THE UNIVERSITY OF ALBERTA

MEASUREMENT OF COMBINE STRAW WALKER GRAIN LOSS

by

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ABSTRACT

An accurate measure of grain loss from straw walkers is required to allow optimisation of harvester feed rate and ground speed control. A single loss monitor at the end of the straw walkers is not sufficient to give an accurate measurement since the loss depends on the amount of separation that has already occured. By measuring grain separation at three locations along the straw walkers, together with the grain separating at the end of the walkers, an approximation of the separation curve could be obtained from which grain loss could be calculated. A series of experiments designed to test these ideas was carried out in the laboratory by feeding pre-measured mixtures of grain and straw over a set of straw walkers. Separation curves were constructed from the weights of grain collected in trays under the walkers, and used to develop and verify algorithms for predicting grain loss on the basis of separation at two or three points along the straw walkers.

As well, data loggers were interfaced with a number of conventional grain loss sensors located under the straw walkers to measure separation. Data from the sensors did not sucessfully replicate the separation curve derived from the weights of grain collected in the trays. If sensing and signal processing circuits could be developed and implemented to correctly define the separation curve, the

use of an on-board microprocessor using the pre-determined algorithms to calculate straw walker grain loss seems feasible.

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TABLE OF CONTENTS

List of Tables

List of Figures

List of Symbols

A	constant in the equation relating S_v to x (kg/m)
a,b,c d,e	constants relating W_L to F_r and G/MOG
B	constant in the equations relating G_r and S_v to position along the straw walker
EFF	overall straw walker efficiency (%)
EFFP	straw walker efficiency (point basis) (%)
F_r	flow of crop material through a combine (kg/min)
GA	amount of grain available to be separated at a given unit area (kg)
G/MOG	ratio of quantity of grain to the material other than grain in the crop entering a combine
G_o	the amount of grain initially passed onto the walkers (kg)
$G_r(x)$	the amount the straw walkers at a distance x (m) from the front of the walkers (kg)
GS	amount of grain separated per unit area (kg)
J,n	parameters of the equation relating W_L to F_r
K,m	parameters of the equation relating W_L to G/MOG
ℓ	the distance to the end of the straw walker (m)
L	walker length (m)
L1	length of sensor #1 (m)
n	sample size
R^2	correlation coefficient of regression

s	standard deviation of a sample
$S_v(x)$	rate of grain separation through the walkers at a distance x (m) from the front of the walkers (kg/m)
S1	the amount of grain separating from the straw at the position of sensor #1 (kg)
t	t-statistic
TGA	total amount of grain entering walkers (kg)
TGS	total amount of grain separated by the walkers (kg)
μ	specified value of population mean
V	volts
W_L	straw walker grain loss (kg)
x1	distance to the center of sensor #1 from the front of the walker (m)
Y	mean value of a sample

1. INTRODUCTION

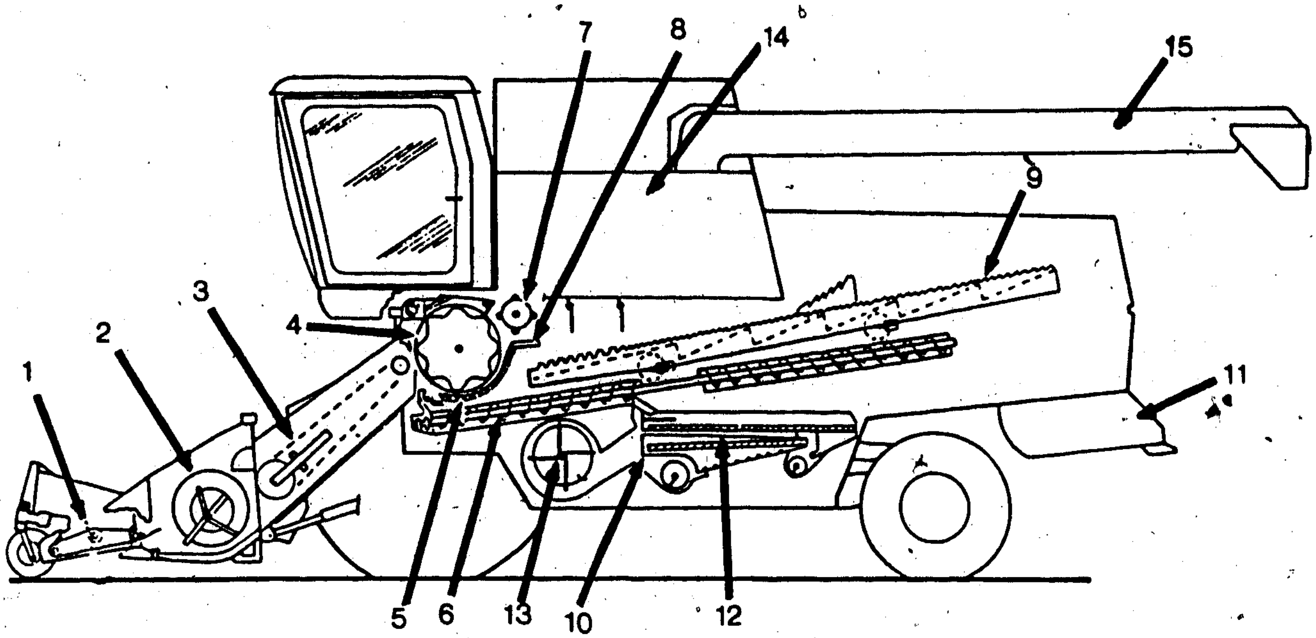
Over the past few decades grain production has benefited greatly from increased technical knowledge. Plant breeders have developed hardier and higher yielding crop varieties, soil scientists have developed more effective fertilizer rations, and agricultural engineers have developed large, high capacity farming equipment. One such piece of equipment is the highly mechanized grain harvester, commonly known as the combine. Combines have evolved from labor intensive, stationary threshing machines to expensive, mobile machines controlled by a single operator.

The high cost of these machines and the limited amount of time available for the harvesting process, necessitate that maximum performance be obtained from these machines whenever possible. Maximum performance requires that optimum settings of machine parameters and ground speed be known, and used, for a particular crop condition to deliver optimum grain quality at acceptable grain loss levels. Consequently, various control mechanisms have been developed in attempts to select automatically machine settings and/or ground speed in response to sensed crop conditions.

Some control systems are dependent on either an indirect or direct indication of grain loss. Currently-available grain loss measuring techniques are of limited use as they sense only the amount of grain separation occurring at the end of the straw walkers or cleaning sieves. Therefore, an improved system that would accurately relate the separation at these points to the total grain loss is required. This thesis discusses work carried out to test a proposed grain loss measurement system mounted on a set of combine straw walkers in the laboratory.

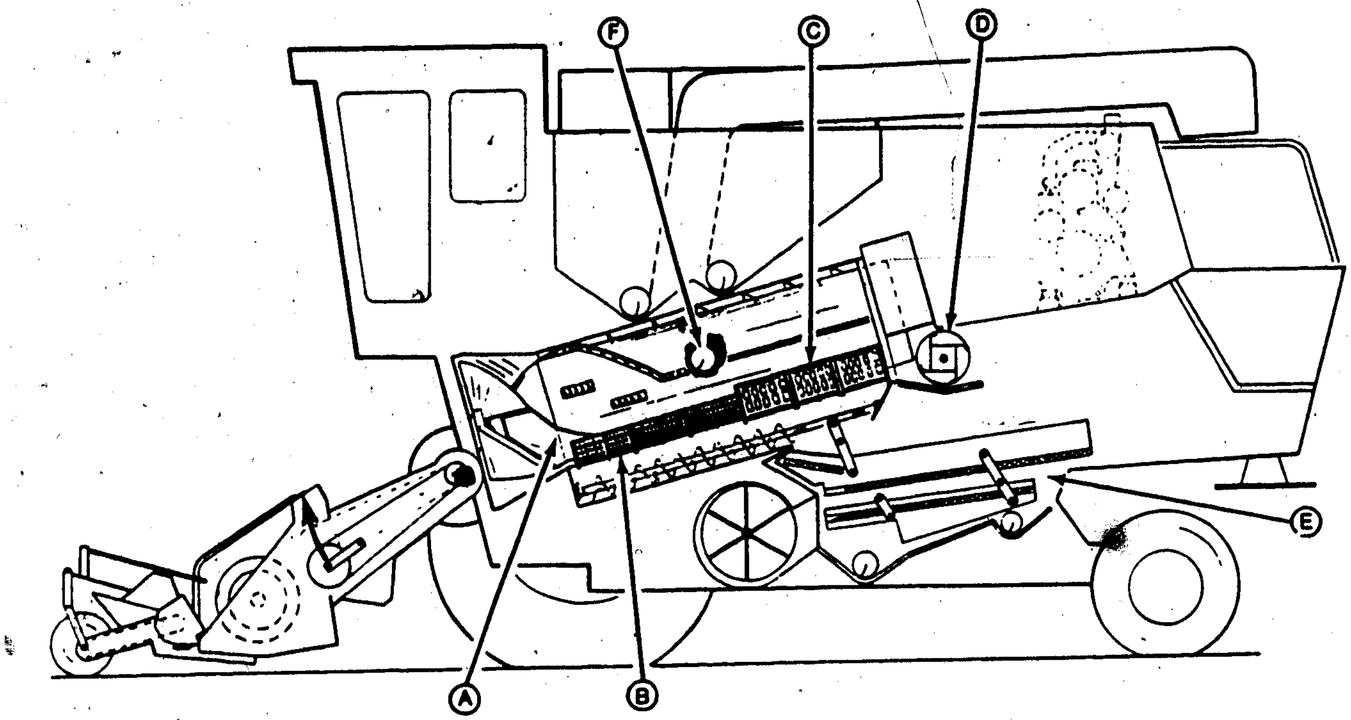
1.1 Grain Harvesting Terminology

Grain harvesting, or combining, is the process of removing the grain kernels from the plant ear and/or stalk and collecting the kernels for subsequent storage and consumption. Grain, in this thesis, will refer to the seed of cereal crops such as wheat, oats, barley, and rye. Appendix A describes the operation of a conventional-type combine as shown in Figure 1.1. The term "conventional-type" refers to those combines which have a threshing cylinder, which loosens the grain from the crop ears, with a horizontal axis perpendicular to the flow of the crop, and a set of oscillating racks, known as straw walkers, which separate the threshed grain from the straw. Recently, rotary-type combines have gained popularity. Rotary-type combines feature one or two threshing and separating rotors with longitudinal axis parallel to the crop flow. These rotors replace the threshing cylinder and straw walkers of the conventional-type combines (see Figure 1.2). The work described in this thesis is applicable to conventional-type combines, however, some research suggests that similar loss



(1) Pickup
(2) Table Auger
(3) Feeder Elevator
(4) Threshing Cylinder
(5) Concave
(6) Grain Pan
(7) Rear Beater
(8) Beater Grate
(9) Straw Walkers
(10) Cleaning Shoe
(11) Straw Chopper
(12) Cleaning Sieves
(13) Cleaning Fan
(14) Grain Tank
(15) Unloading Auger

Figure 1.1 Conventional Style Combine Schematic
(adapted from PAMI, 1981)



(A) Rotor

(B) Threshing Concaves

(C) Separating Concaves

(D) Rear Beater

(E) Cleaning Shoe

(F) Tailings Return

Figure 1.2 Rotor Style Combine Schematic

(adapted from PAMI, 1979)

detection principles may be applied to rotary-type combines (Zoerb *et al.*, 1984).

In both combine types there are various sources of grain loss. Combine grain loss is defined as that portion of the grain existing in the windrow or standing crop (in the case of straight-cut combining), which does not end up in the grain tank in an undamaged state. If the crop is too ripe, or the pickup or reel rotational speed is excessive, some of the grain may shatter out of the ears onto the ground as the crop is conveyed into the combine. This portion of the total grain loss is often referred to as header losses.

If not properly adjusted, the threshing cylinder also can be a source of excessive grain loss. Excessive threshing action (i.e. cylinder speed too fast and/or concave clearance too small) will tend to physically damage some of the grain kernels. This loss is known as breakage loss.

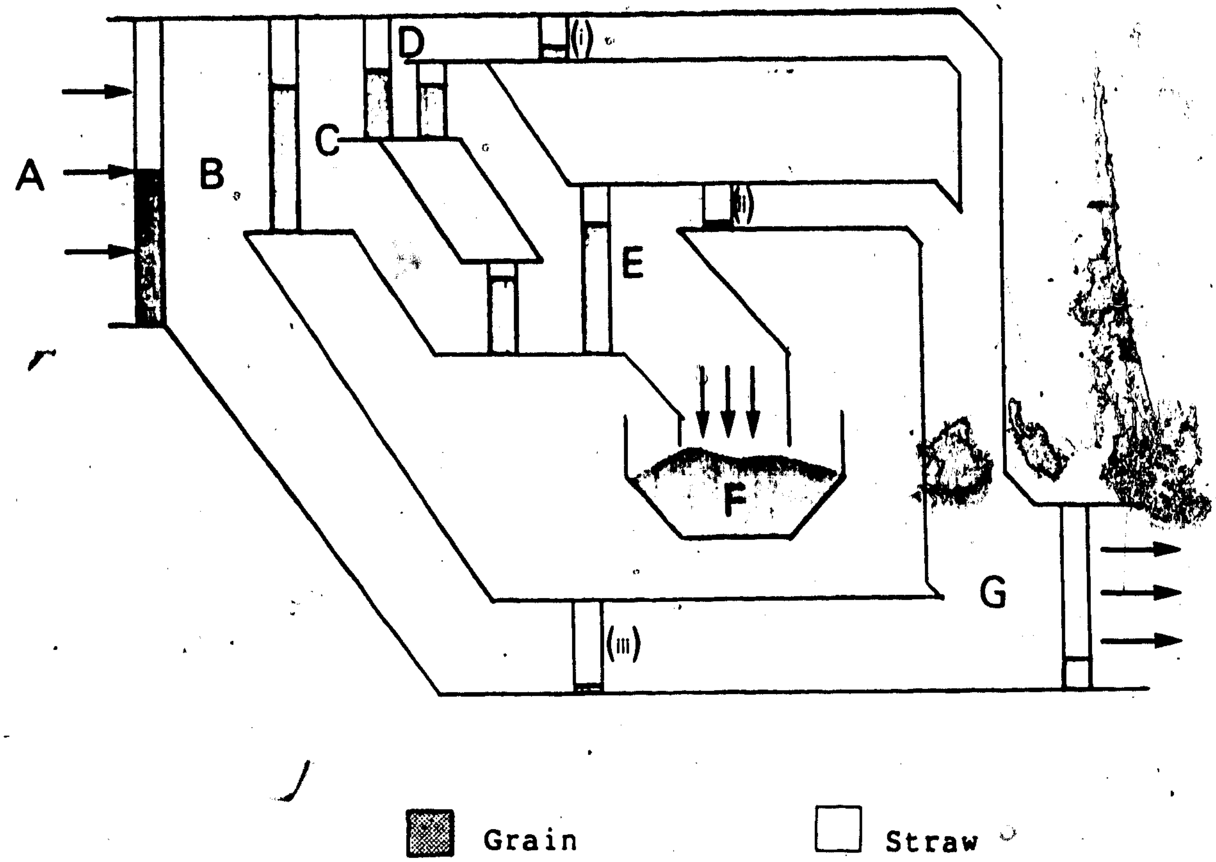
If the threshing action is insufficient (i.e. cylinder speed too slow and/or concave clearance too great), some of the kernels may not be loosened from the ears and will be expelled out of the combine intact with the straw. This type of loss is known as threshing loss. Detection of header, breakage, and threshing losses is difficult to achieve except by careful evaluation of the crop stubble, grain sample, and the combine effluent straw respectively.

Grain loosened from the ear, but still remaining unseparated from the straw mat as it passes over the end of the straw walker is known as walker loss. Walker loss generally is considered the most significant of all forms of combine grain loss (Goss *et al.*, 1958; Nyborg, 1964; Zoerb *et al.*, 1974) and can be as much as five to fifteen percent of the grain in the crop (Nyborg, 1964; Huisman, 1983).

The grain expelled with the chaff over the top sieve of the cleaning shoe is known as sieve loss. Sieve loss often results from excessive fan speeds or the over loading or plugging of a portion of the sieve.

Nyborg (1964) showed that both walker loss and sieve loss were related to the G/MOG ratio and the feed rate of the crop. The G/MOG ratio is the ratio of the weight of the grain to the weight of the materials other than grain in the crop entering the combine. Materials other than grain include straw, chaff, weeds, and other foreign material. The crop feed rate refers to the total weight of the grain and materials other than grain entering the combine per unit time.

Figure 1.3 illustrates the flow of grain and crop material through a conventional-type combine. Threshing, walker, and sieve grain losses occurring during the harvesting process are depicted schematically. The detection of the above types of grain loss is required for optimizing combine performance.



Harvesting Process

A) Cutting/Pickup

B) Transport

C) Threshing

D) Straw Walker Separation

E) Cleaning Shoe Separation

F) Grain Storage

G) Effluent Discharge

Losses

i) Walker Loss

ii) Sieve Loss

iii) Header Loss

Figure 1.3 Flow of Material Through a Conventional Combine

1.2 The Need for Monitoring of the Combine Harvester

Optimum performance of a combine occurs at machine settings which allow the highest throughput of crop material at an acceptable loss level. Crop throughput is determined by the combine ground speed, while loss levels are governed by the adjustment of machine components in response to the crop feed rate. The optimum adjustment of machine components such as cylinder speed, cylinder-concave clearance, fan speed, and size of sieve openings usually are determined from the evaluation of the crop stubble, the grain sample obtained, and the combine effluent, as, or after, the combine is operated in a representative sample of the crop, at trial machine settings and ground speeds (Gullacher and Smith, 1979). Operator experience and manufacturers' guidelines (e.g. International Harvester Co., 1984) provide the basis for the selection of the trial settings.

As it is practically impossible and economically infeasible (McGechan and Glaseby, 1982; Huisman, 1983; Leflufy and Stone, 1983; Palmer, 1984) to operate a combine at a zero grain loss level, usually the combine settings and ground speed that deliver an acceptable, or optimum, grain loss level are chosen. The above authors suggest that there is an optimum combine grain loss level at which the total harvesting losses are a minimum.

The determination of this minimum level requires consideration of not only the grain losses, but also of economic losses arising from the time required to complete the harvest, the costs of grain drying and/or grain quality deterioration, and machine operating costs. As an extreme example, a combine operated at a near-zero grain loss level would travel at such a slow ground speed that labor, fuel, and machine costs, not to mention the costs arising from the risk of not completing the harvest without extra grain drying or crop deterioration due to inclement weather, are likely to be much greater than the savings realized by the reduced loss levels. Therefore, economic and climatic conditions must be considered by the operator when choosing a desired grain loss level at which to operate.

Once the appropriate machine settings have been found, the operator must attempt to maintain, or keep below, the desired loss level by maintaining the associated feed rate. A near constant crop feed rate can be maintained by adjusting the ground speed of the combine in response to variations in crop stand density. However, crop properties other than feed rate, such as G/MOG ratio and moisture content, have an effect on the amount of grain loss. As these properties vary, the feed rate associated with a particular grain loss level also will vary.

The sensing of the crop properties mentioned above, and the control of machine parameters in response to those crop properties are complex tasks. Instrumentation showing the status of crop properties and machine parameters would aid the operator in accomplishing these tasks. However, to date, reliable on-board crop moisture and G/MOG ratio sensors have not been developed. As an alternative, a direct indication of walker and sieve grain loss, along with an understanding of the relationship between grain loss and crop feed rate, would allow the control of combine harvester ground speed in response to changes to any crop variable affecting that grain loss. Such control is usually realized manually by the operator, however, automatic ground speed controllers have been developed recently.

1.2.1 Operator ground speed control

Operator-controlled ground speed adjustments are usually based upon some perception of grain loss. To provide the operator with such a perception, numerous grain loss monitors, based on that developed by Reed *et al.* (1968) are available and are in common use. When a combine is equipped with a grain loss monitor, detecting walker and sieve grain loss, the operator will select a ground speed resulting in a monitor reading that approximates the reading obtained when operating at a previously determined grain loss level. The effectiveness of this type of control is limited not only by the intelligence and experience of the operator responding to the grain loss signal, but also by the accuracy of that signal, which tends to be limited (PAMI, 1976a-e; Gullacher, 1978; Gullacher and Smith, 1979; Huisman, 1983; Cooper, 1984).

Grain loss monitors, as used today on conventional combines, detect grain kernels separating from the straw or chaff just past the rear end of the straw walkers or cleaning shoe. The sample of kernels detected at those points is assumed to be a constant percentage of the total number of kernels passing over the end of the walker or cleaning shoe, respectively. In the case of straw walkers, this assumption has been proven false when tested over the full range of normal combine operating conditions (Gullacher and Smith, 1979; Huisman, 1983).

Also, the theoretical weakness of this assumption is demonstrated by considering the separation characteristics of the straw walkers as illustrated in Figure 3.2. The plot of grain separation along the extent of the straw walkers, has been shown to decay exponentially over the rear portion of the straw walkers (Zoerb *et al*., 1974; Huisman, 1983). The form of this exponential decay curve is determined by the G/MOG ratio, crop and grain moisture content, and other, intrinsic crop properties such as kernel size, weight, and roughness (Zoerb *et al*., 1974; Huisman, 1983). Walker loss is represented by the area under the separation curve extrapolated past the end of the walkers. Both the equation of the curve and the distance from the point where separation becomes exponential to the end of the walkers, need be known to calculate walker loss. Present systems detect only the grain separating at the end of the walkers, and do not consider the shape of the separation curve.

Huisman (1983) introduced a principle for an improved grain loss monitor by suggesting that grain separation should be measured at various points under the walkers. These measured separation values then may be fitted to a curve of exponential decay form, and the equation of that curve be calculated. Once this curve is known, the grain loss may be calculated by integration over the appropriate range.

A major drawback of ground speed control based on grain loss indication is the large time delay between a grain loss reading and the sensed effect of ground speed changes made as a result of that reading. Palmer (1984) estimates this time to be 8-10 seconds. This limitation also affects automatic ground speed control systems, however recent developments have been made by Leflufy and Stone (1983) that attempt to circumvent this problem.

1.2.2 Automatic ground speed control

Numerous attempts at automatic ground speed control have been made in the last thirty years. Many systems consisted of rather crude devices which converted an electrical or mechanical signal of feed rate magnitude into a hydraulic action on the variable ground speed drive of the machine (Dymnich, 1956; Nastenko and Gurarii, 1959; Mikhailov, 1960; Bogdanova, 1960; Gulyaev, 1960; Feiffer, 1964; Zoerb *et al.*, 1966; Brouer and Goss, 1970). Eimer

(1974) supplemented ground speed control with threshing cylinder speed control, also in response to a feed rate sensor's electronic signals. Reed and Grovum (1969) controlled ground speed hydraulically in response to electronic signals obtained from grain loss monitors.

With the exception of Reed and Grovum (1969), the control actions of the the above systems were based on the assumption that a feed rate exists at which an optimum grain loss level is achieved. However that feed rate will vary for a given desired loss level as the moisture content and other crop properties (i.e. G/MOG ratio) vary. Therefore for these systems to be effective, combine operators would need to be able to sense variations in moisture content and other properties. More importantly, the controlling mechanism must be intelligently altered to realize the correct feed rate as the properties other than crop density changed. The system developed by Reed and Grovum (1969), which directly sensed the walker and shoe grain loss, was limited in effectiveness by the accuracy of the grain loss reading. Also, the time delay between a feed rate signal and the grain loss resulting from that feed rate, caused sluggish and/or erratic response.

Recent microprocessor-based feed rate controllers (Famili, 1983a; LeFlufy and Stone, 1983; Krutz and Maillander, 1983) appear more effective than the earlier systems. The microprocessor has the ability to interact with two or more input variables, and instigate control action derived from an algorithm which is selected on the basis of, and performs calculations with, the input variable values. Both Famili (1983a) and Krutz and Maillander (1983) developed systems which combined input from a feed rate sensor with an engine speed signal to give an adjusted measured feed rate value. Both systems were successful in maintaining a near constant feed rate. However, no consideration was given to the varying relationship between crop feed rate and grain loss level.

LeFlufy and Stone (1983) attempted to establish such a relationship with their microprocessor-based system. The microprocessor collected inputs from both grain loss sensors and feed rate sensors located at the lowermost feed elevator shaft. Cross-correlations were performed between averaged grain loss readings and averaged feed rate data occurring at 0.2 second intervals between six and ten seconds before the grain loss readings. The equation relating grain loss to feed rate, resulting from the time interval showing the highest linear coefficient of correlation over forty seconds of data, was used to calculate a desired feed rate for the operator-specified, optimum loss level. Control action was based on the difference between the existing feed rate and the calculated desired feed rate. The feed rate-grain loss relationship was recalibrated every forty seconds, and changed if the new maximum linear coefficient of correlation was greater than 0.60. In this system the grain separated and detected at the end of the straw walkers and cleaning shoe, was assumed to represent grain loss. As a result the grain loss measurement was limited in accuracy as previously discussed and, thus, the control effectiveness would also have been limited. A grain loss measurement system as proposed by Huisman (1983) and tested in this thesis could, theoretically, improve LeFlufy and Stone's (1983) automatic control system.

