THE UNIVERSITY OF MANITOBA

AUTOMATIC BOOM HEIGHT CONTROL AND DESIGN PARAMETERS FOR HYDRAULIC DRIVES ON POTATO HARVESTERS FOR USE IN MANITOBA FIELD CONDITIONS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

WINNIPEG, MANITOBA

OCTOBER, 1977

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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

MASTER OF SCIENCE

IN THE NAME OF ALMIGHTY GOD,

THE MAGNIFICENT, THE MERCIFUL

ACKNOWLEDGEMENTS

It is almost impossible to make note of all those whose inspirations have been vital in the completion of this thesis. I am grateful to all of them. I wish to express my sincerest gratitude and indebtedness to my advisor, Dr. J.S. Townsend for his timely assistance, guidance and encouragements at every stage of this study and his patience in reviewing this manuscript. My deep appreciations are extended to Dr. M.G. (Ron) Britton and Professor W.D. Alexander for reviewing the thesis as the examination committee members.

The Department of Agricultural Engineering, University of Manitoba, as a source of funds for this project, deserves particular mention. The cooperation extended by both A.A. Kroeker and Sons Ltd. in providing a potato harvester and the staff of the Glenlea Research Station in providing a tractor and workshop for testing purposes is highly appreciated.

The assistance rendered by Messrs. Henry Shlosser, Jack Putnam, A.E. Krentz and R.H. Mogan during the fabrication and testing stages is sincerely acknowledged.

With humble regards I offer my deepest indebtedness to my affectionate parents and all other family members for their prayers to Almighty God from thousands of kilometres across the sea.

Special thanks are due to Miss Barbara Latocki and Mrs. W.J. Neil for accomplishing the tiring job of typing this manuscript.

ABSTRACT

AUTOMATIC BOOM HEIGHT CONTROL AND DESIGN PARAMETERS FOR HYDRAULIC DRIVES ON POTATO HARVESTERS FOR USE IN MANITOBA FIELD CONDITIONS

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The boom elevator on potato harvesters elevates and delivers the potatoes into a bulk transport vehicle. On present harvesters the height of fall of the potatoes is adjusted manually. Due to inexperience, fatigue or poor judgement by the operator, drop heights are usually too great to handle the potatoes without damage. The economic loss to the potato industry from mechanical injury to potatoes amounts to millions of dollars each year. An automatic boom height control would help to maintain proper drop heights in relation to the pile formation during loading of the truck and thus reduce potato damage.

A considerable reduction in mechanical damage to potatoes can be achieved by coordinating various conveyor speeds on the harvester with the forward speed and the potato yield. Speed adjustment of the conveyors can be achieved using a variable speed hydraulic drive system. Design data for hydraulic drives would help interested farmers and manufacturers to incorporate this system on potato harvesters.

An electrohydraulic automatic boom height control was designed and fabricated. The system was mounted on a Lockwood Mark 76 potato harvester. The modified potato harvester was tested for correct functioning of the automatic boom height control operating both independently from and simultaneously with manual control of the boom height.

The motors for the variable speed hydraulic drive system were supplied with hydraulic oil from a Massey-Ferguson MF 1100 tractor. The boom elevator and the side elevator were run at five different speeds for several simulated yields of potatoes. Data for the hydraulic chain drives were collected for different speeds of the conveyors running under different load conditions.

The automatic boom height control worked satisfactorily when operated independently from the manual control. However, it did not work when there was provision for manual override because of limitations in the existing tractor hydraulic circuits.

The maximum input power required for running a conveyor at a speed of 3 km/h under a potato yield of 37 t/ha was 2.43 kW. The required running torque was 108.3 N.m with a starting torque of 203.4 N.m. The corresponding hydraulic oil pressures were 3.04 MPa for running and 5.78 MPa for starting. Maximum oil flow for each motor was 35.7 l/min.

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CHAPTER I

INTRODUCTION

1.1 Scope of Study

Potato growers lose millions of dollars each year as a result of potato damage inflicted during the harvesting operation. Research conducted by the Department of Agricultural Engineering, University of Manitoba, indicated that the harvester is a major source of potato damage (Townsend, 1977). The potato grower is interested in reducing damage because the damage to the potato increases in storage since any kind of injury is a means by which a disease organism can develop in the stored potatoes.

1.1.1 Automatic boom height control

It has been estimated that the operator of the present potato harvesters spends from 50 to 75 percent of his time monitoring the boom while he is digging (Johnson et al., 1974a). This often leaves too little time to attend to the operation of the machine. As a result, more potatoes than necessary could be damaged because of improper machine operation.

The boom is often set high above the potatoes in the truck so that less operator time is required to monitor it. Drop heights as high as 78 cm were noted in a photographic survey conducted in East Lothian in 1971 (McRae, 1973).

This height was too high to load the potatoes without damage. To reduce the height of fall and thus potato damage, the operator must adjust the boom height in proportion to the height of the potato pile in the truck box as the height varies with time. The operator, however, may not make the required adjustment due to poor judgement, inexperience or fatigue. The result is higher potato damage. Automatic control of the boom height would have the advantage of reducing tuber damage and freeing the operator for other tasks that require his attention.

1.1.2. Hydraulic chain drives

Peterson et al. (1975) reported that it was possible to reduce one half of the mechanical damage to potatoes by setting the various chain speeds of the harvester according to forward speed, yield and soil conditions. This concept was used by the Department of Agricultural Engineering, University of Manitoba, to design variable speed hydraulic drives of the boom, side and rear cross conveyors for harvesters used under Manitoba conditions.

The hydraulic system was field tested on the 1975 harvest in five different fields. The hydraulic drives significantly reduced potato damage as the conveyors were run at slower speeds. On the average the slower speeds reduced damage to 12.5 from 18.1 percent (Townsend, 1977). This was a 31 percent reduction.

The design of the hydraulic drives was, however, based on many assumptions since no design data were available at that time. Actual design data for hydraulic drives would make it easy for interested farmers and manufacturers to introduce this innovation on commercial machines.

1.2 Objectives

The two main objectives of this study were:

1. To design, build and test a low cost electro-hydraulic boom-height control to eliminate the repetitive work associated with manually controlling the drop height of potatoes leaving the boom.

2. To obtain improved design data for the hydraulic drive specification.

1.3 General Approach

An electro-hydraulic automatic boom-height control system was designed and fabricated. The developments were completed at the end of the 1976 harvesting season. A Lockwood Mark 76 potato harvester was made available by A. A. Kroeker and Sons Ltd. for this study. The harvester, equipped with the automatic boom-height control, was taken to the Glenlea Research Station Workshop for testing purposes. A model for sinusoidal inputs was built to test the performance of the system.

The boom elevator and the side elevator hydraulic motors were driven independently by the tractor hydraulic system. The conveyors were loaded at five different loading rates and run at five different speeds. For each loading rate and conveyor speed, the oil flow, oil pressure and conveyor speed were measured. Starting torque was also measured for each loading.

CHAPTER II

REVIEW OF LITERATURE

2.1 Importance of the Potato

Potatoes are the most important horticultural crop in terms of quantity produced and area planted in Manitoba and Canada (Ahmad, 1971). Today, potatoes form one of the main constituents of the food for many people of the world. Both the nutritional and the medical value of the potato are quite significant compared to its cost (Upadhyaya, 1976). The Bureau of Nutrition and Home Economics of the U.S. Department of Agriculture has recommended 7 to 12 servings of potatoes a week. Recommended amounts range up to 2.72 kg a week for a man engaged in heavy work, with 1.36 kg suggested for a woman who keeps house, 1.36 to 2.27 kg each for growing boys and girls (National Potato Council, 1975).

2.2 Potato Production

The development of equipment for the complete mechanical harvesting and handling of potatoes, the continuing decline in the number of workers for hand picking and contract production for processing firms have contributed towards the establishment of potato production as a special enterprise.

2.2.1 Potato production in Canada

The 1976 potato production in Canada by province compared with 1975 is shown in Table 2.1 (Statistics Canada,

Table 2.1 Potato Production in Canada by Provinces in 1976 Compared with 1975 (Statistics Canada, 1976)

Province	Average Yield kg/m^2 [1]		Total Area 10^6 m^2		Total Production 10^6 kg	
	1975	1976	1975	1976	1975	1976
Prince Edward Island	2.26	2.93	186.16	214.48	420.72	628.43
Nova Scotia	1.66	1.73	17.40	16.19	28.88	28.01
New Brunswick	2.25	2.29	218.53	234.72	491.69	537.51
Quebec	1.61	1.86	200.32	210.44	322.52	391.42
Ontario	2.45	2.70	178.06	196.68	436.25	531.04
Manitoba	1.58	1.36	129.50	149.73	204.61	203.63
Saskatchewan	2.35	2.47	10.12	10.12	23.78	25.00
Alberta	2.12	2.51	72.84	68.80	154.42	172.69
British Columbia	2.80	2.68	40.47	46.54	113.32	124.73
All Canada	2.12	2.28	1053.40	1147.70	2196.19	2642.46

[1] Multiply by 10 for t/ha

1976). In 1976 the total production in Canada was 2 642 460 t which was 120 percent of the 1975 production.

2.2.2 Potato production in U.S.A.

Table 2.2 shows the production of Irish potatoes in the United States and the major growing areas (U.S. Dept. of Commerce, 1975). Total production in the United States in 1974 was 15 440 050 t.

2.2.3 Potato production in Manitoba

The area planted to potatoes in Manitoba in 1976 increased by 15.62 percent over 1975 while the total production in the province in 1976 remained approximately the same as that of 1975 (Statistics Canada, 1976). Potato production in Manitoba during 1975 and 1976 is shown in Table 2.1.

2.2.4 Potato growing areas in Manitoba

About 970 000 ha of land in Manitoba have favourable agro-climatic conditions for fully mechanized potato production (Stone, 1969). Potato growing areas in Manitoba include areas along the Red and the Assiniboine Rivers near Winnipeg and areas at Portage la Prairie, Steinbach and Winkler (Stone, 1970).

2.2.5 Potato varieties in Manitoba

Potato varieties grown in Manitoba for commercial purposes include Red Warba, Norland, Viking, Irish Cobbler,

Table 2.2 Irish Potato Production in United States in 1974 (U.S. Dept. of Commerce, 1975)

State	Average Yield kg/m^2 [1]	Total Area 10^6 m^2	Total Production 10^6 kg
California	3.93	283.28	1113.29
Florida	2.01	125.45	252.15
Idaho	2.67	1363.79	3641.32
Maine	2.91	566.56	1648.69
Michigan	2.62	169.97	445.32
Minnesota	2.08	380.40	791.23
New York	2.91	218.53	635.92
North Dakota	1.91	546.33	1043.49
Oregon	3.92	202.34	793.17
Indiana	2.58	129.50	334.11
Washington	4.71	396.59	1867.95
Wisconsin	3.14	202.34	635.35
Others	2.23	1003.62	2238.07
All U.S.A.	2.89	5588.70	15 440.05

[1]Multiply by 10 for t/ha

Norchip, Norgold, Red Pontiac, La Rouge, Netted Gem, Kennebac and Chiefton (Ahmad, 1971).

2.2.6 Market for Manitoba potatoes

Processing plants have been built in Winnipeg, Portage la Prairie, Carberry and Teulon (Stone, 1970). The growth of the processing industry coupled with the lack of potato production in Eastern Canada and United States due to poor seasons has expanded the market for Manitoba potatoes.

2.3 Potato Cultivation in Manitoba

Advances in the technology of potato handling and processing equipment, expansion in the processing industry, improvements in potato varieties, fertilizing and disease control practices have made growing potatoes a highly specialized business requiring large capital investment.

2.3.1 Soil and climate

The best soil for growing potatoes is a rich, deep, friable, well-drained medium or sandy loam, free from stones, moderately acid, and containing adequate amounts of organic matter and moisture (CDA, 1976). Manitoba has a variety of soils including orthic black, dark grey wooded and podzol soils (Faculty of Agr. & Home Economics, 1968). Potatoes are grown in nearly all types of soils in Manitoba.

Tubers form best when the average day temperature is from 15 to 18°C and the nights are cool (CDA, 1967). These conditions exist in the parts of Manitoba where potatoes are grown (Faculty of Agr. & Home Economics, 1968). Rainfall of 2.5 cm per week throughout the growing season gives best results (CDA, 1967). Precipitation in Manitoba is distributed from 5.0 to 7.6 cm per month from May to August which is quite close to ideal conditions (Faculty of Agr. & Home Economics, 1968).

2.3.2 Cultural practices

Soil is generally prepared by plowing to a depth of 15 to 18 cm in the fall or in the spring. This, in addition to preparing the seedbed and the root bed, enhances soil aeration, conserves moisture, helps to control weeds and helps to make nutrients available to the next crop (CDA, 1967).

In the planting operation, cut tubers are placed 5 to 7 cm deep in rows from 22 to 38 cm apart. The rows are spaced from 0.9 to 1.0 m depending on soil type and potato variety. Generally, planting should be delayed until the soil temperature is 4.5°C or higher (CDA, 1967).

Fertilization usually involves the application of 67 to 90 kg/ha of nitrogen and 34 to 56 kg/ha of phosphorous in order to get good yields from loam and clay textured soils. Sandy soils usually require an additional application of 28 kg/ha of potassium (Faculty of Agr. & Home Economics, 1968).

Intercultivation of the potato crop helps to control weeds, break clods and retain moisture. Pre-emergence spraying may be practiced to kill weeds. The field should be cultivated even if it has been sprayed because the dead weeds can also interfere with the operation of the harvester.

Most of the potatoes are grown under dry land farming in Manitoba. The water requirements of the crop are met by the rainfall which occurs during the growing season (Ahmad, 1971).

2.4 Potato Harvesting and Handling in Manitoba

2.4.1 Harvesting time

The harvesting of the early crop in Manitoba usually starts in August. The main crop harvesting season extends from the middle of September to the middle of October (Ahmad, 1971).

2.4.2 Harvesting methods

In Manitoba tubers are harvested by different methods. These are (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. It has been reported that 42 percent of Manitoba growers use the method of direct harvesting where a potato harvester lifts, cleans and delivers the potatoes to a truck (Stone, 1970).

2.4.3 Handling and storage

Potatoes are carried to storage by trucks (Upadhyaya, 1976). 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.

2.5 Potato Damage

Any injury to potatoes caused by agents other than disease, insects or physiological factors is termed as potato damage. Potato growers lose millions of dollars each year as a result of potato damage (Johnson et al., 1974a). Loss occurs through lower potato prices, increased weight loss and decay during storage, and increased processing costs.

Potato damage is classified into three main groups on the basis of shape, size and cause of injury.

2.5.1 Shatter damage

Shatter damage appears as a fissure or a series of fissures with a discoloration at the fissure edge. Shatter damage may penetrate deeply into the tuber and usually breaks the skin of the tuber (Thornton et al., 1972). This damage is most prevalent when tubers are highly hydrated and cold (Vogt and Thiessen, 1974).

2.5.2 Mechanical damage

Mechanical damage results from mechanical gouging or tearing of tubers. The areas of ruptured cells are exposed on the tuber surface (Upadhyaya, 1976).

2.5.3 Internal blackspot

An internal blackspot usually does not penetrate deeper than 6 to 35 mm and usually does not rupture the potato skin (Thornton et al., 1972). Blackspot appears as a relatively uniform discoloration of the damaged tissue when the potatoes are peeled. It cannot be fully detected unless the whole of the tuber is peeled (Phillipson and Lawrence, 1963). This damage is most prevalent when tubers are deficient in potassium or are relatively dehydrated and warm (Vogt and Thiessen, 1974).

2.6 Mechanical Harvesting of Potato Crop

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 and poses a problem in harvesting by mechanical means. Potato tops are killed prior to actual harvest operation.

2.6.1 Top killing

The potato tops present one of the most difficult problems associated with potato harvesting. When they are green, they hang up on the machine. When they are wet and tough, they hairpin on all obstructions, wrap around shafts and collect around the side of the digger nose. Coulters and discs added to the harvesters can solve the problem but the tough vines resist cutting. The destruction of potato tops prior to harvest reduces work and prevents losses from oversized tubers (Faculty of Agr. & Home Economics, 1968).

Tops killed with chemical spraying can often cause blockage problems. Late spraying can also preserve the green tops as a source of blight spores which can be washed on the tubers (Jones, 1967). The use of a rotobeater may reduce the blockage problem but could increase the cleaning problem.

2.6.2 Digging and lifting

The potato harvester digs or lifts a ridge of soil containing potatoes, stones, clods, and plant material. Table 2.3 gives the proportions of various constituents carried by the digger share from the hill of the potatoes in typical soils (Hawkin, 1957). The share may be a blade (flat or dished, one-piece or divided, M- or V-shaped, deep or shallow), drum, dished disc or rotating rod (Glaves, 1962).

