = length of actuating rod, cm

a = retracted length of actuator, cm

ℓ = stroke, cm

θ = angle of actuation, degrees

Substituting $a = 31.75$ cm (12.5 in.), $\ell = 8.89$ cm (3.5 in.) and $\theta = 10^0$ in Equation A.1 and solving for L gives

$L = 51.33$ cm

Limit switches were used to limit the travel of act-

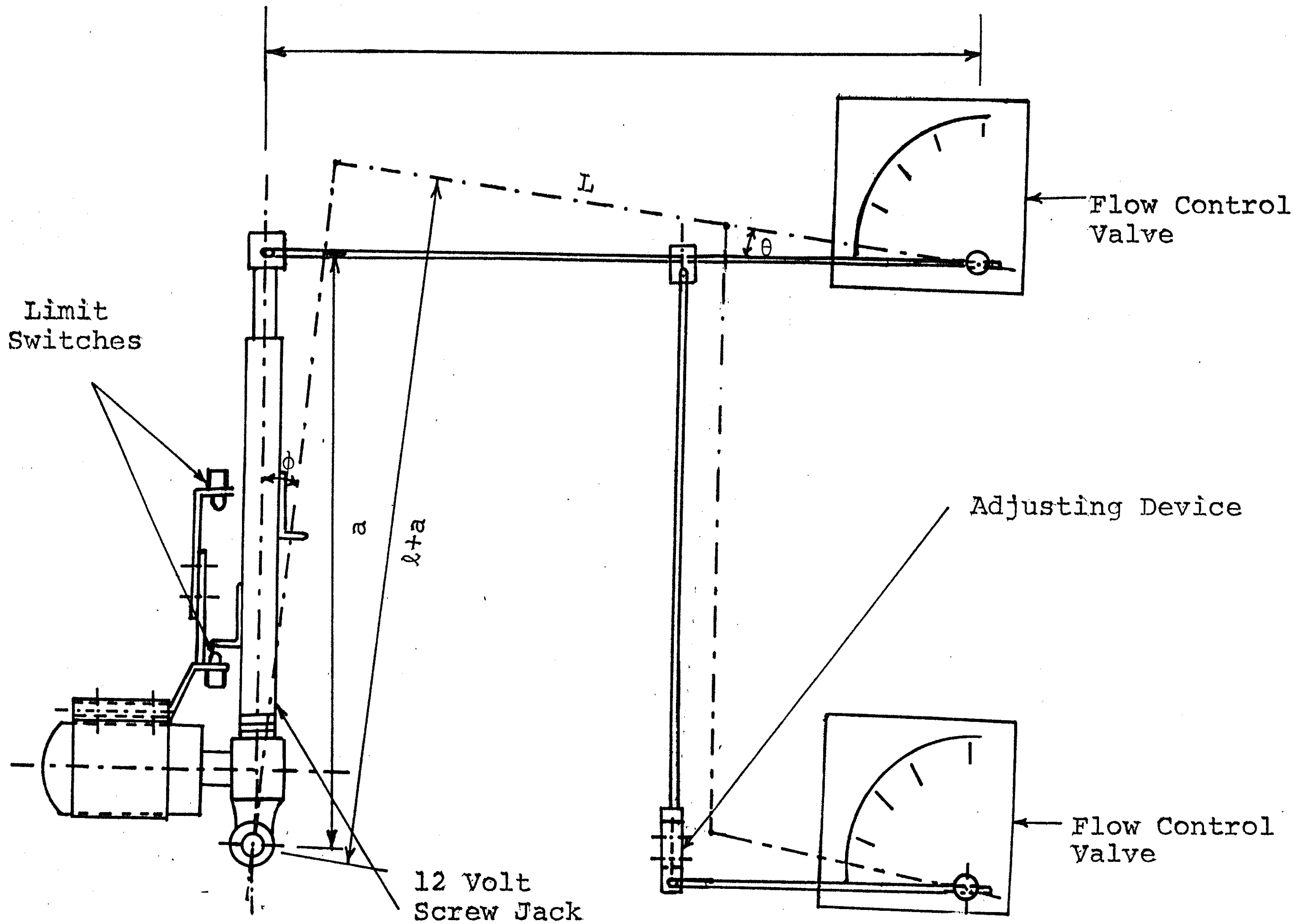

Fig. A.1 Schematic of Remote Control Mechanism.

uator. By adjusting the positions of the limit switches the stroke of actuator was controlled.