1.3 Statement of the Problem

Agricultural economic pressures require that producers attempt to achieve optimum performance from their machines. In the case of grain harvesting, an efficient operator will aim to operate his combine harvester at the machine settings and ground speed which result in a grain loss level less than or equal to a pre-determined acceptable level. One way to realize this is to adjust ground speed (either manually or automatically) in response to the perceived grain loss level. Such a system requires, most critically, an accurate measurement of grain loss. Presently, only monitors detecting grain loss over the sieves and straw walkers are available for conventional combines. Furthermore, these monitors are limited in accuracy, and are better suited to indicate, rather than measure, grain loss.

Huisman (1983) proposed an improved measurement system which would ascertain a walker grain loss value using algorithms defining the separation curve beneath the straw walkers. This thesis describes an attempt to implement such a walker grain loss measuring system.

2 AIMS AND OBJECTIVES

The aim of this project was to obtain experimental evidence demonstrating the feasibility of an improved grain loss measurement system. Conceptually, this system would detect separation of grain at various points under the straw walkers using existing sensors interfaced to a computer. Using appropriate software the system would provide accurate indications of grain loss. Specific objectives which needed to be met to realize this goal included:

a) Development of a laboratory straw walker assembly which would produce separation curves of exponential decay form.

b) Confirmation, using separation data from the laboratory apparatus, that actual grain loss could be predicted accurately from separation measurements at four points below the walkers.

c) Development of hardware and software for interfacing grain loss sensors to a computer which would accurately measure separation at various points under the straw walkers and, thus, provide a measurement of actual grain loss.

3. LITERATURE REVIEW

The efforts to optimize combine performance have resulted in a great deal of literature pertaining to combine operation, the monitoring of that operation, and finally the control of that operation. This review begins by outlining research studying the straw walker grain separation process, in particular the occurrence of grain loss over the straw walkers. A review of monitoring devices of grain combines follows, with considerable emphasis placed on grain loss monitors.

3.1 Grain Loss and Separation Characteristics

In the past thirty years extensive study of the performance of grain combines has taken place. The studies have evolved from establishing general performance relationships of the complete harvesting process (Goss *et al.*, 1958; Nyborg, 1964; Cooper and Neal, 1968; Nyborg *et al.*, 1969; Nyborg and Wrubleski, 1978) to the analysis of the individual unit processes of combining (Boyce *et al.*, 1974; Zoerb *et al.*, 1974; Huynh *et al.*, 1982) and the interactive modeling and simulation of all the processes (Kirk *et al.*, 1978; Huisman, 1983). Of concern to this study are-the characteristics of walker losses and performance.

3.1.1 Grain loss relationships

As conventional style grain combines replaced the traditional stationary threshing machines in Western Canada, farmers and engineers soon became aware that undesirable grain losses resulted from improper operation. As described in Appendix A the losses could originate from various processes.

Goss *et al*. (1958) recorded that straw walkers are the source of the greatest amount of combine grain loss at high crop feed rates, but did not speculate upon the form of the walker loss-feed rate relationship. Interestingly, these authors did not find that walker loss was affected by an increase in the G/MOG ratio from 1.07 to 1.70 while harvesting barley. More recent research has consistently shown that the G/MOG ratio does affect walker loss. Nyborg (1964) approximated the relationships of walker loss (W_L) to feed rate (F_R) and G/MOG respectively as follows:

$$W_L = J(F_R)^n \quad (3.1)$$

$$W_L = K(G/MOG)^{-m} \quad (3.2)$$

where J, K, m, and n are positive parameters whose values depend on crop properties.

Nyborg *et al*. (1969) applied various mathematical regression models to walker loss, feed rate, and G/MOG values. A multiplicative model as follows provided a good fit of walker loss:

$$W_L=a(F_R)^b\cdot(G/MOG)^c \qquad (3.3)$$

The model resolves to the following at constant G/MOG:

$$W_L=d(F_R)^f \qquad (3.4)$$

where a, b, c, d, and f are parameters reflecting crop conditions.

Nyborg and Wrubleski (1978) further verified this model and cited confidence levels of ninety nine percent for walker loss. The data for shoe loss and cylinder loss fit linear regression models relating them to feed rate.

As shown in Figure 3.1, walker loss not only makes up the most significant portion of total loss but, also, increases more rapidly with feed rate than do other losses. Conversely, walker loss levels can be controlled most readily by manipulating the feed rate.

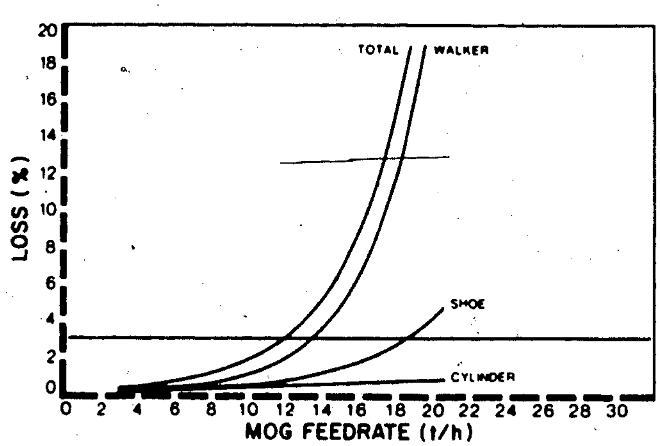


Figure 3.1 Typical Loss-Feed Rate Relationships for a Conventional Combine (adapted from PAMI, 1981)

3.1.2 Grain-straw separation characteristics

Nyborg *et al*. (1969) indicated that a theoretical analysis of grain separation on an oscillating straw walker would be of great value in understanding straw walker loss. Boyce *et al*. (1974), recognizing that straw walker separation efficiency was impeding combine performance, undertook a field study of straw walker separation. A combine was modified to facilitate collecting separated grain from sections below the straw walkers and concave, as well as collecting the non-separated straw walker effluent. These authors defined walker efficiency on a point basis (EFFP), and on an overall basis (EFF) as follows:

$$EFFP = GS/GA \cdot 100\% \tag{3.5}$$

where GS=amount of grain separated per unit area (kg),
GA=amount of grain available to be separated at that area (kg).

$$EFF = TGS/TGA \cdot 100\% \tag{3.6}$$

where, TGS=mass of grain separated along the walkers (kg).
TGA=mass of grain coming onto the walkers (kg).

The study found overall efficiencies exceeded 96% if sufficient walker length was available. Point efficiencies varied from near zero to 50%. The presence of curtains, hanging above the straw walkers, causing a throttling effect on the flow of the grain-straw mixture, improved the point efficiencies in those areas above which the curtain hung. No attempt to fit the relationship of separation rate to position along the walker was reported in this study.

Zoerb *et al.* (1974), in a laboratory straw walker performance study, related grain unseparated at the end of the walkers G_r (kg), to grain initially passed onto the walkers G_o (kg), and the walker length L (m), by:

$$G_r=G_o \cdot e^{(-B \cdot L)} \tag{3.7}$$

where B is a constant, related to feed rate, G/MOG, walker design, moisture content, and other crop properties such as weed contamination, crop variety, presence of awns, etc.

Huisman (1983) explained that the amount of grain separated at a distance (x) along the walkers, $S_v(x)$, is the derivative of the plot of $G_r(x)$, the grain remaining in the straw at any distance (x) along the walkers, and equates to:

$$S_v(x)=-B \cdot G_o \cdot e^{(-B \cdot x)} \text{ (kg/m)} \tag{3.8}$$

The distance, x, is not considered to be measured from the front of the walker but, rather, from a theoretical point where the separation process becomes exponential. The position of this point is influenced by curtain positioning, the beater and walker orientation, crop feed rate, and crop properties as mentioned above. The fact remains, however, that for the rear portion of the straw walkers, the separation curve follows an exponential decay of the form shown in Figure 3.2 where:

$$S_v(x)=A\cdot e^{(-B\cdot x)} \tag{3.9}$$

A and B are constants related to crop feed rate, combine settings (Huynh *et al*., 1982), and crop properties.

Walker loss is represented by the area underneath the separation curve in the interval where x is greater than ℓ, the distance to the end of the walkers (Figure 3.2). Calculation of this area requires that constants A, B, and ℓ be known. From Swokoski (1975), the mathematical derivation for the area representing walker loss, W_L, is solved as follows:

$$W_L=\int_\ell^\infty S_v(x)\cdot dx \tag{3.10}$$

$$=A\cdot\int_\ell^\infty e^{(-B\cdot x)}\cdot dx$$

$$=-[A/B\cdot e^{(-B\cdot x)}]_\ell^\infty$$

$$=0+A/B\cdot(e^{(-B\cdot \ell)})$$

$$W_L=S_v(\ell)/B \tag{3.11}$$

where $S_v(\ell)$=the rate of separation occurring at the end of the straw walker.

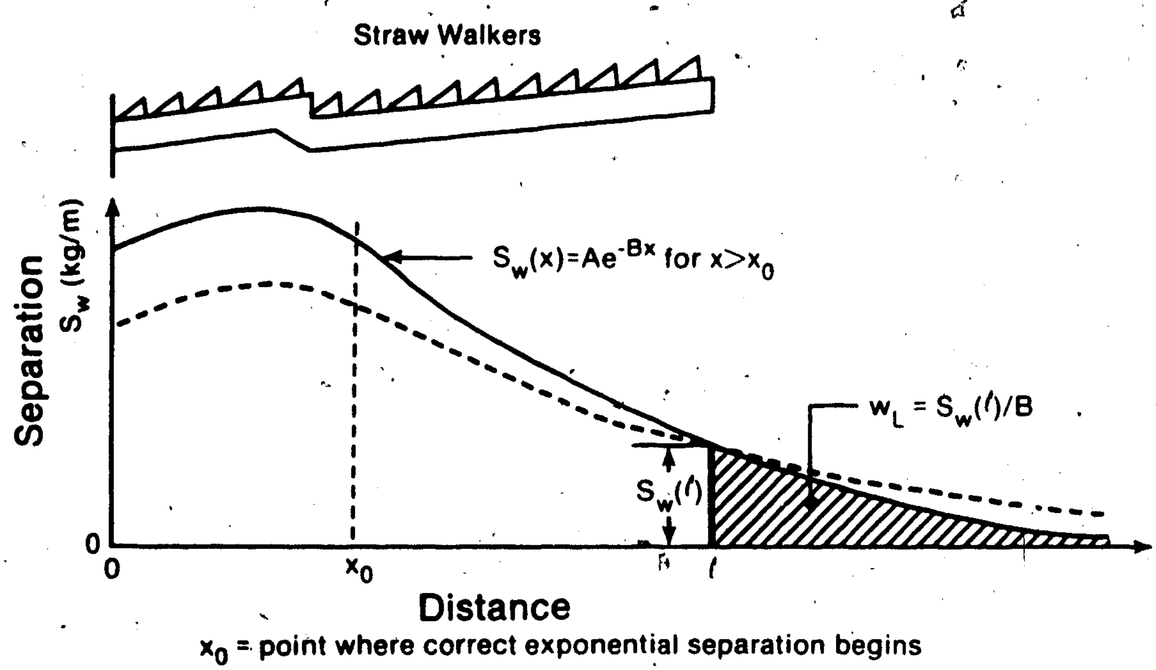


Figure 3.2 Plot of Separation Rate Over Straw Walkers

3.2 Combine Performance Monitors

The process of grain harvesting is by no means a simple one. Machine parameters (i.e. ground speed, threshing cylinder rotational speed, concave-cylinder clearance, fan speed) must be adjusted correctly on the basis of information sensed about the crop (i.e. grain loss, moisture content, and feed rate). Since the optimum operation of a harvester depends on the matching of machine and crop parameters, both of these must be sensed. Although this sensing may be done subjectively by a skilled and experienced operator, the task is suited more to the use of monitoring devices. Two categories of combine monitors, then, may be defined and are described below.

3.2.1 Machine status monitors

This category consists of those monitors which indicate the operating level of machine parameters. Rickerd and Gardner (1971) define a machine status monitor as a device that communicates the state of a machine function (normal, failure, or impending failure) to the operator.

Requirements of improved performance and operator safety have resulted in the numerous machine status monitors available on combines today. The combine or tractor cab is designed for operator comfort, safety and relief of operator fatigue and has, in effect, isolated the operator from the machine (Reed, 1978; Rickerd and Gardner, 1971). The operator must rely on monitors to replace, to a degree, his own senses of sight, sound, smell, and touch to evaluate the status of machine parameters.

As the engine was the most costly and critical combine component, the first types of monitors which became standard on grain harvest combines were those indicating the status of engine functions (Rickerd and Gardner, 1971). Engine functions commonly monitored include the electrical charging rate, cooling system temperature, lubrication pressure, hydraulic pressure, fuel level, engine speed, engine load, and flow restriction in filters. Warning lights, buzzers, and/or analog or digital readouts indicate the state of these functions to the operator (Reed, 1978). The indications can alert the operator to carry out required maintenance which may prevent costly breakdowns.

Also, the knowledge of the state of numerous machine functions can allow the operator to prevent plugging of the combine, as well as those breakdowns caused by excessive pluggings. Reed (1978) refers to a crude type of monitoring application. A piece of wire with a flag on one end is wrapped onto the end of a shaft that, itself, is not in the operators sight. The rotating flag, clearly visible to the operator, indicates when that particular shaft is rotating as it should. Today, more accurate and convenient electronic transducers and displays have replaced the simpler devices. Machine functions commonly monitored include shaft speeds (straw walker oscillations, cylinder speed, ground speed, fan speed, reel speed, etc.), bearing temperatures, straw walker loads, grain tank level, and header height (Reed, 1978; Rickerd and Gardner, 1971; International Harvester Co., 1984; Rayfield, 1984). Either the specific level of operation of a particular function is displayed with analog or digital readouts, or the monitor indicates if the level of a function is outside of pre-set limits, with visual and/or audible alarms. Often the display components of the various monitors are integrated into one common panel where all information is available to the operator (Rayfield, 1984; Rickerd and Gardner, 1971; Kopp, 1978).

3.2.2 Production status monitors

The monitors in this category sense crop properties during the operation. Changes in these properties often illustrate need for control action (i.e. altering a machine parameter setpoint level).

There are a number of crop properties which affect the harvesting process. Included in these are the crop stand density (which, divided by the machine ground speed, determines the feed rate), the moisture content of both the straw and the grain, the G/MOG ratio, the crop variety, and the amount of weeds in the crop sample. These properties all affect the relationship between ground speed and grain loss.

If a ground speed control system based on grain loss measurement is to be completely successful, the grain loss reading may need to be adjusted for varying straw and grain properties. Accurate on-board sensors, and an understanding of the effects that these properties have on the grain loss reading, would be necessary to accomplish the adjustments to ground speed accurately. Also, as Leflufy and Stone (1983) suggest, grain loss readings, expected to result from the existing crop feed rates, may be determined on-board from recorded feed rate and grain loss data. Such a system would improve ground speed control by compensating for the time delay inherent in a strictly grain loss-based control system.

To date, only feed rate and moisture contents have been monitored with some success, as will be discussed below. Other crop properties have not been successfully monitored. Some success has been realized, however, in monitoring the efficiency of straw walker separation, which is dependent upon all the properties listed above. The amount of grain separated out of the straw mat as it passes over the walkers is monitored, and is often considered to indicate straw walker grain loss.

Following, then, is a review of those production status monitors which to date have been applied to the grain harvesting process.

3.2.2.1 Moisture content sensors

Zoerb *et al.* (1974), Huisman (1983), Nyborg (1969), and Boyce *et al.* (1974) all indicate that separation characteristics and, thus, combine efficiency, are affected by the moisture content of both the straw and grain.

Van Loo (1978) had some success in applying a calibration factor, based on straw moisture content, to grain loss monitor output. In this study a meter mounted on the floor of the crop feed elevator measured the electrical resistance of the straw passing over it. The resistance of the straw is a function of the moisture content.

Baskin *et al.* (1981) and Brizgis *et al.* (1978) relate crop moisture content to optimum threshing cylinder speed. These authors experienced difficulty in maintaining a continuous flow of the crop over the sensing probe of the moisture meters used.

Moisture sensing monitors are not common on combines today, however their usage will be essential in the development of automatically controlled combines.

3.2.2.2 Feed rate sensors

Another type of crop control monitor which has been developed for purposes of automatic control of combines is one which can sense the feed rate of material intake. Various parameters have been sensed as indirect indicators of feed rate. Depth of straw in the feed elevator housing, forces on the cutter bar, torque on the table auger, deflection of the lowermost feed elevator shaft, the crop pressure on the feed elevator floor, threshing cylinder torque, straw walker grain loss, and engine intake manifold pressure are examples of feed rate indicators that have been studied (Dymnich, 1956; Nastenko and Gurarii, 1959; Mikhailov, 1960; Fieffer, 1964; Zoerb *et al.*, 1966; Reed and Grovum, 1969; Brouer and Goss, 1970; Eimer, 1974; Huisman *et al.*, 1974; Schueller *et al.*, 1982; Kruse *et al.*, 1982; Huisman, 1983; Famili, 1983b). The work of these authors does not suggest that one particular process variable gives the best indication of feed rate. However, systems sensing a process variable of the crop flow before or as it enters into the feed elevator were considered more suitable to control applications because they permitted an earlier control action on ground speed with respect to the occurrence of a crop density change.

3.2.2.3 Grain loss monitors

In 1965 Reed *et al.* (1968) undertook a study to determine if there were suitable characteristics of the straw, grain, chaff separation process that would indicate reliably the amount of loss occurring in this process. The result of this study was the development of the first commercially available grain loss monitor. Inspired by the audible distinction between grain kernels and straw in combine effluent dispersed by the straw spreader, as the effluent struck the body of a truck, the above authors developed grain kernel impact sensors.

Reed (1978) reported that devices of similar operating principles were developed by Feiffer *et al.* in East Germany, and by K.E. Morgan in the United Kingdom, both in 1965. According to Reed (1978), these people were unaware of each other's developments at the time.

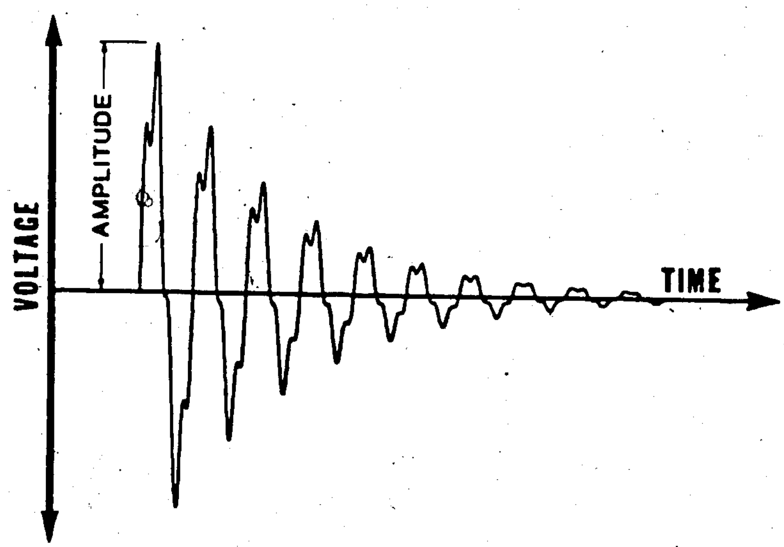


Figure 3.3 Typical Kernel Impact Voltage Signal
(adapted from Gullacher and Smith, 1979)

The heart of these sensors is a piezoelectric crystal. A piezoelectric crystal has the ability to generate an electric potential when subjected to a mechanical strain (Schuler, 1982). The crystal is mounted on a vibration sensitive sounding-board, affixed to a mounting plate by shock absorbing material. The mounting plate is attached rigidly to the combine in a position where the sounding board is in the path of grain kernels which are to be detected. Grain striking the sounding board results in the generation of small electrical pulses. Figure 3.3 shows a typical signal generated by a grain loss sensor due to a single grain kernel impact (Gullacher and Smith, 1979).

Signals from the sounding-board are amplified, discriminated from non-grain impact signals, and converted to an analog voltage representative of the number of impacts per unit time. Reed *et al*. (1968) used signal amplitude as a means of discrimination of grain from non-grain impacts. Straw and chaff, being of much less weight than the grain kernels, created an impact signal of considerably less amplitude than did the grain. However, when small seeded crops are considered, the amplitudes of the seed and non-seed impacts are less easily distinguished. In 1977, Kirk, at the University of Saskatchewan, developed circuitry which distinguished seed impacts from non-seed impacts on the basis of the signal oscillation frequency (Reed, 1978). Another modification evident on some of the loss monitors available today is the conversion of the output analog signal to a reading representing impacts per distance travelled (Wood and Kerr, 1980). This, of course, requires that a measure of ground speed be available.

All commercially available grain loss monitors have some common components. Firstly, all are equipped with vibration sensitive sensors. The sensor may be in one of a variety of configurations (i.e. pads, tubes, or boards). All grain loss monitors have some form of a signal discriminator that distinguishes between grain and non-grain impacts. Usually, this is adjustable to different levels for different crops by means of a sensitivity control. Lastly, all grain loss monitors have circuitry which converts the number of impact signals per unit time into an analog voltage to be displayed by a meter, the response of which is determined by a calibration control.

Since their initial development, grain loss monitors have been the subject of much evaluation. Serious questions about their value, as presently used, have been raised (Cooper, 1984). The Prairie Agricultural Machinery Institute (PAMI) have performed extensive tests of popular models (PAMI, 1976a-e; Gullacher, 1978; Gullacher and Smith, 1979).These authors have concluded that grain loss monitors generally were successful at indicating the presence of grain loss, but did not give accurate readings of loss rates over the normal range of combine operating conditions. To understand these shortcomings, a knowledge of sensor location and operation is required.

On conventional-type combines, grain loss sensors are placed immediately behind and slightly below the straw walkers and cleaning shoe. In these positions they detect a sample of the grain that is being separated from the bulk of straw or chaff at the end of the separating mechanism (walker or shoe). This sample is considered to represent total loss and is displayed as some value determined by the sensitivity and calibration controls of the meter. That meter value is correlated to a meaningful loss rate (i.e. kernels/second, bushel/acre) only by means of a manual calibration procedure involving the measurement of the number of grain kernels in the effluent. As Cooper (1984) has described, such a procedure is very meticulous and time-consuming. Gullacher (1978) explains that the above procedure usually is replaced by one in which the machine is set to produce an acceptable loss level, the meter is calibrated to indicate such, and then, any subsequent meter reading is evaluated relative to the acceptable loss meter reading. This system is effective if the sample of grain sensed remains a constant percentage of total grain loss. Unfortunately, this is not the case.

Referring to the straw walker separation curve shown in Figure 3.2, walker loss is represented by the area under the curve past the end of the walker. Equation 3.11 shows that total walker loss is related to the separation at the end of the walker by a proportionality factor of 1/B. The parameter B, however, is dependent upon feed rate, G/MOG, and other crop properties, and is subject to significant variation throughout a day and/or field. Theoretically, for grain loss monitors to be absolutely correct, recalibration would be required with every change in the parameter B. As there is no method to measure directly the value of the parameter B for the crop entering the combine, accurate readings of grain loss rates in varying crop conditions are impossible to achieve using grain loss monitors in a conventional manner. Cooper (1984) describes the situation well:

> "So we are left with a paradox: the loss monitor itself requires such careful and elaborate monitoring that it's worth becomes a questionable matter."

Other problems exist with grain loss monitors. Figure 3.4 illustrates the phenomenon of sensor saturation. This occurs when impacts are occurring at a rate greater than the rate at which the circuitry can distinguish each individual impact. This problem can be solved by limiting the sample size which is allowed to fall onto the face of the sensor (Gullacher and Smith, 1979).

Another major weakness of grain loss monitors is that they indicate loss which resulted from crop conditions which existed approximately eight to ten seconds beforehand (Huisman, 1983; Famili, 1983a). This is because of the amount of time the crop spends in the combine. Feed rate, or ground speed control based entirely upon walker loss indication could, therefore, be erratic if the crop conditions are highly variable.