A review of work in 1961 showed that in adverse soil conditions from 897 to 1457 tonnes of soil per hectare were lifted by a potato harvester along with some 60 000 to 100 000 tubers. From 25 000 to 55 000 pieces of stems, up to 100 000 stones, similar in size to tubers, and a similar number of clods were also lifted (Sides et al., 1974). On the average a harvester is faced with the task of separating 26.4 t/ha of potatoes from 751.2 t/ha of soil, clods, stones and plant material. Assuming a desirable forward speed of 3.22 km/h the machine must be able to handle each minute about 2.36 t of soil, 0.23 t of stones, 0.27 t of clods,

Table 2.3 The Proportions of Various Constituents lifted by the Potato Harvester Digging Share (Hawkin, 1957)

Soil type and condition	Soil		Clods		Stones		Plant material		Potatoes	
	t/ha	percent	t/ha	percent	t/ha	percent	t/ha	percent	t/ha	percent
Sandy loam dry	1027.82	97.7	Included with soil		16.14	1.5	2.47	0.2	27.80	2.6
Medium loam, stony, moist	654.13	80.3	116.79	14.3	5.16	0.6	Not recorded		38.78	4.8
Medium loam, very stony, moist	546.98	72.2	2.24	0.3	173.96	23.0	Not recorded		34.75	4.6
Sandy loam, very dry	797.15	83.9	125.31	13.2	-	-	4.26	0.4	23.31	2.5
Clay, dry	280.44	70.6	91.01	22.9	-	-	2.24	0.6	23.31	5.9
Clay loam with flints, moist	358.67	76.8	53.58	11.5	41.25	8.8	2.47	0.5	10.76	2.3
Mean	610.87	78.6	77.79	10.0	59.13	7.6	2.86	0.4	26.45	3.4

0.01 t of tops and weeds, and 0.1 t of potatoes (Hawkins, 1957).

2.6.3 Soil separation

Separation of the soil can be done by a rotating drum, a conveyor with agitation, sieving or riddling. The rotating drum tumbles potatoes and causes injury. Sieving or riddling causes no damage except skinning (Upadhyaya, 1976). However, if tubers are dropped onto the separating mechanism, it could lead to damage. The agitated rod-link conveyor is the most common cleaning mechanism (Hawkins, 1957). Usually the conveyors are in two parts, the primary chain immediately behind the share and then the secondary chain. The cleaning efficiency of any chain is influenced by the diameter of the steel rod of which the links are made and the pitch of the links. The drop from the primary chain to the secondary assists in cleaning but if the soil is light and in such condition that all of it falls through the primary chain, the drop may damage the potatoes. Rubber is used extensively on the links to minimize potato damage. The use of rubber rolls to handle the potatoes very gently will reduce the injury. Rubber-covered rolls have the advantage of more positive separation and work well under damp and muddy conditions (Jorgenson and Preston). Rubber-covered rolls were found to operate better for high yields than for low yields.

2.6.4 Removal of plant material

The deviner chain has a space between its consecutive links large enough to allow potatoes, stones and clods to separate from the plant material. A roller about 15 cm in diameter situated near the back of the deviner strips off the potatoes still clinging to the tops. Potato tops and weeds that fall on the rear cross conveyor are removed by the deviner roller located at the junction of the rear cross conveyor and the side elevator.

2.6.5 Separation of stones and clods

The stone and clod separating systems depend on exploiting the differences in physical characteristics such as shape, thickness, width, ratio of thickness to width, length, ratio of length to width, volume, weight, density, hardness, resistance to rotation, resilience, moment of inertia and electrical properties of potatoes on the one hand and stones and clods on the other (McRae, 1973; Sides et al., 1974). Conventional methods of separation include tilted conveyors, elastic strips, floatation in a solution or on a rising air stream, rotating brushes, and optical discriminators controlling mechanical gates.

Tilted conveyors and nylon brushes fail to separate round stones and clods. The method of floatation in soil-water suspensions is a completely successful mechanism but is not practical because of the poor keeping quality of mud-covered potatoes. Air-separation methods have not achieved separation of more than 95 percent of the potatoes and 80 percent of the stones (Eaton and Hansen, 1969). Spectral reflectance with infrared rays, gamma rays and x-rays gives a very high percentage of separation of clods and stones. About 94 to 96 percent separation was achieved by using gamma ray radiation (McRae, 1973). However, this technique was very costly and has the potential hazard of radioactivity to the potatoes and to the farm workers. Slight (1961) achieved nearly perfect separation using x-rays.

2.6.6 Delivery of potatoes to the transport vehicle

In general practice, a cross conveyor and a side elevator convey and elevate potatoes to the separating device (normally a tilted conveyor). The delivery conveyor (boom elevator) elevates the potatoes from the separating conveyor and delivers them into a bulk transport vehicle. The delivery elevator usually has a rubber-covered rod-link conveyor with flights attached to some of the links. Anti-roll belts are found to be advantageous especially on the side elevator where roll back of tubers is common. Anti-roll belts do not need any flights which helps in reducing drop heights because no clearance is required for flights.

2.6.7 Operators

The number of operators required on a machine is determined by the amount of tops, weeds and adverse soil conditions present rather than by the yield of the potatoes.

In general 2 to 5 pickers work on a two-row machine. An inexperienced operator and crew result both in a lower harvesting rate and a higher amount of potato damage.

2.7 Potato Harvest Mechanization

2.7.1 Need for mechanical harvesting

The increased mechanization of potato harvesting has been accompanied by a substantial increase in the total number of damaged potatoes. However, with the increasing demands for potatoes and the ever diminishing labor force, increased mechanization must continue. There are probably three more reasons in favour of complete mechanization of potato harvesting:

(i) the harvest season is very short,

(ii) the farmer desires to be less dependent on casual labour for the harvesting of his important crop and

(iii) mechanical harvesting helps reduce potato production costs.

2.7.2 History of potato harvesters

By 1945, in Idaho, 3951 ha of potatoes were mechanically harvested by 283 machines from a total planted area of 74 645 ha. Practically all of the potato harvesters used prior to 1949 were built in farm shops by farmers or in local job shops by mechanics from ideas developed by farmers (Martin and Humphrey, 1951a; Martin and Humphrey, 1951b).

The major development of equipment for the complete mechanical harvesting and handling of potatoes has occurred since 1950 (Bowman, 1966). By 1952, a substantial number of commercial potato harvesters were in use (French and Levin, 1968). These early harvesters were single-row machines. Later, a two-row indirect harvesting technique made possible increased harvesting rates with single-row harvesters. This method was gradually abandoned with the introduction of potato harvesters designed for a two-row direct operation. The use of a four-row direct-indirect method started in 1962 (French and Levin, 1968). The full capacity of two-row machines in areas with low yields could be utilized by this method.

Many developments have occurred but still the potato industry remains at a low level of overall mechanization. In 1974 the degree of potato harvest mechanization was placed at the fourth level on a scale where 17 represents the highest level of mechanization (Vogt and Thiessen, 1974). Economic losses to the potato industry from mechanical injury to the potatoes have remained high. A low damage potato harvester was designed by the Department 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.

The low damage harvester utilized a number of damage reducing concepts including: a vibrating digger blade, an independent speed control on each chain, an extra long digger section to minimize the lift angle and potato roll back, minimum drop heights at transfer points, an auxiliary roller on the head shaft of the secondary chain and the side elevator to provide a downward rather than an upward tuber trajectory at discharge, return-side drive on the primary chain to minimize drop, staggered loading of the rear cross conveyor and the addition of an anti-roll belt instead of flights, and an automatic boom height control. The initial results showed that the low damage harvester reduced potato injury but the reduction in injury was not as high as expected (Johnson; Johnson and Peterson, 1974; Johnson et al., 1974a; Johnson et al., 1974b). A detailed evaluation of each design concept should be undertaken both to decrease the potato damage and to improve the performance of the harvester.

2.7.3 Mechanization level in Canada

The use of complete potato harvesters in Canada has increased rapidly during recent years. Table 2.4 shows the number of potato diggers and combines sold each year from 1964 to 1975 (Statistics Canada, 1964-1975).

2.7.4 Mechanization level in U.S.A.

Complete harvesters were widely used commercially in the Southeast by 1952 (Bowman, 1966). A survey conducted in 1956 indicated the progress of mechanical potato harvesters

Table 2.4 Sales of Potato Harvesters in Canada from 1964 to 1975 (Statistics Canada, 1964-1975)

Year	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Potato Diggers	166	345	-	58	-	-	-	8	-	-	-	-
Potato Harvesters and Combines	53	146	116	154	87	125	112	57	61	56	235	71

in the different States. In the Red River valley, it was estimated that between 85 and 90 percent of the 68 796 ha of potatoes were being harvested mechanically with 600 to 700 two-row machines. A few self-propelled harvesters were also in use. In Suffolk County (Long Island), with 17 806 ha of potatoes, there were about 200 harvesters, including 70 self-propelled two-row Lockwood machines. Aroostook County (Maine) grew about 55 847 ha of potatoes of which 1645 ha were harvested by mechanical harvesters (West, 1958).

In 1962, it was estimated that there were more than 5000 mechanical potato harvesters and more than 30 000 potato diggers in the United States (Glaves, 1962).

2.7.5 Mechanization level in U.K.

In less than 15 years the use of complete harvesters in Great Britain increased as shown in Table 2.5 (Ministry of Agr. Fisheries & Food et al., 1971; Rutherford, 1973).

2.8 The Potato Combine

2.8.1 Parts

Today's potato harvesters have the following components:

(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

Table 2.5 The Increasing Use of Complete Harvesters in Great Britain (Ministry of Agr. Fisheries & Food et al., 1971; Rutherford, 1973)

Year	Potato Area in Great Britain (ha)	Method of lifting and percent of area lifted by the method			
		Plough	Spinner	Elevating digger	Complete Harvester
1958	289 200	5	72	20	3
1963	276 800	6	45	32	18
1968	243 200	3	25	33	39
1970	236 000	-	15	36	49

tops and weeds;

(iv) a cross conveyor and a side elevator to convey and elevate potatoes to the 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.

2.8.2 Power units

Harvesters can be self-propelled, power-take-off driven or can have a small auxiliary engine to drive the various conveyors. Hydraulic power units powered by the tractor or by an auxiliary engine or both are used to raise the digging units, to adjust the digging depth, to control the tilt of the stone-separating chain and to raise and lower the boom elevator. On the self-propelled Lockwood harvester all steering is done hydraulically and a hydraulic motor is incorporated into the transmission so the forward speed is infinitely variable (West, 1958).

2.9 Potato Damage Investigations

Mechanical damage investigations made in the past have made the potato industry aware of the amount of potato damage and the economic losses involved. Hastings (1931) in North Dakota appears to have been the first to investigate mechanical damage to potatoes. He found that on the average the digger injured 38 percent of the potatoes while manual picking injured an average of 16 percent.

In 1962, the harvesting operation damaged 38 percent of the tubers in Washington (Larsen, 1962). Of the total damage, 7 percent was considered serious. Similar results were found in an investigation at Tulelake, California. It was reported that the total damage amounted to 37 percent of the crop, 12 percent being cutting and 25 percent skinning (Tavernetti and Zahara, 1959).

Humphrey (1950) observed that it was nearly impossible to select 10 injury-free potatoes from the average potato storage. His work resulted in the development of the Idaho Potato Harvester reported by Martin and Humphrey (1951a) and recommendations for the use of harvesting machinery and equipment. Sparks (1957) reported that as much as 50 to 75 percent of the crop in Idaho suffered from mechanical damage in harvesting and handling. His studies showed that 11.5 percent of the damage was serious. Hansen (1970), in Colorado, found that 40 to 90 percent of the potatoes were damaged during harvesting.

In Manitoba, potato damage ranged from 16 to 56 percent of the crop in 1970 with an average total damage of 28.7 percent (Townsend and Ahmad, 1971a). The average damage found before lifting was 4.9 percent while the average damage at the digging blade was 9.2 percent.

At a harvesting demonstration near Ormskirk (U.K.) in 1960, 21.6 percent of the potatoes were found to be undamaged while 58.8 percent were skinned, 10.1 percent were slightly damaged and 9.5 percent were seriously damaged

(Cashmore, 1961; Cashmore, 1962). The amount of damage at this demonstration appears to be high because there was considerable skinning.

In California, damage to potatoes during field harvesting and handling ranged from 40 to 50 percent before the tubers reached the packing shed (Zahara et al., 1961). In Idaho, approximately 10 percent of the tubers did not make U.S. No. 1 grade because of mechanical injury (Sparks, 1957). The average amount of slight and serious damage inflicted by machines in 1969 at Alberta field demonstrations was found to be 18 percent (Jorgenson and Preston). Seven percent of the tubers were found to be left in the field after harvesting by machines. An average amount of severe damage of 22 percent has been reported in Washington (O'leary, 1969).

2.10 Factors Affecting Potato Damage

Six general factors determine the amount of potato damage: soil, tuber characteristics, cultural practices, harvesting method, harvesting operations, and transportation to storage.

2.10.1 Soil

The National Institute of Agricultural Engineering (NIAE) Scottish Station found that a power-driven spinner had a 75 percent higher damage index on dry gravel soil than with dry medium loam (Cashmore, 1961; Cashmore, 1962). Potato damage is usually greater in heavy and compacted soil with high moisture levels than in medium to light and mellow soils with good soil-moisture conditions (Thornton et al., 1972). Medium or heavy soils under damp conditions result in more soil going into storage which could cause rotting (Jones, 1967). Heavy, dry soil results in clod formation, thus increasing potato damage (Thornton et al., 1972). A light soil under dry conditions results in considerable injury to potatoes (Jones, 1967).

Personius and Sharp (1938) and Ophuis et al. (1958) found that damage levels tend to increase at low temperatures. Johnston and Wilson (1969) found a linear relationship between soil temperature and potato damage at harvest time. A 0.5°C increase in soil temperature produced a reduction from 9 to 8 percent damage with a 305 mm drop height. Thornton et al. (1972) found a non-linear response to temperature variations at different tuber hydration levels with respect to potato damage. A pilot study at the NIAE Scottish Station on stored potatoes indicated that internal blackspot tended to fall and shatter damage tended to increase with increasing temperature (McRae, 1975). Potato damage is much higher during the morning than it is during the afternoon and evening because of the lower temperatures in the morning (Thornton et al., 1972). It is advisable to harvest between 11 00 and 23 00 rather than during the traditional 07 00 to 19 00 harvest day. When the temperature becomes quite low, damage levels may be reduced by shortening the daily harvest period to the warmest part of the day.

2.10.2 Tuber characteristics

Potato tubers have clear differences in their resistance to injury depending on variety, moisture content, maturity, size, weight and shape of the tuber.

Varieties differ in the ease with which they are damaged. For example, it has been found that Noordeling is more susceptible to internal blackspot than Eigenheimer, Furore or Voran (Ophuis et al., 1958). At the NIAE Scottish Station the effect of drop height on the 10 most important U.K. varieties was evaluated for different impact surfaces. Results of this study (Table 2.6) clearly indicated the varietal difference to impact injury (McRae, 1975).

Crisp (hydrated) potatoes are highly susceptible to shatter damage but quite resistant to blackspot. The reverse is true for dehydrated tubers (Thornton et al., 1972).

Main crop potatoes should only be lifted when fully matured. Immature tubers are liable to heat in storage causing rotting (Jones, 1967). Cashmore (1961; 1962) reported that Kerr's Pink potatoes harvested at the end of August had a damage index double that of the same crop harvested at the end of October. The explanation is probably that skin thickness increased with maturity.

It is known that smaller tubers are less likely to be damaged than large ones (Ahmad, 1971; Green, 1956). The incidence of splitting and the volume of blackspot increases with tuber weight (Parke, 1963).

Table 2.6 Drop Heights for Different Varieties which Produced 10 Percent Damage (McRae, 1975)

Variety	Drop Height (mm)	
	Surface Flat Steel	Surface Web Rod
Pentland Dell	774	229
Record	732	303
Pentland Ivory	658	198
Redskin	642	218
Maris Piper	617	304
Kerr's Pink	525	223
Majestic	504	210
King Edward	489	-
Pentland Crown	476	-
Desiree	348	-
Mean	576	241

On the average, round potatoes suffer more damage than oval-shaped ones (Cashmore, 1961; Cashmore, 1962; Green, 1956). This is because the round potatoes roll down the elevator and take longer to pass up the elevator. Long potatoes are more vulnerable to damage at their ends.

2.10.3 Cultural practices

Good cultural practices produce favourable soil structure, and, coupled with the minimum number of field operations possible, avoid clod formation and thus reduce damage. Good planting practices such as even spacing and uniform-sized tubers help harvesting operations. Good weed control helps reduce blockage problems and also avoids some loss at harvest time (Upadhyaya, 1976).

2.10.4 Harvesting methods

There is little statistical difference between the amount of potato damage caused by direct or indirect harvesting methods but the trend is in favour of the direct method of harvesting (Larsen, 1962). The rate of harvest is about the same for both methods (West, 1958). An interesting study in California in 1960 indicated that by the time the potatoes reached storage, there was no difference in the amount of damage done by different harvesting methods (Tavernetti and Baghott, 1960). Picking into sacks has been found to be better than picking into baskets from the point of view of potato damage (Martin and Humphrey, 1951a;

Martin and Humphrey, 1951b).

2.10.5 Harvesting operations

Potato damage can occur at any stage of the harvesting operation. About 25 percent of the total damage was done at or before the soil-machine interface (Townsend and Ahmad, 1971a). Peterson (1969), in Washington, analyzed the potato damage at different points on the harvester and reported an average of 54 percent serious damage to the tubers taken from the truck bed. Five percent damage occurred as the potatoes just came onto the digger chain, 16 percent damage at the first drop, 21 percent at the second drop and 12 percent damage during the drop of potatoes into the truck from the boom elevator.