The linear actuator was pivoted on a wooden block by a long bolt and spacers. The free end was hooked to the long rod so that the rod could pivot in the free end. The rod was fixed in position by an Allan screw in the hole provided on the flow divider such that the actuating rod length was 51.3 cm. At about 15 cm from the centre of rotation, a short piece of rod was fixed to a similar control rod on the other flow divider. The length of the connecting rod was made adjustable so that a speed differential could be obtained between the two motors.

The electric control switch was located at the tractor operator's seat so that he could increase or decrease the motor speed as was necessary with changing field conditions.

APPENDIX B

RAW DATA

Table B.1 Raw Data for Damage Studies

Field 1

Slow Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	6.22	1.53/10	4.42/18	0.00/0	0.27/1
2	4.17	1.17/7	3.01/15	0.00/0	0.00/0
3	5.11	1.18/8	3.65/21	0.00/0	0.28/1
4	5.56	1.94/12	2.77/12	0.00/0	0.84/3
5	4.81	1.53/8	1.83/9	0.23/1	1.23/3
6	4.02	2.27/14	1.41/6	0.00/0	0.34/1
7	4.87	3.04/19	1.65/6	0.18/1	0.00/0
8	5.15	3.18/18	1.72/9	0.24/1	0.00/0

Fast Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	5.48	1.28/9	3.88/22	0.33/2	0.00/0
2	6.19	0.66/4	5.25/24	0.00/0	0.29/1
3	7.33	2.01/15	5.03/22	0.30/1	0.00/0
4	5.08	1.08/7	2.59/11	0.60/2	0.80/3
5	5.87	1.67/14	2.89/9	0.32/1	1.00/4
6	4.34	2.20/16	0.83/4	0.73/3	0.58/3
7	5.30	2.48/17	1.78/7	0.61/2	0.43/2
8	5.45	2.15/14	1.98/11	0.53/3	0.79/3

Table B.1 Continued

Field 2

Slow Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	5.87	3.64/22	1.94/11	0.00/0	0.30/1
2	4.73	2.33/17	1.60/10	0.00/0	0.81/3
3	6.15	2.39/7	1.02/5	0.00/0	2.75/6
4	4.84	1.85/10	2.55/14	0.30/2	0.15/1
5	5.81	1.77/9	3.45/14	0.00/0	0.60/2
6	6.11	3.63/21	1.66/10	0.46/1	0.37/2
7	5.27	3.15/16	0.58/9	0.29/2	1.25/4
8	4.53	2.48/14	1.77/7	0.00/0	0.29/1

Fast Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	5.53	2.82/15	1.61/8	0.44/2	0.66/3
2	4.88	1.64/10	1.09/6	0.22/1	1.93/8
3	6.04	3.01/15	1.38/7	0.68/3	0.97/3
4	5.29	0.46/2	3.13/17	0.64/4	1.06/4
5	4.26	1.89/11	2.11/10	0.15/1	0.11/1
6	5.46	2.27/17	1.77/10	0.45/2	0.98/4
7	5.03	2.15/14	1.96/7	0.30/2	0.62/3
8	5.12	2.29/12	2.35/12	0.23/2	0.24/1

Table B.1 Continued

Field 3

Slow Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count) UD	SL	MD	SD
1	6.62	2.93/16	2.88/13	0.00/0	0.82/3
2	5.46	1.90/13	2.20/8	0.33/1	1.03/5
3	6.14	2.90/18	2.56/14	0.00/0	0.69/5
4	6.28	2.57/14	3.14/14	0.00/0	0.56/3
5	6.33	2.41/17	2.90/14	0.54/1	0.47/1
6	4.97	1.87/10	2.40/12	0.00/0	0.69/3
7	5.90	3.13/22	2.46/15	0.31/1	0.00/0
8	5.61	2.78/16	2.52/12	0.00/0	0.31/2

Fast Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count) UD	SL	MD	SD
1	6.89	2.37/15	2.51/8	0.48/2	1.53/6
2	6.24	3.02/25	2.01/10	0.40/2	0.82/5
3	6.17	2.95/23	2.31/12	0.00/0	0.91/6
4	6.08	2.74/19	2.83/12	0.00/0	0.51/2
5	5.90	2.12/16	3.57/20	0.00/0	0.22/2
6	5.65	1.62/14	2.72/15	0.57/3	0.74/3
7	4.48	1.98/14	1.74/11	0.15/1	0.62/3
8	6.23	3.05/18	2.71/13	0.00/0	0.47/2