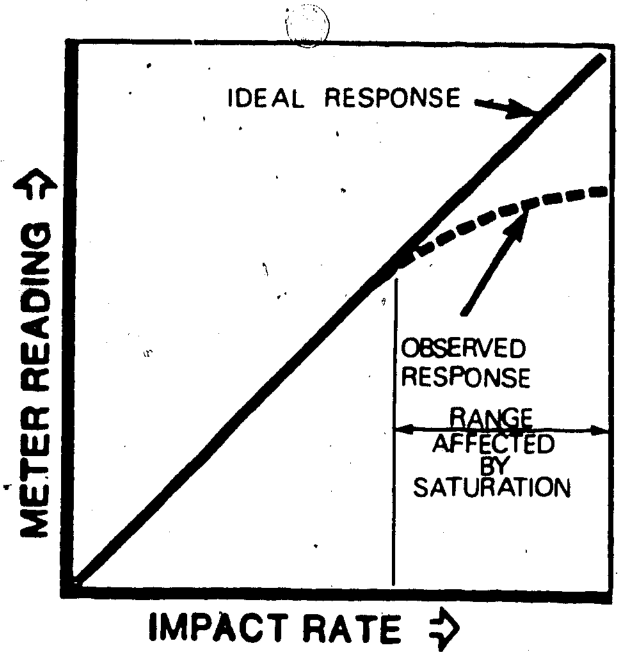


Figure 3.4 Effects of Sensor Saturation
(adapted from Gullacher and Smith, 1979)

4 EXPERIMENTAL DESIGN

The aim of this experiment was to show that, for different separation curves, an accurate indication of grain loss over the end of straw walkers could be obtained using the instrumentation described. Efforts were made to show that this indication was more accurate than conventional grain loss monitor indications. Since it would be very difficult to measure the rates of grain and straw passing onto the straw walkers in a combine in a field application, a laboratory experiment, in which pre-measured rates of threshed grain and straw were passed over a set of straw walkers, was designed. In the experiment, variations in the grain separation curves were produced by varying the ratio of grain rate to straw rate passing onto the straw walkers.

As each run (i.e. production of a separation curve) involved a considerable amount of time, labour, and materials, the experiment was limited to four replications of the ten runs, listed in Table 4.1, chosen to test the system under grain/straw ratios between 0.26 and 0.89. The performance of each run consisted of the separation of a particular flow rate of grain from the quantity of straw delivered to the straw walkers at the chosen straw flow rate. The four replications of the ten runs were performed in efforts to provide improved statistical confidence in the results. In each of the replications the order of the ten runs was randomized.

Unfortunately, the grain delivery system did not deliver exactly the required grain flow rates. Typically, the errors in the grain flow rate were as much as 35%, thus the result was a sample size of forty runs with varying G/MOG ratios. The values for the grain and straw rates used in these runs are typical walker loads under high loss conditions. Reed (1985) indicated similar loading rates were used in a laboratory straw walker study described by Zoerb *et al.* (1974).

TABLE 4.1 DESIRED GRAIN AND STRAW COMBINATIONS

RUN #	GRAIN (kg/min)	STRAW (kg/min)	GRAIN/STRAW
1	14.5	55	0.26
2	14.5	45	0.32
3	20.0	55	0.36
4	14.5	35	0.41
5	27.0	55	0.49
6	31.0	55	0.56
7	27.0	45	0.60
8	31.0	45	0.69
9	27.0	35	0.77
10	31.0	35	0.89

This experiment did not attempt to analyze the effects of one or more variables, such as G/MOG and moisture contents, upon the ability of the system to accurately indicate straw walker grain loss.

The primary hypothesis tested stated that the loss measuring systems could effectively measure grain loss resulting from a wide range of G/MOG ratios of incoming materials. Statistically, the mean of the parameter "calculated/actual loss", which is the ratio between the loss determined by the measuring system and the loss measured by subtracting the amount of grain collected beneath the straw walkers from the amount of grain passed onto the straw walkers, was tested as being equal to 1.0. Steel and Torrie (1980) show the t-statistic distribution provides a suitable test criterion. The t-statistic is given as:

$$t=(Y-\mu)/(s/\sqrt{n}) \qquad (4.1)$$

where Y=mean of a sample [illegible]e n
s=standard deviatio[illegible]ample
μ=specified value of population mean

The test of the above hypotheses is based on the underlying assumption that the values for the parameter "calculated/actual loss" obtained from a loss measurement system that was known to be accurate would be normally distributed about a mean of 1.0.

Also, a second hypothesis tested was that, as indicated by Gullacher (1978), Gullacher and Smith (1979), and Huisman (1983), the separation rate occurring at the end of the straw walker can not, alone, provide an accurate measure of grain loss.

To test this hypothesis, the relationship between the amount of separation sensed at the rear of the straw walker and the actual loss measured was examined.

5 EXPERIMENT COMPONENTS

Experimental procedures described in this thesis were carried out at the Agricultural Engineering research facilities at the University of Alberta's Ellerslie farm. Figure 5.1 is a block diagram showing the components that were involved in the operation of the experiment. At the control of the operator, grain and straw were passed over an assembly consisting of a set of straw walkers situated above a set of trays which collected separated grain. The separated grain was cleaned from the straw and chaff which also was collected, and weighed. Those weights were recorded and stored by a microcomputer on a magnetic disk. Grain separation along the straw walkers was sensed with commercially-available grain loss monitor sensor pads. The output from these sensors was processed with interfacing circuitry, recorded by data acquisition systems, and also stored on magnetic disks. Lastly, the data stored on the disks were analyzed to evaluate the effectiveness of the grain loss measuring systems. Following is a description of both the physical components, as well as the operator interface to the experimental set-up.

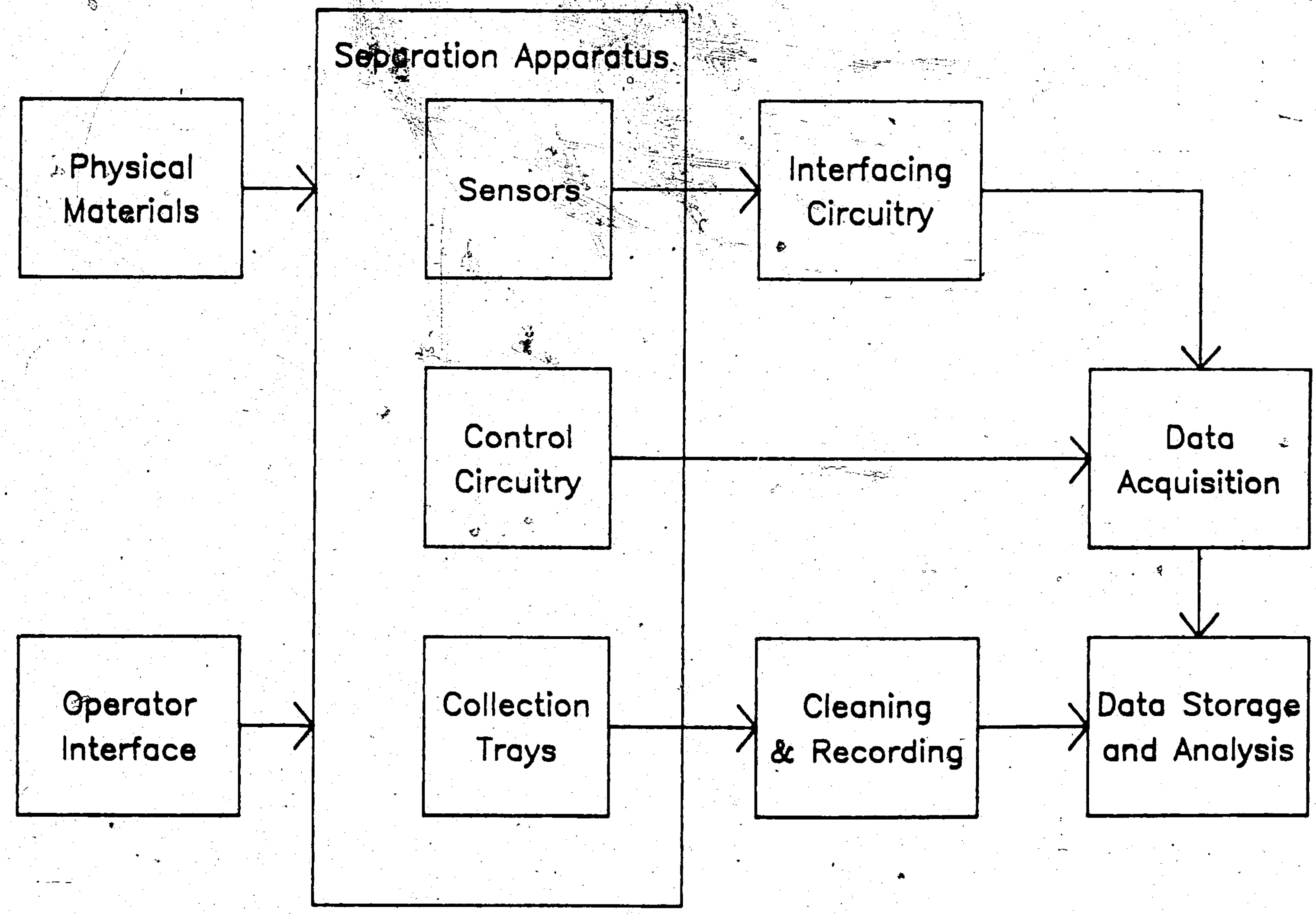


Figure 5.1 Experiment Components

5.1 The Grain Separation Apparatus

The following criteria were established for the grain separation apparatus:

1. The apparatus should be capable of delivering various rates of straw in combination with various rates of grain onto the straw walkers.

2. The delivery and mixing of the grain and straw should be such that the separation of the grain from the straw along the straw walkers closely approximates the exponential decaying form predicted by Zoerb *et al.* (1974).

3. Collection of all the separated grain in trays below the point of separation should indicate an exponential decaying separation curve.

4. The delivery and discharge of the straw should be as uniform and as free from obstructions as possible.

Figures 5.2 and 5.3 are photographs of the straw walkers and grain/straw delivery portions of the grain separation apparatus.

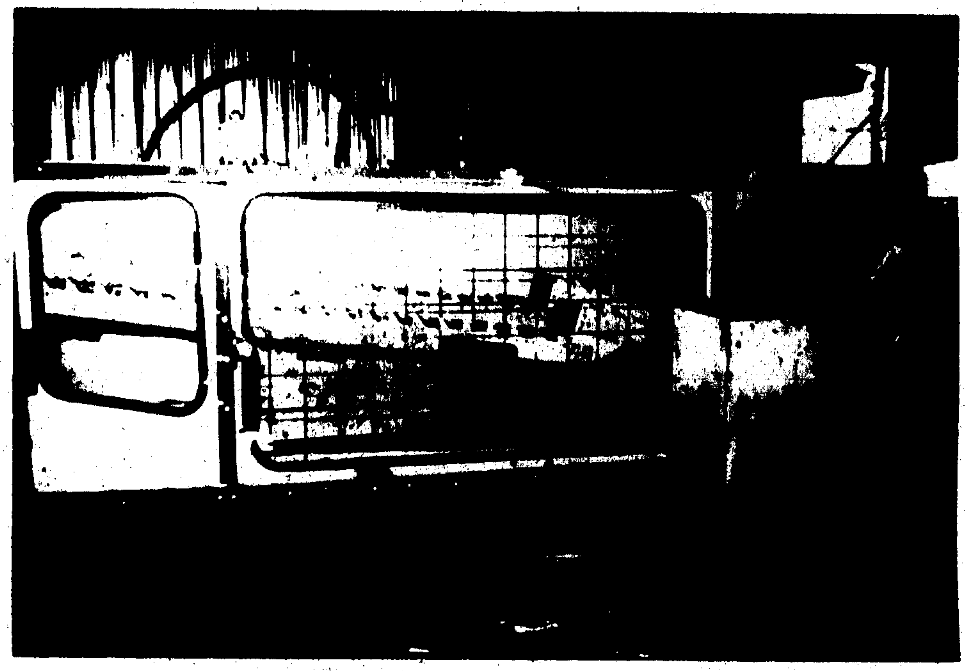


Figure 5.2 Side View of Straw Walker Assembly

Figure 5.3 Grain and Straw Delivery Systems

5.1.1 The straw walkers

The straw walkers used were a set removed from a Massey Ferguson #205 combine. Their dimensions are shown in Figures 5.4 and 5.5. The straw walkers, being open bottomed, allowed for the collection of grain in trays directly below the points of separation. The set consisted of three individual straw walkers, each being approximately 240 mm wide. The crankshaft of the walkers had a throw of 50 mm and a rated rotational speed of 195 rpm. The walkers were powered by a 373 Watt electric motor, with the speed reduced through a chain and sprocket drive.

The straw walker assembly had previously been mounted on a frame enclosed on the top and sides with sheet metal and glass. In this application most of the sheet metal was removed from the top to facilitate unobstructed flow of straw onto and off the straw walkers. The entire frame was supported at a height of 400 mm above the floor, allowing for a rack of collection trays which was rolled underneath the straw walkers. The sides of the collection trays extended up to the bottom of the sides of the straw walker frame, minimizing the chance of separated grain kernels falling outside of the trays. An extra collection tray was required immediately in front of the straw walkers as a considerable quantity of grain was thrown to this region by the oscillating straw walkers.

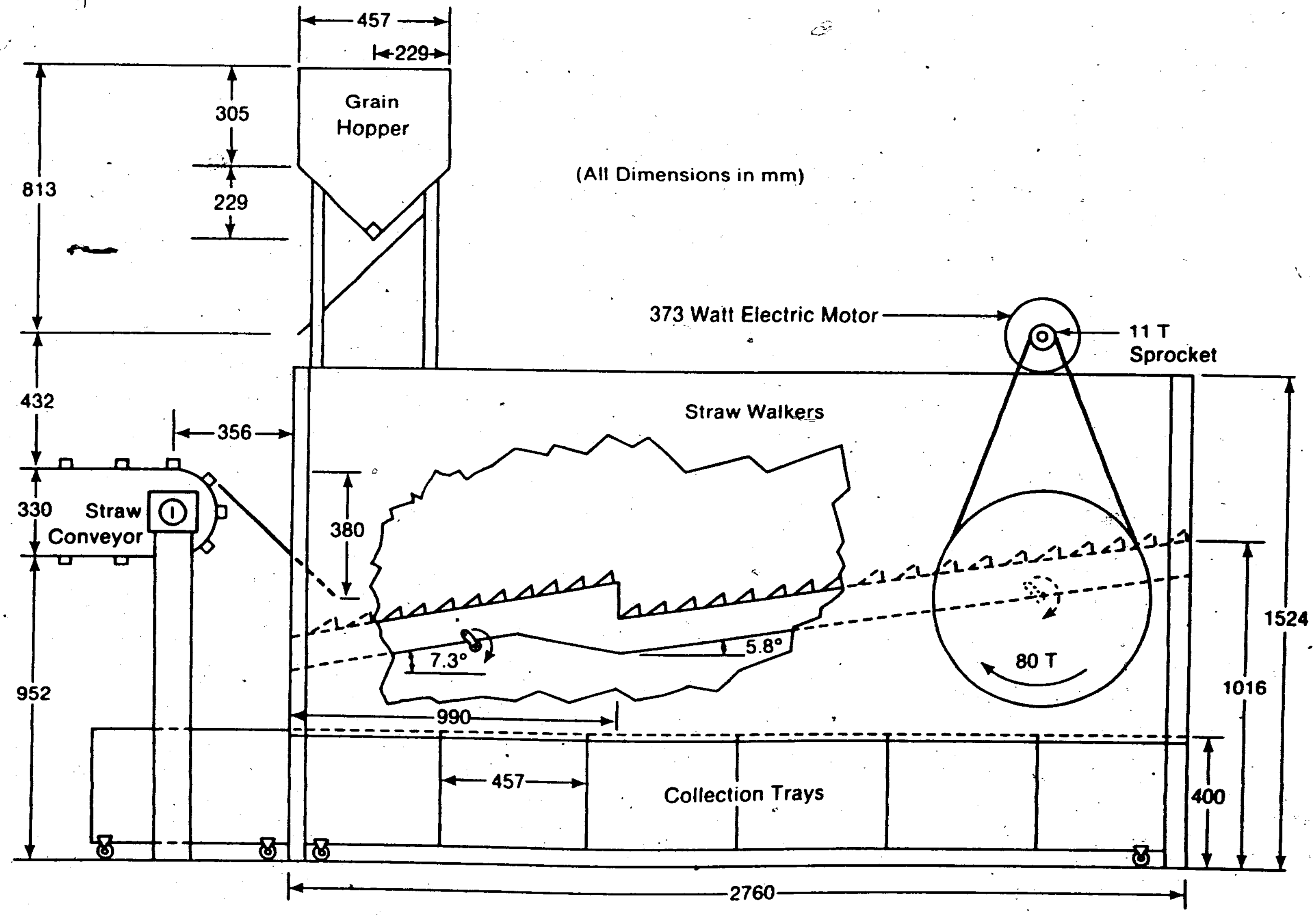


Figure 5.4 Straw Walker Assembly

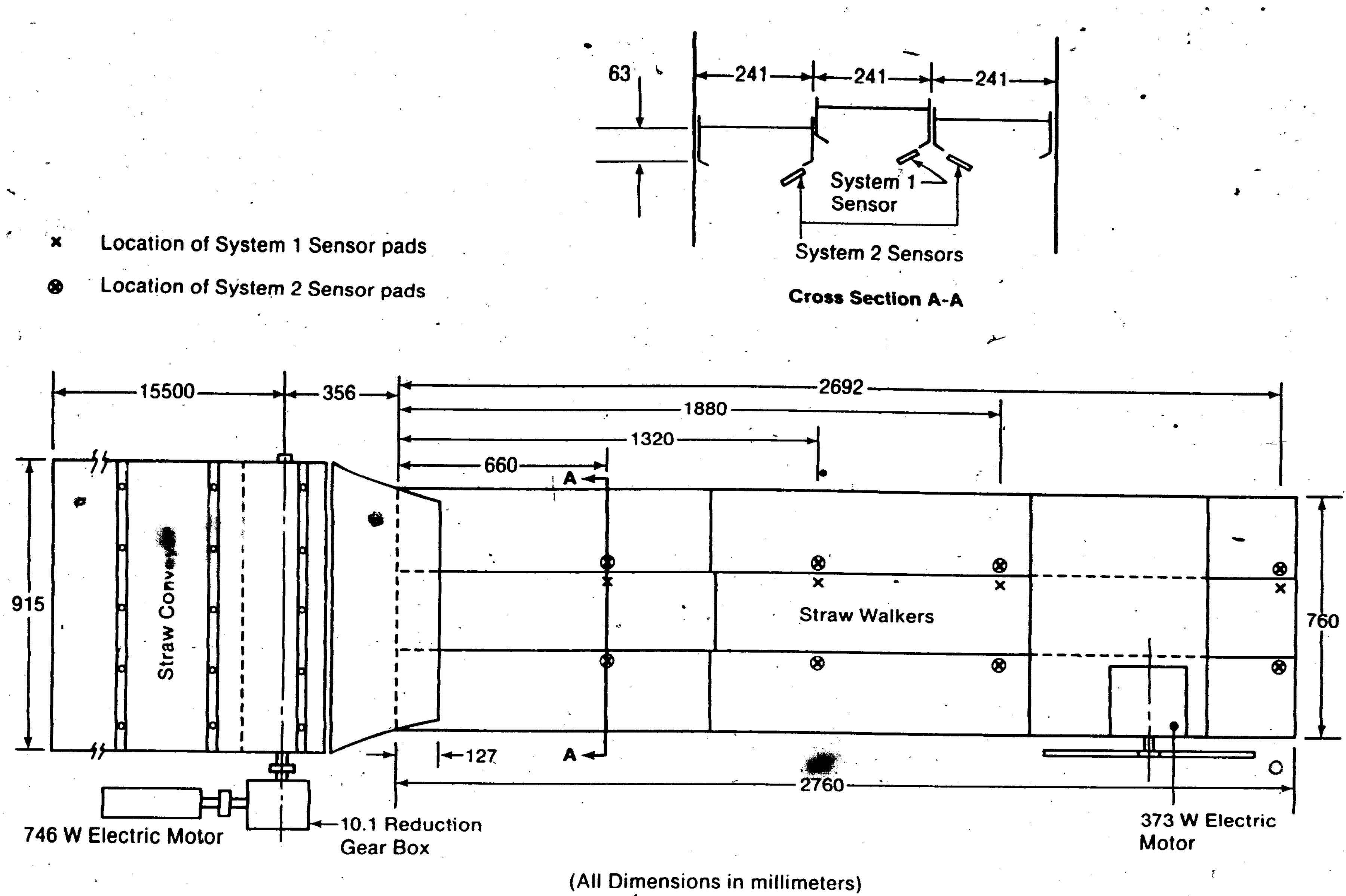


Figure 5.5 Plan View of Straw Conveyor and Straw Walkers

Straw discharged from the straw walkers had to be removed during the course of a run, as, otherwise, it would accumulate and block the flow of oncoming straw. This was done manually with a hay fork by the operator. A chaff wagon was used for the collection and eventual disposal of the straw effluent.

5.1.2 The straw conveyor

Straw was delivered onto the straw walker by means of a belt conveyor. The conveyor had been constructed by employees of the department of Agricultural Engineering for previous experiments. The conveyor was 915 mm wide and spanned a length of 15.5 m. The belt was formed of sections of wood-slatted canvas and was stretched over a 330 mm diameter roller at each end of the conveyor. The driving roller was powered by a 746 Watt electric motor coupled through a 10:1 speed reducing gear box. A rotational speed of 208 rpm at the electric motor produced a linear speed of .36m/s for the conveyor. This linear speed was chosen as it delivered straw onto the walkers at nearly the same speed at which the straw walkers carried the straw through the apparatus. At this linear speed of the conveyor, straw was delivered to the walkers for a duration of 43 seconds each run. Straw throughput rates of 55 kg/min, 45 kg/min, and 35 kg/min resulted from loading rates of 2.52 kg/m, 2.08 kg/m, and 1.61 kg/m respectively.

5.1.3 The grain hopper

Grain was delivered onto the straw entering the straw walker by a gravity-feed hopper assembly (Figure 5.6). The rate of grain delivery was determined by the size of the opening in the bottom of the hopper. The size of the opening was determined by the distance the gate on the bottom of the hopper was allowed to drop when the cord which activated the opening was pulled. To initiate grain flow during a run, the operator manually pulled, and then secured that cord, preventing the hopper from closing. At the completion of the run the operator released the cord to close the hopper. A microswitch was attached to the gate mechanism, as shown in Figure 5.6, which controlled signals to the data acquisition systems and indicated whether the gate was open or closed. A deflector, 720 mm in width, distributed the grain uniformly across the stream of incoming straw.

Calibration procedures were performed to establish the size of the hopper opening required for each of the desired grain flow rates. Gate drops of 12.7 mm, 13.5 mm, 14.3 mm, and 19 mm approximately resulted in the required grain flow rates of 14.5 kg/min, 20 kg/min, 27 kg/min, and 31 kg/min respectively. For convenience, wooden blocks of the above thicknesses were fabricated to allow for quick adjustments to the hopper gate drop.

The grain and straw delivery systems described above were not necessarily expected to accurately simulate the action of the rear beater, delivering the grain and straw onto the straw walkers in a combine. They were, however, expected to create an exponentially decaying separation curve over much of the straw walkers. The results, as discussed later, show that the apparatus was successful in realizing this.