Harvester make and model appears to have no correlation with potato injury (O'leary, 1969; Peterson et al., 1975). Green (1956) could not find any genuine difference between the spinner type and the digger type harvesters with regard to potato damage. However, surveys conducted in 1963 and 1968 gave evidence that the complete harvester leaves less potatoes in the field than does the spinner or elevating digger (Rutherford, 1973). McRae and Blight (1973) reported that spinners gave better performance and caused less potato damage when compared to digger elevators in wet conditions, but the scatter of potatoes following the spinner made hand picking more troublesome.

Results of studies regarding the effect of forward speed on potato damage are contradictory. Humphrey (1950) reported that a field speed of more than 2.41 km/h caused considerable injury to potatoes. The reason for this was that the tubers gained momentum and were damaged when they came in contact with hard clods, stones or parts of the machine. A forward speed of 2.4 km/h with chain speeds of 0.76 m/sec or less was recommended by Humphrey (1950) and Sparks (1957). French and Levin (1968) reported that a forward speed of 6.4 km/h did not cause any excessive damage.

There is evidence that a reasonably high forward speed does not always cause a great amount of damage to the potatoes. In some light soils a high forward speed brings less damage than a slow speed because with the high rate of travel enough soil is retained to provide protection for the potatoes on the primary and secondary chains (Hine and Jamieson, 1964). The output of the harvester can be increased by at least 10 percent and in some cases over 25 percent without increasing damage (Peterson, 1969). During the 1971 harvester evaluation in Washington, harvesting 15 percent slower than the rate selected as optimum by harvester manufacturers increased total damage by 5 percent. Harvesting 21 percent faster than the supposed optimum speed increased total damage by only 1 percent (Peterson et al., 1975).

In the U.K., the main causes of potato damage at harvest time were found to be the harvester blade and agitation on the machine chains (Green, 1956). Damage was estimated to run as high as 45 percent. Hopkins (1956), in a

Maine study, found that nearly all of the major injuries, half of the minor injuries, and one third of the skinning occurred as the tubers were lifted from the ground by the blade.

Johnson (1974) designed and tested a vibrating blade. Results showed a reduction of 50 percent in total potato damage compared to the standard blade. However, the vibrating blade cut more potatoes. The vibrating blade was also found to have lower draft and lower spill out losses. But no net saving in power was realized because of the power expended to operate the vibrating blade. 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 condition (Johnson, 1974).

The main purposes of the conveyors are to remove soil from the potatoes and to convey the tubers to the truck. High chain speeds remove soil faster and hence expose the potatoes to the fast moving chains which damage the tubers. It was reported that potatoes change from zero velocity to the chain velocity in approximately one second in a distance of 90 cm (Humphrey, 1950). Less tuber damage occurs when the chains run slowly but are full so that the tubers do not roll (Johnson and Peterson, 1974). Nearly a 27 percent increase in undamaged tubers was achieved in Manitoba by slowing down the conveyors so as to run full (Townsend and Upadhyaya, 1975).

Studies conducted by Peterson et al. (1975) indicated that it was possible to reduce mechanical damage to potatoes by adjusting the speeds of the various conveyor chains in relation to forward speed, yield and soil conditions. This concept was used in the development of a low damage harvester by Johnson et al. (1974b). The low damage harvester utilized variable speed hydraulic drives.

Chain agitation can be provided to loosen and remove the soil. In loose soils, 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 to 4.5 percent (Finney et al., 1964). It is recommended that the soil-separating area be increased so that agitation can be eliminated.

Studies have clearly indicated that padding the conveyors reduces potato damage (Preston, 1969). Green (1959) and Zahara (1964) reported that the use of padding materials reduced damage by one half while Humphrey (1950) showed that damage was dropped from 15 to 2 percent after covering steel chains with rubber tubing.

In tests conducted both in the field and on a stationary digger, it was found that as the number of chains decreased, the damage decreased. A single chain, the same length as two short chains, caused less damage because of the elimination of the drop (Green, 1956). Hardenburg (1933) also reported less injury with one continuous chain.

More serious potato damage is caused by the boom elevator on account of the greater drop distances which result in violent impact with the truck bottom or the potato pile already present in the truck (Ophuis et al., 1958). The bottom layer of potatoes in a typical farm trailer constitutes about 8 percent of the load (McRae, 1975).

Some harvesters have a 61 to 76 cm free fall of tubers from the boom to the truck (Hansen, 1970). In 1971 a photographic survey of three makes of harvesters on eight farms in East Lothian was made to determine typical transfer conditions from harvester to trailer. It was found that the mean drop height was 78 cm when the trailer began to fill while it was reduced to 49 cm as filling continued (McRae, 1973). On five of the farms no attempt was made to alter the delivery height at all.

Parke (1963) noted that a drop of 26 cm led to severe damage to potatoes. Bruising can be reduced by decreasing the distance a tuber has to drop (Jones, 1967). Potato tubers can be allowed to fall freely only about 15 cm onto any hard surface if all damage is to be avoided (Hawkins, 1957).

The incidence of damage is much less when a tuber is dropped onto a layer of potatoes (Cashmore, 1961; Cashmore, 1962). Evidence has indicated that the damage level when potatoes fall on bare floor boards is 10 times greater than when they drop onto potatoes covering the trailer (McRae, 1975). Weaver et al.(1965) reduced potato damage due to the drop into the truck by harvesting potatoes into water held in a water-tight body. The use of water as a cushioning agent was later utilized by Johnson (1970) in the design of a "water" harvester.

A joint effort between the Agricultural Engineering Department and the Electrical Engineering Department at the University of Idaho was initiated to develop automatic height control for the potato harvester boom (Johnson; Johnson and Peterson, 1974; Johnson et al., 1974a; Johnson et al., 1974b). The sensing unit used high frequency sound to sense the distance from the potatoes. The sensor was located about 76 cm from the potatoes and no part of the device touched the potatoes. The unit was reported to be working well but the cost was too high to be economically feasible.

In an extensive survey conducted in 1968-69, fourteen different operators were compared. It was found that the resulting damage varied from 3 to 47 percent. This showed that the skill of the operator had considerable influence on the potato damage (O'leary, 1969).

2.10.6 Transportation to storage

Potatoes are transported to storage in a variety of vehicles. There is evidence of damage in transit though the proportion of damage attributed to filling, transit and emptying is uncertain. A survey conducted in East Anglia in 1959 indicated that 10 percent total damage, including 6 percent serious damage, was inflicted on potatoes during the transportation of potatoes from the field to the store

(Cashmore, 1961; Cashmore, 1962). In the U.S.A., Weaver et al. (1965) reported that a considerable reduction in potato injury was achieved by using trucks partially filled with water to cushion tubers in handling from harvester to storage. This system is, of course, only applicable to tubers being prepacked after washing and sold shortly after harvest.

CHAPTER III

DESIGN OF AUTOMATIC BOOM HEIGHT CONTROL SYSTEM

3.1 Problem stated

Potato harvesting systems that permit free fall of tubers from the boom into the truck result in a high incidence of damage. The severity of damage depends on the distance the tubers fall. Proper adjustment of the boom height can considerably reduce the risk of damage to potatoes. As the height of the pile in the transport truck changes both with time and with the forward and backward movement of the truck, a proportional change in the boom height is required. With these factors in mind, the operator attempts to manually adjust the boom height.

It has been estimated that operators of present potato harvesters spend from 50 to 75 percent of their time adjusting the boom while digging (Johnson et al., 1974a). This often leaves too little time to attend to the operation of the rest of the machine. To avoid this situation, the boom is often set high above the potatoes in the truck so that less operator time is required for adjustment. This practice reduces the operator fatigue but results in a higher amount of potato damage.

Automatic control of the boom height would have the advantage of reducing tuber damage and freeing the operator for other tasks that require his attention. The following factors were taken into account in designing the automatic boom height control:

1. The free fall of tubers from the boom to the transport truck should be of minimum distance.

2. The boom should follow the changing contours of the potato pile when relative forward and backward movements of the harvester and the transport truck occur.

3.2 Overall Design Concept of Automatic Boom Height Control

The automatic boom height control system designed was a combination of mechanical, electronic and hydraulic components. A mechanical height sensor attached to the end of the outer boom determined the height of the free fall of the tubers. When the sensor touched the bottom of the truck box or the top of the potato pile, the microswitch on the sensor actuated the electronic circuit which in turn operated the electrohydraulic valve. With the microswitch closed, current passed to the double-solenoid hydraulic valve which lifted the boom. Lifting continued for a small time interval. After this small time interval the circuit switched the solenoid valve to the down position. The boom continued to cycle up and down through a distance which depended on the setting of the time delay for upward movement and the flow of oil from the tractor hydraulic supply.

3.3 The Height Sensing Unit

A prerequisite in the design of the sensor to control the boom height was simplicity and low cost. The height sensing unit consisted of a switch mounting bracket to accommodate a microswitch and a sensor with an actuating arm to actuate the microswitch. Field observations during the 1976 harvest established that at least two height sensing units were needed, one for each side of the outer boom. The use of only one sensing unit attached to one side of the boom would be ineffective or would cause excessive injury to tubers when the boom was discharging potatoes near the front or rear of the truck box due to the pile shape.

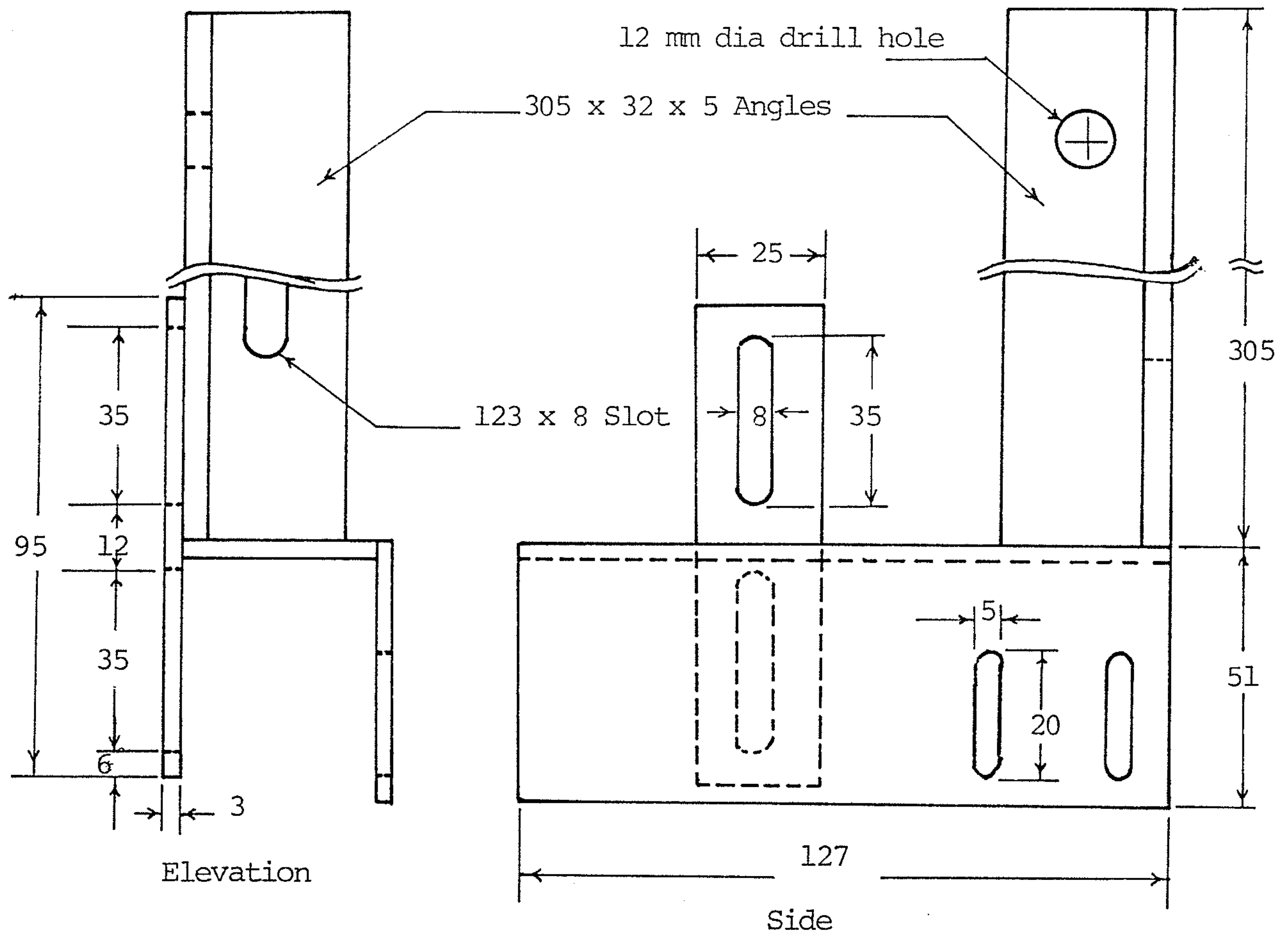
3.3.1 Switch mounting bracket

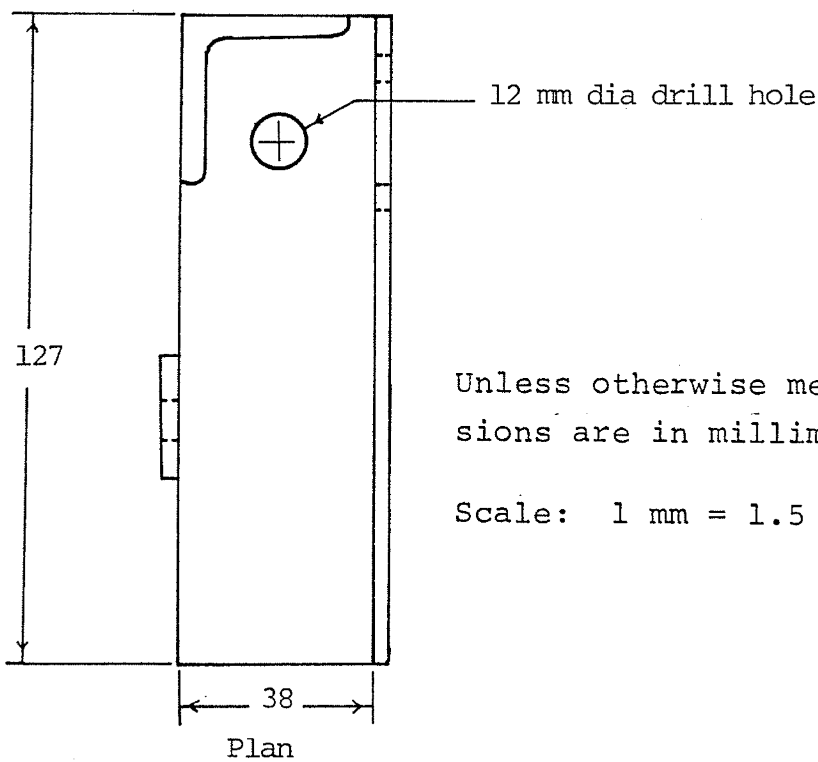
The following considerations were used in the design of the switch mounting bracket (Fig. 3.1).

1. The positions of both the microswitch and the actuating arm should be adjustable, relative to each other.

2. Over travel of the microswitch had to be avoided.

Two microswitches with 162 mm long actuating levers were selected (Camgard No. BZ-2RW863-A2). The maximum over travel for the switch actuator was 15 mm. The material used for the construction of each switch mounting bracket was mild steel angles and plates. Unless otherwise mentioned, the angles were 305 mm x 32 mm x 5 mm and the plates were 3 mm thick. The dimensions of the base and side plates were 127 mm x 38 mm and 127 mm x 51 mm respectively. A 123 mm x 8 mm





Unless otherwise mentioned all dimensions are in millimetres

Scale: 1 mm = 1.5 mm

Fig. 3.1 Switch Mounting Bracket (Right Side) slot was made in the angle so that the sensing unit could be adjustable on the boom. This made field adjustment of the drop height easy.

A 12 mm diameter hole was drilled in the angle while another hole of the same size was drilled in the base plate. These holes were used for wiring purposes. Two 20 mm x 5 mm slots were made in the side plate for mounting the micro-switch. The slots allowed for adjustment in the position of the microswitch if required. The angle was welded to the top of the base plate while the upper edge of the side plate was welded to the base plate at an angle of 90 degrees. Another 95 mm x 25 mm plate with two 35 mm x 8 mm slots was welded to the base plate on the opposite side of the side plate. This plate was used to mount the actuating arm holder (clamp plate) and the slots allowed for the adjustment of the sensor in the vertical plane.

3.3.2 Sensor and actuating arm

A reasonable area of contact, softness and low mass were considered to be the basic requirements for the sensor which was to touch the potato pile for determining the height of fall of the potatoes. A plastic sponge was ideal for this purpose. A 127 mm x 102 mm piece of sponge 50 mm thick was glued to a 114 mm x 95 mm sheet metal plate.