Table B.1 Continued

Field 4

Slow Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	3.99	2.25/16	1.74/9	0.00/0	0.00/0
2	4.76	2.39/15	1.51/9	0.00/0	0.85/1
3	4.44	2.44/13	1.28/6	0.00/0	0.72/2
4	6.11	1.35/9	3.07/16	0.95/3	0.74/2
5	4.64	2.34/19	2.30/11	0.00/0	0.00/0
6	5.92	1.50/10	3.52/9	0.00/0	0.90/3
7	5.32	2.48/19	2.49/16	0.00/0	0.35/2
8	5.37	3.76/26	1.37/6	0.00/0	0.24/2

Fast Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count)			
		UD	SL	MD	SD
1	6.04	1.48/13	3.46/19	0.00/0	1.09/6
2	6.40	1.11/8	3.45/17	0.11/1	1.74/5
3	6.75	1.79/15	3.12/17	0.00/0	1.84/9
4	6.02	2.36/18	2.12/12	0.40/2	1.14/5
5	5.32	1.66/14	2.55/15	0.00/0	1.11/4
6	5.92	2.46/15	3.08/16	0.00/0	0.38/2
7	6.23	2.02/14	2.50/15	0.50/2	1.21/6
8	6.87	2.00/11	4.15/15	0.00/0	0.72/3

Table B.1 Concluded

Field 5

Slow Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count) UD	SL	MD	SD
1	4.94	2.92/22	1.26/6	0.00/0	0.76/2
2	4.63	2.96/30	0.99/5	0.14/1	0.54/3
3	4.37	2.98/22	0.84/5	0.00/0	0.55/4
4	5.41	4.51/26	0.00/0	0.00/0	0.90/3
5	4.10	2.12/19	0.94/4	0.00/0	1.04/5
6	4.86	4.44/25	0.00/0	0.00/0	0.41/1
7	5.06	4.29/32	0.26/1	0.00/0	0.52/4
8	5.73	5.06/33	0.43/1	0.00/0	0.24/1

Fast Speed

Sample Number	Sample Mass (kg)	Mass of Damaged Tubers/Number of Tubers (kg/count) UD	SL	MD	SD
1	4.23	1.83/18	2.02/10	0.00/0	0.38/2
2	5.52	3.83/26	1.36/5	0.00/0	0.33/2
3	4.45	3.18/27	0.85/5	0.00/0	0.42/2
4	4.99	2.29/16	1.62/9	0.00/0	1.08/4
5	5.72	3.50/27	1.61/8	0.00/0	0.61/3
6	4.77	2.68/24	1.47/7	0.00/0	0.62/3
7	5.72	2.82/20	1.06/5	0.59/3	1.26/5
8	5.21	3.22/25	1.28/7	0.00/0	0.71/4

APPENDIX C

CALCULATION OF RESULTS

C.1 Sample Calculations

The raw data were reduced to a percentage basis. Let M be the total sample mass in kg and M_{UD}, M_{SL}, M_{MD} and M_{SD} be the mass in kg of the undamaged, slightly damaged, moderately damaged and severely damaged tubers, respectively, in the sample. Let N_{UD}, N_{SL}, N_{MD} and N_{SD} be the number of tubers classified as undamaged, slightly damaged, moderately damaged and severely damaged in the sample, respectively. The present damage and the average mass in each category were obtained as follows. Sample number one, collected in field one at the slow speed condition was used for the sample calculations.

C.1.1 Percent calculations

(i) Percent undamaged (UD) $= \frac{M_{UD}}{M} \times 100$

$$= \frac{1.53}{6.22} \times 100$$

$$= 24.65$$

(ii) Percent slightly damaged (SL) $= \frac{M_{SL}}{M} \times 100$

$$= \frac{4.42}{6.22} \times 100$$

$$= 71.04$$

(iii) Percent moderately damaged (MD) $= \frac{M_{MD}}{M} \times 100$

$$= \frac{0.00}{6.22} \times 100$$

$$= 0.00$$

(iv) Percent severely damaged (SD) $= \frac{M_{SD}}{M} \times 100$

$$= \frac{0.27}{6.22} \times 100$$

$$= 4.31$$

(v) Percent total damage (MD + SD) $= \frac{M_{MD} + M_{SD}}{M} \times 100$

$$= 0.00 + 4.31$$

$$= 4.31$$

C.1.2 Average mass[1] of tubers in each classification

(i) Average mass of undamaged tubers (UD) $= \frac{M_{UD}}{N_{UD}}$

$$= \frac{1.53}{10}$$

$$= 150 \text{ g}$$

(ii) Average mass of slightly damaged tubers (SL) $= \frac{M_{SL}}{N_{SL}}$

$$= \frac{4.42}{18}$$

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[1]Rounded to two significant digits.