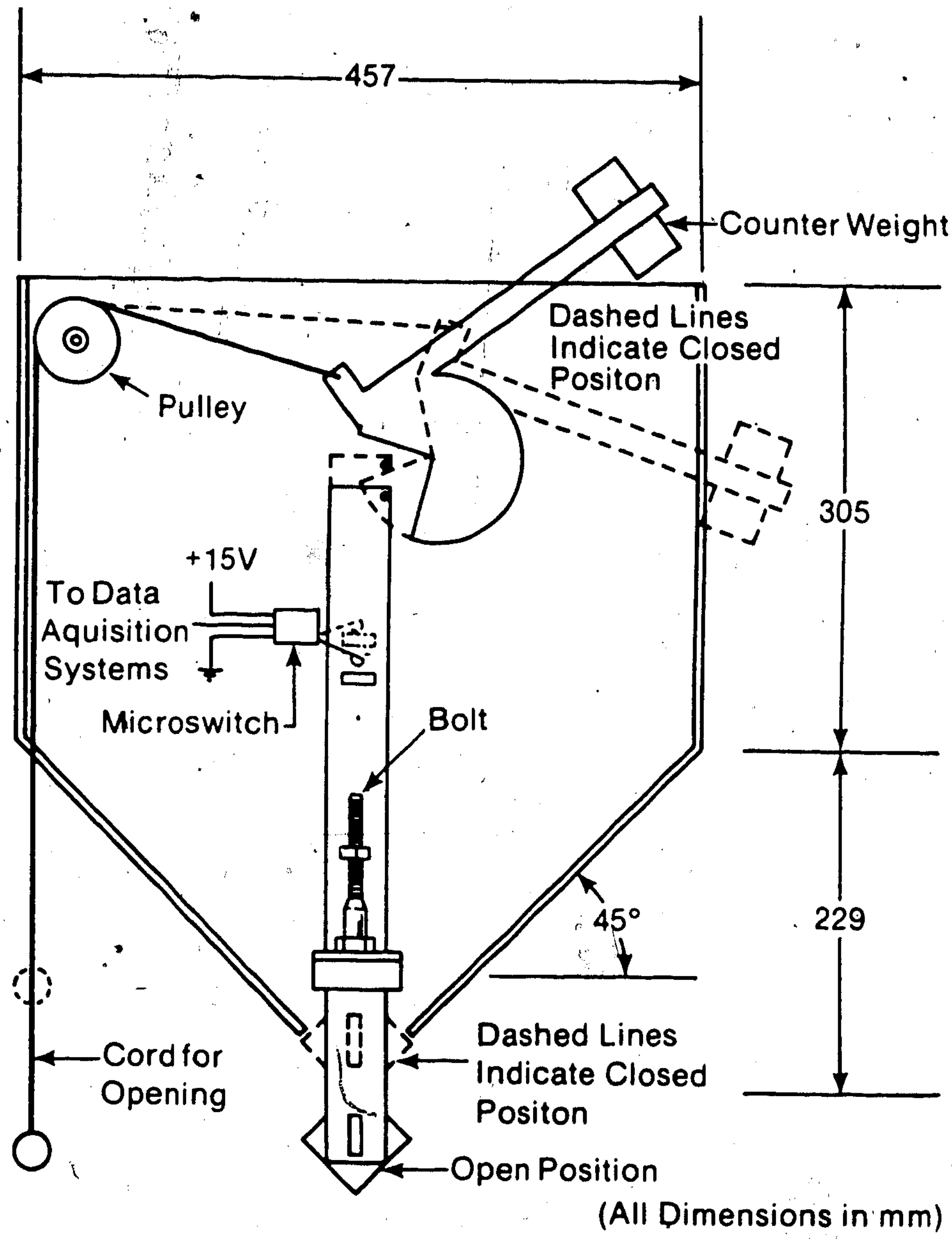


Figure 5.6 The Grain Hopper

5.2 Instrumentation

In this experiment two independent loss measuring systems, hereafter referred to as System 1 and System 2, consisting of kernel impact measuring instrumentation and data acquisition hardware and software were used and evaluated for effectiveness. Instrumentation for each system consisted of four impact sensing and signal interfacing units, and the circuitry controlling the data acquisition from these units. Each System 1 unit consisted of a single sensor, whereas, each System 2 unit consisted of two sensors. Thus, System 1 used four sensor pads, and System 2 used eight sensor pads. The location of the sensors is shown in Figure 5.5. All sensors were 50 mm in width, with System 1 sensors 160 mm long, and System 2 sensors 125 mm long.

5.2.1 Grain impact sensors

The grain impact sensors used in both data acquisition systems were of the type described in Section 3.2.2.3, with a piezoelectric crystal generating a signal resulting from the vibration caused by a grain kernel impact (Figure 3.3). The raw signal is a decaying waveform with a maximum amplitude of 0.1-0.2 Volts. Figure 5.7 is a photograph of a disassembled sensor, similar to those used in this experiment, showing the piezoelectric crystal and the vibration-sensitive sounding board. The sensors used in

System 1 were manufactured by Baker Engineering Enterprises Ltd. (BEE), Edmonton, Alberta and those used in System 2 were manufactured by SED Systems Inc., Saskatoon, Saskatchewan. Figures 5.8 and 5.9 show the orientation of the sensors mounted on the underside of the open-bottomed straw walkers at the locations shown in Figure 5.5, where the walker crankshaft mounts would not interfere with the falling separated grain. At a given location the orientation of a sensor was similar to the manufacturers' suggestions (Baker Engineering Enterprises Ltd., 1979; SED Systems Inc., 1985). The manufacturers, however, advocate the placement of a sensor only at the rear end of a straw walker section.

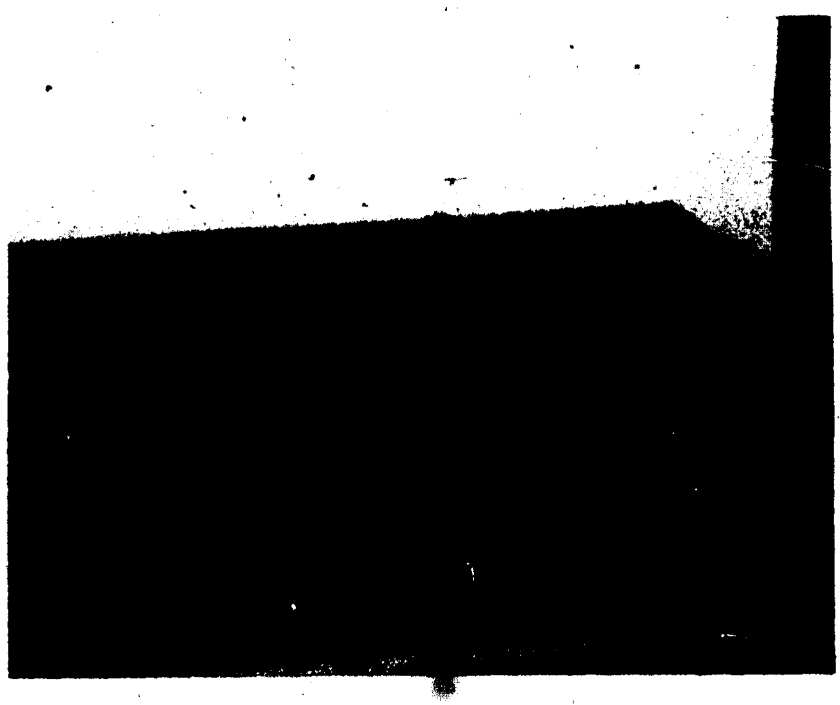


Figure 5.7 Disassembled System 2 Sensor

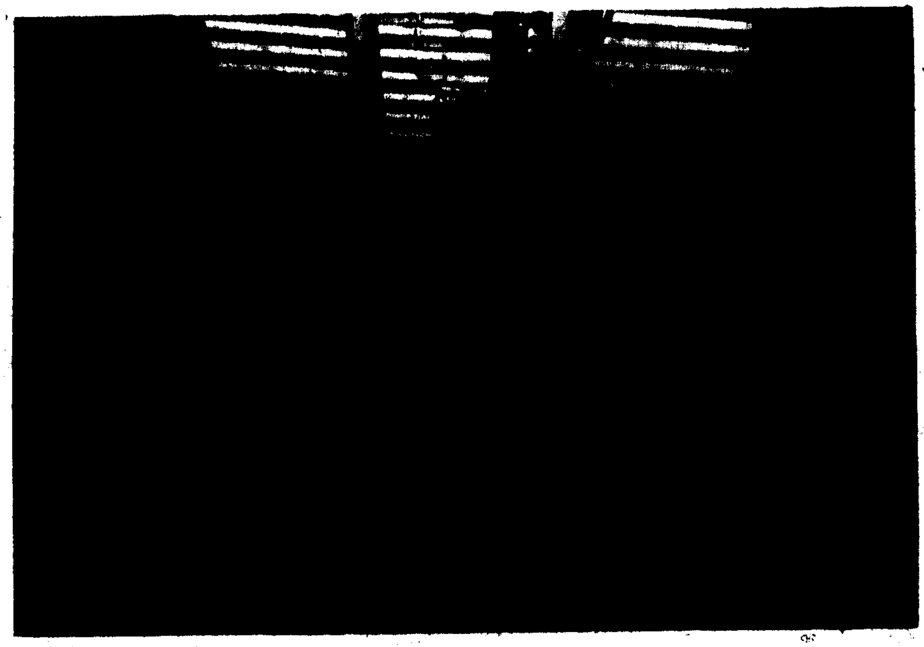


Figure 5.8 Forward Facing View of

Mounted Sensors from Underneath

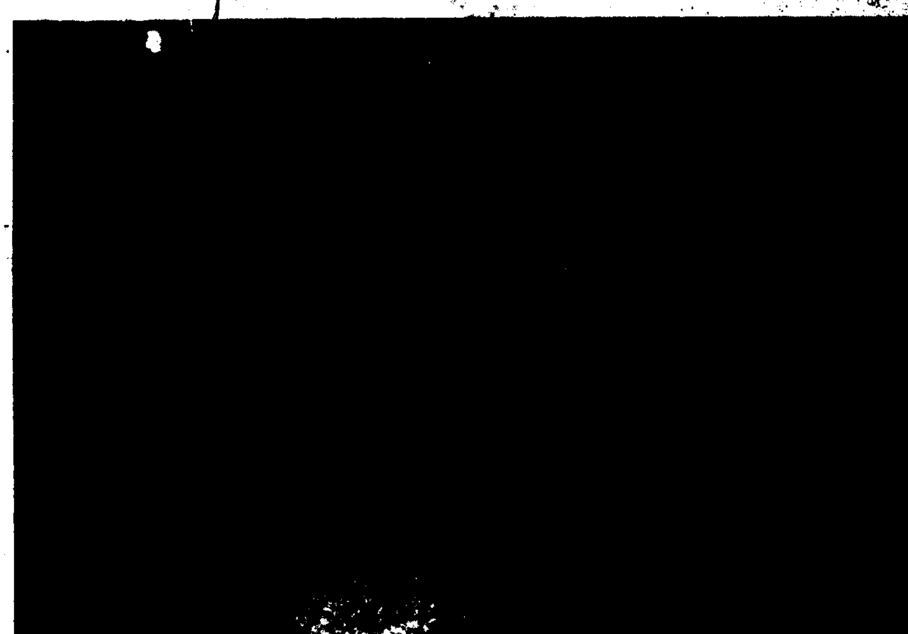


Figure 5.9 View of Mounted Sensors from Rear

5.2.2 The interfacing circuits

Effective grain loss monitor interfacing circuitry must not only convert the occurrence of grain impact signals into analog or digital representations of the rate of those impacts, but also must be capable of distinguishing, and ignoring, signals due to impacts of non-grain particles such as straw and chaff. System 1 used a simple circuit constructed to distinguish grain impacts from non-grain impacts on the basis of signal amplitude alone. System 2, the SED Systems Inc. grain loss monitor, used a more sophisticated circuit which discriminated on the basis of the oscillation frequency of an impact signal.

5.2.2.1 System 1

Figure 5.10 is the circuit diagram for the processing circuit of System 1. The grain impact signal is conditioned by two integrated circuits. The first integrated circuit, IC1, is an inverting operational amplifier with gain which amplifies the signal. A 100 kΩ potentiometer controls the gain. After the negative voltage of the amplified signal is drained to ground through a diode (1N4004), the remaining signal switches a 5 Volt signal through a NPN transistor (2N4400). A smooth curve, approximating the peaks of the signal switched through the transistor is generated by a passive filter comprised of a 680Ω resistor and a 2.2

μF capacitor connected in parallel between ground and the transistor. IC2 is a comparator which generated a square wave pulse whenever it's input signal exceeded a pre-set voltage level of 1.13 V set by the 680Ω and 200Ω voltage-dividing resistors. The generated square pulse switched a transistor, the collector of which was connected to a digital input channel on a data logger (Datataker, Data Electronics (Aust.) Pty. Ltd. Melbourne, Australia) which was programmed to count the pulses and store the count in memory.

The sensors were calibrated by setting the potentiometers such that an equal number of impacts were recorded by each unit at a given grain flow rate. The procedure was performed in the laboratory with the sensors fixed beneath a seed planter adjusted to deliver a known average rate of kernels per second. The potentiometers were adjusted such that the data acquisition system accurately recorded the average number of impacts for rates ranging from 0 to 13 kernels per second

Trial runs of the straw walkers, with collecting bags in the position of the sensors, gave evidence that the maximum impact rate for any sensor would not be likely to exceed 12 kernels per second.

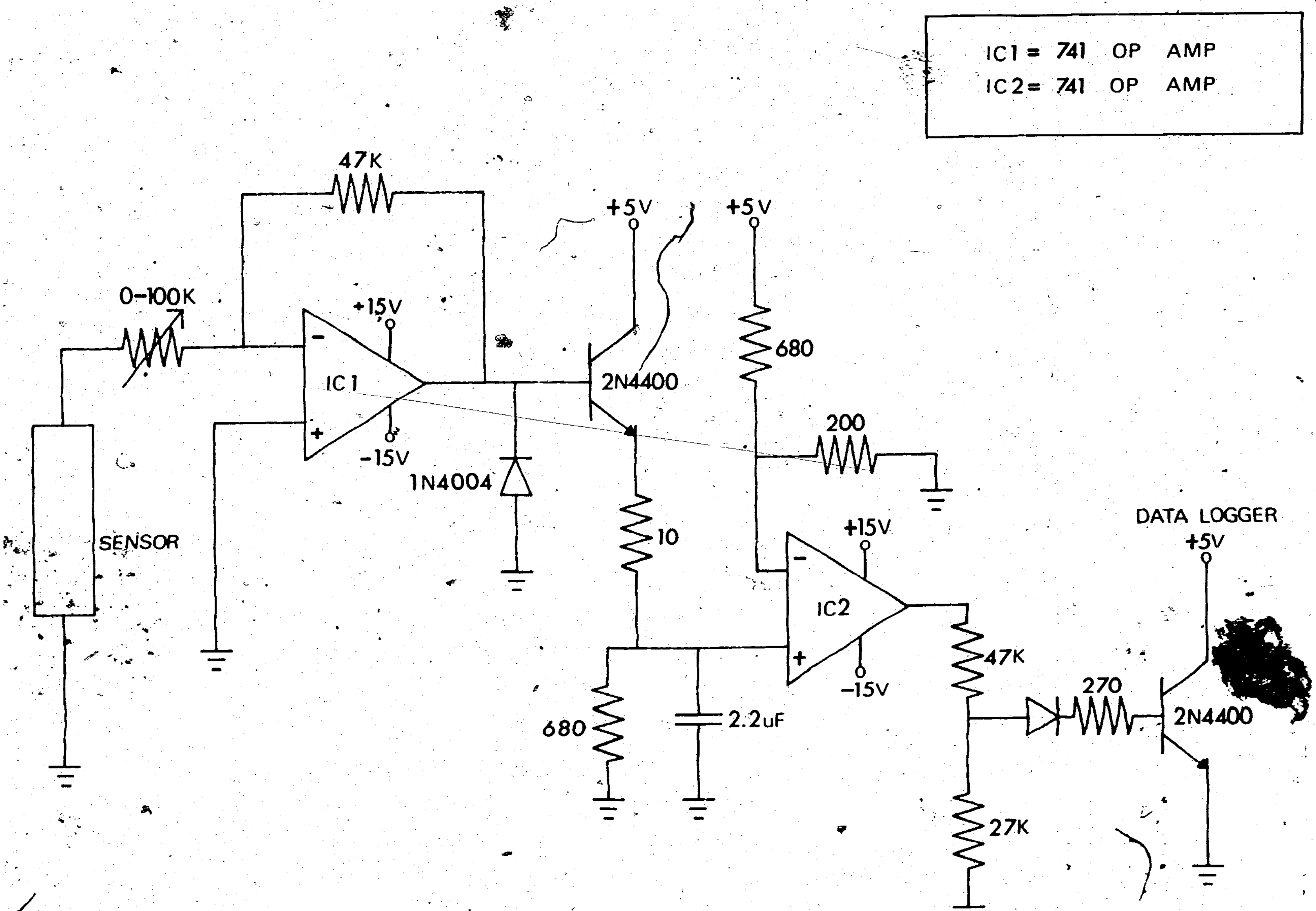


FIGURE 5.10 SYSTEM 1 CIRCUIT DIAGRAM

5.2.2.2 System 2

System 2 made use of the proprietary circuitry existing in the SED Systems Inc. model 912 grain loss monitor (Figure 5.11). For each unit impact signals from two sensors were averaged, and non-grain impacts were discriminated on the basis of the signal oscillation frequencies. The manufacturers (Hjertaas, 1985) indicated that the signal existing immediately prior to being processed for display by the console meter should be a series of square pulses of a frequency representing the rate of impacts sensed. The signal was fed into the analog input section of a laboratory computer (Modular Instrument Computer (MINC), Digital Equipment Corporation) which counted the pulses.

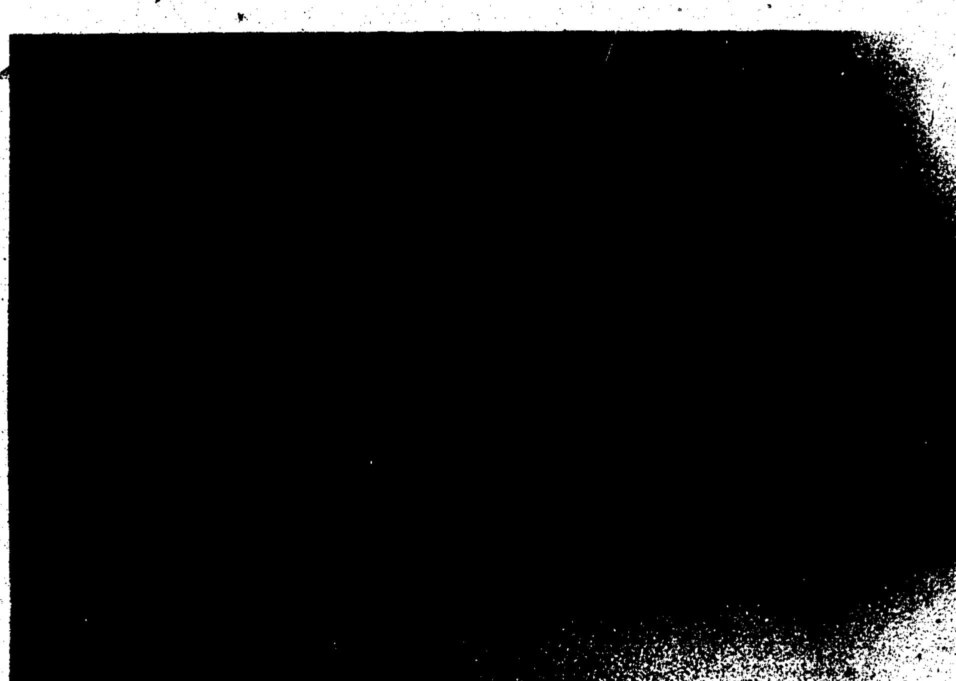


Figure 5.11 System #2 Grain Loss Monitor

5.2.3 Control circuitry

Simple switching circuits were implemented to provide control of the data acquisition systems. System 1 data acquisition was enabled with an operator-controlled toggle switch. At the start of a run, when this toggle was opened by the operator, the state of one of the Datataker's digital channels was switched from low to high. The Datataker was programmed to initiate the data acquisition upon this transition. At the end of each run the operator closed the switch, returning the state of the digital channel to low, and, thus disabling the data acquisition.

A second control switch was mounted on the grain hopper. This microswitch connected input channels of both data acquisition systems to +15V when the box was open and to ground when it was closed. For System 1, the switch held a digital input channel to the Datataker in a high state during the time the hopper was open. This channel was sampled every second and, thus, provided a measure of the duration of grain flow from the hopper for each run.

In System 2. the analog input channel to the MINC which was connected to the microswitch was set to a +15V level when the hopper was open. The data acquisition program initiated sampling when this level was sensed.

Both of the above switching circuits are shown in Figure 5.12, a block diagram of the entire data acquisition system.

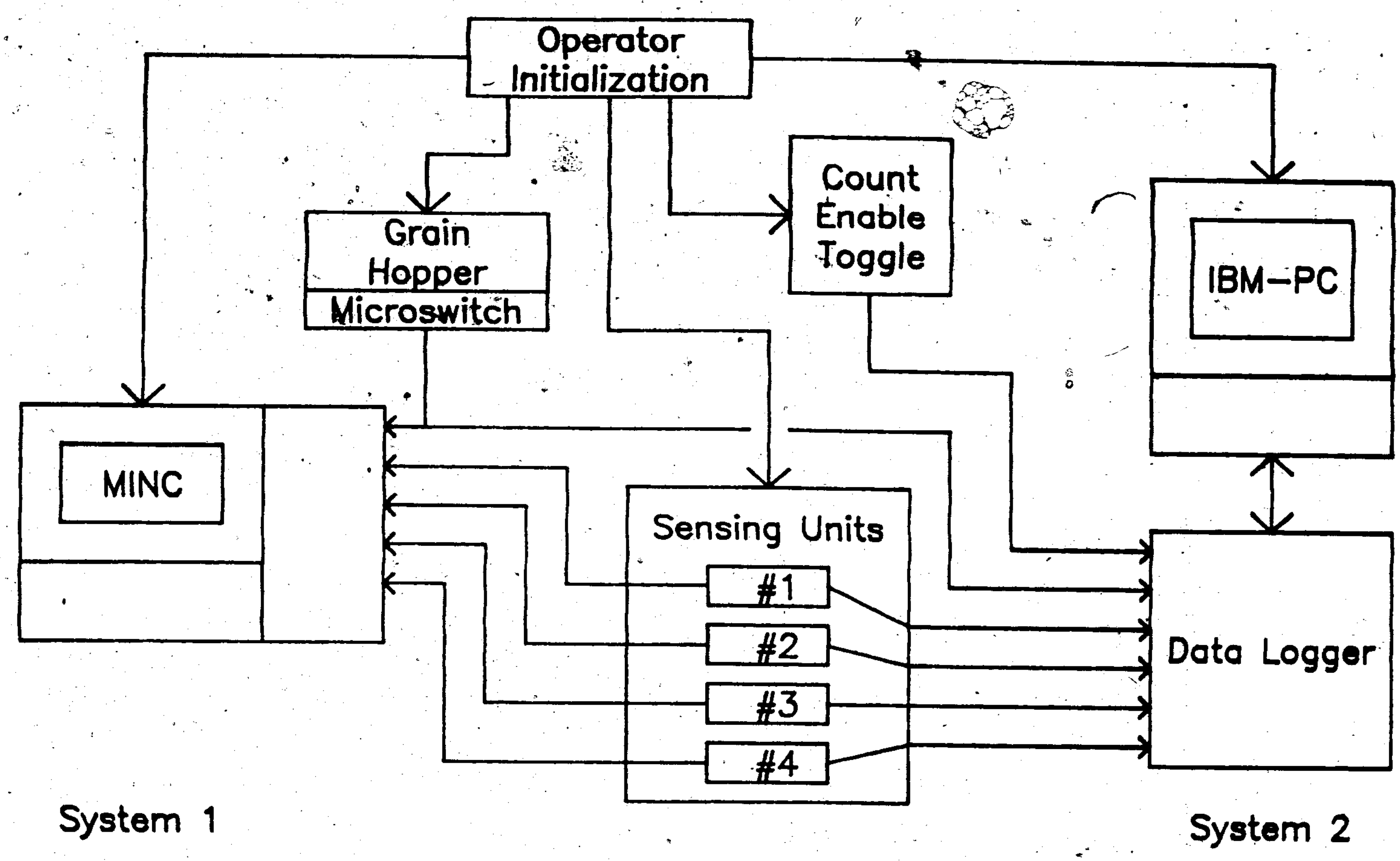


Figure 5.12 Data Acquisition Configuration

5.3 Data Acquisition

Data acquisition was performed with equipment belonging to the Department of Agricultural Engineering. Figure 5.13 is a photograph showing some of the equipment used.

5.3.1 System 1

Data from system 1 were collected with a data logger (Datataker, Data Electronics (Aust.) Pty. Ltd.) that was controlled by a microcomputer (IBM-PC). The data logger counted the number of pulses resulting from grain kernel impacts every second on each of four separate channels. The counting process was started when the input to a fifth digital channel was switched to a high state by the operator and was discontinued when that channel was switched to a low state. A microswitch on the grain hopper switched yet another digital channel high for the time during which the grain was flowing onto the straw.

The data logger counted the pulses by sampling the input voltages over user-programmable intervals. The interval used allowed a sampling rate of 50 samples/second on each channel. Unfortunately the pulses resulting from grain impacts were not uniform. The width of the pulse depended upon the energy associated with the grain kernel impact. As a result, it would be impossible for a sampling technique to count every pulse exactly o[illegible]ver, calibration procedures, as described in Section 5.2.2.1, indicated that at a sampling rate of 50 samples/second, the number of pulses counted could be made approximately equal to the number of kernel impacts, by the adjustment of the 100 kΩ potentiometer. The number of pulses counted every second from each of the four channels, and the digital state of the channel connected to the microswitch, were stored in a magnetic disk file. These data then were evaluated by a computer program, listed in Appendix B, written to sum the impacts sensed by each sensor during a particular run. The accumulated values represented the total amount of grain separation sensed at the location of the sensor for that run.

Figure 5.13 Data Acquisition Equipment

5.3.2 System 2

System 2 data were collected with a modular instrument computer (MINC, Digital Equipment Corporation). The computer program, listed in Appendix B, initiated a sampling technique that was used to count pulses resulting from grain kernel impacts. The microswitch on the grain hopper also was connected to an analog input channel on the MINC. When the box was open an analog voltage level of 15 V appeared on this input channel. The data acquisition program continually tested this channel and, when the voltage level was sensed, initiated the sampling of the four sensor input channels. The sampling continued for the duration of a run. The pulses from the grain loss monitor were sampled at a rate of 10 samples/second per channel was used. In retrospect this sampling rate was much too low to detect all the pulses which were later discovered to have a width of approximately 10 ms. A pulse was counted if the signal sampled exceeded a 1.0 V threshold level when sampled. Finally the computer program executed the summing of pulses detected over the duration of the run for each sensor, and stored the data in magnetic disk files.