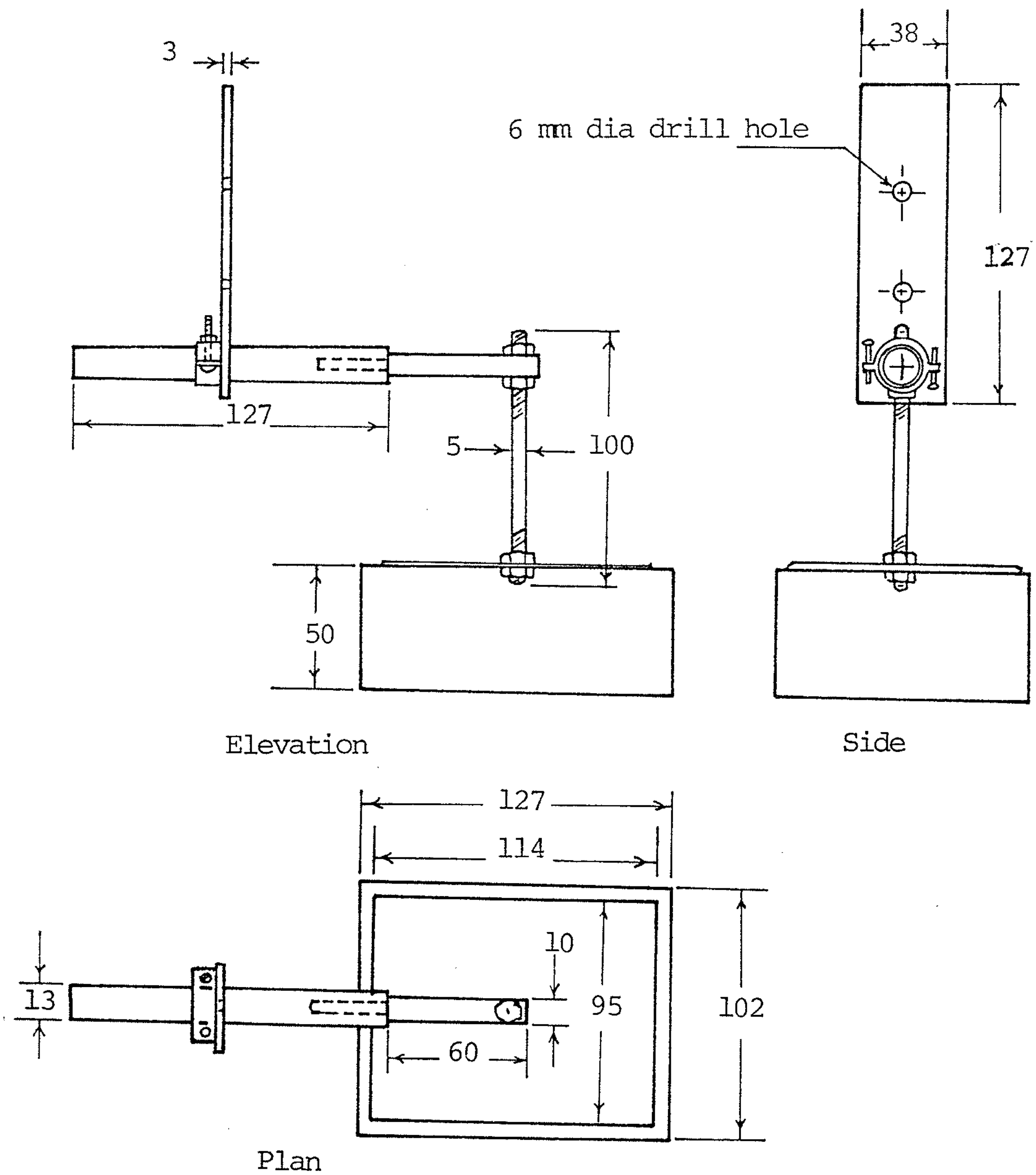
The actuating arm was required to be stiff and flexible at the same time so that it would not be damaged in case the downward movement of the boom continued after the sensor touched the potatoes. A 13 mm diameter, 127 mm long, 5 coils per cm spring was selected (A. Adams, Spring No. 42) for use as the actuating arm. The length of the spring was not long enough for adjustment if required. Therefore, a mild steel rod 10 mm in diameter and 90 mm in length was used to extend the length of the arm. One end of the rod was reduced to 8 mm in diameter for a length of 30 mm. This end was pushed inside of and welded to the spring.

On the other end of the extension rod a 5 mm diameter hole was drilled. A 5 mm diameter, 100 mm long bar, threaded on both ends, was used to connect the sensor and the actuating arm (Fig. 3.2). A 127 mm x 38 mm plate (clamp plate) fastened the sensor to the switch mounting bracket using two 6 mm diameter bolts. A 13 mm diameter hole drilled in the clamp plate made it easy to adjust the effective length of the spring. A two-piece screw clamp, the lower part of which was welded to the clamp-plate, clamped the spring.

3.3.3 Mounting the height sensing assembly

The clamp-plate was bolted to the opposite plate of the switch mounting bracket by two 6 mm diameter bolts. The complete height sensing unit is shown in Fig. 3.3. The microswitch and the actuating arm were positioned in such a way that the microswitch was switched on when the sensor moved the actuating arm up. Over travel on the microswitch was avoided due to the stop provided by the side-plate.

One height sensing unit was mounted on each side of



Unless otherwise mentioned all dimensions are in millimetres

Scale: 1mm = 3 mm

Fig. 3.2 Sensor and Actuating Arm (Right Sensing Unit)

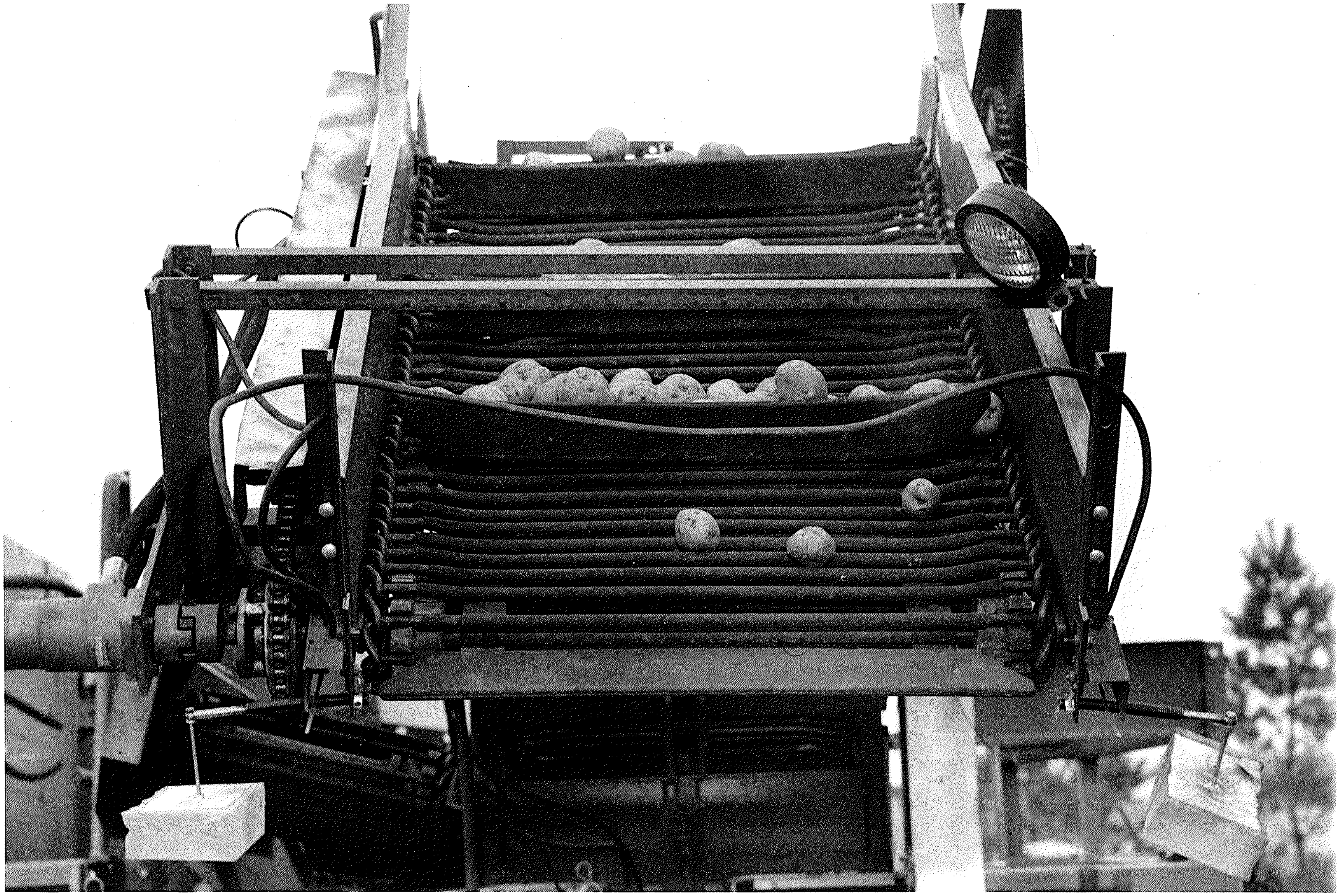


Fig. 3.3 Height Sensing Assembly Mounted on the Outer Boom

the end of the outer boom (Fig. 3.3). Two 8 mm diameter holes, 50 mm apart, were drilled in the boom for the bolts to mount the height sensing unit. The sensing unit was adjusted so that the lower surface of the sensor was slightly below the level of the flights on the boom conveyor. This gave a clearance between the conveyor flights and potatoes. The slot in the mounting angle on the sensing unit made it easy to adjust the height of fall of the potatoes.

3.4 Electronic Circuit

The purpose of the electronic circuit was to control the current to the solenoids of the electrohydraulic valve depending on the position of the sensor. The electronic circuit is shown in Fig. 3.4. Table 3.1 gives an explanation of the symbols and abbreviations used. All of the electronic components except the control switches were enclosed in a control box. If any one or both of the two microswitches of the height sensing units is closed with the automatic control switch on, current from the tractor battery passes to the up solenoid which opens the electrohydraulic valve to lift the outer boom. Lifting continues for a preselected time interval and then the circuit switches the solenoid valve to the down position. The time delay for the down solenoid had a range of from 1.0 to 3.5 s and was adjusted by a multiposition rotary switch. This delay was incorporated in the initial circuit to eliminate the effect of vibrations. A time delay of 1.4 s was used for the up

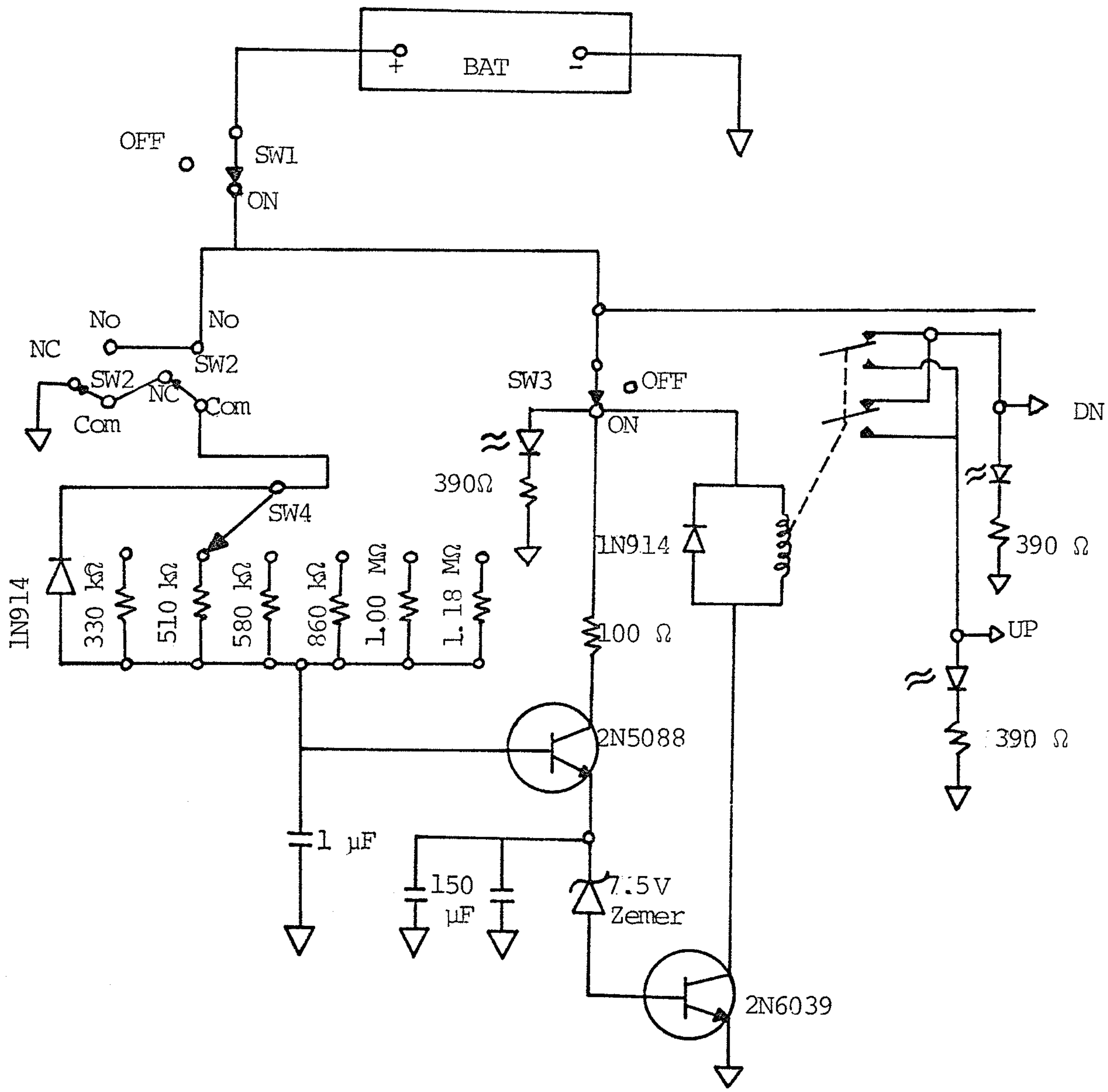
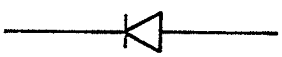
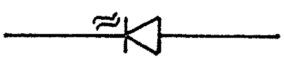
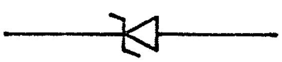
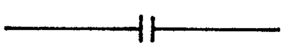
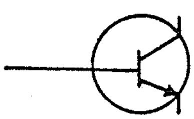
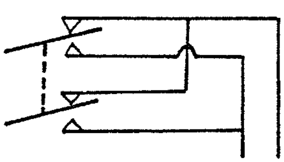


Fig. 3.4 Electronic Circuit for Automatic Boom Height Control (Initial)

Table 3.1 Symbols and Abbreviations used in the Electronic Circuit

Symbol or Abbreviation	Explanation
 BAT	Battery
SW1	Automatic control switch
SW2	Microswitch of sensing unit
SW3	Power on-off switch
SW4	Time delay switch
NO	Normally open terminal
NC	Normally closed terminal
Com	Common terminal
	Diode
	Light emitting diode
	Voltage reducing diode
	Resistance
	Capacitance
	Transistor
	Magnetic relay
	To the negative of battery
 DN	To down solenoid
 UP	To up solenoid

solenoid.

3.5 The Hydraulic Circuit

It was thought that the hydraulic supply from the tractor would do for both the manual and the automatic controls of the potato harvester. Most tractors have two hydraulic supply circuits. One circuit was used for the manual controls and the other was used for the automatic control. The swivel union elbows for outer-boom cylinder oil supply hoses on the manual control unit were replaced by swivel union tees. This permitted connection of the outer-boom cylinder to both the manual and the automatic control valves. The modified hydraulic circuit is shown in Fig. 3.5. Table 3.2 explains and identifies the symbols and components used in the hydraulic circuit.

3.5.1 The electrohydraulic valve

The outer boom was to cycle up and down to follow the changing heights of the potato pile when set to work on automatic control. It was required that the boom should stay in position when the automatic control was shut off so that the manual control could be used to adjust the boom height. A tandem center, 3-position double solenoid hydraulic valve was selected to meet these requirements. Selection of a particular valve depends on the rated oil flow and the oil pressure in the hydraulic system.