$= 250$ g

(iii) Average mass of moderately damaged tubers (SD) $= \frac{M_{MD}}{N_{MD}}$

$= 0$

(iv) Average mass of severely damaged tubers (SD) $= \frac{M_{SD}}{N_{SD}}$

$= \frac{0.27}{1}$

$= 270$ g

Table C.1 Percent Damage and Average Mass for Field Tests

Field 1

Slow Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	24.65/150	71.04/250	0.00/0	4.31/270	4.31
2	27.98/170	72.02/200	0.00/0	0.00/0	0.00
3	23.03/150	71.48/170	0.00/0	5.48/280	5.48
4	34.92/160	49.89/230	0.00/0	15.19/280	15.19
5	31.80/190	38.03/200	4.70/230	25.48/410	30.17
6	56.39/160	35.16/240	0.00/0	8.45/340	8.45
7	62.45/160	33.89/270	3.66/180	0.00/0	3.66
8	61.87/180	33.39/190	4.74/240	0.00/0	4.74

Fast Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	23.28/140	70.78/180	5.95/160	0.00/0	5.95
2	10.60/160	84.78/220	0.00/0	4.62/290	4.62
3	27.38/130	68.54/230	4.08/300	0.00/0	4.08
4	21.31/150	51.04/240	11.89/300	15.75/270	27.65
5	28.36/120	49.17/320	5.45/320	17.02/250	22.47
6	50.65/140	19.19/210	16.74/240	13.42/190	30.17
7	46.83/150	33.66/250	11.47/300	8.04/210	19.51
8	39.48/150	36.32/180	9.73/180	14.47/260	24.20

Table C.1 Continued

Field 2

Slow Speed

Sample Number	Percent Damage/Average Mass(g) UD	SL	MD	SD	Percent Damage MD+SD
1	61.92/170	32.97/180	0.00/0	5.11/300	5.11
2	49.26/140	33.71/160	0.00/0	17.03/270	17.03
3	38.81/340	16.53/200	0.00/0	44.66/460	44.66
4	38.26/190	52.60/180	6.12/150	3.02/150	9.13
5	30.41/200	59.33/250	0.00/0	10.26/300	10.26
6	59.31/170	27.09/170	7.52/460	6.08/190	13.61
7	59.74/200	10.94/60	5.51/140	23.81/310	29.32
8	54.63/180	39.06/250	0.00/0	6.31/290	6.31

Fast Speed

Sample Number	Percent Damage/Average Mass(g) UD	SL	MD	SD	Percent Damage MD+SD
1	51.05/190	29.12/200	7.96/220	11.87/220	19.83
2	33.62/160	22.36/180	4.50/220	39.52/240	44.02
3	49.90/200	22.80/200	11.20/230	16.10/320	27.30
4	8.62/230	59.11/180	12.14/160	20.12/270	32.26
5	44.28/170	49.58/210	3.56/150	2.58/110	6.14
6	41.60/130	32.37/180	8.17/220	17.87/240	26.03
7	42.74/150	39.00/280	5.89/150	12.38/210	18.27
8	44.79/190	45.92/200	4.57/120	4.72/240	9.29

Table C.1 Continued

Field 3

Slow Speed

Sample Number	Percent Damage/Average Mass(g) UD	SL	MD	SD	Percent Damage MD+SD
1	44.20/180	43.42/220	0.00/0	12.38/270	12.38
2	34.79/150	40.21/270	6.11/330	18.89/210	25.01
3	47.17/160	41.63/180	0.00/0	11.20/140	11.20
4	41.01/180	50.00/220	0.00/0	8.99/190	8.99
5	38.14/140	45.88/210	8.59/540	7.39/470	15.99
6	37.70/190	48.41/200	0.00/0	13.89/230	13.89
7	52.98/140	41.73/160	5.29/310	0.00/0	5.29
8	49.48/170	44.96/210	0.00/0	5.56/160	5.56