5.4 Source of Materials

The straw used in this experiment was barley straw removed from round bales purchased from a local farmer. Baled in the autumn of 1984, the straw was stored in an uncovered stack until March of 1985, when it was moved under cover. Some weathering had occurred to the material in the perimeter of the bales, so care was taken to use only unweathered material. The bales were brought inside the laboratory as they were used. Any grain which existed in the straw was assumed to be randomly dispersed and of a negligible quantity.

The grain used in this experiment was from two sources. Barley used in half of the runs was harvested in 1984 by the Department of Animal Science, University of Alberta. Manual counts showed that this barley contained approximately 13 kernels per gram, and a grain moisture meter (Model 919, Labtronics Manufacturing, Winnipeg, Manitoba) indicated a moisture content of 12.9% wet basis.

The barley used for the remaining runs was harvested in 1985 by the Department of Agricultural Engineering, University of Alberta. This barley contained approximately 20 kernels per gram and was at a moisture content of 13.6% wet basis.

5.5 Procedure for an Individual Run

Each individual run involved a multi-step procedure. The first task was the weighing of the required amount of straw with a spring scale. The straw was loaded as uniformly as possible onto the conveyor. A small sample was collected and stored in a sealed plastic bag. The sample was later analyzed for moisture content using an oven-dry procedure as outlined in the ASAE Standard S358.1 (ASAE, 1983).

The next step was to fill the grain hopper with a sufficient amount of barley, and set the size of the hopper opening to the appropriate level. A Sartorius 3807-MP6, electronic scale, with a capacity of 60 kg and an accuracy of ±1.5 g was used for the weighing of the grain samples.

Data acquisition computers were then turned on and data files were created. When satisfied that the instrumentation systems were ready, the operator started the straw walkers, the straw conveyor, and data acquisition programs; all with simple toggle switches. As the straw entered the straw walker assembly the operator opened the grain hopper, activating data collection. During the run straw was forked away from the back of the straw walkers. When the conveyor was nearly empty the grain hopper was closed. The straw conveyor and straw walkers were switched off as each became empty, and the running of the data acquisition programs was discontinued.

Grain remaining in the hopper was removed, weighed with the electronic scale, and those weights were recorded, so that the actual amount of grain delivered to the walkers could be calculated. The contents of the trays beneath the straw walkers were collected in plastic bags labelled as to run and collection tray number. The trays were returned to their locations beneath the straw walkers for the next run to be performed.

The bags were sealed and stored, and their contents were subsequently cleaned as considerable straw and chaff were also collected in the trays. A fanning mill was borrowed from the Department of Plant Science, University of Alberta, for this operation. After the cleaning, the weights of grain separated along the straw walkers over the positions of the trays was measured with the electronic scale, and recorded.

6. RESULTS

Appendix D (Table D.1) shows the raw data recorded for each run performed. This data analysis involved the following phases.

Firstly the weights of the separated grain collected in the trays beneath the straw walkers were analyzed to test whether the grain separation apparatus fulfilled its criteria (Section 5.1).

Secondly, a grain separation curve was determined from these weights, and a grain loss value, calculated using the separation curve, was compared to the actual loss measured. For each run, the actual grain loss was measured as the weight difference between the grain delivered to the apparatus and the total weight of the grain collected in the trays beneath the apparatus.

Thirdly, the relationship between the rate of grain separation measured at the end of the straw walkers and the amount of actual grain loss was examined.

Lastly, the output from the grain loss sensors was analyzed to evaluate the ability of the grain detection system to predict the separation curve, and thus calculate grain loss. The effects that variables, such as G/MOG and straw moisture content, had on the ability of the system to predict grain loss were examined qualitatively.

6.1 Analysis of Separation Weight Data

The analysis of the grain separation weights collected in the trays is recorded in Appendix C (Table C.2). Consecutive subtraction of the weights of separated grain collected in each of the trays, from the total weight delivered during the run, results in values for the weight of grain remaining in the straw at the position along the walker corresponding to the rear edge of each tray. The difference remaining after the weight of grain collected in all the trays was subtracted from the initial weight, resulted in the amount of grain loss measured.

Figure 6.1 shows two typical plots of the amount of grain remaining in the straw, and sensor readings recorded during a run. Common to all of the runs, the amount of grain remaining in the straw decayed in what appeared to be an exponential manner over the all but the forward-most portion of the walkers. All of the four sensor positions were located above the five rearmost separation trays, thus the weights of grain collected in these five trays only were used to establish the curve describing the separation of grain from the straw.

Analysis of the data involved the curve fitting of the amount of grain remaining in the straw, G_r, for $x>0.914$m. The regressions, performed on a microcomputer using Lotus 123 software (LOTUS Development Corporation (1985), Cambridge, MA, USA), involved five data points and, as predicted by Zoerb *et al.*, (1974), displayed a high degree of correlation to the following form:

$$G_r = G_o \cdot e^{(-B \cdot x)} \quad (6.1)$$

G_o and B are positive-valued constants. The high coefficients of correlation (R^2 values) show that the grain separation occurred in a similar fashion in the apparatus as it would through straw walkers in a combine. Also, these values indicate that the five rearmost trays are below the region of correct exponential decay. The values for parameters G_o and B were used to calculate grain loss, or the the amount of grain remaining in the straw at the end of the walkers (x=2.743m). The calculated loss then was compared to the actual loss measured. The ratios between the calculated loss and actual loss, as well as the R^2 values for the regressed equations relating G_r to x, are shown in Table 6.1.

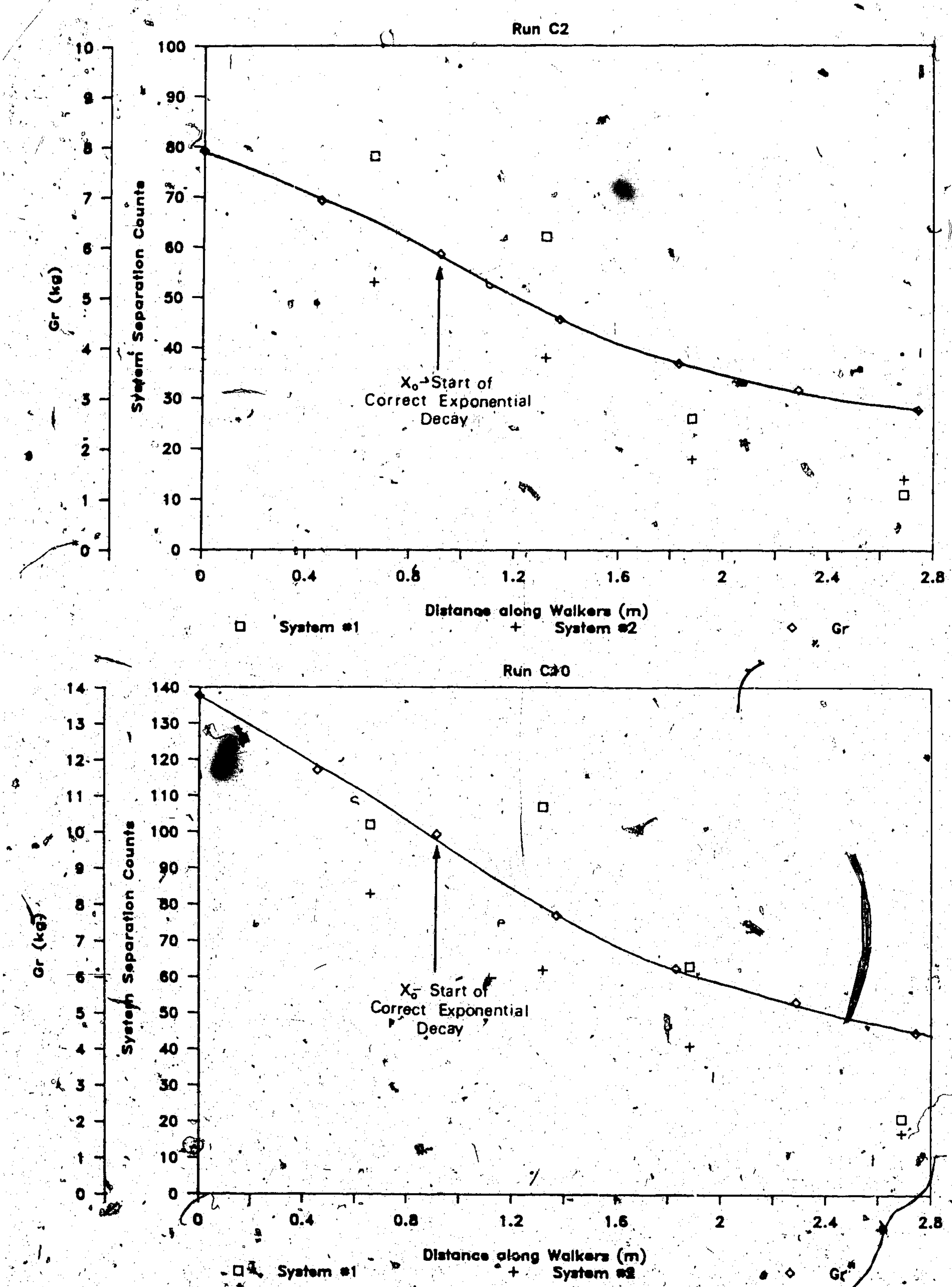


Figure 6.1 Typical Plots of Grain Remaining in the Straw

TABLE 6.1: SEPARATION WEIGHT RESULTS

Run	R^2	Calc/ Actual Loss	Loss/ End Sep. (1/m)
A1	.976	.968	3.43
A2	.976	.954	2.11
A3	.959	.936	2.42
A4	.975	.961	2.82
A5	.992	.985	3.74
A6	.985	.971	3.42
A7	.988	.964	1.86
A8	.974	.952	2.43
A9	.968	.943	2.25
A10	.986	.966	2.41
B1	.981	.972	3.70
B2	.976	.965	2.95
B3	.984	.972	3.49
B4	.970	.937	1.95
B5	.980	.974	4.42
B6	.959	.937	2.32
B7	.994	.983	3.19
B8	.966	.941	2.26
B9	.977	.948	2.02
B10	.979	.954	2.25
C1	.987	.978	3.85
C2	.983	.962	2.50
C3	.995	.989	4.39
C4	.982	.962	2.40
C5	.992	.981	3.03
C6	.988	.977	3.65
C7	.988	.978	3.34
C8	.989	.977	3.08
C9	.974	.955	2.44
C10	.991	.976	2.32
D1	.988	.982	4.23
D2	.980	.964	2.80
D3	.986	.979	4.03
D4	.954	.941	2.60
D5	.990	.983	3.79
D6	.988	.974	2.90
D7	.979	.962	2.67
D8	.977	.955	2.38
D9	.982	.972	3.05
D10	.974	.948	2.22

Lastly, the amount of grain separation occurring at the position of each sensor was calculated. The weight of grain separated from the straw across the total width of the walkers, at the position of a sensor, was equal to the weight of the grain remaining in the straw at the front edge of the sensor subtracted from the weight of grain remaining in the straw at the rear edge of the sensor, as follows:

$$S1=G_o\cdot e^{(-B\cdot(x1-L1/2))}-G_o\cdot e^{(-B\cdot(x1+L1/2))} \qquad (6.2)$$

where
- $S1$=the amount of grain separated from the straw at the position of sensor #1 (kg)
- G_o=regression equation constant (kg)
- B=regression equation constant (1/m)
- $x1$=distance to the center of sensor #1 from the front of the walker (m)
- $L1$=length of sensor #1 (m)

The ratio of the actual loss to the separation rate (kg/m) calculated at the end of the walkers also is shown in Table 6.1.

6.2 Analysis of Sensor Output

The output of the two data acquisition systems is shown in Appendix C (Table C.1). The values were compared to the separation calculated by equation 6.2 to establish the parameters of the equations relating the amount of actual separation to the sensor output for each unit. As a different sample of grain was used in replications A and B, than was used in replications C and D, separate regressions, relating sensing unit outputs to actual separation, were performed with data from each grain sample, for every sensing unit. To allow for possible sensor saturation, second order polynomials were regressed. As well, for each sensing unit, a second order equation for separation was regressed from the average values of of System 1 and System 2 outputs. Appendix C (Table C.3) shows the results of these sensor reading versus measured separation rate regressions. Values for sensed separation rates at the locations of the sensors were calculated using the regression equation, and are shown in Appendix C (Table C.4).

Lastly, for each run the natural logarithms of the sensed separation rates were regressed linearly with the position of the sensors, solving for A and B in a separation equation of the following form:

$$S_w(x)=A\cdot e^{(-B\cdot x)} \quad \text{for } x>0.66\text{m} \qquad (6.3)$$

where $S_w(x)$=separation rate (kg/m) at a distance x (m) from the front of the straw walkers
A,B=equation parameters

The solution of the above equation allows for the calculation of walker loss by:

$$W_L=S_w(\ell)/B \qquad (6.4)$$

where W_L=amount of walker grain loss (kg)
$S_w(\ell)$=the rate of separation occurring at the end of the straw walker (kg/m)
B=parameter of the separation curve (1/m)

The R^2 values of the "sensed separation versus sensor position" regressions and the ratio between calculated and actual grain loss for each run are shown in Table 6.2.

TABLE 6.2: SENSOR OUTPUT RESULTS

Run	System 1 R^2	System 1 Calc/Actual Loss	System 2 R^2	System 2 Calc/Actual Loss
A1	.932	.590	.830	.798
A2	.946	1.269	.984	.752
A3	.944	.827	.998	.983
A4	.956	.532	.960	.724
A5	.861	.682	.763	.621
A6	.918	.369	.990	.655
A7	.995	2.697	.995	6.045
A8	.990	.615	.984	.376
A9	.855	.685	.986	1.093
A10	.941	.631	.879	.496
B1	.644	.598	.977	.515
B2	.841	.837	.966	.614
B3	.855	.610	.548	4.806
B4	.966	1.005	.924	1.337
B5	.691	.667	.400	1.859
B6	.922	.766	.947	.859
B7	.189	4.506	.895	1.814
B8	.984	.464	.963	.735
B9	.883	1.391	.883	1.788
B10	.902	.854	.995	.42[illegible]
C1	.433	1.217	.118	10.175
C2	.799	.854	.717	1.102
C3	.923	.630	.927	1.818
C4	.753	.963	.969	.541
C5	.965	.477	.988	.689
C6	.905	1.063	.808	1.189
C7	.983	.193	.789	1.187
C8	.971	.601	.978	.493
C9	.990	.628	.845	.399
C10	.996	.807	.990	.615
D1	.815	.490	.089	ERR
D2	.967	.697	.941	.871
D3	.873	.706	.804	1.134
D4	.004	49.470	.781	1.153
D5	.934	.552	.503	.843
D6	.961	.382	.972	.517
D7	.979	.676	.989	.871
D8	.963	.499	.866	.517
D9	.977	.776	.912	.432
D10	.968	.509	.956	.601

7. DISCUSSION OF RESULTS

7.1 Separation Weight Data

As shown in Table 6.1 the separation weight data points consistently fitted an exponentially decaying curve with a high coefficient of correlation (i.e., $0.95<R^2<0.9$[illegible]) when weights from the five rearmost trays were [illegible]. When the derived regression equations were used to [illegible] grain loss, the ratios of calcul[illegible] actual grain loss had an mean value of 0.964. Figu[illegible]s a plot of the calculated grain loss value versus [illegible]al grain loss value, showing the position of the points in relation to the line of unity slope that would be formed if the calculated loss was equal to the measured loss. The slope of the best fit line through the calculated loss points was 0.986[illegible] best fit line is, however, slightly below the line of unity slope, with all values of calculated loss being less than actual measured loss. An explanation of this could be that the actual walker loss was less than the measured grain loss. This condition would result if some of the separated grain was not collected in ~~the trays, or, if~~ prior to weighing, not all of the collected grain was cleaned from the straw and chaff collected in the trays. During the performance of the runs, these situations could not be eliminated completely.

These results indicate that the measurements of straw walker loss, calculated from the separation curves, determined from the collection of separated grain beneath the straw walkers, are, at worst, 93% of the true value.

Bearing in mind experimental errors as detailed above, the results provide confirmation of the hypothesis that actual grain loss over the straw walkers can be calculated from an experimentally-fitted exponential separation curve.

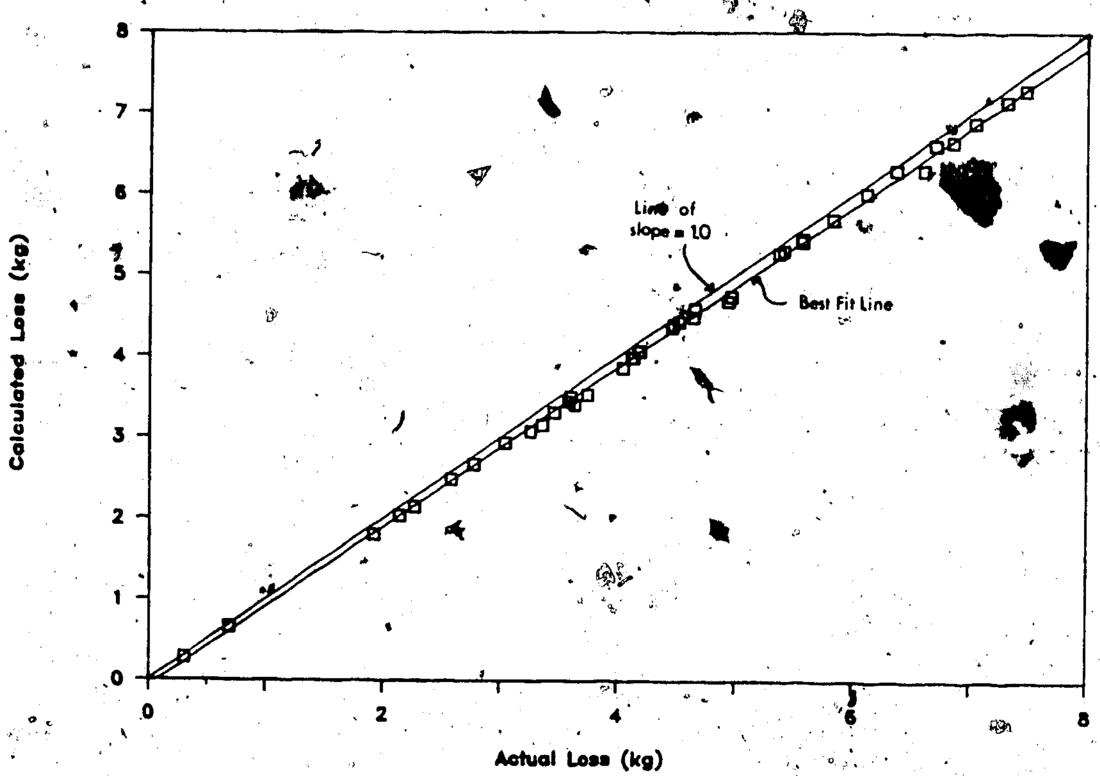


Figure 7.1 Calculated Loss vs. Actual Loss

The effect that several variables had on the accuracy of the loss calculation, based on the separation curve derived from the collected grain weights, are described as follows:

Firstly, Figure 7.2 shows that, as a general trend, the calculated/actual loss ratios were nearer to 1.0 when the correlation coefficients of the grain separation regressions were higher. This result is as expected because the higher R^2 values imply that the actual plot of separation closely describes the form on which the loss calculation was based.

Secondly, figures 7.3, 7.4, and 7.5 show that the G/MOG ratio, straw moisture content, and grain flow rate seemed to have little or no effect on the ability of the system to indicate actual grain loss. Only the straw delivery rate (Figure 7.6), and consequently total straw and grain delivery rate (Figure 7.7) showed a possible effect. These figures show that slightly higher calculated/actual loss ratios were obtained at higher delivery rates. An explanation of these relationships may be that at higher straw throughput rates, the separation apparatus more closely achieves the exponentially decaying form of the separation curve, upon which the loss calculations are based. Perhaps, at lesser straw flow rates, the straw poses less of a hindrance to the separation of grain, and the separation does not occur in an exponentially decaying manner.