The potato harvester in this study was operated in

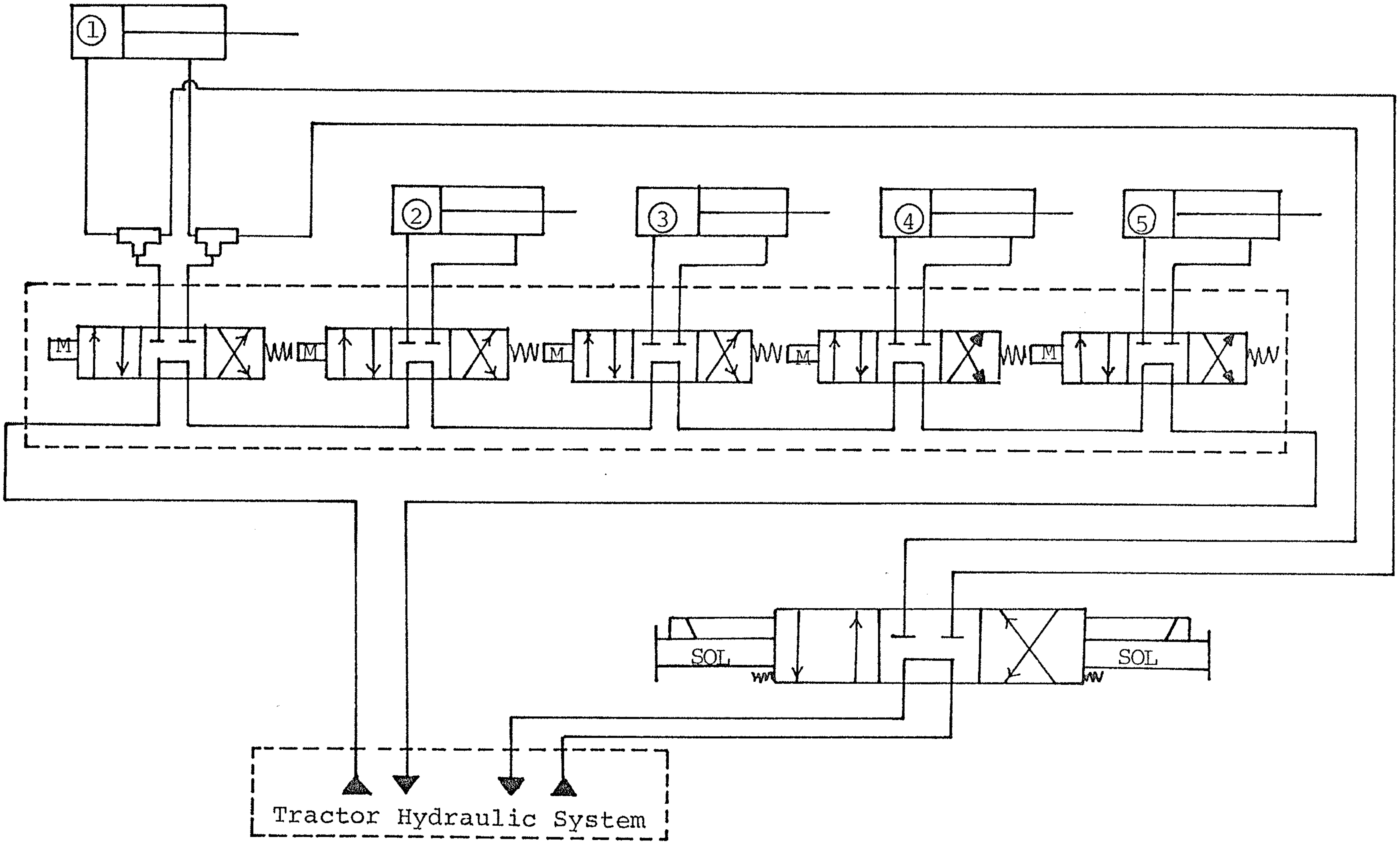
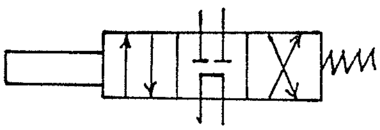
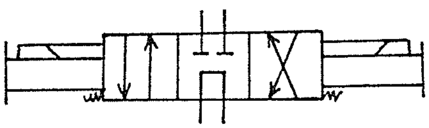
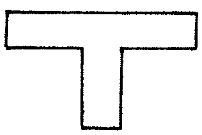
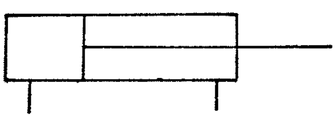


Fig. 3.5 Hydraulic Circuit for Potato Harvester Controls

Table 3.2 Explanation of the Nomenclature Used in the Hydraulic Circuit

Nomenclature	Explanation
 P T	Tandem-center manual control valve
 T P	Tandem-centre double solenoid control valve
	Tee connector
	Double-acting, single-end rod hydraulic cylinder
①	Outer-boom cylinder
②	Inner-boom cylinder
③	Digger cylinder
④	Coulter cylinder
⑤	Steering cylinder

the field by an International Harvester Farmall 1256 tractor. But only a Massey-Ferguson MF 1100 tractor was available for testing purposes. Hydraulic pump information for both of these tractors is given in Table 3.3.

A double solenoid valve was obtained (Pritchard Engineering Co. Ltd., Model DG SM-01X-10). Table 3.4 shows the specifications of the valve. This valve was considered adequate for either of the two tractors. A mounting subplate (Pritchard Engineering Co. Ltd., Model DG 4S4-018C-50) was bolted to the valve. The subplate provided for connection of the hydraulic hoses.

3.6 Mounting of the Automatic Control Unit

The manual controls for the potato harvester are located on the right fender of the tractor. It was desirable to have the automatic control unit near the operator's station on the tractor. A mounting bracket of mild steel angles and plates was made to mount the solenoid valve and the electronic control box (Fig. 3.6). Unless otherwise mentioned, the angles were 241 mm x 38 mm x 5 mm and the plates were 3 mm thick.

A triangular-shaped notch was cut out of one side of the angle. The angle was then bent 90 degrees. Another angle was shaped in a similar fashion. A 318 mm x 38 mm plate was bent twice at 90 degrees to form a J-shape. This plate was welded on top of one angle as shown in Fig. 3.6. Another 152 mm x 38 mm plate was welded on top of the second

Table 3.3 Tractor Hydraulic Pump Specifications

Tractor Make and Model	International Harvester Farmall 1256	Massey-Ferguson MF 1100
Maximum Pressure (MPa)	14	14
Remote working pressure (MPa)	14	14
Maximum oil flow (l/min)	45	76
Remote working oil flow (l/min)	45	49

Table 3.4 Specifications of the Electrohydraulic Valve

Operating Pressure (MPa)	Recommended oil flow (l/min)	Maximum flow without malfunction (l/min)
21	45	45
14	76	76
7	95	114

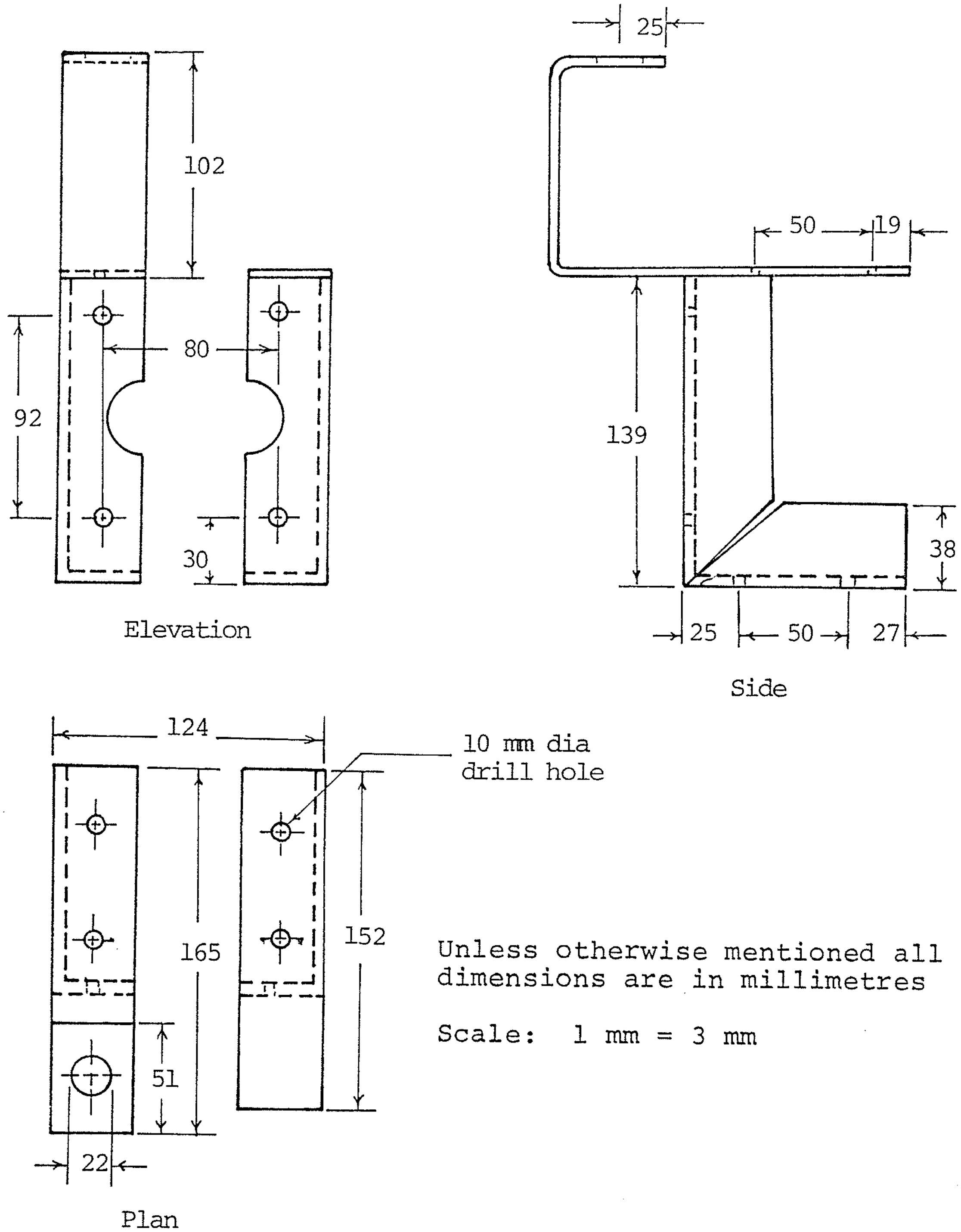


Fig. 3.6 Automatic Control Mounting Bracket

angle. Four 10 mm diameter holes were drilled in the angles and were used for bolts to mount the solenoid valve on the mounting bracket. The control box was bolted on top of the welded plates. The whole unit was mounted at the manual control station using four 10 mm diameter bolts (Fig. 3.7).

Fig. 3.7 View of Mount for Automatic Control Unit

CHAPTER IV

HYDRAULIC DRIVE SPECIFICATIONS

4.1 Hydraulic Drives

Studies conducted by Washington State University have shown that damage to potatoes during harvesting can be considerably reduced by setting various chain speeds according to the forward speed, yield and soil conditions. The primary and secondary chains carry mainly soil and hence their speeds should be adjusted in relation to the forward speed and the soil type. However, the rear cross conveyor, the side elevator and the boom elevator handle mainly potatoes. Thus their speeds should be coordinated with forward speed and yield.

The concept of speed adjustment of the conveyors has been utilized by the Department of Agricultural Engineering, University of Manitoba, for the yield conditions of Manitoba (Upadhyaya, 1976). The mechanical drives of the rear cross conveyor, the side elevator and the boom elevator were replaced by two separate variable speed hydraulic motors on a Lockwood Mark 76 potato harvester. The side elevator and the rear cross conveyor were driven by one motor (Side motor). Another hydraulic motor (Boom motor) drove the boom elevator. Both these motors ran in parallel and directly or indirectly drove the head shafts of the conveyors. The motors were supplied with hydraulic oil from a gear pump which was driven from the main drive shaft on the potato harvester.

4.2 Hydraulic Pump and Motor Specifications

The specifications for the hydraulic motors and the pump of the hydraulic drive system designed by the Department of Agricultural Engineering, University of Manitoba, are given in Table 4.1 (Princess Auto and Machinery Ltd., Buyer's Guide No. 133, Pages 35 and 39).

The selection of a pump actually depends upon the maximum design oil flow required to drive the motors to achieve maximum desired conveyor speed. The required maximum oil flow can be determined from the maximum motor design speed and the motor displacement. For a motor which drives the conveyor head shaft directly, the motor speed is

$$N = 50\ S_C/(3\ \pi d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (4.1)$$

where

N = motor speed, rev/min

S_C = conveyor speed, km/h

d = diameter of head shaft, m

The oil flow required to drive the motor at this speed would be

$$Q = ND \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4.2)$$

where

Q = oil flow, l/min

D = motor displacement, l/rev

From equations 4.1 and 4.2

$$Q = 50\ S_C D/(3\ \pi d) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (4.3)$$

Table 4.1 Specifications for a Hydraulic Drive System incorporated on a Lockwood Mark 76 Potato Harvester

Specification	Boom Motor	Side Motor	Pump
Displacement (l/rev)	0.2442	0.1688	-
Maximum flow capacity (l/min)	56.8	56.8	90.8**
Maximum speed (rev/min)	233*	336*	1800
Maximum pressure (MPa)	6.89	8.27	8.27
Maximum output torque (N.m)	119.5	165.5	-
Remarks	Charlyn hydraulic orbit motor (M-206) Item No. 3201086	Charlyn hydraulic orbit motor (M-204) Item No. 3201084	Hydraulic gear pump Item No. 1201148

*at maximum flow capacity of 56.8 l/min

**at a rated speed of 1800 rev/min

Then, assuming a reasonable motor displacement, the maximum oil flow required can be calculated by substituting the value of maximum conveyor speed in equation 4.3. Conversely if the maximum oil flow is known, the required motor displacement could be calculated.

Design pressure for the hydraulic system depends on the load on the conveyor which in turn is dictated by the forward speed, the conveyor speed on the harvester and the yield of potatoes.

4.3 Forward Speed

The rate of work is determined by the forward speed of the harvester. Hence a reasonable forward speed should be maintained for adequate field capacity. Results obtained by various research workers concerning the effect of forward speed on potato damage do not agree. In general practice the forward speed varies from 2 to 4 km/h depending on the yield of potatoes and the soil conditions. A reasonable field speed of 3 km/h is assumed in this study.

4.4 Conveyor Speed

An attempt was made to develop a relationship between conveyor speed, forward speed and yield. Ideal speeds both for the boom and the side elevators were determined for a potato yield of 30 t/ha with a reasonable forward speed of 3 km/h.

4.4.1 Boom elevator speed

Mohsenin (1970) has given the following values for the physical parameters of potato tubers:

Major diameter, a = 8.2 cm

Intermediate diameter, b = 7.2 cm

Minor diameter, c = 5.2 cm

For this study a potato tuber is assumed to be spherical in shape with a diameter of 7.2 cm. This assumption can be justified since the sphericity of potato tuber is 0.82 as given by the following formula (Mohsenin, 1970):

$$\text{Sphericity} = (abc)^{1/3}/a \quad \ldots\ldots\ldots\ldots \quad (4.4)$$

A perfect sphere has sphericity of 1.0. It is further assumed that the tubers make a uniform layer with depth equal to their diameter on a conveyor of w_c metre width. The total number of potatoes (N_p) per unit metre length of conveyor is

$$N_p = w_c/b^2 \quad \text{tubers/m} \quad \ldots\ldots\ldots\ldots \quad (4.5)$$

If each potato has a unit volume of v, m^3 and a unit density of d_s, kg/m^3, the total mass of potatoes on a unit length of the conveyor would be

$$W_p = N_p v d_s \quad \text{kg/m} \quad \ldots\ldots\ldots\ldots \quad (4.6)$$

where

W_p = mass of potatoes per unit conveyor length, kg/m

Combining equations 4.5 and 4.6

$$W_p = (w_c v d_s)/b^2 \quad \text{kg/m} \quad \ldots\ldots\ldots\ldots \quad (4.7)$$

The time required to harvest one hectare of potatoes with a harvester with a cutting width w metre, working at a constant forward speed of S km/h in a field with Y t/ha yield and at a field efficiency of 100 percent is:

$t = 10/(wS)$ h/ha . . . . (4.8)

A yield of Y t/ha spread uniformally on a conveyor needs a Y/W_p km/ha long conveyor. Therefore the conveyor should travel this distance in t hour if there is to be no build up of tubers. In other words the conveyor should run at a speed of

$S_c = YwS/(10\ W_p)$ km/h . . . . (4.9)

Substituting W_p from equation 4.7

$S_c = YwSb^2/(10w_c vd_s)$ km/h . . . . (4.10)

The use of equation 4.10 is illustrated by calculating the ideal speed of the boom elevator for a yield of 30 t/ha and a reasonable forward speed of 3 km/h. The dimensions of the boom elevator and the physical parameters of the potato tubers used in the equation are:

width of cut of the harvester, $w = 2$ m

width of boom conveyor, $w_c = 0.85$ m

diameter of potato tuber, $b = 0.072$ m

unit volume of potato tuber, $v = 0.0002$ m^3/tuber

unit density of potato tuber, $d_s = 1118.09$ kg/m^3

Substituting into equation 4.10 gives the ideal speed for the boom elevator:

$S_b = 0.5$ km/h

4.4.2 Side elevator speed

The side elevator receives potatoes, stones and clods. Equation 4.10 can be applied to the side elevator as well but must be modified to account for stones and clods present with potatoes. Let n be the ratio by weight of stones and clods to the weight of potatoes lifted. The total weight carried by the side elevator during the harvest of one hectare is equal to the yield of the potatoes plus n times yield. Replacing Y by Y + nY in equation 4.10 gives an expression for the side elevator ideal speed:

$$S_s = Y(1 + n)\ wSb^2/(10\ w_c v d_s) \quad \text{km/h} \quad . \ . \ . \ . \ . \ (4.11)$$

A yield of 30 t/ha and a forward speed of 3 km/h are again assumed to illustrate the use of equation 4.11. The width of the side elevator is 0.85 m. The ratio n is assumed to be 1/3.

Substituting into equation 4.11 gives the ideal speed of the side elevator as:

$$S_s = 0.7 \text{ km/h}$$

4.5 Simulation of Potato Yield

It has been reported that tubers are less damaged if the conveyors run at slower speeds and have a uniform layer of potatoes over the whole conveyor surface (Peterson et al., 1975; Townsend, 1977). Although conveyors may sometimes be required to run at higher speeds, the yield of potatoes was simulated as if the conveyors run at a slow speed uniformally full of potatoes.