Fast Speed

Sample Number	Percent Damage/Average Mass(g) UD	SL	MD	SD	Percent Damage MD+SD
1	34.43/160	36.46/310	6.94/240	22.18/250	29.11
2	48.30/120	32.16/200	6.44/200	13.10/160	19.54
3	47.83/130	37.48/190	0.00/0	14.69/150	14.69
4	45.08/140	46.60/240	0.00/0	8.32/250	8.32
5	35.85/130	60.45/180	0.00/0	3.69/110	3.69
6	28.63/120	48.20/180	10.01/190	13.16/250	23.18
7	44.07/140	38.76/160	3.30/150	13.87/210	17.17
8	49.02/170	43.50/210	0.00/0	7.48/230	7.48

Table C.1 Continued

Field 4

Slow Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	56.33/140	43.67/190	0.00/0	0.00/0	0.00
2	50.34/160	31.71/170	0.00/0	17.96/850	17.96
3	54.95/190	28.74/210	0.00/0	16.31/360	16.31
4	22.07/150	50.20/190	15.55/320	12.18/370	27.73
5	50.43/120	49.57/210	0.00/0	0.00	0.00
6	25.29/150	59.47/390	0.00/0	15.25/300	15.25
7	46.67/130	46.79/160	0.00/0	6.54/170	6.54
8	70.03/140	25.46/230	0.00/0	4.51/120	4.51

Fast Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	24.51/110	57.37/180	0.00/0	18.12/180	18.12
2	17.28/140	53.86/200	1.66/110	27.21/350	28.87
3	26.56/120	46.19/180	0.00/0	27.25/200	27.25
4	39.17/130	35.28/180	6.64/200	18.90/230	25.55
5	31.27/120	47.84/170	0.00/0	20.89/280	20.89
6	41.60/160	51.98/190	0.00/0	6.42/190	6.42
7	32.49/140	40.13/170	8.03/250	19.36/200	27.38
8	29.12/180	60.40/280	0.00/0	10.47/240	10.47

Table C.1 Concluded

Field 5

Slow Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	59.12/130	25.53/210	0.00/0	15.36/380	15.36
2	63.96/100	21.41/200	3.06/140	11.57/180	14.63
3	68.18/140	19.20/170	0.00/0	12.62/140	12.62
4	83.41/170	0.00/0	0.00/0	16.59/300	16.59
5	51.71/110	22.95/240	0.00/0	25.34/210	25.34
6	91.47/180	0.00/0	0.00/0	8.53/410	8.53
7	84.70/130	5.10/260	0.00/0	10.20/130	10.20
8	88.27/150	7.54/430	0.00/0	4.19/240	4.19

Fast Speed

Sample Number	Percent Damage/Average Mass (g) UD	SL	MD	SD	Percent Damage MD+SD
1	43.22/100	47.75/200	0.00/0	9.03/190	9.03
2	69.43/150	24.62/270	0.00/0	5.95/160	5.95
3	71.54/120	19.11/170	0.00/0	9.35/210	9.35
4	45.81/140	32.51/180	0.00/0	21.68/270	21.68
5	61.24/130	28.10/200	0.00/0	10.66/200	10.66
6	56.27/110	30.80/210	0.00/0	12.92/210	12.92
7	49.30/140	18.48/210	10.24/200	21.98/250	32.22
8	61.87/130	24.50/180	0.00/0	13.63/180	13.63

APPENDIX D

ANALYSIS OF VARIANCE

FOR THE DAMAGE STUDY DATA

Table D.1 Analysis of Variance for Damage[1]

Undamaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	22.321	5.580	14.378**
Treatments	1	5.764	5.764	14.852**
Error	74	28.719	0.388	
Total	79	56.804		

Slightly Damaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	22.632	5.658	12.837**
Treatments	1	1.321	1.321	2.997
Error	74	32.615	0.441	
Total	79	56.568		

Moderately+Severely Damaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	1.204	0.301	1.313
Treatments	1	1.567	1.567	6.834*
Error	74	16.963	0.229	
Total	79	19.734		

[1]The sample size was normalised to five kg for analysis of variance
**Significant at one percent level
*Significant at five percent level

Table D.2 Analysis of Variance for Average Mass of Damaged Tubers

Undamaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	0.027	0.007	8.941**
Treatments	1	0.006	0.006	7.964**
Error	74	0.055	0.001	
Total	79	0.087		

Slightly Damaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	0.010	0.002	0.664
Treatments	1	0.000[1]	0.000[1]	0.087
Error	74	0.276	0.004	
Total	79	0.286		

Moderately+Severely Damaged Samples

Source	DF	SS	MSS	F Value
Blocks	4	0.009	0.002	0.174
Treatments	1	0.036	0.036	2.838
Error	74	0.934	0.013	
Total	79	0.979		

[1]Rounded to three significant digits