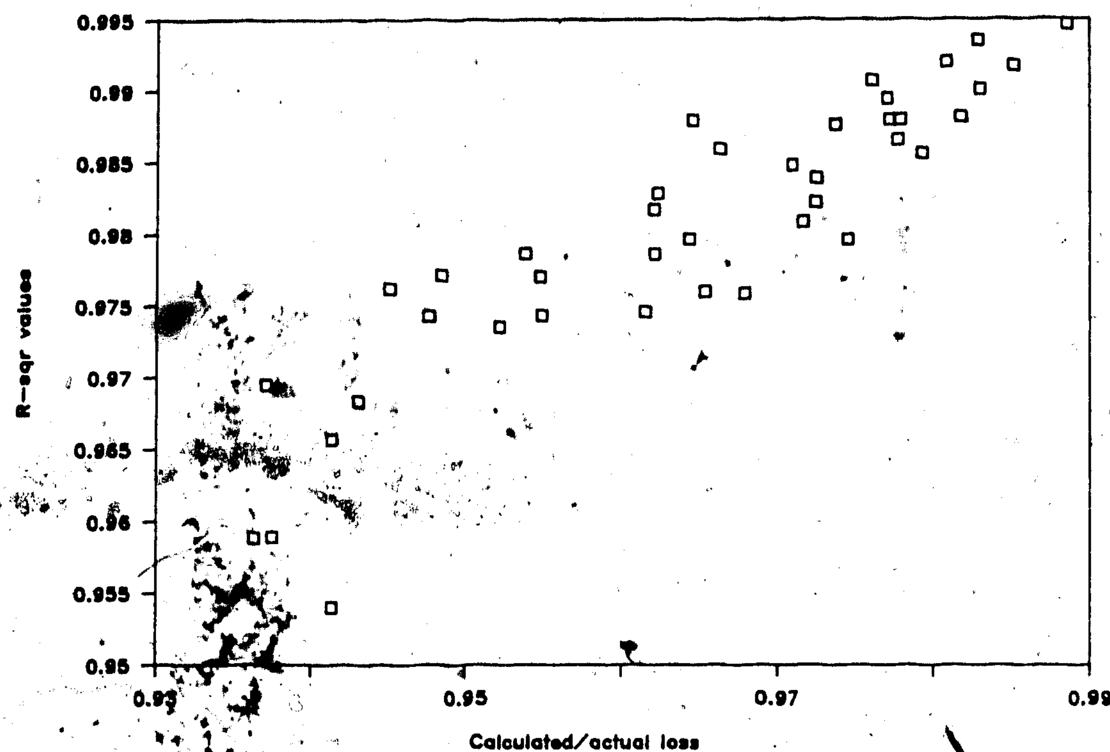


Figure 7.2 Grain Separation R^2 vs. Calc/Actual Loss

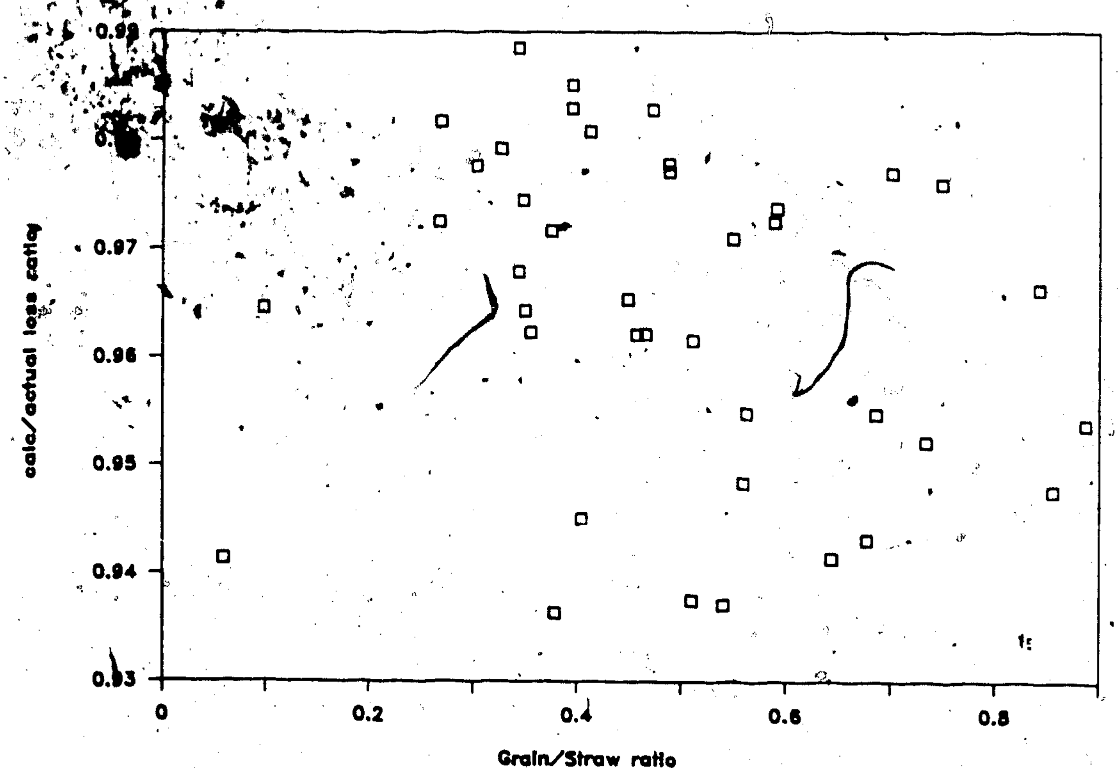


Figure 7.3 Calc/Actual Loss vs. Grain/Straw

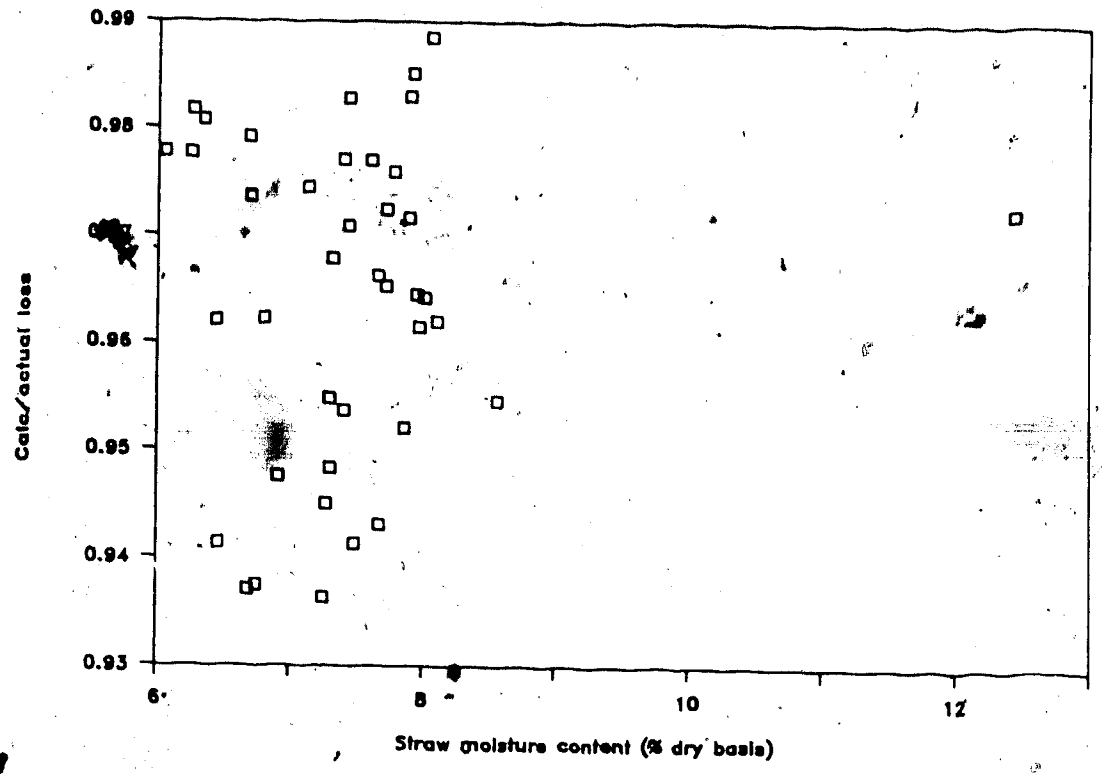


Figure 7.4 Calc/Actual Loss vs. Straw Moisture Content

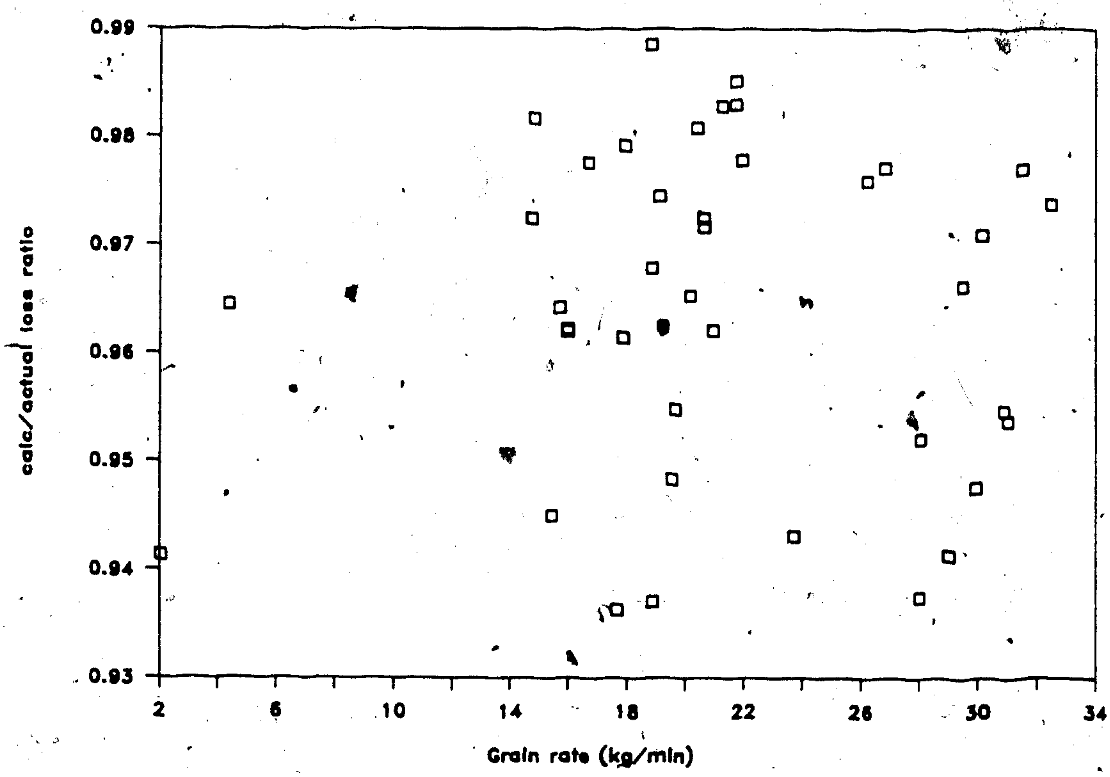


Figure 7.5 Calc/Actual Loss vs. Grain Rate

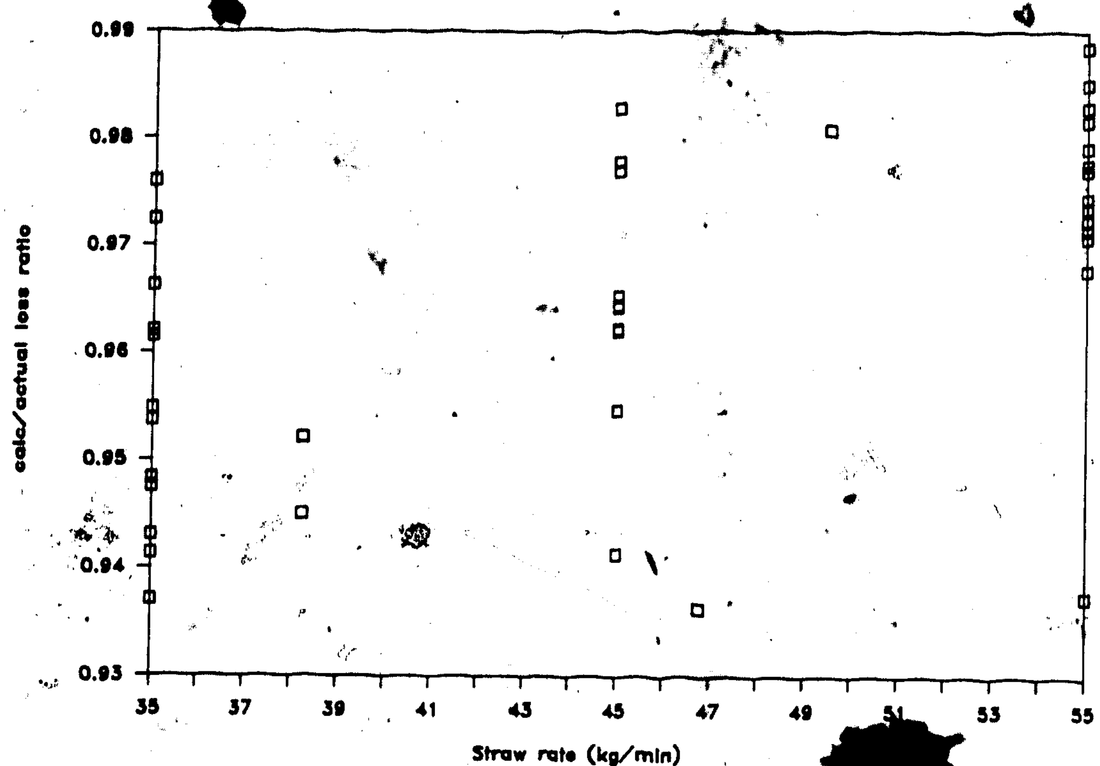


Figure 7.6 Calc/Actual Loss vs. Straw Rate

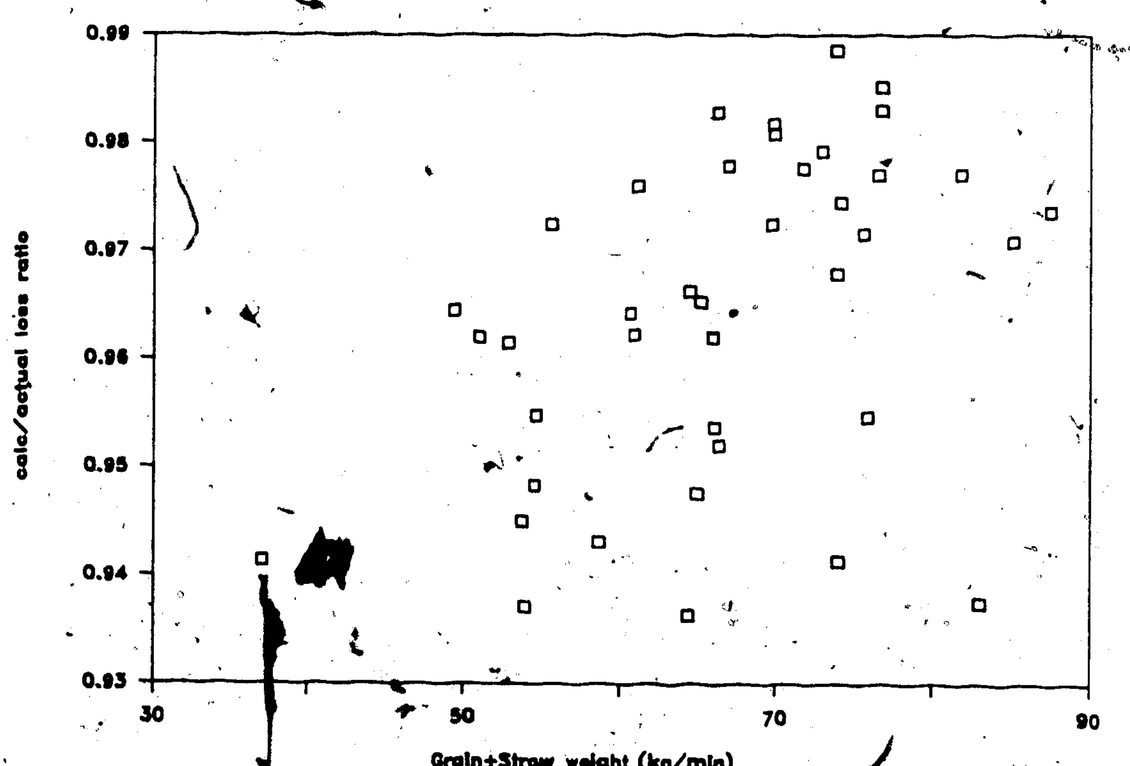


Figure 7.7 Calc/Actual Loss vs. Grain+Straw Rate

7.1.1 Ratio of actual loss to end separation rate

Because of the standard method of mounting and using grain loss monitors, perhaps the most interesting parameter arising from the separation weight data is the ratio of the actual grain loss to the separation rate at the end of the walkers. This parameter had an average value of 2.93 kg/(kg/m) and a variance of .5625. The variability of this parameter illustrates the difficulty of measuring grain loss on the basis of the separation rate at the end of the straw walker only. If this parameter was assumed to be constant, at say the average value of 2.93 kg/(kg/m), calculation of walker loss from the end separation rate only, could be in error as much as 50% of the actual walker loss measured.

An accurate estimation of the ratio of total grain loss to the grain separation occurring at the end of the walker is required for loss to be calculated from end separation values. Figure 7.8 shows that this ratio seems to be somewhat affected by the value of the G/MOG ratio, however no relationship between the (actual loss)/(end separation) ratio and G/MOG, having a correlation coefficient exceeding 0.50, was found.

Correlations of the (actual loss)/(end separation) ratio with grain flow rate, straw flow rate, and straw moisture content were equally poor, suggesting difficulty would be encountered in estimating a value for this ratio on the basis of measurable crop parameters, such as throughput rate, G/MOG ratio, and moisture contents. The fact that the (actual loss)/(end separation) ratio can not be successfully determined from measurable crop properties is the major weakness of using grain loss monitors as conventionally prescribed. In varying crop conditions such use requires that the (actual loss)/(end separation) ratio be constant, or known, for the loss indication to remain accurate.

Conventionally used grain loss monitors indicate only changes in the rate of grain separation from the straw passing over the end of the straw walkers. The extent to which the changes in straw walker end separation reflect total walker loss is not constant, thus walker loss can not be accurately monitored by this type of monitor usage.

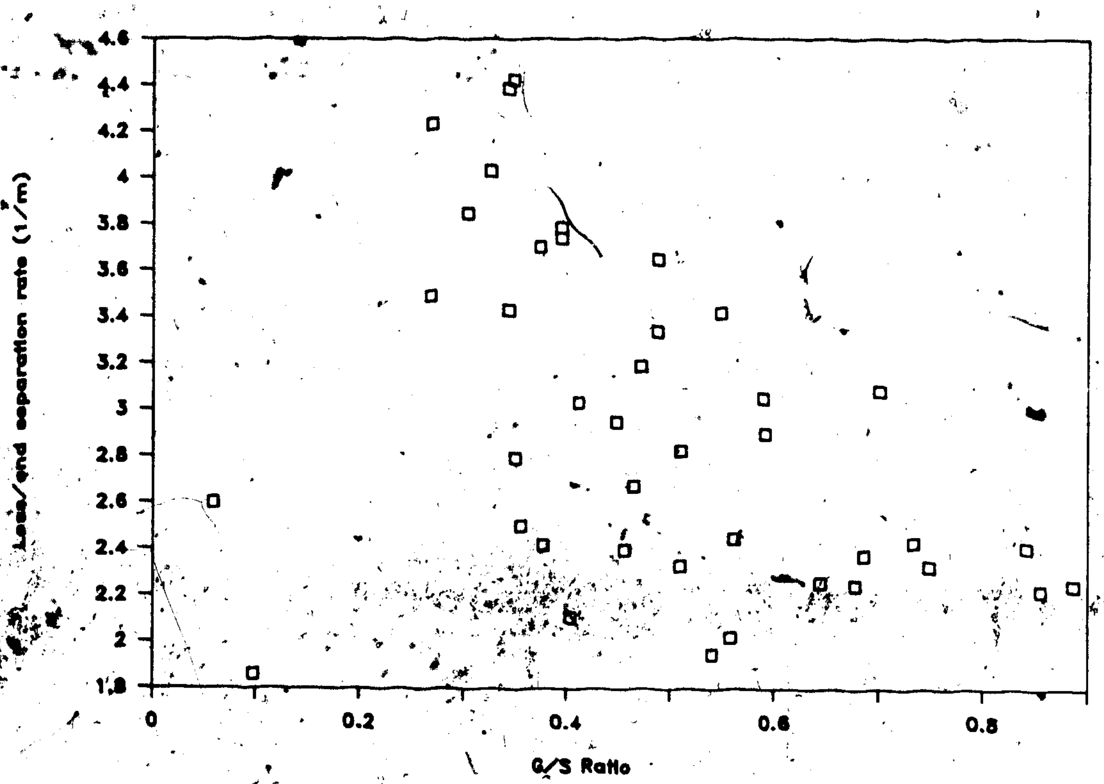


Figure 7.8 Loss/End Separation Rate vs. Grain/Straw Ratio

7.2 Sensor Output

The poor correlation coefficients achieved from the sensor calibration regressions shown in Appendix C (Table C.3) indicate the severely limited ability of the grain impact sensors to provide separation curves equivalent to those derived from separation weight data. Table 6.2 shows the highly variable and often very poor values for calculated/actual loss ratio derived from sensor output.

The loss calculation is based upon the regressed separation curves and the variability of the results is most likely due to the inability of the sensors to consistently record an accurate measure of the grain separation. Possible reasons for the shortcomings of the sensors are given in Section 7.2.1.

The results of those runs meeting the conditions described below were examined to determine whether improved results were obtained when the sensors more accurately described the true separation curves.

The first condition required that the separation curve derived from the sensor outputs have a correlation coefficient of regression greater than 0.50 and a negative slope. This simple condition eliminated those runs for which the sensor output grossly misrepresented the actual separation curve.

Conditions 2, 3, 4, and 5 eliminated those runs for which the sensor derived separation curve did not exist entirely within the respective 99%, 97.5%, 95%, and 90% confidence bands around the actual separation curve.

Table C.5 of Appendix C lists the number of runs which met each condition, the mean and sample standard deviation of the calculated/actual loss values of those runs, the t-statistic, and the degree of confidence at which we can state that the sample of associated runs belong to a population with a mean calculated/actual loss ratio of 1.0.

The results indicate that for both System 1 and System 2, the degree of confidence in the above claim improved slightly for those runs passing more stringent degree of fit conditions. However, too few runs pass conditions 2-5, which require a more accurate fit of the true separation curve by the sensors, to provide statistical confidence in the effectiveness of the loss measuring systems. There seemed to be no improvement when an average of the two systems' output was used to calculate loss.

7.2.1 Weakness of sensor output

The failure of the sensors and data acquisition systems to accurately record the grain separation occurring at the various locations may have resulted due to any or all of the following reasons.

Firstly, perhaps the interfacing circuitry and data acquisition systems failed to provide an accurate count of the kernel impacts on the sensors. Much of the failure of both Systems may be attributed to non-effective sampling techniques. In the case of System 1, where the width of the pulses resulting from an impact was not constant, many impacts may have been counted more than once, or not counted at all. Since System 1 sensing units were calibrated in the laboratory to provide accurate counts of grain kernels, this was not expected to be a serious source of error. However, the fact that the calibration of System 1 units was not tested under operating conditions, (i.e. with the sensors mounted on the oscillating walkers), likely caused the calibrations to be ineffective.

When the sensor is in motion, the velocities of impacting grain and straw particles relative to the sensors is not constant. The particles will have a lesser relative velocity impacting a sensor moving down than they would have impacting a stationary sensor. This may have resulted in some impacts not being detected. On the other hand, the relative velocity of a grain or straw particle impacting a sensor moving upwards would be greater. This may have resulted in the detection of some lighter straw particle impacts. Also grain kernel impacts may have caused wider pulses which were counted more than once. The distortions in the sensor output caused by these straw particle impacts could be expected to be more severe at greater distances from the front of the walker, as we could expect more straw particles to be broken up and separated through the straw walkers as the amount of agitation is greater. Also, the distortions due to the straw particles would not be constant for each run, as they would be dependent upon the straw flow-rate. The greater possible straw particle impact distortions, in comparison with lesser actual separation rates, may explain why for both System 1 and System 2, the sensing unit at the end of the walker showed the poorest results.

System 2 sensing units were assumed to have been calibrated for operating conditions by the manufacturers (SED Systems Inc.), however the slow sampling rate used to acquire data from these sensing units would result in many of the grain impacts being not counted. The fact that System 2 sensor results showed slightly higher R^2 values for the relationships between actual separation rates and sensor output than did System 1 sensing units may be explained by the fact that System 2 impact pulses were of a more uniform width. Thus, while many of these impacts were missed, (as indicated by the low counts from the two-sensor System 2 units as compared to the counts from the one-sensor System 1 units), a more constant percentage of total impacts counted per run, and no double counts, could be expected.

A second cause of error in the sensor data may have been that the number of kernels impacting any sensor may have not all separated through the walker area directly above the sensor. It is possible that some of the kernels, striking a sensor at a particular location, may have been separated from the straw elsewhere, rebounded off the inside of the straw walker, and have been recorded as separation at the location of the sensor; thus distorting the sensed separation curve. Also, kernels which tended to bounce on the sensing pad more than once, would tend to distort the accuracy of the output. Distortions caused by these phenomena would likely be random and may explain some of the generally unsatisfactory results from all the sensing units of both systems.

Thirdly, it is possible that the distribution of the separation of grain occurring at a distance along the walkers is not uniform across the width of the straw walkers. In particular, the amount of separation occurring directly above a sensor may not have been representative of the average separation across the width of the walkers. Non-uniform distributions of grain and straw above the walkers would contribute to this effect. The unavoidable tendency of straw to mat and move in non-uniform bunches, much as it would in an actual combine, may have cased some of this problem. This theory is supported by the fact that System 2 sensing units, which consisted of two sensors across the width of the walkers at a given location, showed better results than did System 1 sensing units. Distortions due to this phenomenon may also be expected to be random for all sensing units.

Lastly, the trajectory of the grain kernels as they separated through the straw walkers may not have been such that the collection of grain in the trays accurately indicated the plot of the true separation curve. That is, some of the grain collected in a tray may not have separated directed above that tray. In particular, at the end of the walkers, some of the separating grain, represented by kernel impacts on the end sensor, may not have been collected in the rearmost tray, and instead, been considered loss.

8. CONCLUSIONS

1) The grain separation apparatus successfully created a separation pattern similar to that predicted by Zoerb *et al.*, (1974) and Huisman, (1983). Separation weight data, collected in trays beneath the straw walkers showed that an accurate measurement of walker grain loss can be calculated using the values for the separation rate at the end of the walkers, as well as at three other locations beneath the walkers.

2) The separation weight data showed significant variation in the ratio between the actual grain loss and the separation rate occurring at the end of the straw walkers. No significant relationship was observed between the value of that ratio and any measurable variable such as grain and/or straw flow rates, G/MOG, and moisture content.

3) The grain sensing and data acquisition systems did not provide an accurate measurement of the grain separation rates existing at the locations of the sensors. Major improvements in the sensing systems are required for this grain loss measurement technique to be successful.

9. RECOMMENDATIONS FOR FURTHER RESEARCH

The results from this project clearly show that much improvement and modification is required for such a grain loss measurement system to be considered feasible for combine application. First and foremost, the accuracy of the separation sensing system must be markedly improved.

9.1 Improvement of the Sensing Systems

With an on-board application of a grain loss measuring system such as the one tested in this project, the luxury of knowing the actual separation curve, as derived from separation weight data, is not available. The relationship between the output from each sensing unit and the separation rates must be known, and highly consistent. Also, the effects that grain kernel characteristics have on these relationships must be equal for each unit if the system is to work consistently well in different types and samples of grain.

Various aspects of the grain sensing systems should be re-evaluated in efforts to improve accuracy. Firstly, the procedure used for counting the grain kernel impact pulses may have resulted in too many missed pulses, or too many pulses counted twice. Perhaps an integration of the pulsing signal would provide a more accurate indication of the kernel impact rate. Another possible counting technique would be use of interrupt capabilities of a microprocessor, which may increment a counter upon the detection of the transition of a signal from a low voltage level to a high voltage level.

If incorrect counts are suspected to be resulting due to the effects of walker motion, as discussed in Section 7.2.1, perhaps the sensors should be mounted in [illegible]ry position independent of the straw walkers. If possible, a technique should be developed that would allow for the calibration of the sensors under operating conditions.

The effects of possible rebounding should be examined and eliminated if possible. Situating the sensors below the center of the straw walker sections may be helpful in minimizing rebounding. Also, screens, allowing only the grain separated directly above a sensor to fall onto that sensor, may be required.

More than one sensor across the width of the straw walkers at a given location appear to detect a more representative sample of grain. Suggested improvements may be to orientate the sensors with there longitudinal axis perpendicular to the straw walkers. Also, some grain loss monitors are equipped with full width sensors. Provided saturation effects, due to the increased number of impacts which would be sensed, are not too extreme, full width sensors would likely improve the results.

Lastly, confidence in the collection tray data may be improved by situating the top of the sides of the trays nearer to the straw walkers. This may be realized either by extending the side of the trays, or by elevating the existing rack of trays.