In this study the conveyors were loaded with sand bags having a weight of W_s kg/m of conveyor length to represent different yield conditions. In relating the loading of the conveyor to the yield of potatoes, ideal speeds of 0.5 km/h for the boom elevator and 0.7 km/h for the side elevator were used respectively (see section 4.4). It was also assumed that the potato harvester worked at a constant forward speed of 3 km/h (see section 4.3).

4.5.1 Loading of the boom elevator

A harvester with a cutting width of w metre working at a constant forward speed of S km/h takes 10/(wS) h/ha to harvest one hectare of potatoes. A conveyor running at S_c km/h exposes a length of $(10S_c)/(wS)$ km/ha during the harvest time. Therefore if the conveyor is loaded with W_s kg/m, then the yield Y t/ha can be given by the following equation:

$$Y = 10S_cW_s/(wS) \quad \text{t/ha} \quad \ldots \ldots \ldots \ldots \quad (4.12)$$

Substituting for S_b, w and S the loading of the boom elevator is related to the potato yield as

$$Y = 0.83\ W_s \quad \text{t/ha} \quad \ldots \ldots \ldots \ldots \quad (4.13)$$

4.5.2 Loading of the side elevator

Since one third of the load on the side elevator is assumed to be the weight of stones and clods, the potato yield estimated by equation 4.12 is 1/3 more than the actual yield. Modifying equation 4.12 for the side elevator gives

$$Y = 20S_sW_s/(3wS) \quad \text{t/ha} \quad \ldots \ldots \ldots \ldots \quad (4.14)$$

Substituting for S_s, w and S the loading on side elevator is related to the potato yield by

$$Y = 0.78\ W_s \quad t/ha \qquad (4.15)$$

CHAPTER V

TESTING PROCEDURE

5.1 Automatic Boom Height Control

5.1.1 Preliminary testing

The automatic boom height control system was checked in the laboratory before mounting it on the potato harvester. The solenoid valve was connected to a double acting, single-end rod hydraulic cylinder. The cylinder was placed horizontally on the floor of the laboratory.

Hydraulic oil was supplied from a Massey-Ferguson MF 150 tractor hydraulic system. The microswitch of the height sensor was switched on and off by hand. The system appeared to work satisfactorily as the hydraulic cylinder gave good response to the operation of the height sensor microswitch.

5.1.2 Testing of modified potato harvester

The automatic boom height control was mounted on the potato harvester. The system was first checked for correct function independent from the manual boom control. One remote hydraulic supply circuit of the tractor (Massey-Ferguson MF 1100) was used for the automatic control. The other circuit remained unused.

An input simulation model was built to represent the potato pile and was placed under the discharging end of the boom (Fig. 5.1). The operation of the boom was observed after the controls were set for automatic operation. A problem of very heavy impact of the boom on the input model due to very fast movements of the boom was observed. The upward movements of the boom were also noted to be greater than desirable.

The problems associated with the initial design were solved by making the necessary changes in the electronic circuit and the actuating arm of the height sensing unit. The use of two flow control valves, one in each of the two oil supply hoses to the cylinder, slowed the upward and downward movements of the boom.

It was also necessary to check the simultaneous operation of the automatic and manual control of the boom height. One remote hydraulic supply circuit of the tractor was used for the manual controls and the other was used for the automatic control. Due to limitations on the existing tractor hydraulic circuits, the automatic boom height control did not work when there was provision for manual override.

5.2 Hydraulic Chain Drives

The hydraulic pump for the variable speed chain drive system was driven through the power-take-off (PTO) shaft of the tractor. Design speed for the hydraulic pump was 1800 rev/min. This speed could be obtained with an input PTO speed of 1000 rev/min.

The potato harvester in this study was operated in

Fig. 5.1 Input Simulator Placed under the Sensor

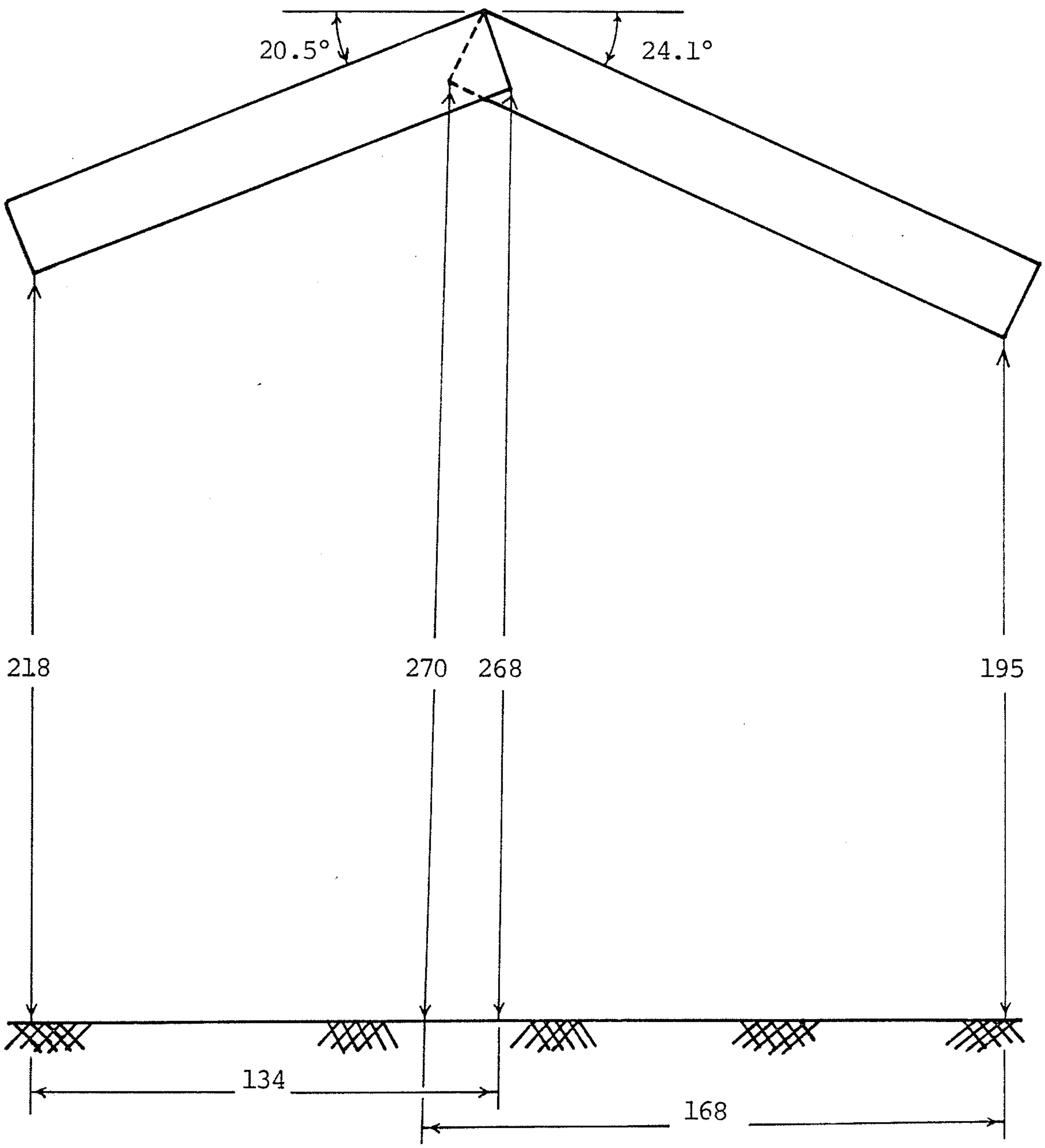
the field by an International Harvester Farmall 1256 tractor with a standard PTO speed of 1000 rev/min. But only a Massey-Ferguson MF 1100 tractor with a standard PTO speed of 535 rev/min was available for testing purposes. This rated PTO speed was too low to drive the hydraulic pump at design speed. Therefore, it was decided to operate the hydraulic motors using the tractor hydraulic system.

The inner and outer boom were set as shown in Fig. 5.2. This position was maintained throughout the tests. During the tests of the side motor, the chain on the clod and stone separating conveyor at the junction of the side elevator and the clod and stone separating conveyor was taken off. This was done so that the sand bags would not cause any interference.

5.2.1 Installation of the hydraulic tester

A Flo-tech hydraulic tester was used to measure the oil flow, the oil pressure and the oil temperature. The hydraulic test unit was installed into the system between the tractor hydraulic pump discharge port and the hydraulic motor under test (Fig. 5.3). Quick disconnect couplers were used to attach the test unit. This made the testing easier and faster and provided a seal for the unit when not in use.

The pressure loading valve of the tester was opened by rotating it counter clockwise. The tractor hydraulic pump was run to warm the oil prior to the actual tests.



Unless otherwise mentioned all dimensions are in centimetres

Scale: 1 cm = 20 cm

Fig. 5.2 Position of the Inter and the Outer Boom during the Tests

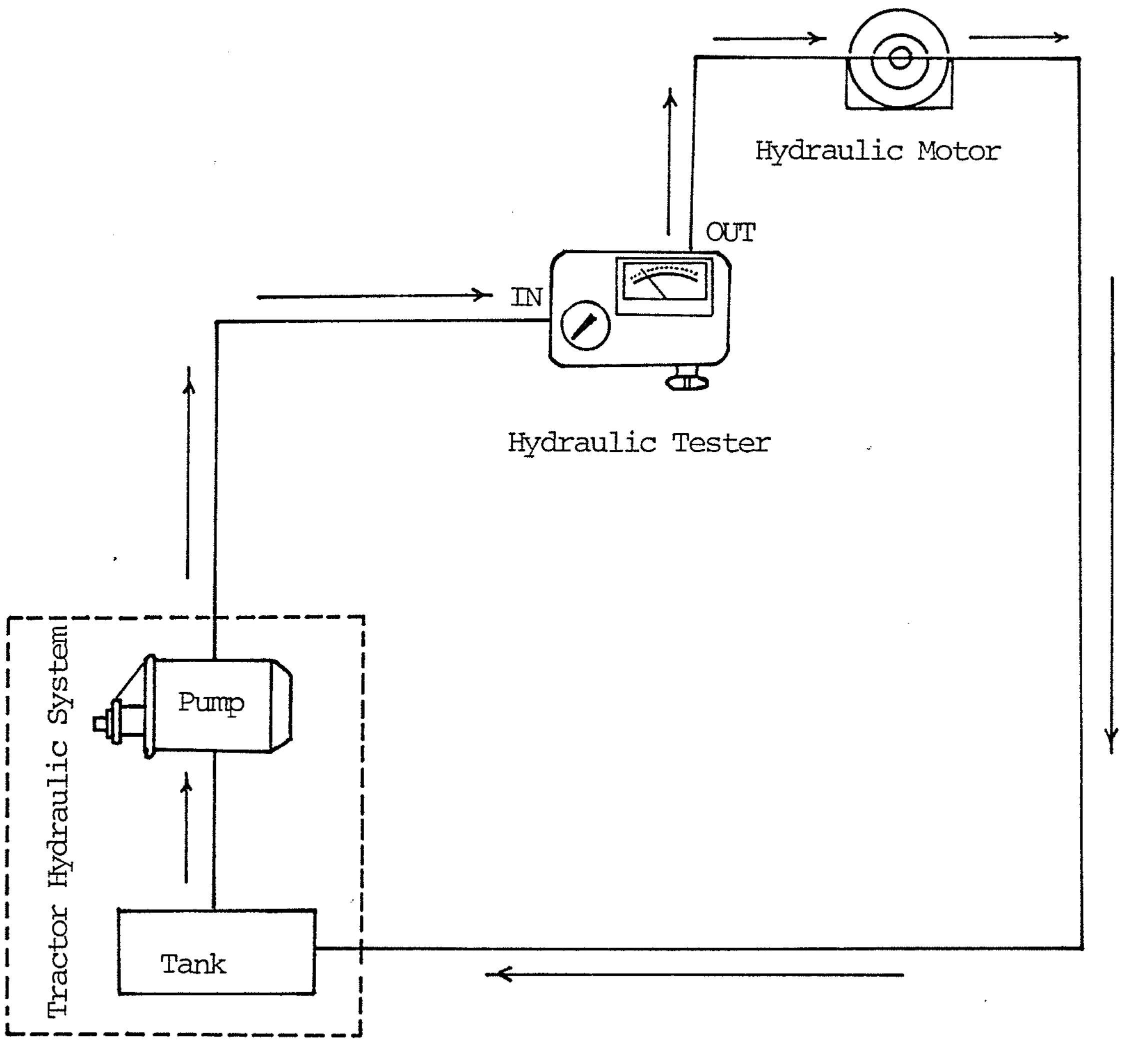


Fig. 5.3 Installation of the Hydraulic Tester

5.2.2 Loading procedure

Sand bags were used to simulate a potato load on the conveyors. The conveyors have flights attached to the links at regular intervals. The span between consecutive flights provided a space to place a sand bag. Half of the length of the conveyor was loaded while it was stationary.

The remaining sand bags for loading the boom elevator while running were stored on the clod and stone separating conveyor at the junction of the clod and stone separating conveyor and the side elevator. The bags were arranged in such a way that they could be dropped easily and quickly when the empty conveyor spaces between flights came along after starting the conveyor to run at a speed set by the tractor engine speed. The discharging bags were collected in a truck under the end of the boom.

The sand bags for loading the side elevator while running were stored on top of a wooden table placed on the ground at the rear of the side elevator. The driving chain for the clod and stone separating conveyor was removed at the junction of the clod and stone separating conveyor and the side elevator. The sand bags were dropped at the end of the side elevator on wooden tables placed under the space where the clod and stone separating conveyor had been taken off. The tables were placed so that the drop distance was minimized and thus wear and tear for the sand bags was reduced.

5.2.3 Conveyor speed measurements

The lengths of the boom elevator and the side elevator were measured. A distinct marker was tied on a link of each conveyor. The time required for the link with the marker to complete one revolution for each tractor engine speed setting was recorded. A simple stop watch was used to measure the time in seconds.

The conveyor speed was calculated using the following equation:

$$S_C = 3.6\ l/t \quad \text{km/h} \qquad (5.1)$$

where

S_C = conveyor speed, km/h

l = length of the conveyor, m

t = time required for one revolution of the conveyor, s

The conveyors were run at five different speeds for each loading rate. The speed of the conveyor was adjusted by setting the tractor engine speed at 700, 1000, 1500, 2000 or 2200 rev/min.

5.2.4 Measurement of oil flow, oil pressure and oil temperature

Readings of the oil flow and oil pressure were recorded during the time the conveyor was running under load. Oil temperature was also noted. At each loading rate the conveyor was run at five different speeds. For each loading rate and conveyor speed, the oil flow, the oil pressure and the oil temperature were measured using the Flo-tech hydraulic tester installed in the circuit (Fig. 5.3).

5.2.5 Starting torque measurements

The conveyors were loaded by placing one sand bag in each space between consecutive flights. A clamp made by bending a 1.25 cm square rod was hooked to two adjacent spacers on the motor sprocket. An ordinary torque wrench placed on the clamp was used to measure the torque required to start the conveyor under load. Three readings were taken at each loading rate and the maximum value obtained was recorded.

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Operation of Automatic Boom Height Control

6.1.1 Automatic control without manual control

Laboratory demonstrations of the automatic boom height control indicated that the system was satisfactory. During tests conducted at the Glenlea Research Station workshop to check the operation of the automatic control system while mounted on the potato harvester, some problems associated with the initial design were observed. The problems encountered and the attempts made to solve them are discussed below.

The very first problems faced were improper time delay settings. Time delay for downward movements ranged initially from 1.0 to 3.5 s. A delay as short as 0.25 s was also tried later. But any delay caused damage to the simulated potato pile due to the continued downward movement of the boom after the sensor touched the potato pile.

Lift heights of the boom were dependent on the time delay setting for upward movement and the oil flow rate from the tractor hydraulic system. Time delay for upward movement was set at 1.4 s in the initial circuit. This delay coupled with the oil flow of the tractor hydraulic system resulted in excessive lift heights during each cycle of operation. Greater lift heights were not desirable from the point of view of potato damage. To overcome these problems the time delays for both lowering and raising of the boom were set to zero. The lift heights of the boom were reasonable after this adjustment. The final electronic circuit is shown in Fig. 6.1. All the symbols and abbreviations used in the circuit have been explained in Table 3.1.

Zero seconds time delay for the downward movements minimized the risk of damage to the actuating arm and the potato pile but resulted in a new problem. Vibrations of the actuating spring caused the boom to undergo sudden movements. This was because the vibrating spring made rapid contact in closing the microswitch which in turn repeatedly opened and closed the electrohydraulic valve. The solution to this problem was the replacement of the spring by an actuating arm which reduced the vibrations.

A 190 mm long, 10 mm square rod was selected to replace the spring. A 6 mm diameter hole was drilled on one end and 5 mm diameter hole was drilled on the other end of the actuating rod. The clamp plate was replaced by a 90 mm x 32 mm x 5 mm mild steel plate. Two 6 mm diameter holes 45 mm apart were drilled in the plate for bolting it to the opposite plate of the height sensing unit. A 6 mm in diameter 50 mm long rod was welded to the bottom of the plate. The rod was used to hinge the actuating arm (Fig. 6.2).

Another 100 mm x 38 mm x 3 mm mild steel plate with 35 mm x 6 mm and 50 mm x 13 mm slots was bolted to the side plate of the height sensing unit. The bigger slot in this

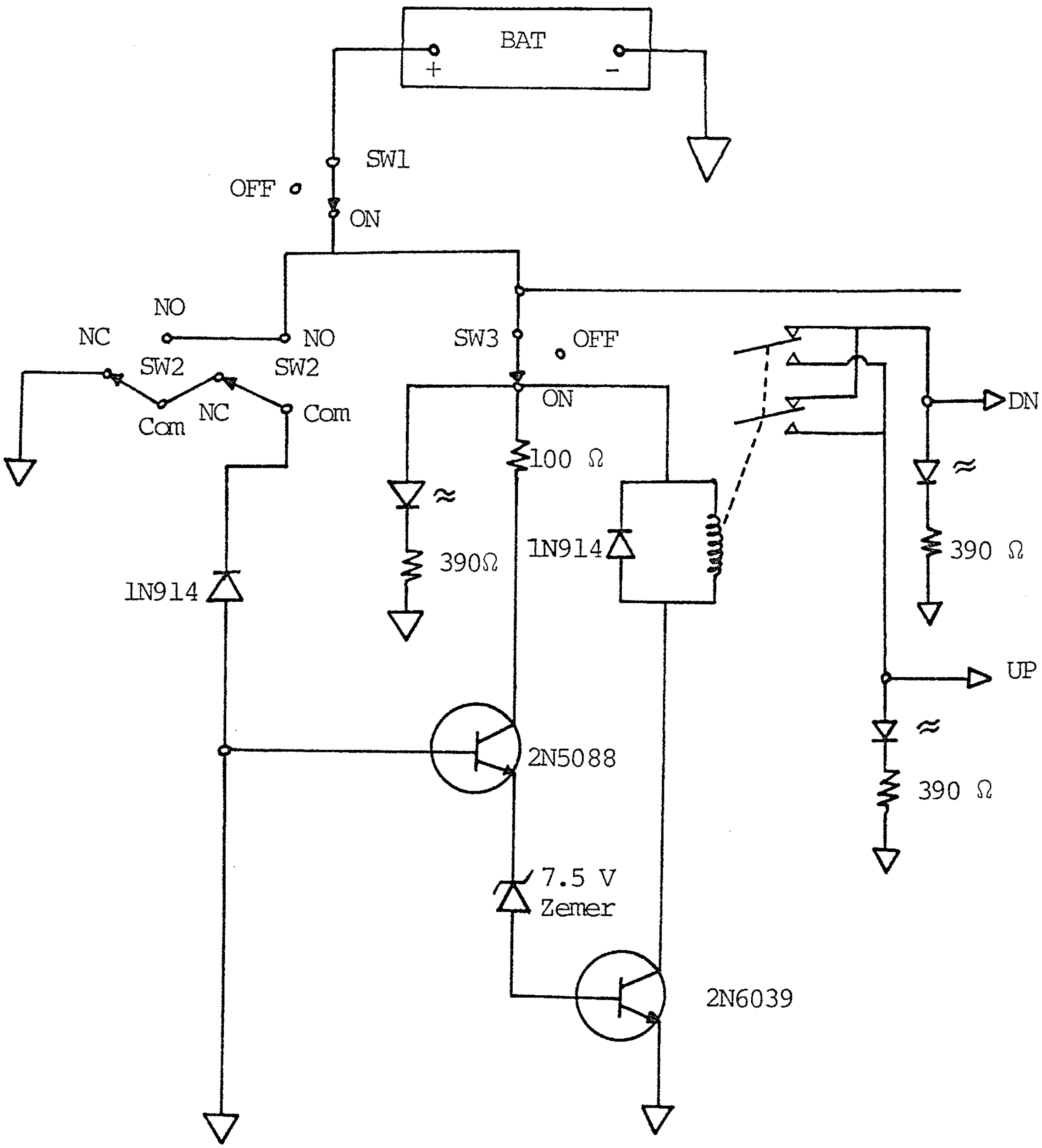


Fig. 6.1 Final Electronic Circuit for Automatic Boom Height Control

Fig. 6.2 Final Version of Actuating Arm for Activating the Microswitch

plate provided free movements of the actuating arm. The smaller slot helped to adjust the position of the actuating rod (see Fig. 6.2).

Another problem which occurred was the impact of the boom on the simulated input of the potato pile. This impact was due to very fast movements of the boom. The use of two flow control valves, one in each of the oil supply hoses to the outer boom cylinder, provided adjustment of the lifting and lowering rates of the boom. These adjustments helped to eliminate the impact. After initial setting no further adjustment of the flow control valves was necessary.

After the above adjustments, no difficulty was faced in the operation of the automatic boom height control system.

6.1.2 Automatic control with manual boom control

In practice the automatic boom height control has to work along with the other manual controls of the potato harvester. A manual override for boom control is required for safety. Therefore, it was necessary to check if the automatic boom height control would function properly if operated in conjunction with manual control. When both the tractor hydraulic circuits were used for both types of control none of the manual controls worked when the automatic control was shut off. The automatic control did not function either. Attempts were made to overcome these problems.

A flowmeter installed in the return line of the manual control unit indicated a flow of 14 l/min back to the tractor hydraulic system when both the manual and automatic controls were shut off. The flowmeter was then installed in the return line of the electrohydraulic valve. Both control valves are of the tandem center type. Theoretically about equal amounts of oil should flow back to the tractor through each control valve if both the tractor hydraulic circuits work independently. But there was little flow from the electrohydraulic valve. This was probably an indication that the electrohydraulic valve provided restrictions to the oil flow in the hydraulic circuit used for the automatic boom height control system. This also indicated that all the oil would flow through one circuit if restrictions were imposed in the other circuit.

When any of the manual controls were operated with the automatic control switch off, oil flow of about 14 l/min was noted flowing back through the electrohydraulic valve and the manual control could not perform the task. The explanation for this is that oil follows the path of least resistance to flow. Due to the restrictions created by the manual controls when operated the oil found less resistance to flow in the automatic boom height control hydraulic circuit. The two circuits were not properly separated.

An attempt was made to operate the manual controls while the automatic control switch was switched on. In this condition the manual controls were able to do their tasks. But the automatic control did not work. No oil flow through the electrohydraulic valve was observed. The smaller size of the spool openings on the electrohydraulic valve seemed to be creating more restrictions compared to that of the manual control valve. This would have caused no problem if the two tractor hydraulic circuits had worked independently.

The manual controls functioned correctly when the automatic control switch was on or off when the return line from the electrohydraulic valve was plugged. This was so because the oil had only one path to follow through the manual circuit and thus the manual controls worked properly.

6.2 Hydraulic Drives for the Conveyors

The raw data obtained during the tests of the boom motor and the side motor are listed in Appendix A. Appendix B contains calculations for reducing the data of the oil flow and the conveyor speeds to average values for each tractor engine speed. Sample calculations for the power requirements and the running torque of the hydraulic motors are also presented in Appendix B.

6.2.1 Oil flow and conveyor speed

For each simulated yield condition the conveyors were run at five different speeds adjusted by varying the tractor engine speed. The tractor engine speeds were set at 700, 1000, 1500, 2000 or 2200 rev/min.

Conveyor speed was directly proportional to the oil flow rate which in turn depended on the tractor engine speed. It was assumed that at each engine speed the oil flow and the conveyor speed would be constant regardless of the amount of load on the conveyor. But Appendix A shows a continuous decrease in the oil flow rates and the conveyor speeds at higher loading rates. The reduction was probably due to the increased leakage of oil at higher pressures. Average oil flow and average conveyor speeds for each tractor engine speed were calculated as explained in Appendix B and tabulated in Table B.1, B.2, B.3 and B.4.

6.2.2 Power requirements

Power requirements for the boom motor and the side motor are listed in Table 6.1 and Table 6.2 respectively. Calculations of the simulated potato yield, the motor speed, power requirements and the output running torque are illustrated in Appendix B.

On the basis of the tests conducted, the maximum power required to run the boom motor at 90.04 rev/min (conveyor speed of 1.85 km/h) at a simulated yield of 37 t/ha was 1.13 kW. Assuming an efficiency of 90 percent, the maximum running torque of this motor at 90.04 rev/min was 108.3 N.m. The maximum power required for the side motor to run at 109.51 rev/min (conveyor speed of 2.25 km/h) at a simulated yield of 44 t/ha was 0.89 kW. The maximum running torque of this motor was 70.1 N.m at an assumed efficiency of 90 percent.

Inspection of the results show that the power requirements for the boom motor are higher than the side motor.

Table 6.1 Results of Boom Motor Tests

Conveyor Loading Rates (kg/m)	Simulated Potato Yield (t/ha)	Starting Torque (N.m)	Conveyor Speed (km/h)	Motor Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Hydraulic Power (kW)	Running Torque (N.m)
0.00	0	162.7	1.36	66.19	16.3	0.98	0.27	34.6
			1.48	72.03	17.7	1.23	0.36	43.3
			1.66	80.79	19.9	1.47	0.49	51.9
			1.83	89.07	22.0	1.86	0.68	65.8
			1.85	90.04	22.4	1.96	0.73	69.8
11.07	9	169.5	1.36	66.19	16.3	1.18	0.32	41.6
			1.48	72.03	17.7	1.27	0.37	44.7
			1.66	80.79	19.9	1.57	0.52	55.4
			1.83	89.07	22.0	1.86	0.68	65.8
			1.85	90.04	22.4	1.96	0.73	69.8
16.59	14	176.3	1.36	66.19	16.3	1.27	0.35	44.8
			1.48	72.03	17.7	1.47	0.43	51.7
			1.66	80.79	19.9	1.67	0.55	58.9
			1.83	89.07	22.0	1.96	0.72	69.3
			1.85	90.04	22.4	2.21	0.83	78.8

Table 6.1 Concluded

Conveyor Loading Rates (kg/m)	Simulated Potato Yield (t/ha)	Starting Torque (N.m)	Conveyor Speed (km/h)	Motor Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Hydraulic Power (kW)	Running Torque (N.m)
22.12	18	179.0	1.36	66.19	16.3	1.47	0.40	51.9
			1.48	72.03	17.7	1.57	0.46	55.3
			1.66	80.79	19.9	1.86	0.62	65.6
			1.83	89.07	22.0	2.21	0.81	78.2
			1.85	90.04	22.4	2.35	0.88	83.7
31.85	26	189.8	1.36	66.19	16.3	1.67	0.45	58.9
			1.48	72.03	17.7	1.86	0.55	65.5
			1.66	80.79	19.9	2.26	0.75	79.7
			1.83	89.07	22.0	2.55	0.94	90.2
			1.85	90.04	22.4	2.70	1.01	96.2
44.24	37	203.4	1.36	66.19	16.3	1.96	0.53	69.1
			1.48	72.03	17.7	2.26	0.67	79.5
			1.66	80.79	19.9	2.55	0.85	90.0
			1.83	89.07	22.0	2.84	1.04	100.5
			1.85	90.04	22.4	3.04	1.13	108.3

Table 6.2 Results of Side Motor Tests

Conveyor Loading Rates (kg/m)	Simulated Potato Yield (t/ha)	Starting Torque (N.m)	Conveyor Speed (km/h)	Motor Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Hydraulic Power (kW)	Running Torque (N.m)
0.00	0	67.8	1.75	85.17	14.7	0.88	0.22	21.8
			1.82	88.58	15.4	1.08	0.28	26.9
			1.91	92.96	16.4	1.27	0.35	32.1
			2.09	101.72	18.2	1.67	0.51	42.8
			2.25	109.51	19.5	1.77	0.58	45.1
14.19	11	74.6	1.75	85.17	14.7	1.08	0.26	26.7
			1.82	88.56	15.4	1.23	0.32	30.6
			1.91	92.96	16.4	1.37	0.37	34.6
			2.09	101.72	18.2	1.67	0.51	42.8
			2.25	109.51	19.5	1.77	0.58	45.1
21.25	17	77.3	1.75	85.17	14.7	1.18	0.29	29.2
			1.82	88.58	15.4	1.27	0.33	31.6
			1.91	92.96	16.4	1.47	0.40	37.1
			2.09	101.72	18.2	1.77	0.54	45.4
			2.25	109.51	19.5	1.86	0.60	47.4

Table 6.2 Concluded

Conveyor Loading Rates (kg/m)	Simulated Potato Yield (t/ha)	Starting Torque (N.m)	Conveyor Speed (km/h)	Motor Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Hydraulic Power (kW)	Running Torque (N.m)
28.34	22	81.3	1.75	85.17	14.7	1.27	0.31	31.4
			1.82	88.58	15.4	1.37	0.35	34.1
			1.91	92.96	16.4	1.67	0.46	42.2
			2.09	101.72	18.2	1.86	0.56	47.7
			2.25	109.51	19.5	1.96	0.64	50.0
42.50	33	94.9	1.75	85.17	14.7	1.47	0.36	36.3
			1.82	88.58	15.4	1.67	0.43	41.6
			1.91	92.96	16.4	1.96	0.54	49.5
			2.09	101.72	18.2	2.21	0.67	56.6
			2.25	109.51	19.5	2.26	0.73	57.6
56.69	44	108.5	1.75	85.17	14.7	1.86	0.46	46.0
			1.82	88.58	15.4	2.16	0.55	53.8
			1.91	92.96	16.4	2.35	0.64	59.4
			2.09	101.72	18.2	2.55	0.77	65.4
			2.25	109.51	19.5	2.75	0.89	70.1

The reason is that the boom elevator carries more total load than the side elevator. However, for simplicity the boom and side motor power requirements can be assumed equal using the specifications of the boom motor. The results also reveal that the power requirements would be higher if the conveyors were to be run at higher speeds. The actual speeds of the side elevator and the boom elevator on a new machine operated at standard PTO speed of 1000 rev/min were reported as 2.06 and 2.10 km/h respectively (Upadhyaya, 1976). The conveyors could sometimes be required to run at even higher speeds.

To facilitate the determination of the maximum power requirements, a relationship between the power requirements and the conveyor speed for a potato yield of 37 t/ha is shown in Fig. 6.3. The results plotted are for the boom motor. But the same relationship can be assumed for the side motor. Inspection of Fig. 6.3 shows that 2.43 kW input power is required for the hydraulic motor in order to run the conveyor at 3 km/h with a potato yield of 37 t/ha. Oil flow of 35.7 l/min would be required for a conveyor speed of 3 km/h with this motor.

6.2.3 Starting torque and oil pressure

The measurements of starting torque for the conveyors were not constant for one complete revolution of the driving sprockets. As the sprocket teeth made contact between the links, the torque increased, reached a maximum and then de-

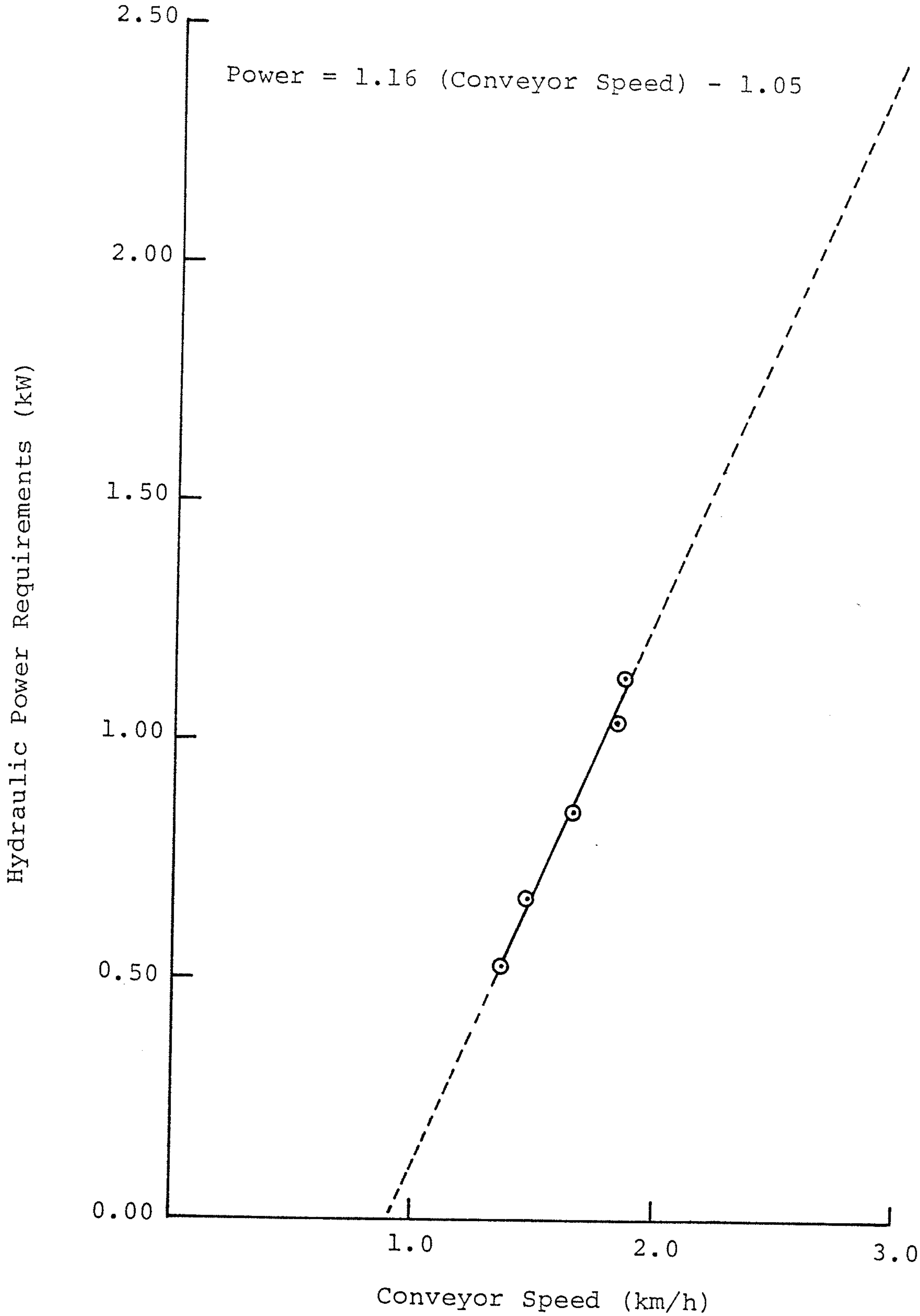


Figure 6.3 Power Requirements of the Hydraulic Motor for 37 t/ha Potato Yield

creased as the teeth disengaged. The maximum value of three torque readings taken for each simulated potato yield was recorded. Starting torque requirements for the boom elevator and the side elevator for different potato yields are tabulated in Table 6.1 and Table 6.2 respectively.