9.2 Application of a Microprocessor

Obviously, for this system to be implemented on board a combine, a microprocessor would be required to handle the computer algorithms used to calculate loss. As discussed above, a microprocessor also may be useful for signal acquisition and conditioning. A microprocessor could also perform some screening of unacceptable data. For example, the microprocessor could be programmed to reject a regressed separation curve having a correlation coefficient less than 0.50, or a positive valued slope. Finally, if such a system were installed on a combine, the microprocessor would need to be programmed to account for the sensor results when the combine is entering or exiting the crop (i.e. turning corners, stopping for servicing, and other common combining procedures). These tasks could easily be performed by a microprocessor interfaced to appropriate and effective sensing elements.

9.3 Alternate Sensing Techniques

This project has shown that if the rate of grain separation can be measured at four positions beneath a set of combine straw walkers, the grain loss over those straw walkers can be calculated. In light of the limited effectiveness of the kernel impact sensing piezoelectric crystals, the use of other grain separation measuring techniques warrants consideration.

Perhaps an optical or sonic motion transducer could detect the separating grain kernels. Another possibility would be either a continuous flow, or a batch-type weighing scale, which would be adapted to weigh a sample of the separating grain. Such a set-up would require that the straw and chaff be removed from the grain sample weighed.

Obviously, whatever sensing technique used, the two following conditions must be met.

Firstly, the sensor must detect only the grain kernels separated, and must ignore the straw and chaff particles.

Secondly, the technique must sense a representative sample of separation at the sensor locations for the output to be meaningful.

The development of an effective grain sensing technique, based on impact sensing piezoelectric crystals or otherwise, meeting the above conditions, is crucial to the implementation of a straw walker grain loss measurement system as described in this thesis.

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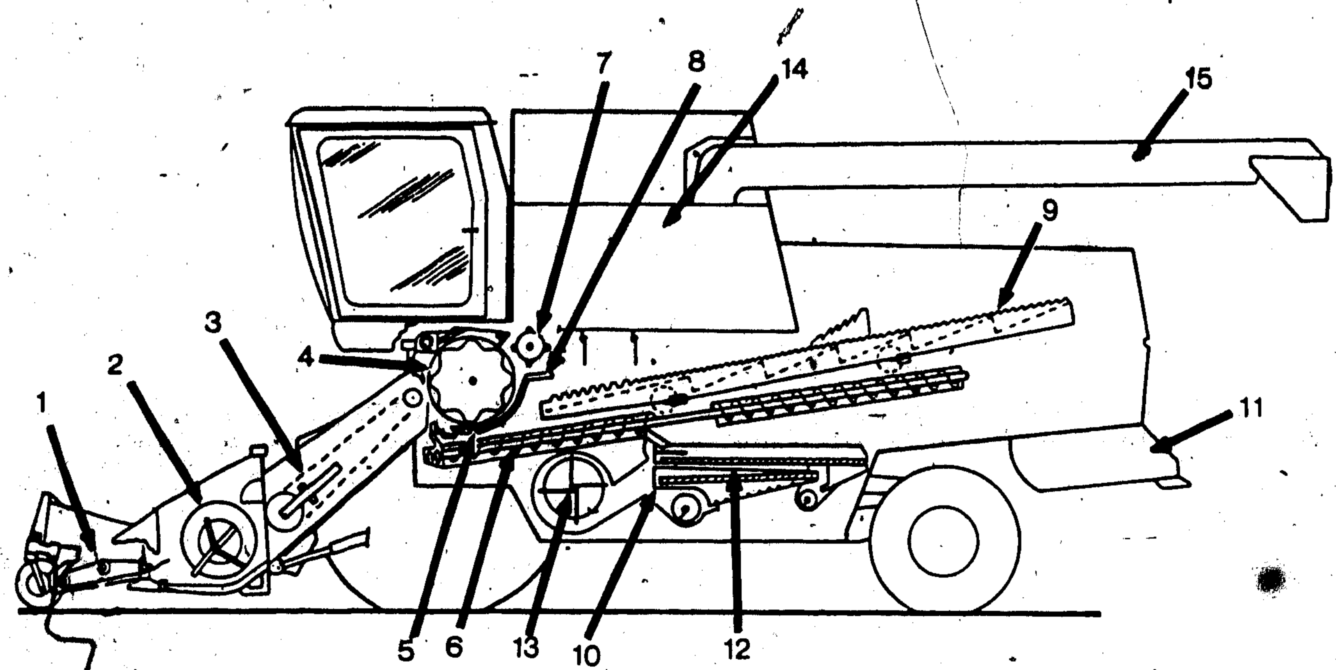
11. APPENDIX A

A.1 Conventional-Type Combine Operation

The grain combine has numerous functions to perform. It must either cut the standing crop or pick up an existing windrow, convey the crop to the threshing area, thresh the grain from the crop ears (or heads), separate the grain from the straw, clean the chaff from the grain, collect and unload the grain, and expel the straw and chaff. Figure A.1 is a cross-sectional view of a typical conventional-type combine on the market today.

At the front is a pickup (1), which feeds windrows to the table auger (2). Straight-cut machines, used to harvest un-cut or standing crops, have a cutter bar and a reel instead of a pickup. The feeder elevator (3), often referred to as the feeder chain, conveys the unthreshed crop to the threshing cylinder (4). The threshing cylinder rotates at high speeds (800-1200 rpm) and the rasp bars on the perimeter beat the straw and unthreshed ears against the concave (5), loosening the grain from the ears. The concave has many slots through which much of the grain separates from the straw and falls onto the grain pan (6). The remaining grain and straw is propelled by the rear beater (7), over the beater grate (8), onto the straw walkers (9). The straw walkers are oscillating slotted racks which agitate the grain straw mat as it is conveyed out to the rear of the machine. This agitation causes separation of most of the remaining grain from the straw through the slotted tops of the straw walkers. Straw carried by the straw walkers is dropped into the straw chopper (11), which chops and spreads the straw onto the field. The grain separated by the straw walkers is collected on the grain pan (6). From the grain pan the grain is conveyed onto the cleaning shoe (10). The cleaning shoe consists of two reciprocating sieves (12). The top sieve, aided by an air stream generated by the cleaning fan (13), separates the grain and unthreshed heads from the chaff and short pieces of straw which are blown out the back of the combine. The lower sieve separates the threshed grain, which is conveyed to the grain tank (14), from the unthreshed heads, commonly called tailings, which are conveyed back to the threshing cylinder to be rethreshed. Grain is unloaded from the grain tank (14) by the unloading auger (15) as required. Numerous machine parameters such as ground speed, pickup speed, table auger speed, threshing cylinder speed, threshing cylinder-concave clearance, fan speed, and size of sieve openings are variable and must be intelligently set by the operator to achieve maximum machine performance.



(1) Pickup
(2) Table Auger
(3) Feeder Elevator
(4) Threshing Cylinder
(5) Concave
(6) Grain Pan
(7) Rear Beater
(8) Beater Grate
(9) Straw Walkers
(10) Cleaning Shoe
(11) Straw Chopper
(12) Cleaning Sieves
(13) Cleaning Fan
(14) Grain Tank
(15) Unloading Auger

Figure A.1 Conventional Style Combine Schematic

(adapted from PAMI, 1981)

13. APPENDIX B

B.1 System #1 Data Evaluation Program

```
10 REM   Basic program written to sum counts from Datataker
         with an IBM-PC microcomputer..
20 REM   Programmer: John Lunty
30 REM
40 REM   Prompt operator for name of data file (i.e. run
         number.
50 REM   Open input and Output data files.
60 PRINT "SUMMING PROGRAM"
70 PRINT "ENTER RUN NUMBER-RETUTN"
80 LINE INPUT R$
90 OPEN R$ FOR INPUT AS #1
100 PRINT "ENTER S-RUN NUMBER-RETURN"
110 LINE INPUT S$
120 OPEN S$ FOR OUTPUT #2
130 REM
140 REM  Initialize run duration counter.
150 D=0
160 REM
170 REM  Clear run flag.
180 S=0
190 REM
200 REM  Set countdown timer.
210 J=5
220 REM
230 REM  Dimension data arrays.
240 DIM A(9)
250 DIM B(8)
260 REM
270 REM  Test to see if run has just completed. If so,
         sample sensor channels for five more seconds.
280 IF S=1.0 THEN J=J-1 ELSE 320
290 IF J=0 THEN 570 ELSE 370
300 REM
310 REM  Initialize input variables.
320 FOR K=0 TO 9
330 A(K)=0
340 NEXT K
350 REM
360 REM  Read channel numbers and counts from sensor
         channels.
370 FOR I=0 TO 8
380 INPUT #1,P(I)
390 REM
400 REM  Add counts to accumulated totals.
410 A(I)=A(I)+P(I)
```

```
420 NEXT I
430 REM
440 REM  Read state of switch channel.
450 INPUT #1,B
460 A(9)=B
470 REM
480 REM  If switch is on, increment duration counter and set
         run flag. If switch is off, begin countdown (5
         seconds).
500 IF A(9)=0 THEN 280
510 D=D+1
520 S=1.0
530 GOTO 370
540 REM
550 REM  Print duration of run, and accumulated counts for
         each sensor, to screen and output file.
570 PRINT #2,D,A(1),A(3),A(5),A(7)
580 PRINT D,A(1),A(3),A(5),A(7)
590 CLOSE
600 END
```

B.2 System #2 Data Acquisition Program

```
10 REM   Program written to acquire data through the analog
         input channels of the MINC.
         Programmer: John Lunty
20 REM   Determine if new run is to be started and open up
         data files if so.
30 PRINT "START NEW RUN?"
40 GETCHAR(F$) \ IF F$="" THEN 40
50 IF F$="Y" THEN 80
60 IF F$="N" THEN 600
70 GO TO 40
80 CLEAR
90 PRINT "ENTER RUN NUMBER-PRESS RETURN"
100 LINPUT R$
110 OPEN R$ FOR OUTPUT AS FILE #1
120 PRINT "ENTER S-RUN NUMBER RETURN"
130 LINPUT S$
140 OPEN S$ FOR OUTPUT AS FILE #2
150 REM
160 REM  Dimension array to collect channel voltage
         readings.
170 DIM A(2399)
180 REM  Check voltage level of microswitch channel. If low
         continue checking. If high instigate the sampling
         of the sensor channels at the rate of 1/10 of a
         second for the duration of a complete minute.
190 AIN(,T,,,4,)
200 IF T>1.0 THEN 190
210 PRINT "RUNNING"
220 AIN(,A(),2400,1/10,0,4)
230 REM  When the data collection is completed, add the
         pulses counted for each channel in every second,
         and total the pulses counted for each channel for
         the duration of the run and print the results to
         the output files.
240 I2=0
250 J2=0
260 K2=0
270 L2=0
280 FOR Q=0 TO 2399
290 IF A(Q)<1 THEN 320
300 A(Q)=1.0
310 GO TO 330
320 A(Q)=0
330 NEXT Q
340 I=0
350 S=0
360 I1=0
370 J1=0
380 K1=0
390 L1=0
400 J=1+1
```

```
410 K=I+2
420 L=I+3
430 I1=A(I)+I1
440 J1=A(J)+J1
450 K1=A(K)+K1
460 L1=A(L)+L1
470 I=I+4
480 S=S+1
490 IF S<10 THEN 400
500 I2=I2+I1
510 J2=J2+J1
520 K2=K2+K1
530 L2=L2+L1
540 PRINT #1,I1,J1,K1,L1
550 IF 1<2400 THEN 350
560 PRINT #2,I2,J2,K2,L2
570 CLOSE #1
580 CLOSE #2
590 GO TO 30
600 END
```

14. APPENDIX C

The results of the data aquisition and evaluation are presented in the following tables.

Table C.1 lists the raw data collected for each run, including the flow rate of grain and straw, the moisture contents of the grain and straw, the mass of grain separated into each tray, and the output from each sensing unit.

Table C.2 shows the analysis of the measured separation weight data. This analysis involved the regression of the relationship between the mass of grain remaining in the straw, and the position along the straw walker. Also, on the basis of this relationship, a value for grain loss was calculated and compared to the actual measured loss value.

Table C.3 shows, for all sensing unit-grain sample combinations, the regression statistics of the relationship between the measured separation rate and the sensing unit output. For sensing unit #1 of System 1, a broken wire disabled the output for runs A1, A2, A3, A8, A9, B4, B7, and B10. Regressions were performed with the data from the remaining runs for this sensing unit.

Table C.4 shows the analysis of the sensor output adjusted with the relationships regressed in Table C.3 for each run. This analysis involved the regression of the relationship between the adjusted sensor output and the sensors' location. Once again a value for loss was calculated on the basis of the regression of the sensor data. For System 1, the analysis was performed using the output from only three sensors for those runs where sensing unit #1 was disabled.

Table C.5 shows the results of the analysis of the ratio between loss as calculated in Table C.5 and actual loss, for those runs meeting different conditions classifying how well the sensor output indicated the true separation curve.

TABLE C.1 EXPERIMENTAL DATA COLLECTED

Run #	(m)	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Grain (kg/min)		18.867	15.448	17.673	17.850	21.701	30.152	4.390	28.065	23.707	29.478
Straw (kg/min)		55.000	38.250	46.750	35.000	55.000	55.000	45.000	38.250	35.000	35.000
G/MOG		0.343	0.404	0.378	0.510	0.395	0.548	0.098	0.734	0.677	0.842
Straw Moisture %		7.320	7.273	7.255	7.970	7.916	7.437	7.951	7.858	7.669	7.659
Grain Moisture %		12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900
Separation Tray Collections (kg)	0.000	0.194	0.731	0.428	0.696	0.301	0.633	0.153	0.981	0.878	0.970
	0.457	1.113	1.841	2.123	1.729	1.008	1.359	0.532	3.633	2.499	2.706
	0.914	1.185	1.389	2.048	1.278	1.072	1.328	0.437	3.395	2.029	2.097
	1.372	1.296	1.477	2.139	1.507	1.576	1.865	0.534	3.540	2.053	2.030
	1.829	0.830	0.951	1.220	0.932	1.168	1.424	0.309	2.155	1.216	1.324
	2.286	0.534	0.515	0.669	0.546	0.801	0.970	0.191	1.234	0.642	0.828
	2.743	0.402	0.354	0.401	0.439	0.749	0.646	0.158	0.901	0.463	0.659
System #1 Sensor Outputs	0.660	143.000	213.000	173.000	190.000	138.000	148.000	50.000	348.000	306.000	183.000
	1.321	75.000	107.000	116.000	86.000	77.000	57.000	25.000	209.000	134.000	101.000
	1.880	25.000	45.000	53.000	42.000	48.000	31.000	16.000	77.000	38.000	35.000
	2.692	22.000	31.000	25.000	17.000	30.000	21.000	7.000	62.000	38.000	28.000
System #2 Sensor Outputs	0.660	23.000	15.000	50.000	78.000	69.000	69.000	30.000	65.000	17.000	81.000
	1.321	39.000	50.000	54.000	54.000	44.000	60.000	18.000	97.000	48.000	42.000
	1.880	41.000	22.000	36.000	36.000	30.000	42.000	5.000	73.000	29.000	32.000
	2.692	11.000	9.000	16.000	16.000	24.000	25.000	6.000	30.000	14.000	13.000

Run #	(m)	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Grain (kg/min)		20.609	20.150	14.719	18.898	19.100	28.020	21.215	28.986	19.524	31.022
Straw (kg/min)		55.000	45.000	55.000	35.000	55.000	55.000	45.000	45.000	35.000	35.000
G/MOG		0.375	0.448	0.268	0.540	0.347	0.509	0.471	0.644	0.558	0.886
Straw Moisture %		7.891	7.718	7.721	6.684	7.133	6.749	7.439	7.485	7.302	7.405
Grain Moisture %		12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900	12.900
Separation Tray Collections (kg)	0.000	0.236	0.475	0.202	0.768	0.172	0.681	0.370	0.597	0.594	1.142
	0.457	0.885	1.531	0.585	2.393	0.675	2.445	1.172	2.107	1.423	3.171
	0.914	1.005	1.598	0.702	1.754	0.789	2.234	1.112	2.043	1.293	2.330
	1.372	1.434	1.829	0.959	1.593	1.186	2.143	1.326	2.414	1.522	2.367
	1.829	1.036	1.108	0.744	0.851	0.845	1.168	1.012	1.363	0.940	1.488
	2.286	0.677	0.678	0.462	0.467	0.611	0.618	0.702	0.735	0.487	0.845
	2.743	0.489	0.561	0.352	0.329	0.394	0.424	0.604	0.520	0.386	0.636
System #1 Sensor Outputs	0.660	205.000	215.000	197.000	189.000	160.000	189.000	109.000	218.000	165.000	189.000
	1.321	59.000	106.000	73.000	108.000	49.000	89.000	60.000	117.000	89.000	124.000
	1.880	31.000	43.000	27.000	29.000	32.000	34.000	38.000	34.000	52.000	61.000
	2.692	37.000	42.000	25.000	21.000	33.000	27.000	55.000	20.000	23.000	29.000
System #2 Sensor Outputs	0.660	65.000	80.000	45.000	15.000	54.000	77.000	30.000	88.000	20.000	21.000
	1.321	46.000	72.000	38.000	32.000	33.000	53.000	50.000	61.000	52.000	51.000
	1.880	32.000	39.000	26.000	9.000	40.000	37.000	40.000	48.000	25.000	33.000
	2.692	43.000	37.000	31.000	8.000	25.000	39.000	21.000	19.000	16.000	9.000

Run #	(m)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Grain (kg/min)		16.673	15.968	18.823	15.964	20.387	26.826	21.914	31.522	19.642	26.205
Straw (kg/min)		55.000	45.000	55.000	35.000	49.500	55.000	45.000	45.000	35.000	35.000
G/MOG		0.303	0.355	0.342	0.456	0.412	0.488	0.487	0.700	0.561	0.749
Straw Moisture %		6.250	6.809	8.052	8.100	6.345	7.401	6.058	7.607	7.297	7.776
Grain Moisture %		13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600
Separation Tray Collections (kg)	0.000	0.204	0.326	0.117	0.443	0.274	0.226	0.377	0.547	0.474	0.643
	0.457	0.664	0.999	0.496	1.351	1.158	0.891	1.102	1.744	1.365	2.061
	0.914	0.707	1.069	0.693	1.066	1.251	1.087	1.220	1.701	[illegible]	1.770
	1.372	1.034	1.293	1.107	1.342	1.695	1.667	1.589	2.311	[illegible]	2.241
	1.829	0.811	0.870	0.937	0.826	1.250	1.377	1.158	1.683	[illegible]	1.459
	2.286	0.525	0.523	0.662	0.505	0.833	0.879	0.748	1.109	0.626	0.933
	2.743	0.420	0.398	0.598	0.402	0.735	0.689	0.648	0.928	0.491	0.838
System #1 Sensor Outputs	0.660	70.000	78.000	55.000	292.000	91.000	57.000	158.000	90.000	126.000	102.000
	1.321	55.000	62.000	53.000	75.000	75.000	60.000	88.000	114.000	108.000	107.000
	1.880	28.000	26.000	36.000	49.000	42.000	42.000	46.000	63.000	49.000	63.000
	2.692	34.000	11.000	55.000	30.000	12.000	17.000	4.000	39.000	14.000	21.000
System #2 Sensor Outputs	0.660	33.000	53.000	42.000	64.000	80.000	51.000	58.000	72.000	56.000	83.000
	1.321	37.000	38.000	35.000	41.000	68.000	39.000	38.000	65.000	35.000	62.000
	1.880	28.000	18.000	34.000	21.000	45.000	43.000	40.000	42.000	13.000	41.000
	2.692	19.000	14.000	18.000	9.000	24.000	20.000	23.000	19.000	9.000	17.000

Run #	(m)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Grain (kg/min)		14.797	15.716	17.916	2.055	21.699	32.504	20.914	30.873	20.601	29.955
Straw (kg/min)		55.000	45.000	55.000	35.000	55.000	55.000	45.000	45.000	35.000	35.000
G/MOG		0.269	0.349	0.326	0.059	0.395	0.591	0.465	0.686	0.589	0.856
Straw Moisture %		6.265	8.010	6.687	6.469	7.897	6.700	6.450	8.561	12.447	6.915
Grain Moisture %		13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600	13.600
Separation Tray Collections (kg)	0.000	0.146	0.242	0.252	0.103	0.280	0.330	0.558	0.542	0.441	1.044
	0.457	0.594	0.947	0.916	0.215	1.008	1.857	1.707	2.265	1.285	3.091
	0.914	0.730	0.984	0.703	0.152	1.034	2.031	1.554	2.133	1.176	2.732
	1.372	0.861	1.230	1.194	0.164	1.412	2.658	1.830	2.685	1.488	3.022
	1.829	0.733	0.811	0.900	0.085	1.087	1.868	1.168	1.674	0.948	1.876
	2.286	0.449	0.485	0.578	0.048	0.705	1.201	0.694	0.962	0.596	1.025
	2.743	0.396	0.384	0.494	0.032	0.651	0.996	0.549	0.723	0.528	0.739
System #1 Sensor Outputs	0.660	48.000	88.000	51.000	25.000	60.000	110.000	118.000	130.000	74.000	142.000
	1.321	45.000	71.000	46.000	16.000	60.000	131.000	96.000	162.000	76.000	170.000
	1.880	18.000	37.000	31.000	5.000	30.000	52.000	55.000	67.000	38.000	76.000
	2.692	4.000	9.000	7.000	1.000	10.000	19.000	18.000	16.000	13.000	17.000
System #2 Sensor Outputs	0.660	32.000	50.000	40.000	11.000	48.000	84.000	55.000	89.000	52.000	85.000
	1.321	25.000	33.000	27.000	5.000	25.000	64.000	46.000	67.000	52.000	59.000
	1.880	32.000	22.000	24.000	0.000	36.000	58.000	32.000	31.000	25.000	39.000
	2.692	31.000	11.000	13.000	2.000	37.000	24.000	14.000	21.000	9.000	20.000

TABLE C.2 SEPARATION WEIGHT DATA

Separation weight data	x(m)	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
	0.000	9.554	8.795	12.238	10.014	13.081	14.443	2.847	21.471	12.161	13.769
Mass of grain remaining	0.457	8.441	6.954	10.115	8.285	12.073	13.084	2.315	17.838	9.662	11.063
in straw at x distances	0.914	7.256	5.565	8.067	7.007	11.001	11.756	1.878	14.443	7.633	8.966
shown (kg)	1.372	5.960	4.088	5.928	5.500	9.425	9.891	1.344	10.903	5.580	6.936
	1.829	5.130	3.137	4.708	4.568	8.257	8.467	1.035	8.748	4.364	5.612
	2.286	4.596	2.622	4.039	4.022	7.456	7.497	0.844	7.514	3.722	4.784
	2.743	4.194	2.268	3.638	3.583	6.707	6.851	0.686	6.613	3.259	4.125
Total mass separated (kg)		5.554	7.258	9.028	7.127	6.675	8.225	2.314	15.839	9.780	10.614
Mass of grain lost (kg)		4.194	2.268	3.638	3.583	6.707	6.851	0.686	6.613	3.259	4.125
% of grain loss		43.024	23.809	28.723	33.455	50.120	45.443	22.867	29.454	24.994	27.987
B		-0.297	-0.490	-0.432	-0.362	-0.268	-0.297	-0.542	-0.423	-0.461	-0.421
A		9.159	8.215	11.150	9.296	13.771	15.015	2.929	20.099	10.881	12.644
R-sqr		0.976	0.976	0.959	0.975	0.992	0.985	0.988	0.974	0.968	0.986
Gr(.274m)=Loss (kg)		4.059	2.143	3.406	3.445	6.607	6.652	0.662	6.296	3.073	3.986
Calc/actual loss		0.968	0.945	0.936	0.961	0.985	0.971	0.964	0.952	0.943	0.966
Actual loss/actual end separtion rate (kg/(kg/m))		3.431	2.107	2.417	2.822	3.740	3.418	1.860	2.429	2.247	2.4[illegible]7

Separation weight data	x(m)	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
	0.000	11.099	11.951	7.403	9.311	10.333	12.395	10.591	12.930	8.192	14.886
Mass of grain remaining	0.457	10.214	10.420	6.818	6.918	9.658	9.950	9.419	10.823	6.769	11.715
in straw at x distances	0.914	9.209	8.822	6.116	5.164	8.869	7.716	8.307	8.780	5.476	9.385
shown (kg)	1.372	7.775	6.993	5.157	3.571	7.683	5.573	6.981	6.366	3.954	7.018
	1.829	6.739	5.885	4.413	2.720	6.838	4.405	5.969	5.003	3.014	5.530
	2.286	6.062	5.207	3.951	2.253	6.227	3.787	5.267	4.268	2.527	4.685
	2.743	5.573	4.646	3.599	1.924	5.833	3.363	4.663	3.748	2.141	4.049
Total mass separated (kg)		5.762	7.780	4.006	8.155	4.672	9.713	6.298	9.779	6.645	11.979
Mass of grain lost (kg)		5.573	4.646	3.599	1.924	5.833	3.363	4.663	3.748	2.141	4.049
% of grain loss		49.166	37.389	47.324	19.089	55.526	25.719	42.542	27.708	24.368	25.262
B		-0.274	-0.345	-0.290	-0.533	-0.229	-0.448	-0.314	-0.460	-0.509	-0.456
A		11.486	11.555	7.759	7.772	10.661	10.769	10.851	12.456	8.197	13.495
R-sqr		0.981	0.976	0.984	0.970	0.980	0.959	0.994	0.966	0.977	0.979
Gr(.274m)=Loss (kg)		5.415	4.485	3.500	1.803	5.684	3.153	4.583	3.528	2.030	3.862
Calc/actual loss		0.972	0.965	0.972	0.937	0.974	0.937	0.983	0.941	0.948	0.954
Actual loss/actual end separtion rate (kg/(kg/m))		3.702	2.950	3.491	1.950	4.424	2.328	3.187	2.257	2.020	2.246

Separation weight data	x(m)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	0.000	8.688	7.924	10.863	8.071	12.298	13.634	12.041	16.790	10.329	13.770
Mass of grain remaining	0.457	8.024	6.925	10.367	6.720	11.140	12.743	10.939	15.046	8.964	11.709
in straw at x distances	0.914	7.317	5.856	9.674	5.654	9.889	11.656	9.719	13.345	7.524	9.939
shown (kg)	1.372	6.283	4.563	8.567	4.312	8.194	9.989	8.130	11.034	5.690	7.698
	1.829	5.472	3.693	7.630	3.486	6.[illegible]44	8.612	6.972	9.351	4.578	6.239
	2.286	4.947	3.170	6.968	2.981	6.111	7.733	6.224	8.242	3.952	5.306
	2.743	4.527	2.772	6.370	2.579	5.376	7.044	5.576	7.314	3.461	4.468
Total mass separated (kg)		4.365	5.478	4.610	5.935	7.196	6.816	6.842	10.023	7.342	9.945
Mass of grain lost (kg)		4.527	2.772	6.370	2.579	5.376	7.044	5.576	7.314	3.461	4.468
% of grain loss		50.911	33.600	58.015	30.291	42.762	50.823	44.903	42.187	32.037	31.000
B		-0.262	-0.407	-0.228	-0.424	-0.331	-0.276	-0.301	-0.327	-0.419	-0.431
A		9.089	8.142	11.768	7.942	13.064	14.687	12.467	17.516	10.442	14.229
R-sqr		0.987	0.983	0.995	0.982	0.992	0.988	0.988	0.989	0.974	0.991
Gr(.274m)=Loss (kg)		4.426	2.667	6.297	2.481	5.273	6.883	5.452	7.146	3.305	4.361
Calc/actual loss		0.978	0.962	0.989	0.962	0.981	0.977	0.978	0.977	0.955	0.976
Actual loss/actual end separtion rate (kg/(kg/m))		3.847	2.502	4.386	2.398	3.031	3.652	3.340	3.080	2.444	2.325

Separation weight data	x(m)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
	0.000	8.239	7.878	10.199	0.993	12.016	18.089	11.642	15.409	10.203	17.428
Mass of grain remaining	0.457	7.645	6.931	9.283	0.778	11.008	16.232	9.935	13.144	8.918	14.337
in straw at x distances	0.914	6.915	5.947	8.580	0.626	9.974	14.201	8.381	11.011	7.742	11.605
shown (kg)	1.372	6.054	4.717	7.386	0.462	8.562	11.543	6.551	8.326	6.254	8.583
	1.829	5.321	3.906	6.486	0.377	7.475	9.675	5.383	6.652	5.306	6.707
	2.286	4.872	3.421	5.908	0.329	6.770	8.474	4.689	5.690	4.710	5.682
	2.743	4.476	3.037	5.414	0.297	6.119	7.478	4.140	4.967	4.182	4.943
Total mass separated (kg)		3.909	5.083	5.037	0.799	6.177	10.941	8.060	10.984	6.462	13.529
Mass of grain lost (kg)		4.476	3.037	5.414	0.297	6.119	7.478	4.140	4.967	4.182	4.943
% of grain loss		53.381	37.401	51.804	27.099	49.764	40.599	33.934	31.139	39.290	26.759
B		-0.238	-0.864	-0.250	-0.400	-0.265	-0.348	-0.382	-0.432	-0.331	-0.464
A		8.436	7.954	10.533	0.839	12.446	18.922	11.347	15.489	10.094	16.706
R-sqr		0.988	0.980	0.986	0.954	0.990	0.988	0.979	0.977	0.982	0.974
Gr(.274m)=Loss (kg)		4.394	2.928	5.302	0.280	6.015	7.281	3.983	4.742	4.067	4.684
Calc/actual loss		0.982	0.964	0.979	0.941	0.983	0.974	0.962	0.955	0.972	0.948
Actual loss/actual end separtion rate (kg/(kg/m))		4.232	2.795	4.029	2.599	3.786	2.898	2.671	2.375	3.051	2.223

TABLE C.3 SENSOR REGRESSION RESULTS

System 1 Sensors

	Replications A+B		Replications C+D	
#1 Regression Output:				
Constant		2.16E-01		-9.60E-02
Std Err of Y Est		1.32E-01		1.42E-01
R Squared		5.20E-01		6.04E-01
No. of Observations		2.00E+01		2.00E+01
Degrees of Freedom		1.70E+01		1.70E+01
X Coefficient(s)	1.12E-03	2.29E-06	9.71E-03	-2.76E-05
Std Err of Coef.	1.86E-03	4.40E-06	1.93E-03	6.06E-06
#2 Regression Output:				
Constant		1.98E-01		-2.77E-02
Std Err of Y Est		7.34E-02		6.87E-02
R Squared		5.77E-01		7.69E-01
No. of Observations		2.00E+01		2.00E+01
Degrees of Freedom		1.70E+01		1.70E+01
X Coefficient(s)	7.41E-04	5.74E-06	6.10E-03	-1.64E-05
Std Err of Coef.	1.53E-03	6.50E-06	1.72E-03	8.60E-06
#3 Regression Output:				
Constant		1.30E-01		1.15E-02
Std Err of Y Est		6.40E-02		6.16E-02
R Squared		5.24E-01		7.20E-01
No. of Observations		2.00E+01		2.00E+01
Degrees of Freedom		1.70E+01		1.70E+01
X Coefficient(s)	2.58E-03	2.17E-05	8.23E-03	-3.50E-05
Std Err of Coef.	5.07E-03	5.41E-05	3.17E-03	3.66E-05
#4 Regression Output:				
Constant		9.10E-02		1.15E-01
Std Err of Y Est		5.49E-02		7.28E-02
R Squared		4.09E-01		3.05E-01
No. of Observations		2.00E+01		2.00E+01
Degrees of Freedom		1.70E+01		1.70E+01
X Coefficient(s)	4.31E-03	-1.27E-05	1.08E-02	-1.71E-04
Std Err of Coef.	4.11E-03	5.60E-05	4.14E-03	7.54E-05

System 2 Sensors

Replications A+B

#1 Regression Output:

Constant		-1.53E-02
Std Err of Y Est		5.54E-02
R Squared		8.30E-01
No. of Observations		1.10E+01
Degrees of Freedom		8.00E+00
X Coefficient(s)	4.82E-03	1.21E-05
Std Err of Coef.	7.17E-03	5.98E-05

#2 Regression Output:

Constant		5.36E-02
Std Err of Y Est		5.14E-02
R Squared		6.60E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	3.90E-03	2.46E-06
Std Err of Coef.	2.97E-03	2.52E-05

#3 Regression Output:

Constant		1.01E-01
Std Err of Y Est		4.44E-02
R Squared		6.24E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	2.59E-03	1.57E-05
Std Err of Coef.	2.14E-03	2.74E-05

#4 Regression Output:

Constant		3.50E-02
Std Err of Y Est		4.58E-02
R Squared		3.26E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	1.13E-02	-2.00E-04
Std Err of Coef.	4.52E-03	9.33E-05

Replications C+D

#1 Regression Output:

Constant		-1.49E-02
Std Err of Y Est		6.43E-02
R Squared		8.68E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	6.69E-03	7.95E-06
Std Err of Coef.	3.26E-03	2.88E-05

#2 Regression Output:

Constant		1.03E-02
Std Err of Y Est		5.51E-02
R Squared		7.57E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	6.88E-03	-1.78E-05
Std Err of Coef.	3.21E-03	3.72E-05

#3 Regression Output:

Constant		4.95E-02
Std Err of Y Est		4.89E-02
R Squared		7.[illegible]1E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	5.75E-03	-2.84E-06
Std Err of Coef.	2.79E-03	4.58E-05

#4 Regression Output:

Constant		-1.83E-02
Std Err of Y Est		4.35E-02
R Squared		5.93E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	1.94E-02	-3.97E-04
Std Err of Coef.	4.31E-03	1.07E-04

Combined Sensors

Replications A+B

#1 Regression Output:

Constant		5.92E-02
Std Err of Y Est		1.08E-01
R Squared		5.03E-01
No. of Observations		1.10E+01
Degrees of Freedom		8.00E+00
X Coefficient(s)	2.69E-03	2.22E-06
Std Err of Coef.	5.78E-03	2.93E-05

#2 Regression Output:

Constant		9.76E-02
Std Err of Y Est		5.87E-02
R Squared		6.59E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	2.47E-03	2.79E-06
Std Err of Coef.	1.88E-03	1.04E-05

#3 Regression Output:

Constant		4.22E-02
Std Err of Y Est		4.22E-02
R Squared		7.39E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	5.31E-03	1.53E-06
Std Err of Coef.	2.67E-03	3.02E-05

#4 Regression Output:

Constant		5.62E-02
Std Err of Y Est		4.99E-02
R Squared		3.83E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	6.60E-03	-5.37E-05
Std Err of Coef.	5.61E-03	1.01E-04

Replications C+D

#1 Regression Output:

Constant		-2.51E-01
Std Err of Y Est		1.07E-01
R Squared		7.18E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	1.49E-02	-6.29E-05
Std Err of Coef.	2.49E-03	1.27E-05

#2 Regression Output:

Constant		-1.64E-02
Std Err of Y Est		5.41E-02
R Squared		8.20E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	6.39E-03	-1.74E-05
Std Err of Coef.	1.96E-03	1.41E-05

#3 Regression Output:

Constant		1.63E-02
Std Err of Y Est		2.90E-02
R Squared		9.22E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	5.68E-03	2.04E-05
Std Err of Coef.	1.85E-03	2.67E-05

#4 Regression Output:

Constant		-1.24E-02
Std Err of Y Est		5.34E-02
R Squared		5.29E-01
No. of Observations		2.00E+01
Degrees of Freedom		1.70E+01
X Coefficient(s)	2.04E-02	-3.99E-04
Std Err of Coef.	5.39E-03	1.35E-04

TABLE C. . SENSOR DATA RESULTS

SYSTEM 1 DATA

		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
Separation weight data	x (m)										
	0.660	0.415	0.541	0.467	0.498	0.406	0.423	0.276	0.841	0.740	0.503
Calibrated sensor readings	1.321	0.279	0.330	0.347	0.295	0.282	0.254	0.219	0.563	0.382	0.320
(kg) at distance x(m).	1.880	0.208	0.289	0.326	0.276	0.303	0.230	0.177	0.454	0.259	0.246
	2.692	0.181	0.215	0.192	0.161	0.211	0.177	0.121	[illegible]	0.240	0.204
Regression Results	b	0.411	0.436	0.416	0.523	0.290	0.406	-0.408	-0.468	-0.553	-0.441
	ln a	1.147	1.421	1.367	1.432	1.078	1.141	0.837	1.936	1.728	1.351
	R-sqr	0.932	0.946	0.944	0.956	0.861	0.918	0.995	0.990	0.855	0.941
calc loss (kg)		2.475	2.879	3.011	1.906	4.578	2.528	1.850	4.071	2.233	2.607
calc/actual loss		0.590	1.269	0.827	0.532	0.682	0.369	2.697	0.615	0.685	0.631

		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Separation weight data	x (m)										
	0.660	0.526	0.545	0.511	0.496	0.444	0.496	0.360	0.551	0.452	0.496
Calibrated sensor readings	1.321	0.257	0.329	0.276	0.332	0.245	0.300	0.258	0.349	0.300	0.362
(kg) at distance x(m).	1.880	0.230	0.280	0.215	0.223	0.234	0.242	0.259	0.242	0.322	0.366
	2.692	0.236	0.254	0.192	0.177	0.222	0.200	0.297	0.173	0.185	0.207
Regression Results	b	0.366	0.362	0.469	0.518	0.312	0.436	-0.079	-0.572	-0.403	-0.401
	ln a	1.204	1.335	1.314	1.421	1.049	1.314	0.727	1.565	1.287	1.415
	R-sqr	0.644	0.841	0.855	0.965	0.691	0.922	0.189	0.984	0.883	0.902
calc loss (kg)		3.338	3.892	2.196	1.934	3.889	2.577	21.015	1.738	2.980	3.423
calc/actual loss		0.598	0.837	0.610	1.005	0.667	0.766	4.506	0.464	1.391	0.854

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Separation weight data	x (m)										
	0.660	0.485	0.539	0.377	1.031	0.621	0.392	0.937	0.615	0.809	0.685
Calibrated sensor readings	1.321	0.278	0.312	0.268	0.374	0.374	0.302	0.432	0.538	0.514	0.511
(kg) at distance x(m).	1.880	0.218	0.204	0.268	0.341	0.303	0.303	0.325	0.409	0.341	0.409
	2.692	0.286	0.213	0.195	0.286	0.220	0.249	0.155	0.278	0.233	0.267
Regression Results	b	0.258	0.466	0.301	0.582	0.496	0.205	-0.855	-0.402	-0.618	-0.461
	ln a	1.059	1.367	1.014	1.966	1.604	0.989	2.260	1.670	1.993	1.771
	R-sqr	0.433	0.799	0.923	0.753	0.965	0.905	0.983	0.971	0.990	0.996
calc loss (kg)		5.509	2.344	4.013	2.484	2.566	7.489	1.076	4.397	2.176	3.607
calc/actual loss		1.217	0.854	0.630	0.963	0.477	1.063	0.193	0.601	0.628	0.807

		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Separation weight data	x (m)										
	0.660	0.324	0.603	0.347	0.134	0.414	0.729	0.770	0.827	0.512	0.878
Calibrated sensor readings	1.321	0.227	0.355	0.232	0.067	0.302	0.600	0.466	0.698	0.378	0.720
(kg) at distance x(m).	1.880	0.149	0.274	0.237	0.052	0.231	0.357	0.372	0.426	0.280	0.461
	2.692	0.155	0.198	0.182	0.126	0.206	0.259	0.254	0.244	0.227	0.249
Regression Results	b	0.380	0.536	0.288	0.036	0.349	0.540	-0.532	-0.625	-0.408	-0.637
	ln a	0.861	1.597	0.889	0.545	1.123	1.915	1.858	2.154	1.402	2.222
	R-sqr	0.815	0.967	0.873	0.004	0.934	0.961	0.979	0.963	0.977	0.968
calc loss (kg)		2.196	2.117	3.827	4.693	3.380	2.858	2.803	2.482	3.246	2.520
calc/actual loss		0.490	0.697	0.706	49.470	0.552	0.382	0.676	0.499	0.776	0.509

SYSTEM 2 DATA

Separation weight data	x (m)	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
	0.660	0.293	0.343	0.338	0.432	0.373	0.373	0.140	0.723	0.297	0.452
Calibrated sensor readings	1.321	0.209	0.254	0.270	0.270	0.229	0.295	0.124	0.451	0.245	0.221
(kg) at x(m) distance.	1.880	0.232	0.165	0.214	0.214	0.192	0.236	0.114	0.370	0.189	0.199
	2.692	0.135	0.121	0.165	0.165	0.191	0.193	0.096	0.194	0.154	0.148
Regression Results	b	-0.343	-0.532	-0.358	-0.466	-0.319	-0.329	-0.185	-0.628	-0.333	0.515
	ln a	1.077	1.360	1.231	1.469	1.161	1.294	0.239	2.470	1.086	1.467
	R-sqr	0.830	0.984	0.998	0.960	0.763	0.990	0.995	0.984	0.986	0.879
calc loss (kg)		3.347	1.706	3.578	2.594	4.165	4.493	4.147	2.490	3.562	2.047
calc/actual loss		0.798	0.752	0.983	0.724	0.621	0.655	6.045	0.376	1.093	0.496

Separation weight data	x (m)	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
	0.660	0.347	0.446	0.225	0.210	0.279	0.425	0.317	0.500	0.297	0.384
Calibrated sensor readings	1.321	0.237	0.345	0.205	0.180	0.184	0.266	0.254	0.299	0.262	0.258
(kg) at x(m) distance.	1.880	0.199	0.225	0.178	0.125	0.229	0.217	0.260	0.260	0.175	0.203
	2.692	0.151	0.179	0.193	0.113	0.193	0.171	0.184	0.178	0.165	0.121
Regression Results	b	-0.400	-0.468	-0.084	-0.329	-0.138	-0.436	-0.247	-0.488	-0.320	0.561
	ln a	1.235	1.576	0.606	0.734	0.783	1.427	1.095	1.635	1.078	1.491
	R-sqr	0.977	0.966	0.548	0.924	0.400	0.947	0.895	0.963	0.883	0.995
calc loss (kg)		2.868	2.855	17.296	2.573	10.843	2.889	6.129	2.756	3.828	1.703
calc/actual loss		0.515	0.614	4.806	1.337	1.859	0.859	1.314	0.735	1.788	0.421

Separation weight data	x (m)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	0.660	0.214	0.360	0.279	0.443	0.566	0.345	0.397	0.504	0.382	0.589
Calibrated sensor readings	1.321	0.252	0.258	0.240	0.276	0.433	0.264	0.258	0.417	0.240	0.400
(kg) at x(m) distance.	1.880	0.207	0.151	0.240	0.168	0.300	0.289	0.273	0.284	0.123	0.278
	2.692	0.210	0.177	0.205	0.125	0.223	0.214	0.222	0.210	0.125	0.199
Regression Results	b	-0.037	-0.383	-0.141	-0.638	-0.472	-0.208	-0.256	-0.451	-0.587	0.541
	ln a	0.624	1.207	0.881	1.632	1.825	1.125	1.227	1.721	1.399	1.880
	R-sqr	0.118	0.717	0.927	0.969	0.988	0.808	0.789	0.978	0.845	0.990
calc loss (kg)		46.063	3.053	11.579	1.395	3.595	8.378	6.619	3.607	1.381	2.751
calc/actual loss		10.175	1.102	1.818	0.541	0.689	1.189	1.187	0.493	0.399	0.615

Separation weight data	x (m)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
	0.660	0.207	0.338	0.264	0.060	0.323	0.597	0.375	0.637	0.352	0.605
Calibrated sensor readings	1.321	0.177	0.227	0.189	0.045	0.177	0.411	0.307	0.428	0.342	0.383
(kg) at x(m) distance.	1.880	0.229	0.173	0.185	0.050	0.251	0.370	0.229	0.223	0.190	0.267
	2.692	0.208	0.148	0.168	0.019	0.166	0.223	0.177	0.217	0.125	0.214
Regression Results	b	0.037	-0.406	-0.206	-0.522	-0.257	-0.466	-0.380	-0.566	-0.554	0.516
	ln a	0.430	1.187	0.800	-0.292	0.990	1.867	1.360	1.926	1.523	1.843
	R-sqr	0.089	0.941	0.804	0.781	0.503	0.972	0.989	0.866	0.912	0.956
calc loss (kg)		ERR	2.646	6.141	0.342	5.159	3.872	3.608	2.561	1.808	2.972
calc/actual loss		ERR	0.871	1.134	1.153	0.843	0.517	0.871	0.517	0.432	0.601

COMBINED SENSOR DATA

Separation weight data	x (m)	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
	0.660	0.287	0.391	0.411	0.467	0.370	0.386	0.180	0.718	0.431	0.477
Calibrated separation (kg)	1.321	0.247	0.306	0.325	0.282	0.256	0.251	0.152	0.527	0.342	0.287
from combined sensors at	1.880	0.218	0.221	0.280	0.250	0.250	0.237	0.098	0.445	0.221	0.221
distance x(m).	2.692	0.151	0.168	0.170	0.151	0.198	0.182	0.097	0.254	0.194	0.170
Regession Results	b	-0.280	-0.437	-0.377	-0.510	-0.265	-0.356	-0.606	-0.376	-0.440	-0.443
	ln a	0.874	1.290	1.299	1.466	1.027	1.229	0.486	1.857	1.389	1.395
	R-sqr	0.994	0.963	0.994	0.964	0.847	0.999	0.921	1.000	0.983	0.938
calc loss (kg)		3.976	2.510	3.449	2.095	5.099	3.623	0.510	6.063	2.730	2.702
calc/actual loss		0.947	1.106	0.948	0.589	0.760	0.528	0.743	0.916	0.837	0.655

Separation weight data	x (m)	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
	0.660	0.470	0.511	0.425	0.246	0.381	0.464	0.331	0.529	0.330	0.504
Calibrated separation (kg)	1.321	0.234	0.336	0.243	0.282	0.203	0.285	0.241	0.336	0.284	0.332
from combined sensors at	1.880	0.210	0.261	0.183	0.143	0.234	0.232	0.272	0.261	0.248	0.294
distance x(m).	2.692	0.240	0.239	0.202	0.141	0.206	0.220	0.235	0.166	0.166	0.164
Regession Results	b	-0.425	-0.540	-0.384	-0.270	-0.272	-0.434	-0.214	-0.522	-0.296	-0.513
	ln a	1.353	1.572	1.143	0.714	1.074	1.382	0.975	1.594	1.025	1.593
	R-sqr	0.905	0.976	0.712	0.990	0.874	0.952	0.997	0.984	0.947	0.951
calc loss (kg)		2.835	2.025	2.845	3.602	5.088	2.783	6.914	2.248	4.176	2.344
calc/actual loss		0.508	0.435	0.790	1.872	0.872	0.827	1.483	0.600	1.951	0.579

Separation weight data	x (m)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	0.660	0.357	0.468	0.331	0.500	0.584	0.379	0.658	0.562	0.608	0.614
Calibrated separation (kg)	1.321	0.257	0.279	0.246	0.321	0.390	0.276	0.347	0.476	0.390	0.453
from combined sensors at	1.880	0.192	0.151	0.240	0.240	0.302	0.295	0.298	0.371	0.212	0.367
distance x(m).	2.692	0.289	0.189	0.279	0.256	0.245	0.249	0.201	0.293	0.177	0.252
Regession Results	b	-0.190	-0.417	-0.228	-0.623	-0.346	-0.137	-0.585	-0.385	-0.641	-0.468
	ln a	0.891	1.265	0.913	1.555	1.497	0.935	1.719	1.640	1.753	1.758
	R-sqr	0.509	0.751	0.856	0.963	0.822	0.409	0.850	0.985	0.959	0.980
calc loss (kg)		7.598	2.712	5.848	1.375	4.995	12.733	1.912	4.649	1.550	3.434
calc/actual loss		1.687	0.978	0.918	0.533	0.929	1.808	0.342	0.636	0.448	0.769

Separation weight data	x (m)	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
	0.660	0.249	0.492	0.303	0.019	0.379	0.630	0.589	0.661	0.450	0.667
Calibrated separation (kg)	1.321	0.195	0.289	0.204	0.050	0.238	0.513	0.388	0.585	0.352	0.585
from combined sensors at	1.880	0.171	0.202	0.188	0.031	0.226	0.390	0.302	0.344	0.216	0.410
distance x(m).	2.692	0.240	0.158	0.158	0.017	0.279	0.269	0.227	0.249	0.171	0.249
Regession Results	b	-0.246	-0.567	-0.350	-0.034	-0.272	-0.389	-0.503	-0.449	-0.541	-0.439
	ln a	0.721	1.454	0.967	-1.980	1.065	1.759	1.616	1.797	1.474	1.793
	R-sqr	0.796	0.906	0.998	0.289	0.859	0.975	0.918	0.970	0.947	0.984
calc loss (kg)		4.257	1.593	2.874	3.752	5.044	5.138	2.513	3.918	1.833	4.098
calc/actual loss		0.951	0.524	0.530	12.635	0.824	0.687	0.607	0.789	0.438	0.829

TABLE C.5: CALCULATED/ACTUAL LOSS STATISTICS

a) System 1 Results

Condition	Number of runs	Mean	Std. Dev.	Degree of Confidence %
1	37	0.75	0.41	1
2	9	0.87	0.12	1
3	4	0.93	0.12	36
4	4	0.93	0.12	36
5	1	1.01	-	-

b) System 2 Results

Condition	Number of runs	Mean	Std. Dev.	Degree of Confidence %
1	37	1.08	1.12	>50
2	9	0.96	0.19	>50
3	6	0.96	0.11	45
4	4	0.95	0.11	45
5	3	0.98	0.12	>50

c) Combined Sensor Results

Condition	Number of runs	Mean	Std. Dev.	Degree of Confidence %
1	38	0.83	0.37	1
2	12	0.91	0.09	1
3	10	0.93	0.08	2
4	9	0.94	0.08	4
5	6	0.95	0.02	1