The position of the inner and the outer boom during the torque measurements is shown in Fig. 5.2. From Table 6.1 the maximum torque required for the boom elevator to start when loaded with sand bags at a rate of 44.24 kg/m was 203.4 N.m. Table 6.2 shows that the maximum starting torque required for the side elevator was 108.5 N.m when loaded with sand bags at a rate of 56.69 kg/m. These values are higher than the values obtained by Upadhyaya (1976). He reported 135.0 and 109.0 N.m torque required for the rear cross conveyor and side elevator and the boom elevator respectively when they were partially filled with soil.

The reason for the differences in the starting torque requirements reported is probably because of the difference in the load on the conveyor. Moreover, Upadhyaya (1976) recorded the average value while in this study the maximum value of three readings was recorded. Torque requirements of the boom elevator may also vary with the position of the boom conveyor.

For simplicity the starting torque requirements of the side elevator can be assumed equal to the boom elevator torque requirements. Since the starting torque required was 1.9 times the running torque, the hydraulic oil pressure required must be 1.9 times what is needed for running. Therefore, a maximum oil pressure of 5.78 MPa would be required for starting the conveyors under load.

CHAPTER VII

CONCLUSIONS

The following conclusions were drawn from the results of this project as presented in Chapter VI:

1. The automatic boom height control worked satisfactorily when operated independently from the manual control.

2. The electrohydraulic valve caused more restriction of the hydraulic fluid flow than the manual control valve.

3. Due to limitations in the hydraulic system of the tractor used in this simulated testing, the automatic boom height control did not work when there was provision for manual override.

4. The maximum input power requirement for the hydraulic motor driving the boom elevator or the side elevator at a speed of 3 km/h was 2.43 kW for a simulated potato yield of 37 t/ha.

5. Maximum required oil flow for each motor was 35.7 l/min for a maximum conveyor speed of 3 km/h.

6. The maximum required running torque was 108.3 N.m for the boom motor at a simulated load of 37 t/ha.

7. If the boom conveyor was to be started under load the torque requirement would be 203.4 N.m.

8. The required hydraulic oil pressures were 3.04 MPa for running and 5.72 MPa for starting the conveyor under load.

CHAPTER VIII

RECOMMENDATIONS FOR FUTURE STUDY

Recommendations for future study are as follows:

1. An independent hydraulic circuit should be used in order to simplify the circuit for the automatic boom height control.

2. The automatic boom height control should be field tested.

3. The existing hydraulic systems of some large modern tractors may have sufficient hydraulic capacity to supply the required oil flow to the hydraulic motors. A list of such tractors should be prepared.

4. Hydraulic drives for conveyor chains should be further investigated in the field to make final recommendations.

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APPENDIX A

RAW DATA

Table A.1 Raw Data for Boom Motor Tests

Loading on the conveyor = 0.00 kg/m
Starting torque = 162.7 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	16.6	0.98	16	34.0
1000	18.6	1.23	16	30.3
1500	21.9	1.47	20	25.8
2000	25.1	1.86	24	22.5
2200	26.1	1.96	25	21.6

Loading on the conveyor = 11.07 kg/m
Starting torque = 169.5 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	18.1	1.18	14	31.2
1000	19.5	1.27	16	29.0
1500	20.9	1.57	16	27.0
2000	23.1	1.86	17	24.5
2200	23.5	1.96	20	24.0

Table A.1 Continued

Loading on the conveyor = 16.59 kg/m
Starting torque = 176.3 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	17.4	1.27	16	32.5
1000	18.8	1.47	17	30.0
1500	22.1	1.67	20	25.5
2000	24.6	1.96	24	23.0
2200	26.3	2.21	25	21.5

Loading on the conveyor = 22.12 kg/m
Starting torque = 179.0 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	17.1	1.47	10	33.0
1000	18.2	1.57	12	31.0
1500	18.8	1.86	13	30.0
2000	20.7	2.21	13	27.3
2200	21.7	2.35	15	26.0

Table A.1 Concluded

Loading on the conveyor = 31.85 kg/m
Starting torque = 189.8 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	14.7	1.67	10	38.4
1000	15.1	1.86	12	37.5
1500	17.6	2.26	10	32.0
2000	19.1	2.55	10	29.5
2200	18.2	2.70	10	31.0

Loading on the conveyor = 44.24 kg/m
Starting torque = 203.4 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	14.0	1.96	10	40.4
1000	15.9	2.26	11	35.5
1500	18.1	2.55	10	31.2
2000	19.2	2.84	10	29.4
2200	18.8	3.04	10	30.0

Table A.2 Raw Data for Side Motor Tests

Loading on the conveyor = 0.00 kg/m

Starting torque = 67.8 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	15.7	0.88	14	17.0
1000	17.5	1.08	16	15.2
1500	20.0	1.27	17	13.3
2000	22.2	1.67	18	12.0
2200	24.2	1.77	21	11.0

Loading on the conveyor = 14.19 kg/m

Starting torque = 74.6 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	16.6	1.08	21	16.0
1000	17.3	1.23	21	15.4
1500	18.5	1.37	20	14.4
2000	21.8	1.67	20	12.2
2200	23.8	1.77	22	11.2

Table A.2 Continued

Loading on the conveyor = 21.25 kg/m
Starting torque = 77.3 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	17.7	1.18	18	15.0
1000	18.7	1.27	18	14.2
1500	19.9	1.47	17	13.4
2000	22.2	1.77	19	12.0
2200	22.9	1.86	23	11.6

Loading on the conveyor = 28.34 kg/m
Starting torque = 81.3 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	14.3	1.27	20	18.6
1000	15.2	1.37	19	17.5
1500	15.8	1.67	15	16.8
2000	17.7	1.86	19	15.0
2200	18.2	1.96	21	14.6

Table A.2 Concluded

Loading on the conveyor = 42.50 kg/m
Starting torque = 94.9 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	12.4	1.47	9	21.5
1000	12.1	1.67	8	22.0
1500	12.4	1.96	8	21.5
2000	12.8	2.21	8	20.8
2200	13.7	2.26	8	19.4

Loading on the conveyor = 56.59 kg/m
Starting torque = 108.5 N.m

Tractor Engine Speed (rev/min)	Oil Flow (l/min)	Oil Pressure (MPa)	Oil Temperature (°C)	Time for one revolution of conveyor (s)
700	11.6	1.86	8	23.0
1000	11.8	2.16	7	22.6
1500	11.8	2.35	7	22.5
2000	12.7	2.55	7	21.0
2200	14.2	2.75	9	18.8

APPENDIX B

CALCULATIONS OF RESULTS

B.1 Simulation of Potato Yield

B.1.1 Boom elevator loading

The equation for the simulated yield of potatoes from the loading on the boom elevator was given by equation (4.13)

$$Y = 0.83\ W_s$$

For the highest loading on the boom elevator from Table A.1,

$$W_s = 44.24\ \text{kg/m}$$

Thus

$$Y = (0.83)(44.24)$$
$$= 37\ \text{t/ha}$$

B.1.2 Side elevator loading

Equation (4.15) was used for calculating the simulated yield of potatoes from the loading on the side elevator.

$$Y = 0.78\ W_s$$

For the highest loading on the side elevator from Table A.2,

$$W_s = 56.69\ \text{kg/m}$$

Therefore

$$Y = (0.78)(56.69)$$
$$= 44\ \text{t/ha}$$

B.2 Average Oil Flow Rates

Let Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6 be the oil flow rates measured for six different loadings on the conveyor at any tractor engine speed. The average flow Q would be given by:

$$Q = (Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6)/6$$

B.2.1 Oil flow for the boom motor

From Table A.1 the values of Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6 for a tractor engine speed of 2200 rev/min are 26.1, 23.5, 26.3, 21.7, 18.2 and 18.8 l/min respectively. Thus

$$Q = (26.1 + 23.5 + 26.3 + 21.7 + 18.2 + 18.8)/6$$
$$= 22.4 \text{ l/min}$$

The calculated oil flow rates for the boom motor are tabulated in Table B.1.

B.2.2 Oil flow for the side motor

From Table A.2 the values of Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6 for a tractor engine speed of 2200 rev/min are 24.2, 23.8, 22.9, 18.2, 13.7 and 14.2 l/min respectively. Therefore

$$Q = (24.2 + 23.8 + 22.9 + 18.2 + 13.7 + 14.2)/6$$
$$= 19.5 \text{ l/min}$$

The calculated oil flow rates for the side motor are listed in Table B.2.

B.3 Conveyor Speeds

Conveyor speed was calculated using equation (5.1).

$$S_c = 3.6 \text{ l/t}$$

Table B.1 Average Oil Flow Rates for Boom Motor at different Tractor Engine Speeds

Tractor Engine Speed (rev/min)	Oil flow rates (l/min) Loading Rates (kg/m)						
	0.00	11.07	16.59	22.12	31.85	44.24	Average Flow
700	16.6	18.1	17.4	17.1	14.7	14.0	16.3
1000	18.6	19.5	18.8	18.2	15.1	15.9	17.7
1500	21.9	20.9	22.1	18.8	17.6	18.1	19.9
2000	25.1	23.1	24.6	20.7	19.1	19.2	22.0
2200	26.1	23.5	26.3	21.7	18.2	18.8	22.4

Table B.2 Average Oil Flow Rates for Side Motor at different Tractor Engine Speeds

Tractor Engine Speed (rev/min)	Oil flow rates (l/min) Loading Rates (kg/m)						
	0.00	14.19	21.25	28.34	42.50	56.69	Average Flow
700	15.7	16.6	17.7	14.3	12.4	11.6	14.7
1000	17.5	17.3	18.7	15.2	12.1	11.8	15.4
1500	20.0	18.5	19.9	15.8	12.4	11.8	16.4
2000	22.2	21.8	22.2	17.7	12.8	12.7	18.2
2200	24.2	23.8	22.9	18.2	13.7	14.2	19.5

If one complete revolution of the conveyor takes t_1, t_2, t_3, t_4, t_5 and t_6 seconds at any tractor engine speed setting with six different loading rates on the conveyor, the average time t would be

$$t = (t_1 + t_2 + t_3 + t_4 + t_5 + t_6)/6$$

B.3.1 Boom conveyor speed

From Table A.1 the values of t_1, t_2, t_3, t_4, t_5 and t_6 at a tractor engine speed of 2200 rev/min are 21.6, 24.0, 21.5, 26.0, 31.0 and 30.0 s respectively. Thus

$$t = (21.6 + 24.0 + 21.5 + 26.0 + 31.0 + 30.0)/6$$
$$= 25.7 \text{ s}$$

and

$$l = 13.2 \text{ m}$$

Therefore

$$S_c = (3.6)(13.2)/25.7$$
$$= 1.85 \text{ km/h}$$

The calculated boom elevator speeds are presented in Table B.3.

B.3.2 Side conveyor speed

From Table A.2 the values of t_1, t_2, t_3, t_4, t_5 and t_6 at a tractor engine speed of 2200 rev/min are 11.0, 11.2, 11.6, 14.6, 19.4 and 18.8 s respectively. Thus

$$t = (11.0 + 11.2 + 11.6 + 14.6 + 19.4 + 18.8)/6$$
$$= 14.4 \text{ s}$$

and

Table B.3 Average Boom Elevator and Motor Speeds at different Tractor Engine Speeds

Tractor Engine Speed (rev/min)	Time(s) required for one revolution of the conveyor — Loading Rates (kg/m)						Average Time(s)	Boom Elevator Speed (km/h)	Boom Motor Speed (rev/min)
	0.00	11.07	16.59	22.12	31.85	44.24			
700	34.0	31.2	32.5	33.0	38.4	40.4	34.9	1.36	66.19
1000	30.3	29.0	30.0	31.0	37.5	35.5	32.2	1.48	72.03
1500	25.8	27.0	25.5	30.0	32.0	31.2	28.6	1.66	80.79
2000	22.5	24.5	23.0	27.3	29.5	29.4	26.0	1.83	89.07
2200	21.6	24.0	21.5	26.0	31.0	30.0	25.7	1.85	90.04

$l = 9.0$ m

Therefore

$$S_c = (3.6)(9.0)/14.4$$

$$= 2.25 \text{ km/h}$$

The calculated side elevator speeds are shown in Table B.4.

B.4 Motor Speed

The speed of the hydraulic motor was calculated using equation (4.1)

$$N = 50\ S_c/(3\pi d)$$

where

$$d = 0.109 \text{ m}$$

B.4.1 Boom motor speed

From Table B.3 at a tractor engine speed of 2200 rev/min,

$$S_c = 1.85 \text{ km/h}$$

Thus

$$N = (50)(1.85)/((3\pi)(0.109))$$

$$= 90.04 \text{ rev/min}$$

The calculated boom motor speeds are listed in Table B.3.

B.4.2 Side motor speed

From Table B.4 for a tractor engine speed of 2200 rev/min,

Table B.4 Average Side Elevator and Motor Speeds at different Tractor Engine Speeds

Tractor Engine Speed (rev/min)	Time(s) required for one revolution of the conveyor — Loading Rates (kg/m)							Side Elevator Speed (km/h)	Side Motor Speed (rev/min)
	0.00	14.19	21.25	28.34	42.50	56.69	Average Time(s)		
700	17.0	16.0	15.0	18.6	21.5	23.0	18.5	1.75	85.17
1000	15.2	15.4	14.2	17.5	22.0	22.6	17.8	1.82	88.58
1500	13.3	14.4	13.4	16.8	21.5	22.5	17.0	1.91	92.96
2000	12.0	12.2	12.0	15.0	20.8	21.0	15.5	2.09	101.72
2200	11.0	11.2	11.6	14.6	19.4	18.8	14.4	2.25	109.51

S_c = 2.25 km/h

Therefore

$N = (50)(2.25)/((3\pi)(0.109))$

$= 109.51$ rev/min

The calculated side motor speeds are tabulated in Table B.4.

B.5 Power Requirements

The power requirements of a hydraulic motor can be calculated using

Hydraulic Power = PQ/60 kW

where

P = Oil pressure, MPa

Q = Oil flow, l/min

The values of the average oil flow and the oil pressure at a tractor engine speed of 2200 rev/min were used in the sample calculations.

B.5.1 Power requirements of boom motor

The average oil flow rate of the boom motor was 22.4 l/min (Table B.1). The oil pressure at the loading rate of 44.24 kg/m was 3.04 (Table A.1). Thus

Hydraulic Power = (3.04)(22.4)/60

= 1.13 kW

B.5.2 Power requirements of side motor

From Table B.2,

$Q = 19.5$ l/min

From Table A.2, for a loading rate of 56.69 kg/m,

$P = 2.75$ MPa

Therefore

$$\text{Hydraulic Power} = (2.75)(19.5)/60$$
$$= 0.89 \text{ kW}$$

B.6 Running Torque

The mechanical output power (P_o) of the hydraulic motor can be given by the following equation:

$$P_o = 2\pi NT/60\ 000 \quad \text{kW}$$

From this equation, the running torque (T) would be

$$T = 60\ 000\ P_o/(2\pi N)$$

Assuming an efficiency of 90 percent,

$$P_o = 3\ PQ/200$$

Hence

$$T = 450\ PQ/(\pi N)$$

The average values of oil flow and oil pressure at the tractor engine speed of 2200 rev/min were used in calculations of the running torque.

B.6.1 Boom motor

From Table B.1,

$Q = 22.4$ l/min

From Table B.3,

$N = 90.04$ rev/min

From Table A.1 for a loading rate of 44.24 kg/m, P = 3.04 MPa

Thus

$$T = (450)(3.04)(22.4)/(90.04\pi)$$

$$= 108.3 \text{ N.m}$$

B.6.2 Side Motor

From Table B.2,

Q = 19.5 l/min

From Table B.4

N = 109.51 rev/min

From Table A.2 for a loading rate of 56.59 kg/m,

P = 2.75 MPa

Therefore

$$T = (450)(2.75)(19.5)/(109.51\pi)$$

$$= 70.1 \text{ N.m}$$